ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

ZZZ-Mate: Pulse Driven White Noise Generator

Team #20

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1 Introduction

1.1 Problem

According to the CDC, about 70 million Americans suffer from sleep deprivation. Lack of sleep causes various issues in our daily lives such as tiredness, lack of concentration, memory issues, and high blood pressure. In cases of chronic sleep deprivation, these issues can escalate to cardiovascular disease, diabetes, and depression.

White noise machines have been a widely accepted tool for masking background noise, which many people use as a sleeping aid today. There are currently various white noise machines out in the market, however, all of these devices output a single, continuous signal. According to one article[1], "the continuous background noise also known as white noise which comes from machines and other appliances, can harm your brain, it does so by overstimulating your auditory cortex." By constantly sending auditory information during the entire night, the brain is overstimulated and does not have any actual time to rest.

Another problem caused by the continuous white noise signal is prolonged exposure to dangerous levels of sound, which can lead to hearing damage.

1.2 Solution

White noise is typically beneficial during the earlier sleep stages, when people are more likely to be awoken by distracting noises or thoughts. However, rather than continuously playing background noise through the night and overstimulating the auditory cortex, our design aims to combat typical sleep deprivation issues by supporting users through all stages of their sleep cycle: wake, light sleep, deep sleep, REM, and repeat. By introducing adaptive sound levels, the user will not be exposed to dangerous decibel levels continuously, as the white noise machine will only reach its highest volume levels during REM sleep.

We will take pulse rate measurements as an indicator of the user's current sleep stage and our sound generation device will adjust the volume of the white noise. A wristband with a photosensor will be used to detect the user's heart rate and will wirelessly relay the information to the white noise generator to adjust the volume as necessary.

1.3 Visual Aid

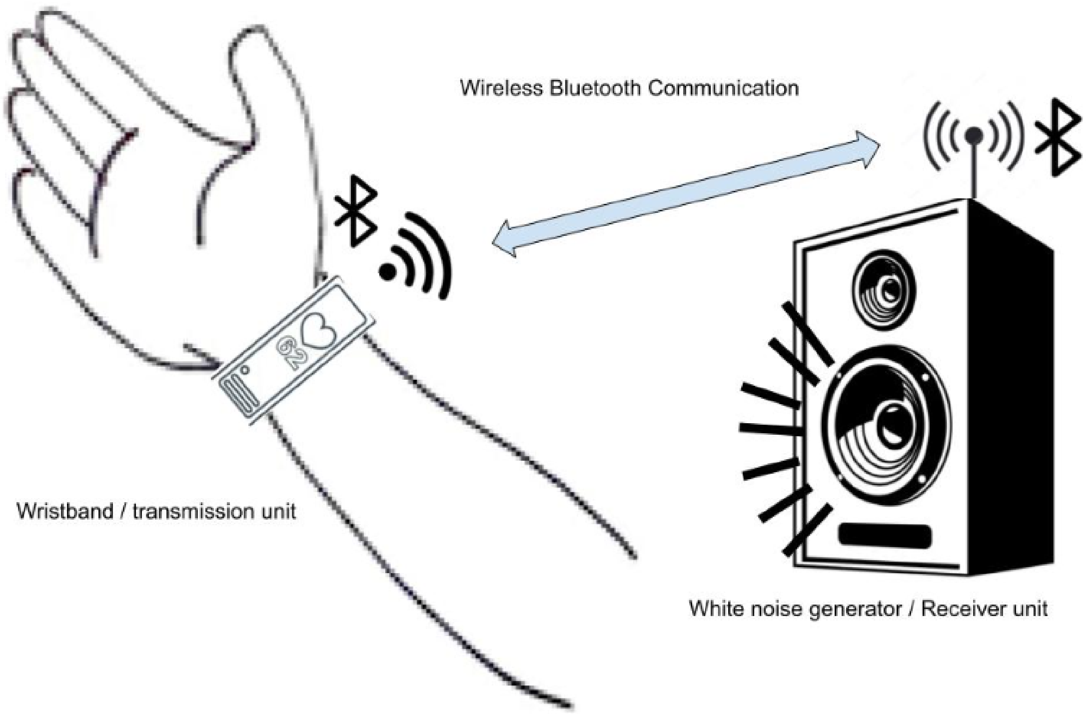

Figure 1: Visual Representation of System

1.4 High-level Requirements List

- Average heart rate measurement (BPM) measured over the course of five minutes must be within ±5% tolerance against a third party pulse measurement device (i.e. fingertip pulse sensor, Apple Watch, FitBit, etc).

- The output volume maintains a linear relationship with the user's heart rate. The output will range from 0 to 46dB with ±5dB tolerance based on the user's current sleep stage identified using their real time heart rate outlined in our Sleep Stage to Volume Reference Table (Figure 8).

- Battery life of the wristband device must be at least 7.5 hours.

2 Design

2.1 Block Diagram

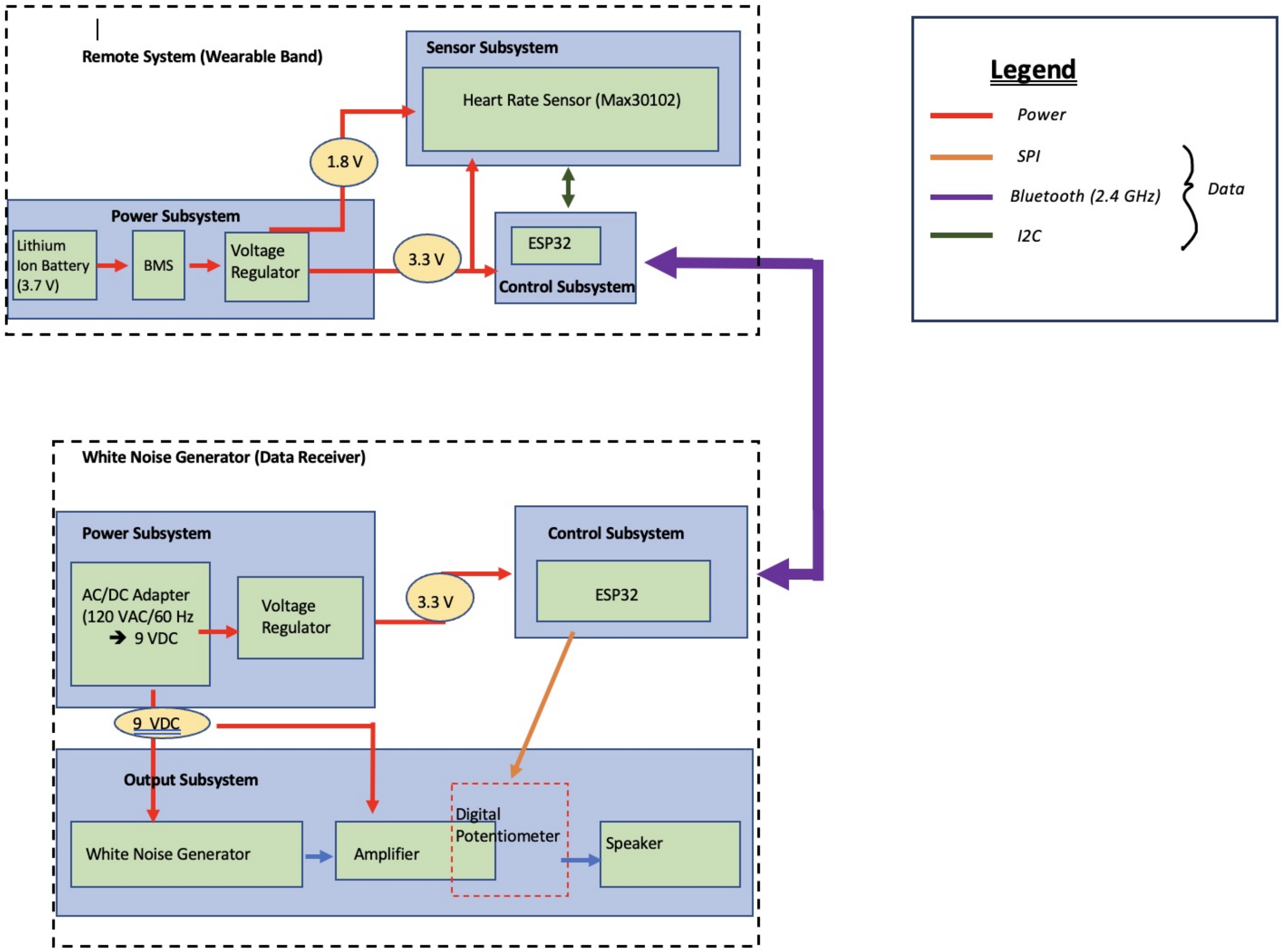

Figure 2: Block Diagram

2.2 Subsystem Overview and Requirements

2.2.1 White Noise Generator/Data Receiver

One of the two components of our system is the main white noise generator. This unit will contain one of the two microcontrollers, along with the main audio source, an amplifier, and a loudspeaker. The microcontroller will communicate wirelessly with the wearable wristband and process the provided heart rate information to determine the output audio level.

i. Power Subsystem

Overview

The main source of power to this unit will be provided via an AC to DC converter. This will be used to power the audio source as well as the power amplifier in the output subsystem. As the recommended operation condition for ESP32 microprocessor is rated for 3.3V at 500mA, a voltage regulator rated to output 3.3V at 500mA will also be incorporated to power the ESP32. The power amplifier system will dissipate at most 1.25W (per LM386 manual). Since the supply voltage will be rated for 9v, this will consume about 138mA (1.25/9). Summing all of these components, a supply current of 800mA will suffice the safe operational requirement of the overall system.

Requirements

Requirements	Verifications
1. Main 9V power net is supplying appropriate voltage and current when hooked up to the load.	a. Connect the load under the supply b. Probe across the power net and ground with voltmeter to verify the voltage reading of 9±0.3V c. Place an ammeter in series with the voltage supply and the load. Verify that at least 800±50mA of current is being supplied to the load
2. Regulated voltage net used for MPU power supply is outputting proper voltage and current level for ESP32's recommended operational condition.	a. Probe across the 3.3V net (voltage regulator output) and ground with voltmeter to verify the proper voltage level of 3.3 ±0.2V b. Place an ammeter in series with the net and load and verify that the supplied current is at 500mA ±50mA

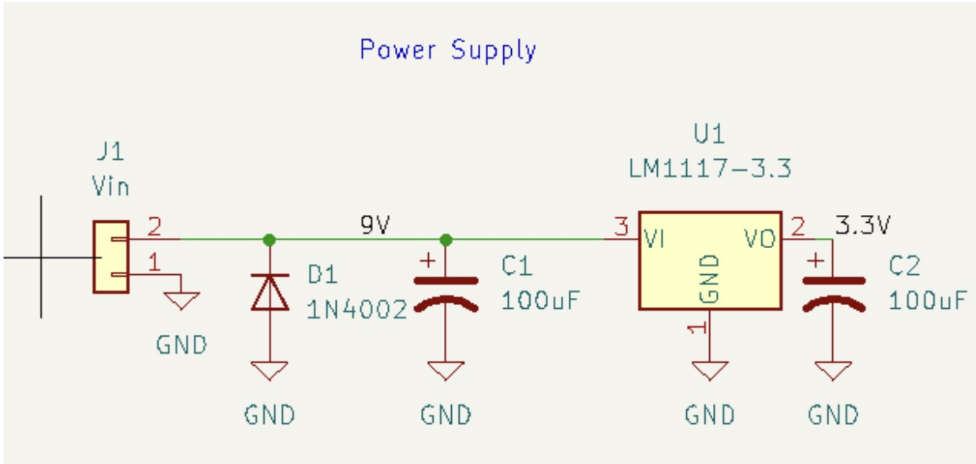

Figure 3: Power Supply Schematic

ii. Control Subsystem

Overview

This is the main interface of the entire system, where the ESP32 microcontroller will be utilized to receive the heart rate data from the wristband and apply appropriate change to the output noise level. Communication between the paired microcontrollers will be performed wirelessly via Bluetooth at 2.4GHz. The microcontroller will also be responsible for adjusting the output volume with the utilization of digital potentiometer via SPI communications.

Requirements

Requirements	Verifications
1. WNG ESP32 can successfully send data to the digital potentiometer through SPI protocol	a. Confirmation is outputted onto the screen after decibel range transmission is completed i. Through SPI protocol, the host will receive a descriptor confirming the completion of the data transmission b. Using ohmmeter verify the proper change in resistance of wiper to ground connection
2. WNG ESP32 can successfully receive data wirelessly from the WB ESP32 chip via Bluetooth.	a. Confirmation of heart rate data reception by WNG ESP32 through Bluetooth is outputted onto the screen

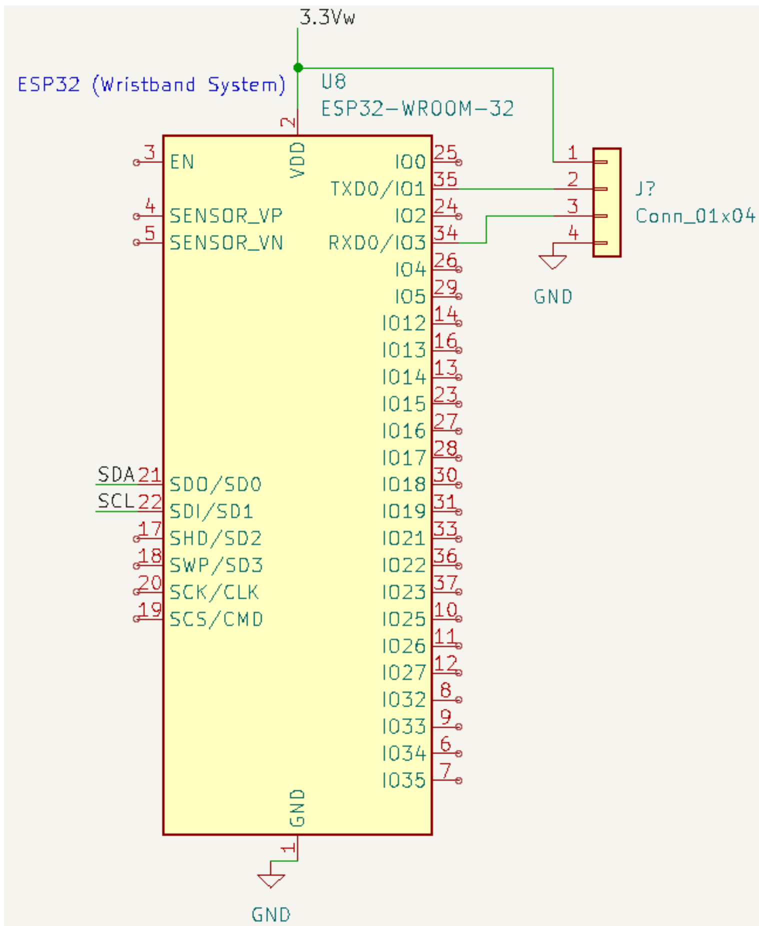

Figure 4: Primary microcontroller schematics

iii. Output Subsystem

Overview

This subsystem is responsible for generating the white noise and amplifying the signal up to an audible level for it to be outputted by a loudspeaker. The white noise generation circuit will be constructed with a general purpose NPN BJT transistor and a single opamp. The power amplifier section will be built around the LM386 audio power amplifier chip. This portion of the output system will interact with the control system to allow for a varying output level using digital potentiometer.

Requirements

Requirements	Verifications
1. Speaker output system has a range of 0-46 dB ± (as per the linear decibel relationship implemented)	a. Verify ambient noise level in decibels with decibel meter (with WNG speaker turned off). Decibel meter should be placed one foot away from the speaker for measurement taking. b. Verify noise level of testing environment in decibels with decibel meter. Verify that the maximum decibel level is 46 dB ± 5 dB. Decibel meter should be placed one foot away from the speaker for measurement taking.
2. Digital potentiometer properly responds to SPI protocol sent by WNG ESP32	a. Verify the change in the wiper position using ohmmeter as prompted by ESP32 b. Verify the change in the output volume

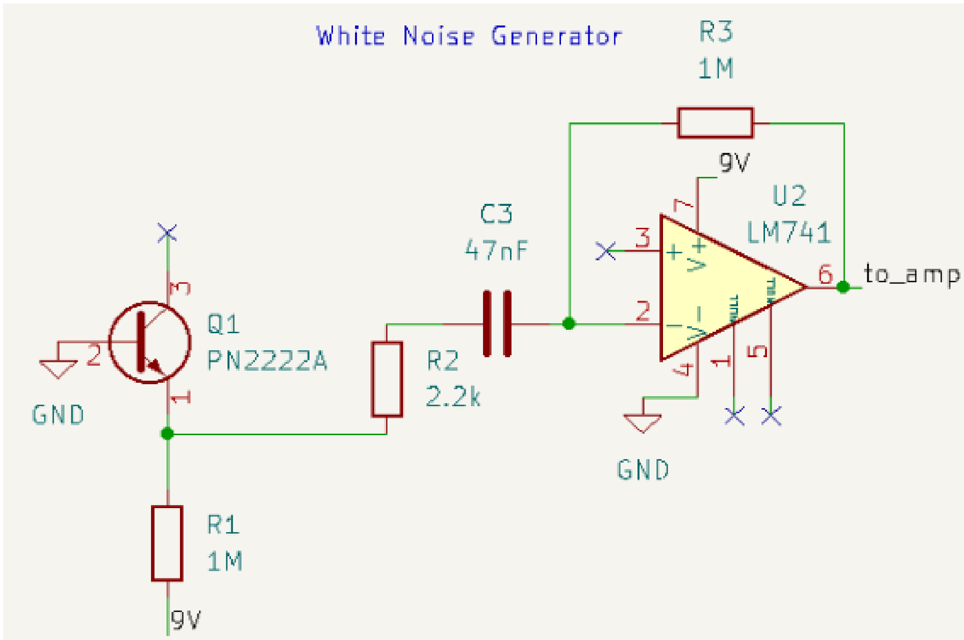

Figure 5: White noise generator schematics

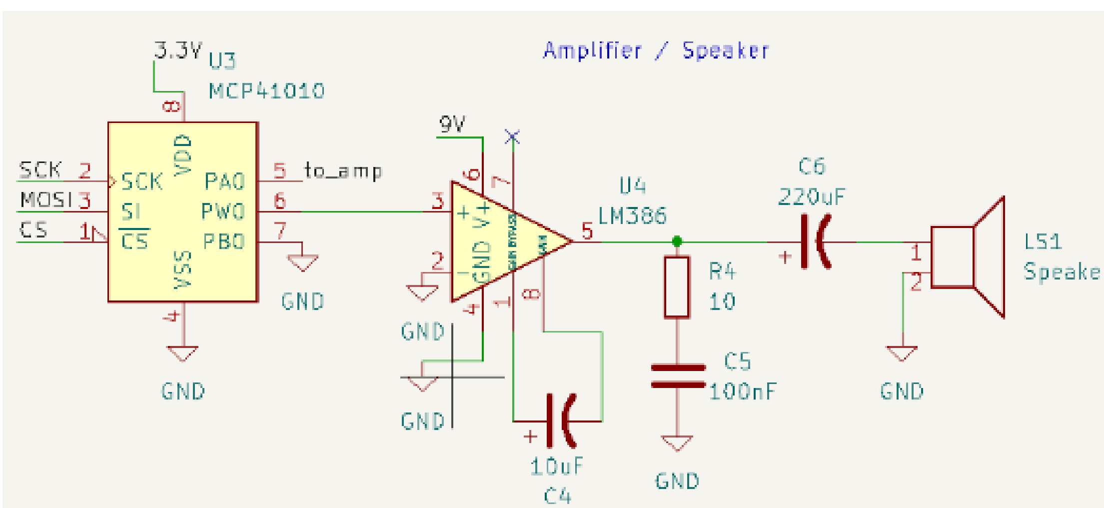

Figure 6: Amplifier/speaker unit schematics

2.2.2 Wearable Band

The other major system of the ZZZ-Mate system is the wearable wristband. This device will be worn around the user's wrist to track the heart rate and transmit the collected data to the microprocessor in the white noise generator. The heart rate sensor will be utilized for data collection.

i. Power Subsystem

Overview

The main source of power for this unit will come from a lithium ion battery. A battery management system using AP9101, or a related chip, will be utilized for protection by detecting overcharge/overdischarge of voltage and current. As the ESP32 is recommended to be operated under 3.3V at 500mA, a voltage regulator will again be used to achieve the appropriate level. The MAX30102 heart rate sensor will also require a 3.3V source for LED, along with 1.8V for operating voltage. The MAX30102 manual specifies that the maximum supply current is rated at 1200 uA, along with LED current rated at 50mA. Summing all of these components, a supply current of 700mA will suffice the safe operational requirement of the overall system.

Requirements

Requirements	Verifications
1. Regulated voltage net used for MPU and LED power supply is outputting proper voltage and current level for its recommended operational condition.	a. Probe across the 3.3V net (voltage regulator output) and ground with voltmeter to verify the proper voltage level of 3.3 ±0.2V b. Place an ammeter in series with the net and load and verify that the supplied current is at 550mA ±50mA
2. Regulated voltage net used for heart rate sensor power supply is outputting proper voltage and current level	a. Probe across the 1.8V net (voltage regulator output) and ground with voltmeter to verify the proper voltage level of 1.8 ±0.2V b. Place an ammeter in series with the net and load and verify that the supplied current is below 100mA
3. Measured temperature outside of the enclosure is below safe level	a. Measure the external temperature using a thermometer heat gun. Verify that the measured temperature is below 20°C.

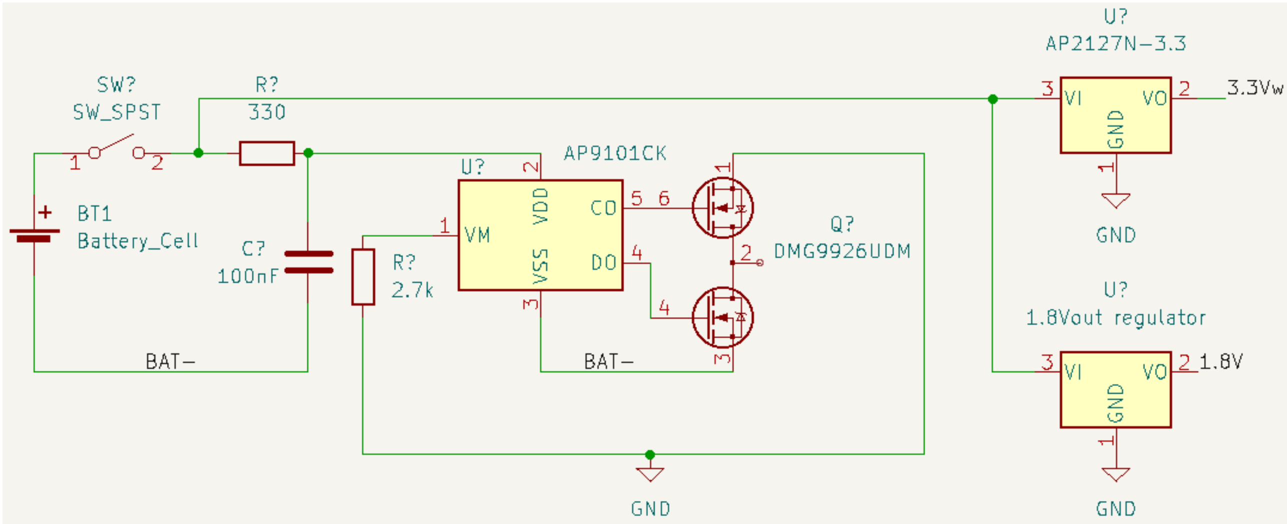

Figure 7: Power subsystem with BMS schematics

ii. Control Subsystem

Overview

This is the interfacing portion of the wristband portion. Using I2C communication, The ESP32 microprocessor will receive data from the heart rate sensor and transmit the information wirelessly to the noise generator/receiver unit.

Requirements

Requirements	Verifications
1. WB ESP32 can successfully send data wirelessly to the WNG ESP32 chip via Bluetooth	a. Confirmation of heart rate data transmission by WB ESP32 through Bluetooth is outputted to screen
2. WB ESP32 can successfully receive data from the heart rate sensor (MAX30102) through the I2C protocol	a. Confirmation of heart rate data reception by WB ESP32 is outputted to screen after I2C master provides the ACK bit
3. WB ESP32 and WNG ESP32 are properly programmed to determine the user's current sleep stage	a. Program ESP32s to output the heart rate data, sleep stage, and chosen decibel range to the screen and compare values against the Sleep Stage to Volume Reference table to check for accuracy

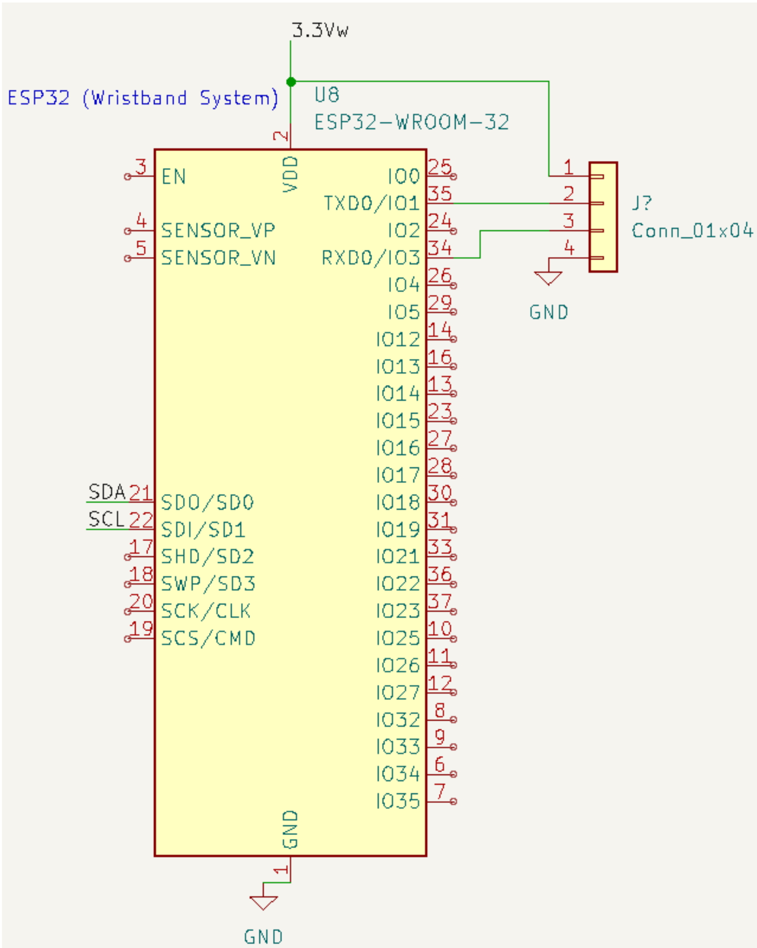

Figure 8: Secondary microprocessor schematics

iii. Sensor Subsystem

Overview

This is the main sensor module to be used to collect the heart rate information. MAX30102 oximeter sensor module will be used for this application to collect the data. The embedded LED will be emitted through the users' skin, and photodetector will measure the blood's absorbance of such lights. The MAX30102 module requires 3.3V and 1.8V for both chip power supply and LED. These will be provided through two voltage regulators and will be verified as discussed previously

Requirements

Requirements	Verifications
1. Measured heart rate within 5% tolerance when compared against a third party pulse measurement device	a. Attach the sensor module on a subject's arm along with another pulse sensing device (i.e. Apple Watch) or alternatively by taking a pulse with finger tip b. Subject will be timed to rest for five minutes c. Compare the measured results between the two devices

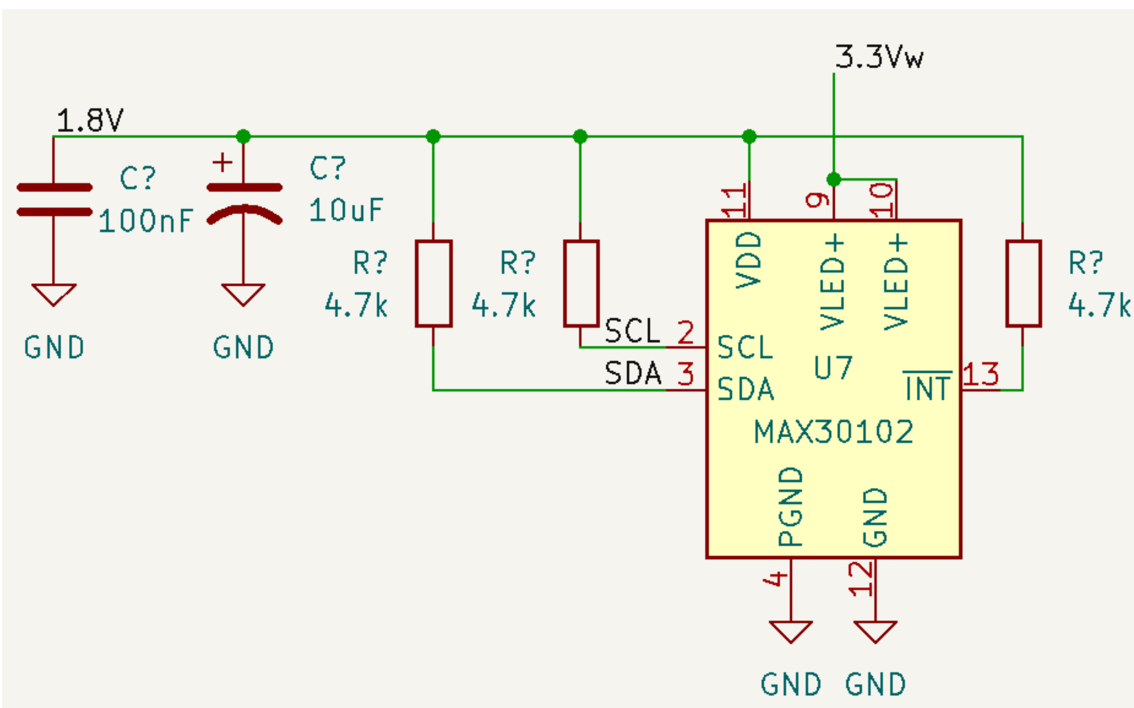

Figure 9: Heart rate sensor schematics

2.3 Tolerance Analysis

The most crucial bottleneck to this project derives from the fact that everyone has different resting and sleeping heart rates. Determination of the sleep stages is also very vague and arbitrary. To compensate for these differences, we calculated each sleep stage to be associated with a heart rate range personalized for the user's baseline resting heart rate.

Based on studies conducted by the Bio-Medical Engineering Laboratory in the Electrical Engineering Department at the University of Texas in Austin, the average decrease in heart rate between each sleep stage from wake to deep sleep is measured to be around 10% (around 5-7 bpm). When the individual enters the REM stage their heart rate increases again until it is similar to the individual's resting heart rate and the cycle starts over.

We are able to divide a subject's sleep cycle into five distinct categories, each associated with a specific range of heart rates. We do this by first establishing the subject's baseline heart rate using the following equation, where m represents the number of buffer lengths being used, n represents the maximum number of samples that can be stored represented in one buffer length (16 with the MAX30100), and x represents each measured heart rate (in bpm).

$$Baseline\ Heart\ Rate\ (BHR) = \frac{1}{mn}\sum_{i=1}^{mn} x_i \quad where\ m = 2$$

After the BHR is calculated, we are able to calculate the starting range value for the REM/Wake stage (Stage 1) by obtaining the lower floor value when dividing by 5. The upper end of the range is calculated by adding 5 to the HRF value, and the subsequent stage calculations are demonstrated in Figure 9.

$$Heart\ Rate\ Floor\ (HRF) = ((int)\,\frac{BHR}{5}\,) \times 5$$

To identify which stage the subject is currently in, and which volume range to set the white noise generator at as a result, a current heart rate is continuously calculated every time the FIFO buffer is filled up (every 16 measured heart rate values). The algorithm will then use the established heart ranges calculated using the BHR to identify which sleep stage the CHR falls into, and set the volume range to the appropriate dB range, as demonstrated in the Figure 9.

$$Current\ Heart\ Rate\ (CHR) = \frac{1}{mn}\sum_{i=1}^{mn} x_i \quad where\ m = 1$$

Volume Range (dB)	Sleep Stage	Heart Rate Range (bpm)
≈ 46	REM/Wake (1)	HRF – (HRF + 5)
$\approx 29 - 45$	REM/Wake or N1/N2 (1.5)	(HRF - 5) – (HRF)
$\approx 14 - 29$	N1/N2 (2)	(HRF - 10) – (HRF - 5)
$\approx 0 - 14$	N1/N2 or Deep Sleep (2.5)	(HRF - 15) – (HRF - 10)
≈ 0	Deep Sleep (3)	(HRF - 20) – (HRF - 15)

Figure 10: Sleep Stage-to-Volume Reference Table

To account for discrepancies in the heart rate sensor's readings as well as the subject's actual heart rate cycles during sleep, we included intermediate sleep stages (Stages 1.5 and 2.5), where it is harder to pinpoint what stage exactly the subject may currently be in. Having an intermediate volume range in between stages helps create a more gradual change in volume.

Output volume range can now be assigned to these heart rate ranges. This will be done by dividing up the minimum and maximum output level of the speaker system. The implemented power amplifier will follow the provided schematic in TI's datasheet for LM386 [2] to achieve a gain of 200. This gain is then verified with the following equation:

$$A_v = \frac{V_{OUT}}{V_{IN}}$$

Decibel change could then be calculated using the following equation:

$$dB = 20\,log_{10}\,(A_v)$$
$$dB = 20\,log_{10}\,(200)$$
$$\approx 46$$

If we assign the output volume to be minimum at heart rate of 60bpm and maximum at the heart rate of 75, we could assign the following:

$$\Delta dB \;\; per \;\; bpm = dB \;\; range/(Max \;\; bpm - min \;\; bpm)$$
$$= 46 \;\; dB/(75 \;\; bpm - 60 \;\; bpm)$$
$$\approx 3\,dB \;\; per \;\; bpm$$

Therefore, volume range should change approximately by 15dB per each sleep stage (3dB/bpm * 5bpm). The tolerance of ±5dB will be applied to this.

3 Cost and Schedule

3.1 Cost Analysis

The cost breakdown of our design will be made up of our labor wages and electronic parts. Based on the average starting salaries for ECE graduates from UIUC, we calculated our wages to be $35/hour and we estimate our workload for this project to be an average of ten hours a week for the next ten weeks until our final demo.

3.1.1 Labor

$$Cost_{labor} = \$/hour \times 2.5 \times hours/week \times number\,of\,weeks \times team\,members$$

$$Cost_{labor} = \$35/hour \times 2.5 \times 10\ hours/week \times 10\ weeks \times 3 = \textbf{\$26,250}$$

3.1.2 Electronic Parts

Part	Cost (x Quantity)
Microcontroller (WROOM 32 ESP32)	$5.98 x 5 = $29.99
Battery Holder (to fit OR/LIR2450)	$0.625 x 10 = $6.25
Battery (LIR 2450)	$4.48 x 4 = $17.99
Speaker (Visaton R10S)	$21.44
Heart Rate Sensor (MAX30100)	$6.87
Voltage Regulator (LD1117)	$0.84 x 5 = $4.20
Digital Potentiometer (MCP4131)	$0.96 x 3 = $2.88

Figure 11: Total Cost of Electronic Parts

$$Electronic\ \ Parts = \$89.62$$

3.1.3 Total

$$Grand\ \ Total\ \ Cost = \textbf{\$26,339.62}$$

3.2 Schedule

Week	Task	Sanjana	Haruya	Vakaris
September 18 - 24	Design doc initialization Order parts	Design doc (Collect heart rate data samples, heart rate/sleep stage connection algorithm)	Design doc (subsystem requirement fix, physical design)	Design (Design and ethics) Research heart rate / sleep stages
September 25 - October 1	9/26 Design Document Check 9/29 Design Document Submission 9/30 Soldering Assignment due	- Collect heart rate data during sleep - Start developing heart rate monitoring algorithm to identify sleep stages - Set up ESP-IDF	- Circuit schematic design - PCB design - Breadboard the circuit - Design doc	Design doc PCB Design
October 2 - October 8	Design Review 10/4 PCB Board Review	- Finish developing heart rate monitoring algorithm - Test ESP-IDF with physical ESP32	- Further testing with acquired components - Tolerance test for the components	- Enclosure design - Tolerance test for the components
October 9 - October 15	10/11 PCB order 10/12 Teamwork Evaluation	- Research/Understand ESP-IDF + bluetooth interface - Evaluate partners	- Evaluate partners - Digi-pot implementation	Evaluate partners

Figure 12: Group Work Schedule

October 16 - October 22	- Work on subsystems	- Translate algorithm into Python code to use in ESP-IDF	- ESP assistant - PCB design - interface - Test correlation between heart rate and device output	- Test correlation between heart rate and device output
October 23 - October 29	- Test and refine subsystems	- Wifi interface - Test correlation between heart rate and device output	- ESP assistant - PCB design	- Test correlation between heart rate and device output
October 30 - November 5	10/31 Second Round PCB Order 11/1 Individual Progress Reports	- Work on Bluetooth connection - Refine algorithm - Progress report	- Order PCB - Progress report - Meetup with Machine shop for enclosure	- Progress report
November 6 - November 12	- Prepare for mock demo	- Prepare for mock demo	- Prepare for mock demo	- Prepare for mock demo
November 13 - November 19	Mock demo	- Prepare for mock demo	- Prepare for mock demo	- Prepare for mock demo
November 20 - November 26	Revision, further testing, etc	- Final Demo Preparation	- Final Demo Preparation	- Final Demo Preparation
November 27 - Dec 3	Final Demo	- Final Paper	- Final Paper	- Final Paper
Dec 4 - 9	Final Presentation Dec 7 - Final Papers due Dec 8 - Lab Notebooks due, Final Peer Evaluation	Party Teamwork Evaluation	- Teamwork Evaluation - party	Party Teamwork Evaluation

Figure 13: Group Work Schedule Cont.

4 Ethics and Safety

4.1 Ethics and Safety

4.1.1 Ethics and Safety

Our team will strive to uphold the standards of ethics and safety outlined by IEEE and will take precautions ”to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices.” [3] The overall design of ZZZ-Mate will be constructed upon a relatively low voltage and power level, minimizing the potential physical hazard. In terms of circuit protection, various components will be added, such as a reverse polarity protection diode for the main DC source in the noise generator unit. Another concern for potential physical hazard includes the wristband device, whose circuitry could be harmful if any external contents come into contact with the PCB. The PCB can be encased in a housing to prevent any damage to the device, as well as protect the user. The PCB will be encased in a housing to prevent any circuitry exposure, to protect the user as well as the device. As the voltage regulators will be emitting dangerous temperatures when stepping down the voltage, temperature is a serious concern with regards to the safety of the user. By taking the mounting style of the PCB into account, sufficient clearance will be provided for the voltage regulators. The enclosure for the wristband system will be sourced with temperature and burn ratings in mind.

Another potential hazard for the ZZZ-Mate is the audio level of the white noise generator. Since the user will be exposed to speaker sounds for a prolonged period of time, these decibel levels cannot exceed dangerous levels. According to the CDC, volume above 70 dB for a prolonged period of time, or above 120 db for any amount of time is harmful for hearing, and according to our design. [4] To uphold the safety standards of the IEEE we will make sure the maximum volume capabilities are limited to safe levels in time and volume.

4.1.2 Data Privacy

Our design includes collection of personal health data in the form of the user’s continuous heart rate throughout the night. This information is very sensitive as it could also be used to calculate a person’s heart rate variability (HRV), which has been known to be used to identify a variety of diseases affecting the heart, lungs, and mental health. [5] In addition to ensuring that the data is only used to calculate the appropriate volume of our white noise generator, we are responsible for protecting the data and its owner’s privacy. According to the ACM code of conduct, we must take “precautions to prevent re-identification of anonymized data or unauthorized data collection, ensuring the accuracy of data, understanding the provenance of the data, and protecting it from unauthorized access and accidental disclosure.” [6] We will take extra precautions not to attach any identifying information to a user’s heart rate data and make sure that the data is not being accessed by any outside entities.

References

[1] T. Abdulgafar. “”How Background Noise is Secretly Killing You”.” (2021), [Online]. Available: https://krisp.ai/blog/background-noise-impact/ (visited on 09/15/2022).

[2] T. Instruments. “”LM386 Low Voltage Audio Power Amplifier”.” (2004), [Online]. Available: https://www.ti.com/lit/ds/symlink/lm386.pdf (visited on 09/15/2022).

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[4] N. C. for Environmental Health. “”What Noise Causes Hearing Loss?”” (2019), [Online]. Available: https://www.cdc.gov/nceh/hearing_loss/what_noises_cause_hearing_loss.html (visited on 09/15/2022).

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[6] A. for Computing Machinery. “”ACM Code of Ethics and Professional Conduct”.” (2018), [Online]. Available: https://www.acm.org/code-of-ethics (visited on 09/15/2022).