ECE 445

Senior Design Laboratory

Design Document

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Ambient Lighting System

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Team 41

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1 Introduction

1.1 Problem

In many environments, the ambiance is heavily influenced by lighting, which often requires manual adjustment to match the mood of the space. This can be inconvenient and limits personalization. What if we had a system that could track how you are feeling and adjust the lighting system accordingly? We propose an individual lighting experience that acts as a dynamic lighting system, reacting to sound and heart rate to provide a personalized, immersive environment. This system would eliminate the need for manual intervention, offering a more cohesive ambiance that changes based on both noise and the user's emotional state.

For example, if a user is watching an action movie or playing music, the system will synchronize lighting with the intensity of the scene or sound. In addition, the system adjusts the brightness based on the user's heart rate, creating a unique experience tailored to their mood and activity.

1.2 Solution

Our project proposes the development of an intelligent lighting system that connects LED strips, which can be placed behind a TV, painting, or near a speaker. The system automatically synchronizes with the background noise of the user's activity, while also adjusting intensity based on the user's heart rate. This enhances the user experience by providing adaptive lighting that is highly personal and responsive.

At a high level, we have an audio system that collects background audio and sends signals to change the color of the LED strip. Additionally, a heart monitor system connects to the circuit via Bluetooth and sends signals to adjust the intensity of the LED strip—brighter for higher heart rates and dimmer for lower heart rates.

1.3 Visual Aid

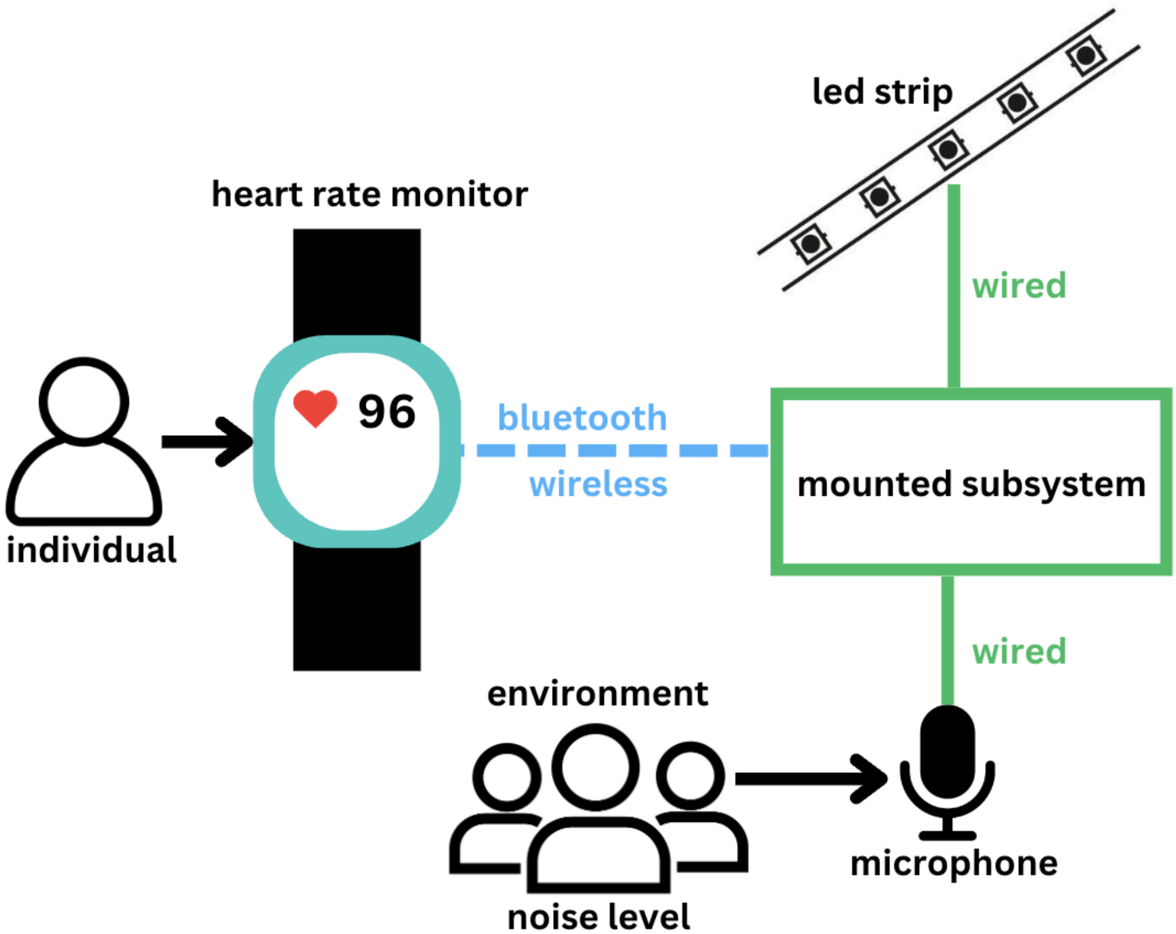

Figure 1: Visual Aid

1.4 High-Level Requirements

- The system must detect and respond to changes in noise levels, adjusting the LED color within 50ms.
- The heart rate monitor must accurately transmit data, allowing for brightness adjustments within 100ms of detecting a change in heart rate.
- The LED strip must support a full range of 10 colors and brightness levels from 200 lumens to 450 lumens, allowing for highly customizable lighting experiences based on sound and heart rate.

2 Design

2.1 Block Diagram

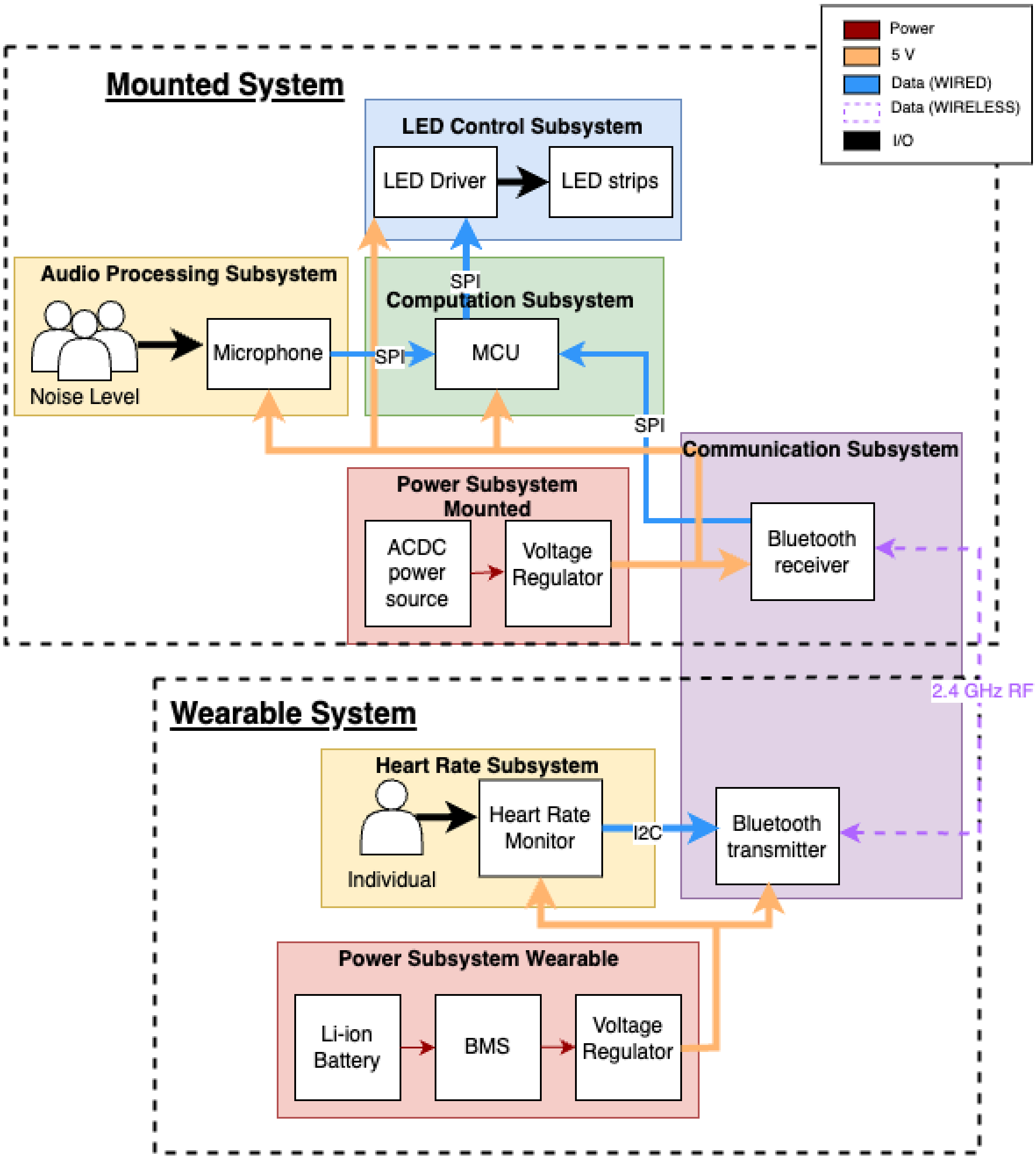

Figure 2: Block Diagram

2.2 Audio Processing Subsystem

This subsystem captures and processes audio input to detect noise levels and changes in frequency. Using a MEMS microphone, it converts sound waves into electrical signals. These signals are processed by the MCU using algorithms like Fast Fourier Transform (FFT) or amplitude-based analysis to interpret noise levels and frequency variations. This data is crucial for adjusting the LED colors, allowing the system to respond to the surrounding audio environment dynamically.

This subsystem interfaces directly with the MCU, providing audio data that influences the LED Control System for color adjustments. The power subsystem directly supplies power to the microphone. The audio processing system isn't influenced by the communication subsystem, the wearable subsystem, or the heart rate subsystem and it has no direct interaction with it.

- This subsystem is responsible for capturing the audio input to the LED control system. The MEMS microphone converts the sound waves into electrical signals that can be analyzed. The amplitude-based analysis is used to determine the beat and noise level of the music which will be sent to the LED system and change the colors and brightness.
- This subsystem is important because always the LED changes based on surrounding sound and without it there would be no detection of sound level which leads to failure to change the color which is a high-level requirement.
- Interfaces with Other Subsystems:
  - Microphone to MCU
    - The microphone will receive the analog sound input and convert it to be sent to the MCU. The MCU must receive signals within a voltage range 0-3.3V.
  - Audio Data to LED
    - The data must be updated every 150 ms to ensure synchronization of the LED's behavior to the audio input being sent.
- List of Requirements

Requirement	Verification
Power must be supplied to the microphone of 1.8-3.3V.	1. Connect a multimeter to the power source and the microphone to measure the voltage. 2. Turn on the power source and measure the supplied voltage with the multimeter. 3. Verify that the measured voltage is consistently within the 1.8-3.3V

	range. 4. Subject the microphone to different operational conditions (e.g., different temperatures, loads) and measure the voltage again.
The microphone must be able to capture audio data within 20 dB of the actual sound to ensure an accurate representation of the environment or video. Without this, the LED response will not be accurate and reflect the real audio.	1. Prepare a calibrated sound meter to generate known sound levels. 2. Produce sounds at different decibel levels (e.g., 60dB, 80dB, 100dB) near the microphone. 3. Measure the output from the microphone using the reference sound meter. 4. Check if the microphone captures audio within ±20dB of the actual sound level generated.

2.3 Heart Rate Monitoring Subsystem

This subsystem collects heart rate data using the pulse oximeter and sends it to the MCU via a Bluetooth module. The MCU then uses this information to regulate the intensity of the LED strip, adjusting brightness in real-time. The heart rate data ensures that the system can react to physiological changes, creating an interactive lighting effect based on the user's heart rate.

This subsystem transmits heart rate data to the MCU, which combines it with audio data to adjust the brightness of the LED lights. It will also receive power to the heart rate monitor from the power subsystem.

- The heart rate sensor must provide accurate data within ±10 BPM.
  - If heart rate data was not accurate, the reaction of the lights would not be proportional to the reaction that the user is experiencing.
- Heart rate data should be transmitted to the MCU via Bluetooth within 150 ms of measurement.
  - Brightness should adjust proportionally to heart rate changes.
  - Something to note is that the MCU is also connected to the rest of the mounted system(shown in the block diagram above)
  - If the data isn't transmitted within that time frame, the reaction will be delayed and the lights will not align with the movie or the heart rate.

- Brightness should adjust proportionally to heart rate changes. For every 10 BPM change, there should be a 10% change in brightness.
  - The entire point is for there to be a reaction to the heart rate, so if there is no change, the heart rate does not contribute to the user experience.
- List of Requirements:

Requirement	Verification
Power has to be supplied to the heart monitor or else the heart monitor would stop working.	1. Connect the heart rate monitor to its power source. 2. Connect the multimeter probes to the power supply terminals of the heart rate monitor. 3. Turn on the power supply and record the voltage across the heart rate monitor's power source. 4. Ensure that the voltage reading is within the acceptable 5V input range. 5. If the voltage is within 5V, the test passes. If not, troubleshoot the power delivery system.
The bluetooth transmitter also has to work for seamless wireless data transfer to the bluetooth receiver in the mounted subsystem, or else we cannot analyze the data to provide a proper output.	1. Ensure the heart rate monitor is transmitting data to the Bluetooth transmitter. 2. Initiate a data transmission from the heart rate monitor to the Bluetooth receiver and start the timer. 3. Measure the time it takes for the data to be received on the mounted subsystem. 4. Ensure that the data transmission time is within the 150ms range. 5. If the data transmission occurs within 150ms, the test passes. If it exceeds 150ms, investigate possible transmission delays or interference.

Heart rate monitor must work and not be faulty to ensure that correct data is transferred	1. Use a reference heart rate monitor (e.g., Apple Watch) known for accuracy, and place it alongside the heart rate monitor being tested. 2. Record the heart rate readings from both the reference monitor and the test monitor. 3. Compare the readings to ensure the heart rate monitor being tested is within a 10 bpm accuracy range of the reference monitor. 4. Ensure that the test monitor provides accurate readings across a heart rate range of 60 bpm to 150 bpm. 5. If the heart rate monitor is consistently within 10 bpm across the entire range, the test passes. If not, the heart rate monitor may be faulty or require recalibration.

2.4 LED Control Subsystem

It manages the color and brightness of the LED strips. The LED driver receives control signals from the MCU, which processes both the audio input and heart rate data. Pulse Width Modulation (PWM) is used to control the brightness, based on heart rate, while color changes are driven by the audio analysis. This allows for fine-tuned, real-time control over the LED display, making it responsive to both environmental sounds and physiological signals.

This subsystem is controlled by the MCU, which uses data from both the Audio Processing and Heart Rate Monitor subsystems to adjust the LED lights. The LED driver will also receive power from the voltage regulator in the power subsystem.

- The LED control system adjusts both the color and brightness of the LED strip depending on the output from the MCU
- The components are LED drivers and the actual LED strip
- List of Requirements

Requirement	Verification

Must be able to change the LEDS over 20 different colors. If the colors don’t change, the LEDs don’t have any effect on the user or the user's experience.	1. Ensure that the LED strip is powered and connected to the control system. 2. Run a color change cycle to transition through at least 10 different colors. 3. Observe the LED strip and manually verify that the color transitions occur smoothly through at least 10 distinct hues. 4. Continue the color cycle and check that the LED strip can display over 20 different colors as required.
The LEDs must be able to pulse a maximum 120 beats per minute. If the LEDs don’t pulse, then the user won't be able to experience the sync of whatever they are watching to the LEDs	1. Configure the LED control system to pulse the lights at varying speeds up to 120 beats per minute. 2. Position a light sensor to accurately measure the pulse rate of the LEDs. 3. Record the actual pulse rate of the LEDs using the light sensor to ensure it matches the expected rate. 4. Ensure that the measured pulse rate is within a 20 bpm tolerance of the target 120 bpm rate. 5. Visually observe the LED pulse to ensure that the color transition and pulsing effect is smooth and consistent across the range of 120 bpm.

2.5 Power Management Subsystem (Mounted)

This subsystem converts the incoming 120V AC power supply into a stable 5V DC output, which is used by the mounted subsystems, including the MCU, LED control system, and audio processing system. It ensures that all components receive the appropriate voltage and current to function correctly without overloading or damaging the system. This subsystem is crucial for the continuous operation of the system, as power instability would disrupt the functionality of the entire setup.

The mounted power management system powers the MCU, the LED Control System, the Audio Processing subsystem, and the bluetooth receiver, which is part of the communication subsystem with a constant 5 V output and up to 100mA of current. It does not interact with the wearable power management subsystem, the heart rate monitor, or the transmitter part of the communication subsystem.

- This subsystem is required to power the LED Driver, the MCU, and the Audio processing unit. It provides a steady output of 5V to power all of these subsystems to ensure proper functionality. The subsystem consists of an AC/DC converter, since this will be plugged into a wall outlet, and a voltage regulator to output the 5V.
- List of Requirements

Required	Verification
Must be able to accurately convert the AC 120V input to a more usable 5V output for various other mounted subsystems. If there is no power, or it is too high of a voltage, then the system won't be able to operate or the parts will burn out.	1. Safely connect the oscilloscope probes to the output terminals of the power conversion circuit that converts the AC 120V input to 5V output. 2. Ensure all connections are secure and insulated to prevent electrical hazards. 3. Turn on the AC power source supplying 120V to the conversion circuit. 4. Ensure the system is powered correctly and all safety measures are in place. 5. Set the oscilloscope to the appropriate settings to measure DC voltage.

2.6 Power Management Subsystem (Wearable)

The wearable power management subsystem powers the heart rate monitoring subsystem, ensuring that the heart rate sensor and Bluetooth transmitter have enough power to function correctly. It manages the battery to prevent it from drawing more than 500mA of current, extending battery life and enabling uninterrupted use. If the wearable power management fails, the heart rate monitor would lose power, leading to a loss of synchronization between the heart rate and the lighting system.

The wearable power management system directly powers the heart rate system and the transmitter part of the communication subsystem. It does not interact directly with any other subsystem.

- This subsystem will power the bluetooth transmitter and the heart rate monitor. It consists of a 5V battery, a battery management system, and a voltage regulator. It will output a consistent 5V to all of the other subsystems.
- If this subsystem fails, then the bluetooth and heart rate monitor won't operate as expected.
- List of Requirements

Requirements	Verification
Must not draw more than 500mA of current to preserve battery life.	1. Connect a multimeter to the power source to test how much current is being drawn. 2. Measure the current drawn to the entire subsystem using a multimeter in series with a power supply. Ensure that this current does not exceed 500mA.
If the battery dies, then the fundamental part of the entire system (heart rate monitor) doesn't contribute to the user experience.	1. Monitor battery life before performing any tests and ensure it provides a consistent 5V.

2.7 Communication Subsystem

This subsystem allows for communication between the wearable heart rate monitor and the mounted system, which has the MCU and does all the computation. This subsystem consists of a bluetooth transmitter and a bluetooth receiver.

The communication subsystem takes the data from the heart rate monitor and communicates that with the MCU in the mounted subsystem. It gets power from the wearable power subsystem. This subsystem does not directly interact with the mounted power subsystem, the LED driver, or the audio processing subsystem.

- This subsystem is used for the bluetooth transmitter and receiver. It connects the wearable system to the mounted system via wireless connection. It requires 5V to be powered
- If this subsystem fails, then the heart rate monitor's data will not properly be sent to the mounted system
- List of Requirements

Requirements	Verification
Must work within a range of 10 meters	1. Set up markers at three different distances from the Bluetooth receiver. 2. Test within different intervals (2m, 5m, 10m) to ensure that the data is transmitted properly
The Bluetooth transmitter should successfully pair with the receiver	1. Ensure both the Bluetooth transmitter (from the wearable system) and receiver (mounted system) are powered on and within the specified range for connectivity. 2. Ensure that any necessary pairing codes or confirmations are provided as required. 3. Observe the connection status on both the transmitter and receiver displays or software interfaces. 4. If disconnections occur, troubleshoot the issue by examining the environment (interference, distance) or the devices themselves.
Must reliably transmit heart rate data from the wearable system to the mounted system without inconsistencies	1. Continuously log heart rate data from the wearable system as it transmits to the mounted system. 2. Compare the heart rate data from both logs to ensure consistency.

2.8 Computation Subsystem

This subsystem takes the audio information from the audio processing subsystem and the heart rate information from the wearable subsystem and does the necessary calculations to convert that into RGB values that that LED driver will read so the LED strip changes to the appropriate color at the appropriate time.

This subsystem consists of an MCU. It is powered by the mounted power subsystem, takes in input from the audio processing subsystem, the communication subsystem and outputs that data to the LED control system. It doesn't interact with the wearable power subsystem or the heart rate monitor.

- This subsystem is used to calculate all the data given by the Audio Processing subsystem along with the Communication Subsystem which will then have an output for the LED driver that signals the luminescence and color of the led
- If this subsystem fails, then the LED lights will not accurately display the proper output
- List of Requirements

Requirements	Verification
Must receive and process audio information from the audio processing subsystem	1. Ensure the audio processing subsystem is powered on and connected to the Microcontroller Unit (MCU). 2. Transmit a range of audio signals (e.g., tones or music) from the audio processing subsystem to the MCU. 3. Check the MCU's input to ensure it is receiving the audio signals. 4. Utilize appropriate tools (e.g., oscilloscope or sound level meter) to visualize the received signals.
Must accurately process the audio and heart rate data to convert it into the correct RGB values and luminescence that the LED driver can interpret for color changes	1. Input test data for audio (between 40-60 dB) and heart rate > 100 bpm and ensure that luminescence is bright and color is red 2. Record the RGB values and luminescence levels to verify consistency with the audio and

	heart rate data.

2.9 Circuit Schematics

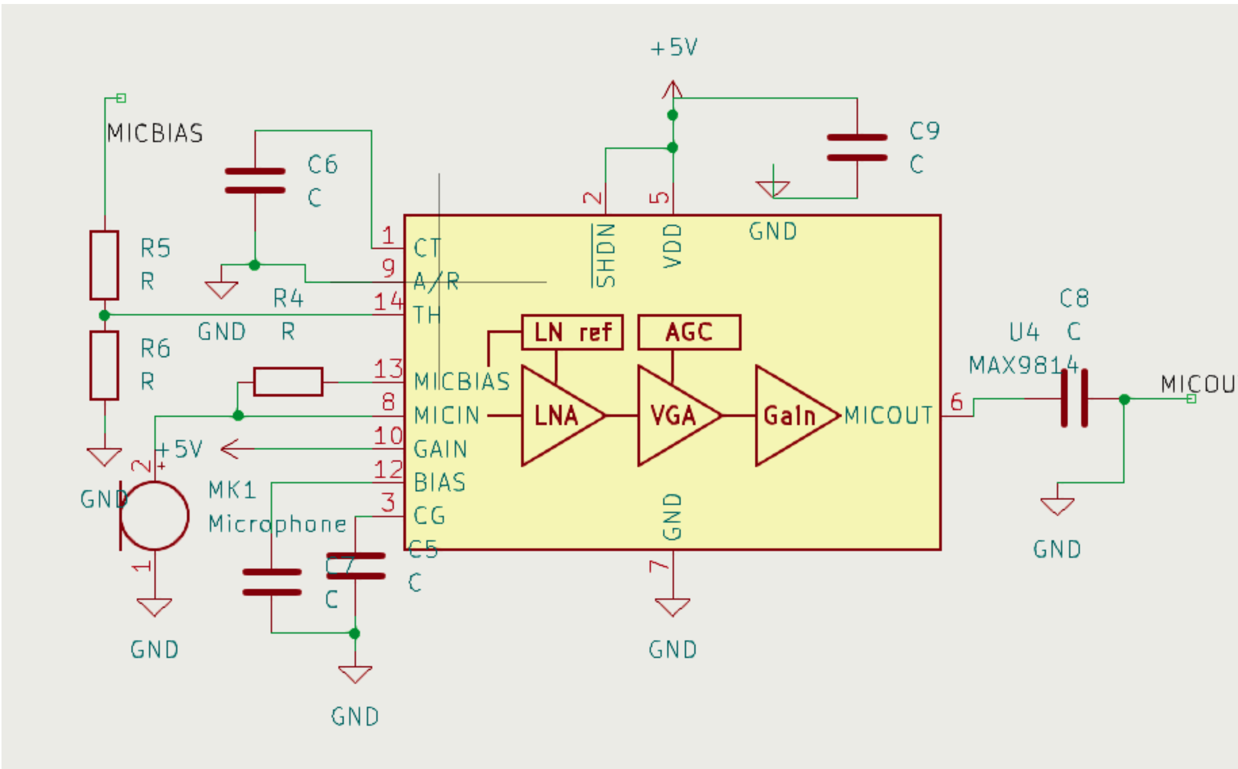

Figure 3: Microphone Subsystem

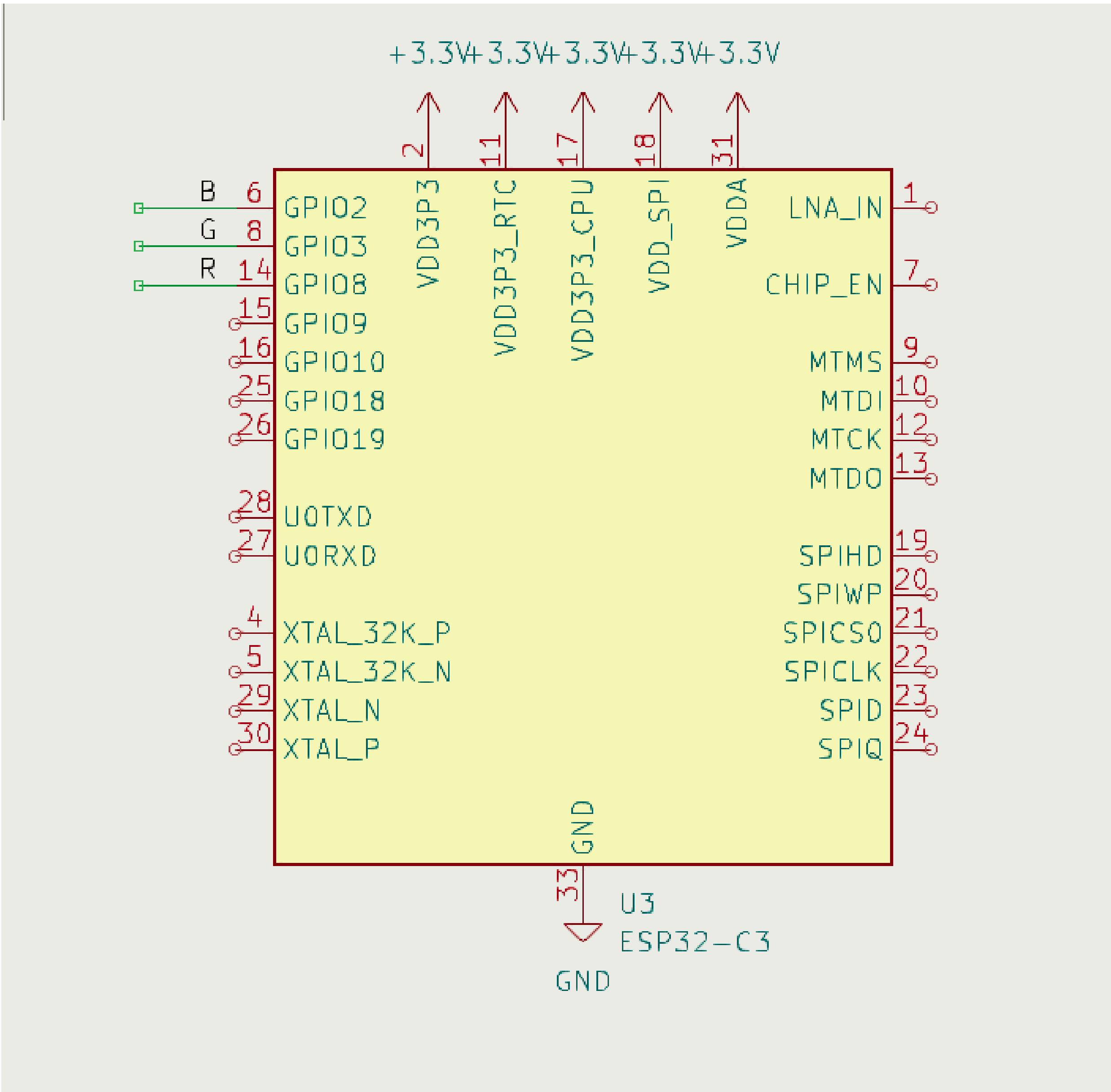

Figure 4: MCU/Bluetooth/LED - ESP32-C3 chip

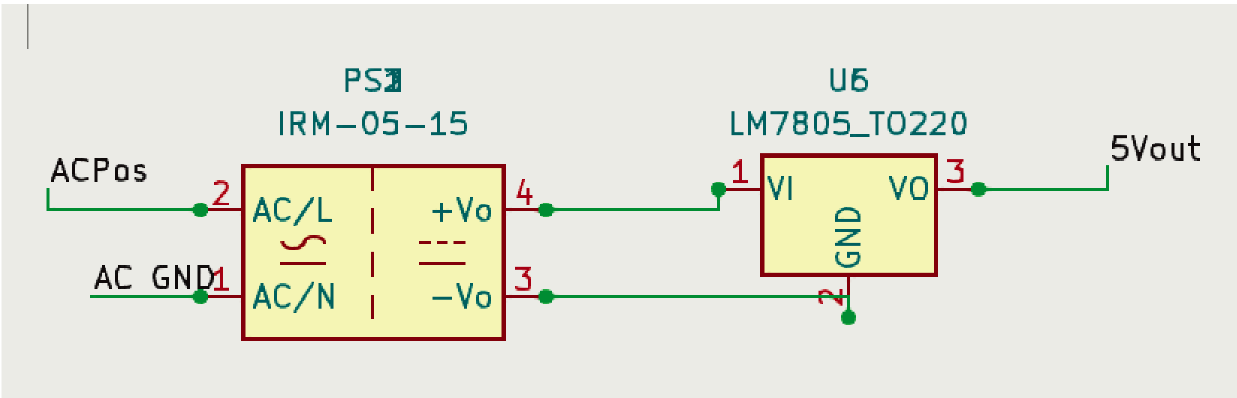

Figure 5: AC/DC converter for Power Supply

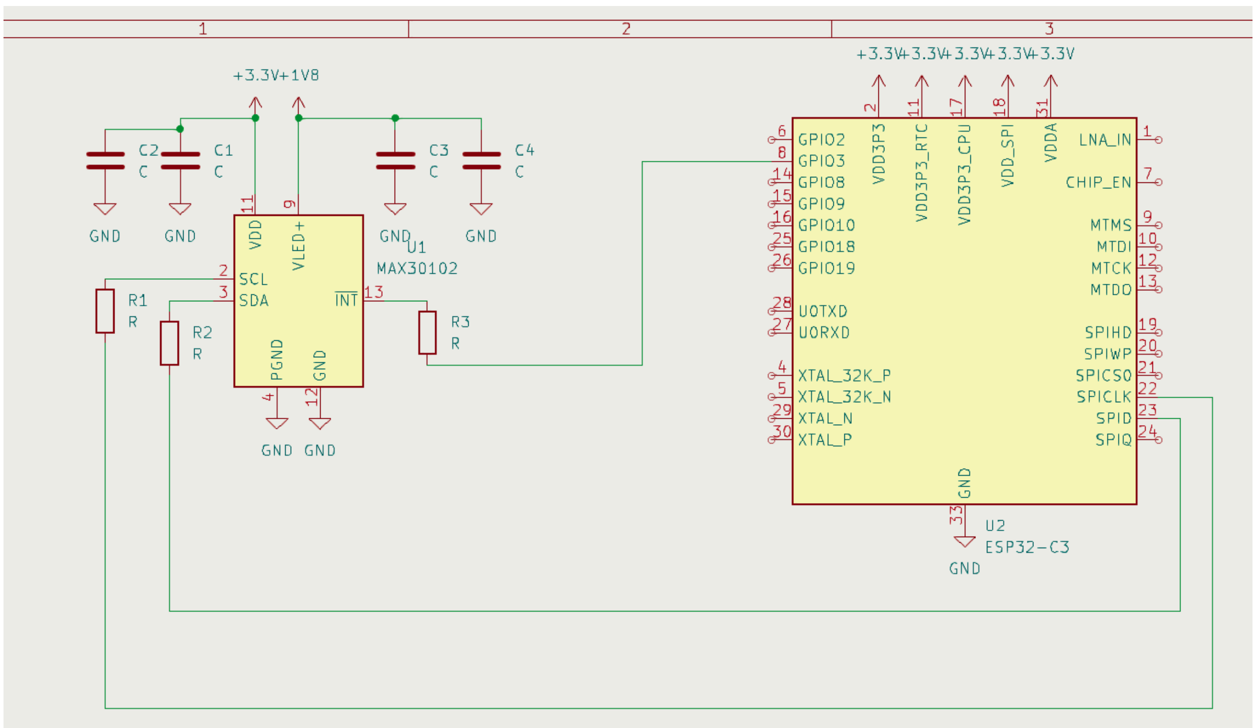

Figure 6: Heart Rate Monitor Subsystem

2.10 Tolerance Analysis

1. **Data Size and Transmission Feasibility:**
   - Data Size for Heart Rate: Assuming the heart rate value is an integer, it requires 4 bytes (32 bits) for transmission.

- Bluetooth Bandwidth: At 1 Mbps, the Bluetooth module transmits 1 Megabit per second or 1,000,000 bits per second.
- **Transmission Time Calculation:**
  - Time to Transmit 32 bits: The time to transmit the 32-bit integer is: Transmission Time=1,000,000 bits/sec32 bits=32×10−6 sec=32 microseconds.
  - This time is negligible compared to the requirement of 50 ms for transmission, so the transmission rate is well within the allowable tolerance.

2. **Transmission Latency and Buffering:**
   - Bluetooth Latency: Standard Bluetooth Low Energy (BLE) has a typical latency of 10 ms to 20 ms depending on environmental factors like interference. To account for worst-case scenarios, we assume the maximum latency of 20 ms.
   - Total Latency: The total communication delay will be the sum of the Bluetooth transmission time and any additional system processing or buffering. Since the transmission time is negligible (32 microseconds), the total latency is effectively dominated by the Bluetooth latency, which is 20 ms.
   - This leaves a 30 ms buffer for processing at the MCU, well within the requirement of 50 ms.
3. **Power Supply Tolerance:**
   - The Bluetooth transmitter operates at 5V, with a tolerance of ±0.1V. Power fluctuations could cause performance degradation or interruptions.
   - Power Tolerance: The voltage regulation circuitry needs to ensure that the Bluetooth module is supplied with a stable 5V ± 0.1V. This is achievable with standard voltage regulators that maintain accuracy within 1-2% of the nominal voltage. Hence, the power supply tolerance will not pose a significant challenge.
4. **Mathematical Analysis of Time Constraint:**
   - Let’s define the variables:
     - t_s= sampling interval = 100 ms,
     - t_{bt} = Bluetooth transmission time (including latency) = 20 ms,
     - t_{proc}= MCU processing time = 10 ms (worst case).
     - Total time, t_{total}, for data sampling, transmission, and processing: $t_{total}=t_s+t_{proc}+t_{proc}$=100 ms+20 ms+10 ms=130 ms
   - Since the system must complete the heart rate monitoring cycle within 150 ms, we have.

     t_{total}=130 ms<150 ms.

   - Therefore, the timing requirements are feasibly met, with a 20 ms buffer.

By analyzing the heart rate data transmission subsystem, we can see that the **Bluetooth transmission time**, **latency**, and **processing time** all fit well within the given **150 ms constraint**. The power supply requirements also fall within standard tolerances. Hence, with the given design parameters, the subsystem can **feasibly meet** its performance requirements, and the risk of failure due to timing or power issues is minimal.

3 Cost and Schedule

3.1 Cost Analysis

- Labor:

Name	Weekly Hours	Hourly Pay	Weeks	Cost (USD)
Anusha	15	21	12	3,780
Chinmayee	15	21	12	3,780
Manushri	15	21	12	3,780
Total	45	21	12	**11,340**

- Parts:

Description	Part #	Cost per unit	Amount	Link
Pulse Oximeter Sensor	MAX30100EFD+T	$3.80	1	Digikey
MCU with integrated Wi-Fi and Bluetooth	ESP32-C3	$1.00	2	Digikey
LED Strip	WS2812B	$27.99	1	Amazon
Electret Microphone	MAX9814	$0	1	445 inventory
AC DC converter	IRM-05-15	$6.94	3	Digikey
Op-Amp	LM324DR	$0.23	1	Digikey
Voltage	LM7805CT/	$1.97	2	Digikey

Regulator (Mounted)	NOPB			
Battery Management (Wearable)	MCP73831T-2ACI/OT	$0.76	1	Digikey
Diodes	1N4007	$0.10	1	Digikey
Resistors ¼ Watt	(VAL)XBK-ND	$0.07	6	ECE shop
Capacitors 1uF	75-562R5HKD10	$0.24	9	ECE shop
Total Cost		$62.22		

- Sum of costs:
    - 11340 + 62.22 = $11402.22 total to produce this project

3.2 Schedule

Week	Anusha	Chinmayee	Manushri
Week of 10/7	-Finalize and review PCB design schematic	-Research microcontrollers and heart rate sensors	-Research sound detection
Week of 10/14	-Finalize subsystem schematics after getting feedback	-Order all necessary components including PCB, LED strip, heart rate sensors, bluetooth transmitters, and MCU	-Start with the basic setup of MCU programming
Week of 10/21	-Receive PCB and inspect to make sure there are no defects	-Begin the soldering process and assembling the Audio Processing and Heart Rate Monitor subsystems	-Test individual components for functionality
Week of 10/28	-Complete assembly of Audio Processing and Heart Rate Monitor	-Start assembling LED subsystem -Test initial MCU	-Conduct tests on individual subsystems and see if any areas need

	subsystems	functionally for the audio data processing	improvement -Begin working on Bluetooth communication for heart rate data
Week of 11/4	-Integrate LED control with MCU	-Conduct unit test on LED color and brightness adjustments	-Begin assembling the power management system both mountable and wearable
Week of 11/11	-Integrate Audio Processing, Heart Rate Monitor, and LED Control subsystems.	-Establish reliable Bluetooth communication between wearable and mounted systems.	-Test data transmission and debug and resolve integration issues
Week of 11/18	- Perform comprehensive system integration tests.	- Ensure real-time responsiveness of lighting adjustments.	- Conduct user testing to gather feedback on system performance. - Begin refining the PCB layout based on testing results (if necessary).
Week of 11/25	Fall Break	Fall Break	Fall Break
Week of 12/2	- Develop the final presentation, including slides and demonstration scripts. - Prepare the final demo setup, ensuring all components are functioning correctly.	- Develop the final presentation, including slides and demonstration scripts. - Test with varying heart rate and sounds and ensure there are no issues	- Develop the final presentation, including slides and demonstration scripts. - Perform last-minute testing and troubleshooting.
Week of 12/9	Final presentation and final papers	Final presentation and final papers	Final presentation and final papers

4 Discussion of Ethics and Safety

Our project involves the use of heart rate data and background noise, which raises ethical concerns around data privacy and user safety. To address these concerns, we adhere to the ACM Code of Ethics (Section 1.6) by ensuring that users' personal data is protected. We will avoid storing their data and will implement measures to prevent unauthorized access. Additionally, as required by the IEEE Code of Ethics (Section 1), we will inform users of potential risks and obtain explicit consent before any data is collected or used. Users will be made aware of how their data is processed with clear consent procedures in place and we will not store their data anywhere.

Accessibility is another ethical priority. According to the ACM Code of Ethics (Section 1.4), fairness and non-discrimination are essential, meaning the system must be accessible to individuals with disabilities. We will issue a warning before system use to mitigate risks posed by lights flashing or changing intensity, which could potentially harm users' eyes. Rapid light flickering or intense brightness can cause eye strain or migraines, so we will ensure the system minimizes these effects, keeping brightness transitions gradual and flicker rates safe. There will be a warning to all users before using this product to ensure their safety.

On the safety side, the wearable heart rate monitor will comply with the IEC 60601-1 standard to ensure user safety. The device will be designed to avoid overheating or malfunctioning, as these risks could harm users. Protecting users from excessive heat is critical, and careful testing will be conducted to verify device reliability.

Finally, we will provide users with an easy way to turn off the system if they experience discomfort from the lights. By following these ethical guidelines and safety standards, our project prioritizes user safety and privacy throughout the design process.

5 Citations

Adafruit Industries. *WS2812B Intelligent Control LED*. Datasheet, cdn-shop.adafruit.com/datasheets/WS2812B.pdf.

Analog Devices, Inc. *ADMP401 MEMS Microphone with Bottom Port and Analog Output*. Obsolete Data Sheet, www.analog.com/media/en/technical-documentation/obsolete-data-sheets/ADMP401.pdf.

Analog Devices, Inc. *MAX30100 Pulse Oximeter and Heart-Rate Sensor IC*. Datasheet, www.analog.com/media/en/technical-documentation/data-sheets/MAX30100.pdf.

Analog Devices, Inc. *MAX9814 Microphone Amplifier with Automatic Gain Control*. Datasheet, www.analog.com/media/en/technical-documentation/data-sheets/MAX9814.pdf.

Espressif Systems. *ESP32-C3 Wi-Fi and BLE SoC*. Datasheet, www.espressif.com/sites/default/files/documentation/esp32-c3_datasheet_en.pdf.

MEAN WELL USA. *IRM-05 Series 5W AC/DC Converter*. Datasheet, www.meanwellusa.com/upload/pdf/IRM-05/IRM-05-spec.pdf.

Microchip Technology Inc. *MCP73831 Family Single-Cell Li-Ion/Li-Polymer Charge Management Controller*. Datasheet, ww1.microchip.com/downloads/en/DeviceDoc/MCP73831-Family-Data-Sheet-DS20001984H.pdf.

SameSky Devices. *CMA-4544PF-W MEMS Microphone*. Product Datasheet, www.sameskydevices.com/product/resource/cma-4544pf-w.pdf.

Texas Instruments. *LM324 Low Power Quad Operational Amplifier*. Datasheet, www.ti.com/lit/ds/symlink/lm324.pdf.

Texas Instruments. *LM7800 Series 3-Terminal Positive Voltage Regulators*. Datasheet, www.ti.com/lit/ds/symlink/lm7800.pdf.