ECE 445

Design Document

BioSteady

Team 46

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1. INTRODUCTION

1.1 Problem

Coffee and caffeinated beverages have become amongst the most sought after stimulants consumed by individuals who experience high stress levels due to the fast-paced and demanding nature of their academic and professional lives. We are constantly in an environment where the presence of cafes and vending machines are all around which makes it difficult for individuals to resist when they are looking for a way to maintain productivity for long periods of time. In such scenarios, we fail to acknowledge the negative physiological changes that affect our overall health in the long term.

Both stress and caffeine independently trigger these responses which particularly include increase in heart rate and changes in skin conductance. It is challenging to differentiate between the overlapping effects, which leads to overconsumption of caffeinated beverages with detrimental effects on one's health. Research suggests that the intake of caffeine, especially under mentally stressful conditions can increase the risk of developing anxiety or depression in young adults. This makes it essential for us to find a reliable way to differentiate between the physiological changes triggered by caffeine and stress in real-time so that we are able to make informed health-related decisions in the long term.

1.2 Solution

Our proposed solution is to ideate and build a wearable device that collects physiological data through the sensors used to estimate and report to users whether their bodily changes are likely influenced by caffeine intake or stress. This information will help users decide whether consuming caffeine at a given moment is advisable. Stress causes a "fight or flight" response which is induced by adrenaline, leading to rapid spikes in heart rate and sudden fluctuations in skin conductance. On the other hand, caffeine causes a slow and gradual increase in heart rate over 10-20 minutes with an eventual rise in skin conductance.

This report will be displayed through a custom built web application which will also provide recommendations to users regarding caffeine consumption and stress management techniques. A considerable amount of research led us to a study which graphically demonstrates a significant difference in sensor readings with respect to stress and caffeine. Leveraging these trends and machine learning algorithms, we can effectively classify levels of stress and caffeine intake in one’s body (Villarejo et al., 2012). The table below summarizes our expected sensor readings:

	HEART RATE (HR)	**SKIN CONDUCTANCE (GSR)**
STRESS	Sudden spike in heart rate because of adrenaline release	Sudden and irregular fluctuations in skin conductance
CAFFEINE	Gradual and steady increase over 10-15 minutes	Initially stable or low for about 200 seconds followed by a steep increase

1.3 Visual Aid

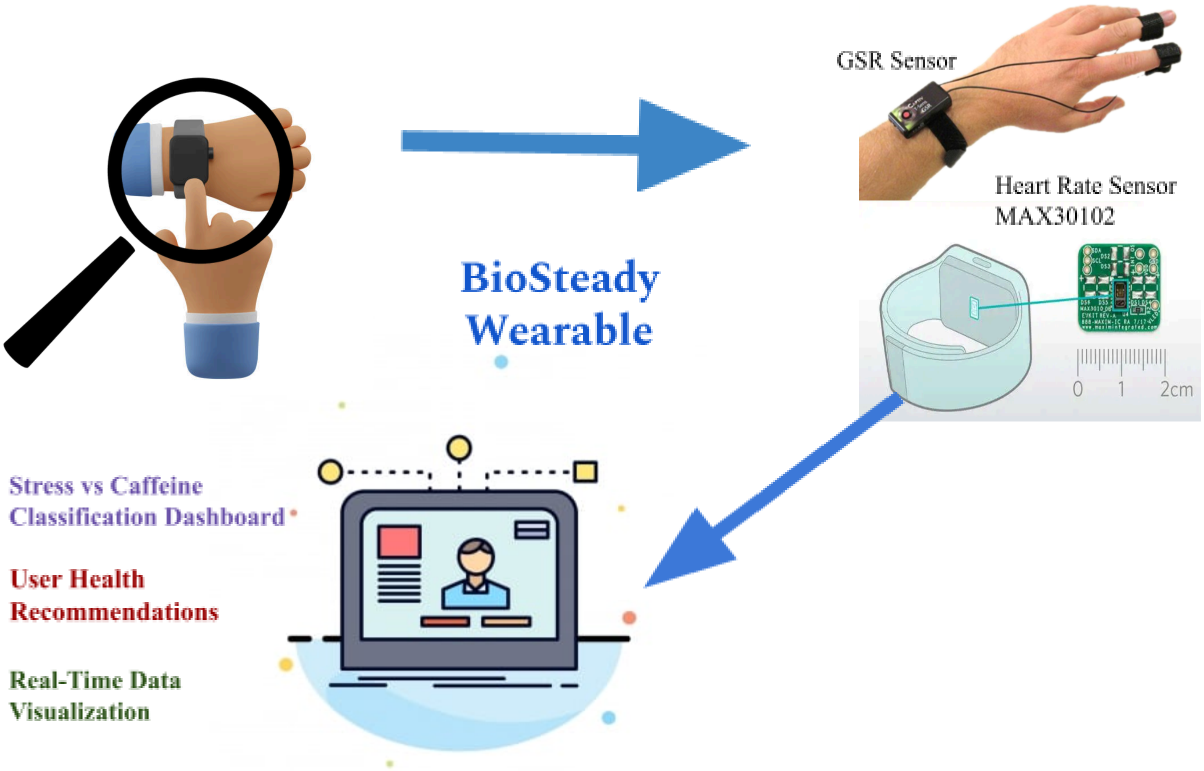


Figure 1: Visual Aid for BioSteady Project

1.4 High Level Requirements

1) Data Collection and Processing : The real-time physiological data input collected from the heart rate sensor (MAX30102) and the Elecbee GSR sensor must be processed efficiently by the microcontroller(STM32L432KC) with minimum errors to classify between stressed and caffeinated individuals correctly. The microcontroller must efficiently process this data by performing filtering to improve the data classification accuracy.

2) Data Transmission and Communication Compatibility : The data from the microcontroller must be integrated into a web application with the right communication protocols (I2C for MAX30102 and ADC for GSR) and no significant latency upon data transmission. The data should then be processed by the microcontroller via UART and then transmitted from UART to USB to an external device, which will most likely be a computer.

3) User Interface: The web application must be able to correctly display the physiological state analysis output of the user along with effectively differentiating between stress-induced and caffeine-induced responses with actionable recommendations regarding the user’s health.The UI must be at least 83% reliable using a data classification algorithm. Users must be able to receive information in a user-friendly manner where they can understand the data collected by the wearable device. The web application should include graphical visualizations of the data that is interpretable for the user.

2. DESIGN

2.1 Block Diagram

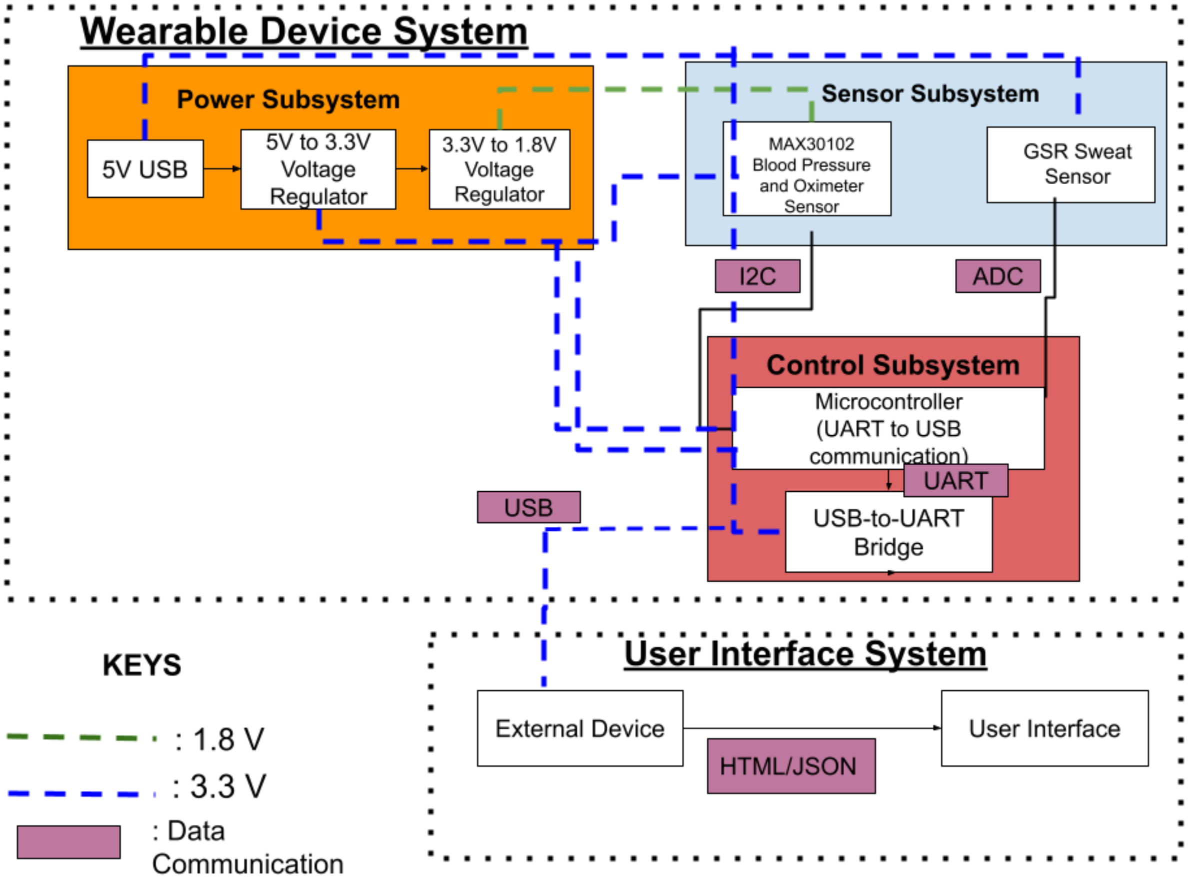


Figure 2: Block diagram for BioSteady Device

The above figure represents our block diagram for our BioSteady Device including both the wearable device and user interface systems. For the wearable device, we have three subsystems: power, sensor, and control. For the power, we will have two voltage regulators to provide a 3.3 V source to the sensor subsystem and the control subsystem as well as a 1.8 V source for the MAX30102 heart rate sensor. Our sensor subsystem will comprise of both the MAX30102 Heart rate and oximeter sensor and the GSR sensor. The MAX30102 will take a 1.8 V and 3.3 V source input from the power subsystem and then send data to the control subsystem through I2C communication. The GSR sensor will take a 5V input from the subsystem and send data to the control subsystem through analog communication. Our control subsystem comprises both the STM32L432KC microcontroller and a USB-to-UART bridge. Our MCU will take the data inputs from the sensor subsystem and send it to the USB-to-UART bridge to send to an external device using UART communication. Then, our USB-to-UART bridge will send the data from the MCU to an external device using USB-A serial protocol. Finally, our user interface subsystems will consist of the external device that receives the data from our wearable device and use HTML/JSON to create a user interface that will allow the user to have access to the data collected by the wearable device.

2.2 Physical Design

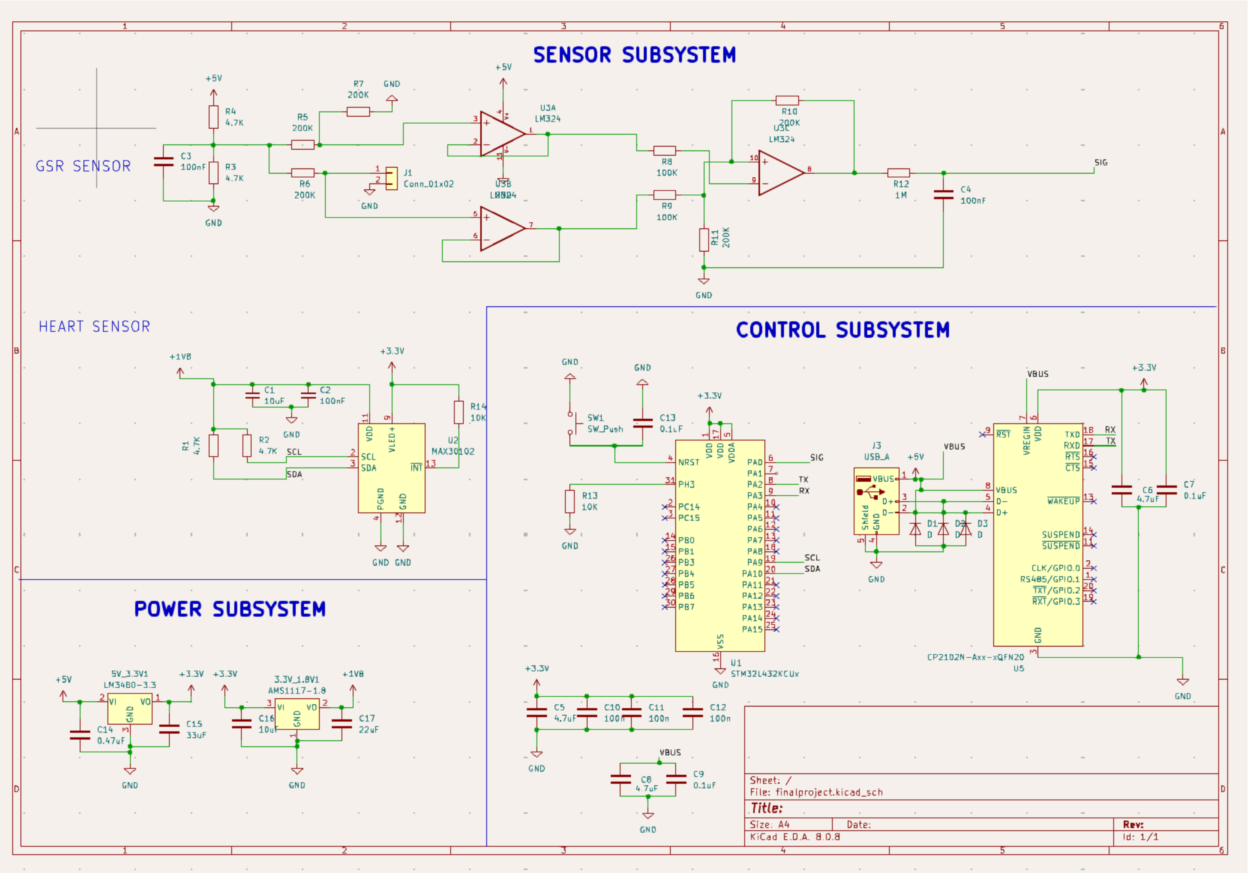


Figure 3 : Wearable Device Schematic

Figure 3 is the physical design schematic for our wearable device that has our three subsystems : Sensor subsystem, power subsystem, and control subsystem. For our Power subsystem, our 5V battery comes from our USB A connector seen in our control system. Our 5V gets stepped down to 3.3V and 1.8V to provide power to the control and sensor subsystem. In our sensor subsystem, we included both our MAX30102 heart sensor schematic and our GSR sensor schematic. The MAX30102 heart sensor requires both a 1.8V and 3.3V input from the power subsystem and outputs a SCL and SDA signal which then gets routed to our control subsystem. Our GSR sensor has three LM324PW OP amps which are connected to our 5V power as well as multiple resistors. The GSR sensor will then output a SIG analog signal which also gets routed to the control subsystem.

The control subsystem includes our STM32L432KC microcontroller, a CP2102 USB-to-UART bridge, and a USB-A connector. Our microcontroller has decoupling capacitors for our VDD and VDDA signals. We implement a NRST button so that the user can reset the microcontroller when they want to start recording data from the sensors. Additionally, our PH3 pin is pulled down to ground so that our BOOT0 mode is in flash memory to store our application code. The SDA, SCL, and SIG output signals are connected to the MCU where the SDA and SCL are I2C communication and the SIG is analog communication. The data will then get transmitted to our CP2101 UART-to-USB bridge through the TX pin. Finally, the USB-A connector that will allow our plugged-in device to receive information from the MCU through the USB-TO-UART bridge communication.

2.3 SUBSYSTEMS OVERVIEW AND BLOCK DESCRIPTIONS

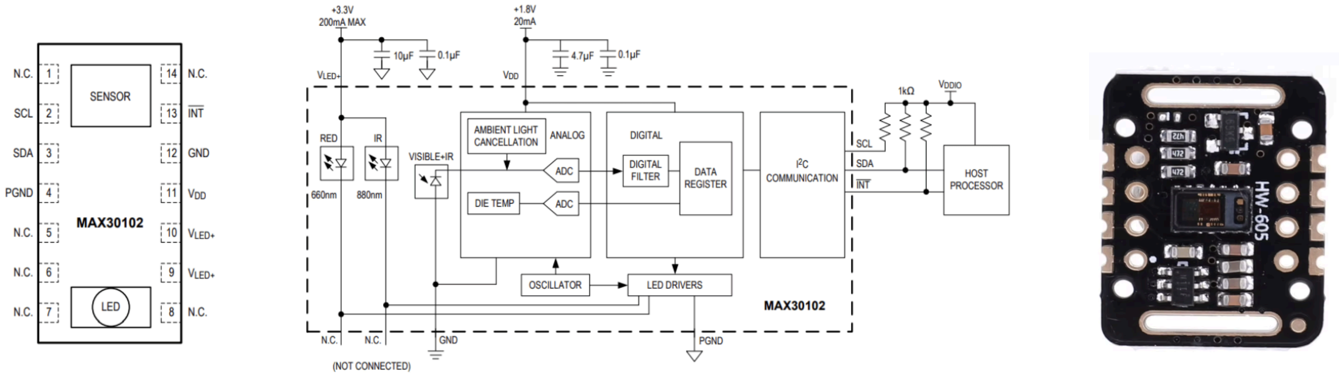
2.3.1 Biomedical Sensing

This subsystem collects physiological data from the user such as heart rate, skin conductance and oxygen saturation levels that is compared to the users resting stats and then transmitted to the microcontroller for further analysis.

Heart Rate and Oximeter Sensor

The MAX30102 sensor measures heart rate and oxygen levels using light absorption through the skin. It sends this data to the microcontroller using I2C, where it is processed and compared to the user's normal readings.

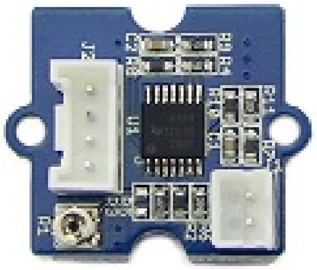
- Sensor Name: MAX30102
- Utility: Measures heart rate, oxygen saturation levels using photoplethysmography (PPG)
- Communication: I2C



Heart Rate and Oximeter Sensor Block Diagram and Image

The MAX30102 heart rate and oximeter sensor is an essential component of our project because of its highly precise ability to detect and measure heart rate by emitting infrared light through the skin and detecting variations in the absorption of the light that is caused by changes in heart rate. It operates between 1.8 and 3.3 V and communicates with the MCU via the I2C bus. This sensor was chosen because of its small and compact size and integrated infrared and red LEDs. It also is able to reduce noise due to its programmable sampling rate at 100 Hz. It is essential for our device since its readings will be instrumental in analyzing stress and caffeine effects on a person.

Galvanic Skin Response Sensor



GSR Sensor

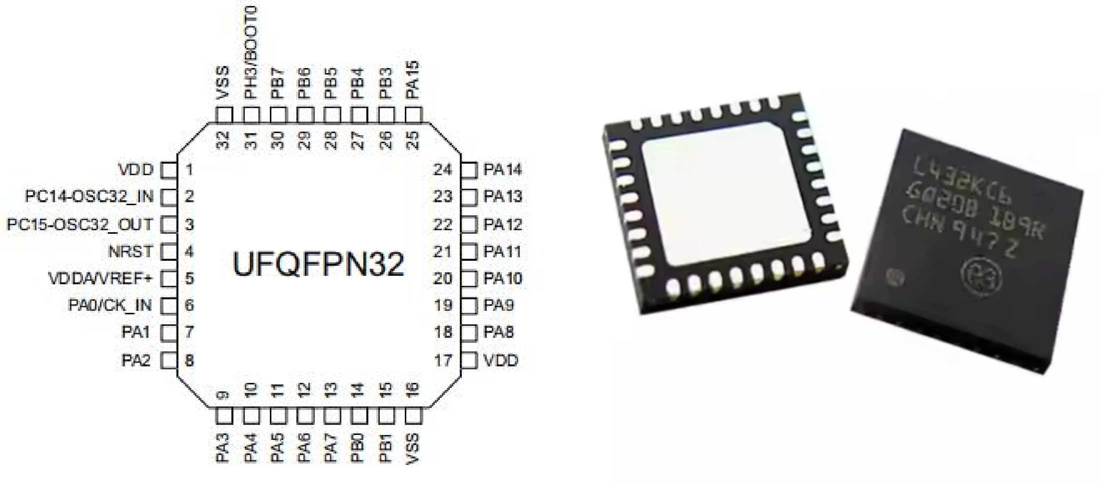
The GSR Skin Sensor Module detects variations in skin conductance by measuring the electrical resistance between two electrodes placed on the skin. These fluctuations are influenced by sweat gland activity, which tends to increase during emotional responses such as stress or excitement. The sensor generates an analog voltage signal proportional to skin conductivity, which is continuously transmitted to the microcontroller. This data is then processed and analyzed alongside other physiological metrics to provide insights into the user's autonomic nervous system activity.

- Sensor Name: Grove GSR Skin Sensor Module
- Utility: Measures skin conductance
- Communication: Analog voltage signal that varies with skin conductance

2.3.2 MCU and Power Management

This subsystem serves as the central processing unit for physiological data collection and communication with external interfaces. The microcontroller manages sensor inputs, handling I2C communication for the MAX30102 heart rate and oximeter sensor and ADC conversion for the GSR sensor. It also facilitates USB-to-UART communication, enabling seamless data transfer to the web application. To ensure stable operation, voltage regulation is provided by the LM39401-A, which converts 5V to 3.3V for the microcontroller and sensors, and the ASM1117-1.8, which steps down 3.3V to 1.8V for the MAX30102's core.

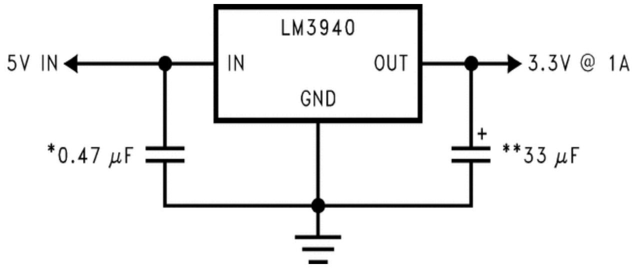
Microcontroller: STM32L432KC



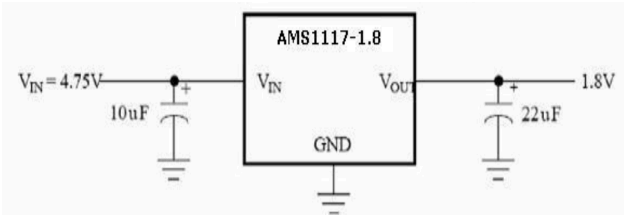
STM32L432KC Microcontroller

- Interfaces: Two I2C connections for MAX30102, ADC for GSR sensor
- Power Supply: 1.71V to 3.6V for I/Os, 1.62V to 3.6V for ADCs
- Functionality: Collects sensor data and facilitates USB-to-UART communication for the the web application.

Voltage Regulators:



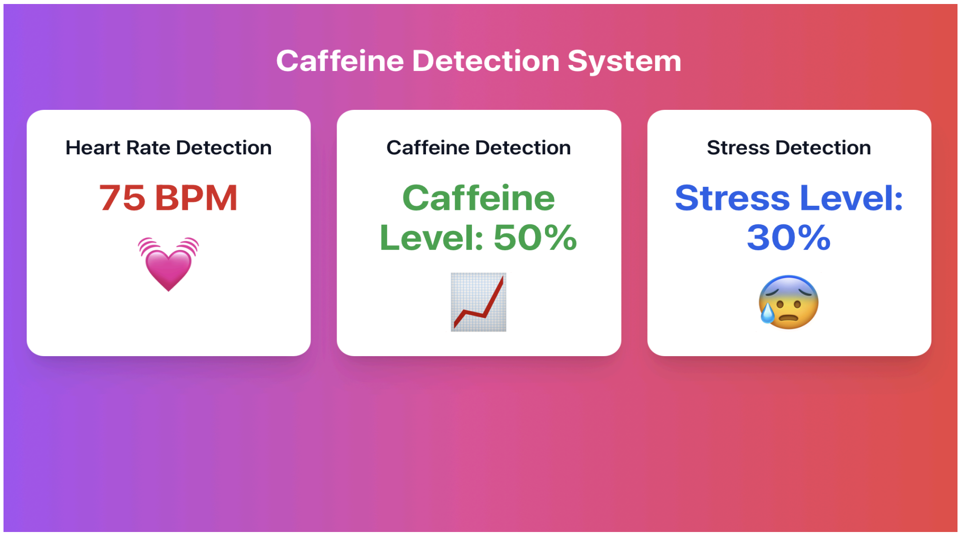
LM39401-A Voltage Regulator



ASM1117-1.8 Voltage Regulator

- LM39401-A: Converts 5V to 3.3V for MCU and MAX30102 sensor
- ASM1117-1.8: Converts 3.3V to 1.8V for MAX30102 core

2.3.3 Integration with Web Application



Caffeine Detection System

Heart Rate Detection

75 BPM 💓

Caffeine Detection

Caffeine Level: 50% 📈

Stress Detection

Stress Level: 30% 😰

Sample Landing Page UI

The Control Subsystem, including the MCU and USB to UART Bridge, facilitates data transmission to an external web application. This integration enables real-time visualization and analysis of the collected biomedical data, making it accessible for remote monitoring and further processing. We plan for the backend of the web application to be in python on the device to read the UART device as it provides a REST API for the frontend. For the frontend, we plan to use HTML/JSON for a user-friendly interface. Therefore, the STM32 will collect the data from the sensors, transmit it to the device via the UART-to-USB bridge, and the web application will fetch the data through the backend and visualize the data through the frontend.

2.4 SUBSYSTEM REQUIREMENTS AND VERIFICATIONS

2.4.1 Biomedical Sensing

The MAX30102 Sensor must reliably do the following:

- Accurately measure heart rate with a precision of ±2 BPM.
- Communicate data via I2C protocol at a standard rate of 100kHz.

The GSR Sensor must reliably do the following:

- Provide analog voltage output in the range of 0–3.3V.
- Detecting changes in skin conductivity

REQUIREMENTS	**VERIFICATION**	**SUCCESS CRITERION**
The MAX30102 sensor must detect and measure heart rate in the range of 60-120 BPM with a precision of ±2 BPM.	Measure heart rate using a personal EKG/ECG heart rate monitor and compare these outcomes to the MAX30102 sensor's outcomes for 15 test subjects.	The readings of the sensor and the personal EKG/ECG device must match within ±2 BPM for majority (~85-90%) of the readings
The Grove GSR Sensor must provide an analog voltage output that lies between 0 to 3.3V.	Use a calibrated variable resistor to prompt skin resistance change and measure output voltage using an oscilloscope	The analog output voltage must lie between 0 to 3.3V.
The response time of the sensor must range from 0.1 to 1 second if sudden change in skin conductance is detected.	Use a calibrated variable resistor to prompt skin resistance change and measure the sensor's response time using an oscilloscope	The response time in 90% of the trials must lie between 0.1 to 1 second.

2.4.2 MCU and Power Management

MCU (STM32L432KC):

- Must support I2C communication for the MAX30102 and analog input for the GSR sensor.
- Process and forward sensor data with minimum latency
- Operate efficiently on 3.3V to minimize power consumption.

Power Management:

- Voltage regulators must provide stable outputs of 1.8V and 5V, with a tolerance of ±5%.
- Ensure noise filtering to avoid interference with sensor measurements.

REQUIREMENTS	VERIFICATION	SUCCESS CRITERION
I2C communication between STM32L432KC micro-controller and MAX30102 sensor must have ≤2% error rate at 100kHz clock speed under regular operating voltage	Use STM32 firmware to log No Acknowledgement (NACK) errors from the I2C and record those errors over 500+ transactions and compute error rate	I2C communication between the microcontroller and sensor must exhibit an error rate not greater than 2% for 500+ transactions
Voltage regulators must provide stable outputs of 1.8V and 5V, with a tolerance of ±5% under load current variations of 10mA to 100mA.	Ensure that voltage outputs are within ±5% tolerance through measuring voltage regulator output via an oscilloscope for load currents between 10mA and 100mA.	Voltage regulators must provide stable voltage output within ±5% tolerance (i.e. (3.3V ±0.165V, 1.8V ±0.09V)
Input data from the sensors must be processed and must be transmitted via the USB to UART bridge within 50-80 milliseconds to ensure real-time updates	Note timestamps for the time taken to process sensor input and transmit output via UART	The time taken must lie between 50-80 milliseconds for 85-90% of the inputs.

2.4.3 Integration with Web Application

USB to UART Bridge:

- Reliably transmit processed data at a baud rate of 115200 or higher.
- Support plug-and-play connectivity for seamless integration with a web application.

The Web Application Integration must:

- Receive data from the USB interface in JSON or a similar structured format.
- Support real-time visualization and analysis.

REQUIREMENTS	VERIFICATION	SUCCESS CRITERION
USB to UART Bridge must reliably transmit processed data at a rate of 115200 bps at minimum to ensure smooth relay of information	Set baud rate on UART firmware, then send known amount of data via the USB-UART bridge and measure rate of transmission to the receiving device	The data should be successfully transmitted at a rate of 115200 bps or higher without errors
There should be minimum to no loss of data during data transmission from microcontroller to the web application	Log errors in data reception by transmitting known data	There should be very little to no data loss (≤1%) during data transmission
Support real-time visualization and analysis by ensuring that the physiological data is displayed within 100ms of data reception to display on the web application	Transmit known sensor data over to the web application and analyze time taken to render on UI by using web inspection tools	Data must be rendered on UI in less than 100ms

2.5 TOLERANCE ANALYSIS

Tolerance analysis ensures system reliability under component, operational, and environmental variations. The following sections detail the key tolerance considerations for biomedical sensing, MCU and power management, and web application integration.

2.5.1 Biomedical Sensing

The following table summarizes the tolerance related problems that may arise in our project:

Component	Tolerance Range	Failure Impact	Mitigation Strategy
MAX30102 Heart Rate Sensor	3.25V–3.35V (I2C voltage)	Communication errors, incorrect heart rate readings	Voltage regulation
MAX30102 LED Intensity	Temp-based variations	Incorrect heart rate estimations	Recalibrate with moving average filter

Grove GSR Sensor	Noise < 5%	Signal corruption in sweat measurement	Use moving average for smoothing
GSR Sensor Temperature Impact	±2°C variation	Resistance affecting GSR output	Recalibrate with variable resistor input

1) The MAX30102 Heart Rate Sensor requires a 3.3V stable voltage with 5% tolerance:

   $Vmin = 3.25V, \quad Vmax = 3.35V$

   $Allowed\ error\ rate = ((|Vmeasured - 3.3V|)/3.3V) * 100\%$

2) Grove GSR Sensor (5% tolerance)

   $Voutput = I * Rskin$

   $\Delta\ Rskin = 0.05 * Rskin$

   Where Rskin is skin resistance, Voutput is output voltage, I is current.

3) Voltage Regulators

   $For\ 3.3\ voltage\ regulation:\ 3.25\ V \le Vadjust \le 3.35\ V$

   $For\ 1.8\ voltage\ regulation:\ 1.75\ V \le Vadjust \le 1.85\ V$

4) USB to UART Display (2% tolerance)

   $$Transmission\ time\ t = (1/115200) = 8.68\ us$$

   $$\Delta t \le 8.68 * 0.02 = 0.174\ us$$

5) Web Application Display

   $Real\text{-}time\ display\ delay =$

   $Data\ retrieval\ time + Backend\ processing\ time + Frontend\ processing\ time \le 100ms$

2.5.2 MCU and Power Management

Component	Tolerance Range	Failure Impact	Mitigation Strategy
MCU (STM32L432KC)	Drift ±10%	Data processing delays	Temp-stable Oscillator
Voltage Regulators	±5% output variance	System instability, sensor failures	Switching Regulators
Power Supply Load Variations	Peak vs. normal operation	Voltage dips leading to sensor resets	Capacitor bank

Power Supply Feasibility

Subsystem	Voltage	Current (Avg.)	Power Consumption
MAX30102 Sensor	3.3V	0.6mA	1.98mW
Grove GSR Sensor	3.3V	1mA	3.3mW
STM32 MCU	3.3V	25mA	82.5mW
Voltage Regulator Losses	5V–3.3V	~5% loss	5mW (est.)

2.5.3 Integration with Web Application

Component	Tolerance Range	Failure Impact	Mitigation Strategy
USB to UART Bridge	Timing error < ±2%	Communication failures, data loss	Retry
Frontend Web Application	Acceptable delay < 100ms	Lag in real-time analysis	Data buffering, asynchronous processing
Packet Loss Handling	< 1% acceptable loss	Corrupt data output	Error-checking & retransmission

3. COST AND SCHEDULE

3.1 Cost Analysis

We found that a reasonable average hourly rate of an ECE graduate from the University of Illinois Urbana-Champaign is about $44/hour. Based on this finding, we believe that the total labor cost will be as follows:

Team Member	**Hourly Rate**	**Multiplier**	**Hours to Complete**	**Total Individual Cost** **(Hourly Rate*Multiplier*Hours to Complete)**
Asmita Pramanik	$44	2.5	120	$13200
Alisha Chakraborty	$44	2.5	120	$13200
Pranav Nagarajan	$44	2.5	120	$13200
Total Labor Costs				**$39600**

Cost Analysis: Team

Description	**Manufacturer**	**Part #**	**Link**	**Qty.**	**Cost**
Heart Rate and Oximeter Sensor	Analog Devices Inc./Maxim Integrated (VA)	MAX30102EFD+TTR-ND-TR	LINK	1	$12.05
STM32L432 KCM	STMicroelectronics	497-16592-ND	LINK	1	$4.88
CP2102 USB to UART Bridge	Silicon Labs	336-1160-2-ND	LINK	1	$10.41
USB-A Connector	Molex	WM4078-ND	LINK	1	$1.52
LM324 Op AMP	Texas Instruments	595-LM324PW	LINK	1	$0.85
STM32L432 KCM Microcontroller	STMicroelectronics	497-16578-ND	LINK	1	$4.88

JST-PH connector for GSR sensor	JST Sales America	455-B2B-XH-A-ND	LINK	1	$0.10
4.7 K Ohm resistor	STMicroelectronics	497-16578-ND	LINK	3	$19.52
10K OHm resistor	Murata Electronics	13-RC1206FR-7W10KLTR-ND	LINK	2	$0.32
1M ohm resistor	Murata Electronics	490-GRM155C61E475ME15JTR-ND	LINK	1	$0.1
200K Ohm resistor	YAGEO	311-200KFRTR-ND	LINK	5	$0.50
100k Ohm resistor	YAGEO	13-RC1206FR-13100KLTR-ND	LINK	2	$0.20
0.1uF capacitor	Murata electronics	490-10931-2-ND	LINK	9	$3.24
4.7uF capacitor	Murata electronics	490-GRM155C61E475ME15JTR-ND	LINK	3	$0.60
0.47uF capacitor	Murata electronics	490-3266-2-ND	LINK	1	$0.10
33uF capacitor	TDK Corporation	445-5986-2-ND	LINK	1	$0.77
22uF capacitor	Samsung electro-mechanics	1276-1274-2-ND	LINK	1	$0.10
Total Cost					**$60.14**

Cost Analysis: Project Parts

Total Cost of Project: $39600 + $60.14 = $39 660.14

3.2 Schedule

Weekly Schedule	**Team Objectives**
3/10	Alisha: Complete PCB design with integration of both sensors and submit a second round of PCB design

	Asmita: Start working on the breadboard connections and web application Pranav: Conduct research on heart rate datasets and work on web application All: Prepare for breadboard demo session. Start software design of project : data collection
3/24	Alisha: Begin soldering PCB. Asmita: Design overall design and functionality of web application Pranav: Prepare layout of UI landing page All: Debug/Test data collection of sensors and modify PCB if necessary. Start data processing of software design
3/31	Alisha : Submit third round PCB design if necessary. Debug Add any necessary PCB changes for the fourth round of PCB design. Asmita, Pranav: Test/Debug data collection and processing portion of the software design, ensuring accurate collection and processing of both sensors.
4/7	Alisha : **(IF NECESSARY:** Submit fourth round of PCB design**)** Finalize PCB design to ensure that the PCB is fully functional for both sensors. Asmita: Test/debug data transmission from MCU to UART-to-USB bridge for reliable communication with external devices. Pranav: Analyze and display sensor data formatted properly on UI
4/21	Pranav: Finalize data collection and processing of sensors to external devices. Alisha : Ensure complete integration of hardware components and software components. Asmita: Further test software design and add any required modifications. All: Prepare for Mock Demo.
4/28	Asmita, Pranav: Finalize UI for software design for project. All : Complete Mock Demo and Mock Presentation. Complete optional EC video assignment
5/5	All: Complete final presentation. Submit final papers and lab notebook.

4. Ethics and Safety

4.1. Ethical Concerns

Privacy and Data Security: Our project collected biometric data which can raise ethical concerns with the user's privacy and data security. We will follow the IEEE Code of Ethics Section 1.5 [3] requires that collected physiological data must be handled securely to prevent misuse by doing. We will also follow the ACM Code of Ethics section 1.6-.17 [4] by ensuring that the data collected by the Biomedical sensor subsystem is handled with the utmost privacy. Users will have full transparency on when data is collected, how data is collected, and how it is used. User data will not be shared to anywhere other than the power subsystem and the USB-to-UART system, and users will have full access to the data collected by sensors through the software component.

Team Ethics: Our team will follow the IEEE Code of Ethics Section II and III during this project to provide a safe environment for team members. We will treat each other fairly and value every person's work equally. We will strive to provide a positive work environment where collaboration is encouraged.

4.2 Safety Concerns

Electrical Safety: Since our project has sensors that require direct contact with skin, it is imperative that it is user-safety is the top priority. We will follow safety guidelines for the electrical components to mitigate potential safety hazards. We first are using sensors that operate at voltages less than or equal to 3.3V. The GSR and MAX30102 sensors operate at 3.3V and 1.8V, respectively. To ensure failure risks between parts, our PCB design will incorporate voltage regulation between the biomedical sensor subsystem and control subsystem.

FDA Medical Device Regulations: Our device is not intended for medical use or diagnosis, and users will be notified that the device should not be used as a medical device to measure any health risks. For commercial use, we will follow the Quality Management System Regulation Final Rule issued by the FDA [5].

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