

Vitaband

Emily Allendorf, Vidhi Challani, and Sharia Farhan

Department of Electrical and Computer Engineering,
Carnegie Mellon University

Abstract—VitaBand is a wearable heat stress monitoring system designed to reduce the risk of heat-related illness in outdoor workers through continuous physiological assessment. The device estimates core body temperature using arm temperature and heart rate measurements, computes the Physiological Strain Index (PSI) at 1 Hz, and applies a time-qualified state machine to classify risk into OK, WARNING, CRITICAL, and EMERGENCY states. Unlike consumer wearables that rely solely on heart rate or environmental indices, VitaBand performs on-device risk evaluation and delivers alerts within 30 seconds of sustained threshold violation while maintaining 12-hour battery life and reliable 10 m BLE connectivity.

I. INTRODUCTION

Heat-related illness (HRI) is globally a significant occupational safety challenge. Outdoor workers in construction, agriculture, landscaping, etc. are routinely exposed to high ambient temperatures, solar radiation, and physical exertion. These factors increase physiological strain, elevate core body temperature and heart rate, and place workers at risk of heat exhaustion. The use case for VitaBand is continuous, real-time monitoring of physiological heat strain in outdoor workers during extended work shifts. The device is worn on the upper arm and operates unobtrusively throughout the day, estimating core temperature, computing Physiological Strain Index (PSI), and classifying risk levels to provide timely warnings before dangerous thresholds are reached.

Current heat safety practices are largely reactive and compliance-driven rather than data-driven. Workers are typically instructed to follow hydration schedules, take periodic breaks, and self-monitor symptoms such as dizziness or fatigue. Supervisors rely on visual observation and environmental heat indices, which do not account for individual variability in physiology or workload. As a result, early indicators of excessive strain are often missed. A wearable system that continuously quantifies physiological stress provides objective insight into worker safety, reducing the probability of severe heat-related outcomes.

The primary users of VitaBand are outdoor laborers and their supervisors. The worker benefits from immediate haptic alerts when entering warning or high-risk states. This way, they are able to take preventative measures. The system is designed to function autonomously at the wearable level, with device-level computation of risk to ensure independence from persistent phone connectivity.

Existing competing technologies include consumer-grade smartwatches (e.g., Apple Watch and Fitbit), and environmental heat index monitors. Consumer wearables provide heart rate monitoring but do not compute validated

physiological heat strain metrics nor do they deliver risk classification. Environmental monitors measure ambient conditions but cannot account for metabolic load or individual physiology. VitaBand differentiates itself by combining non-invasive physiological sensing with embedded real-time computation of core temperature estimates and PSI, optimized specifically for occupational heat monitoring.

The primary goals of this project are to (1) design and prototype a wearable device capable of continuously estimating physiological strain during a full 12-hour work shift, (2) implement and validate firmware-level risk classification algorithms with quantifiable accuracy and stability, (3) maintain reliable Bluetooth Low Energy (BLE) communication with a mobile application within the required operating range, and (4) demonstrate power efficiency and usability appropriate for field deployment. Through this, VitaBand aims to provide a scalable, data-driven solution to a critical occupational safety problem.

II. USE-CASE REQUIREMENTS

The primary use case for VitaBand is continuous physiological and safety monitoring for outdoor workers during a full work shift. The device is worn as an upper-arm armband and must operate reliably while the user performs moderate-to-high intensity labor in outdoor environments. From the user's perspective, the system must (1) continuously monitor heart rate and temperature, (2) detect dangerous heat strain in time to intervene, (3) detect fall events with minimal delay, (4) maintain connectivity even if the phone is not on the wearer's body, and (5) remain comfortable and operational for an entire shift. The following quantitative requirements define the measurable performance necessary to satisfy this use case.

VitaBand shall continuously measure heart rate and temperature at a rate of 1 Hz, meaning the user's physiological state is updated once per second. In addition, the inertial measurement unit (IMU) shall sample at 50–100 Hz to support reliable fall detection under dynamic motion conditions. These sampling rates ensure that both gradual heat strain progression and rapid fall events are captured with sufficient temporal resolution to enable meaningful intervention.

The system shall maintain a Bluetooth Low Energy (BLE) communication range of at least 10 meters under typical outdoor job-site conditions. This requirement ensures that the device remains connected to the mobile application even if the phone is not directly on the wearer, such as when it is placed nearby or carried by a supervisor.

Battery performance is a critical operational constraint. The wearable shall provide a minimum of 12 hours of continuous operation to cover a full outdoor work shift without requiring recharge or battery replacement. The system must be rechargeable to support daily reuse in occupational settings.

Alert latency is also a key user-facing requirement. For heat strain detection, the system shall issue a warning within 30 seconds of crossing the defined physiological risk threshold, ensuring intervention occurs before dangerous escalation. For fall detection, the system shall issue an alert within 10 seconds

of a detected fall event, reflecting the rapid increase in injury risk immediately following impact.

Finally, wearability and comfort are essential for real-world adoption. The total armband mass shall be less than 300 grams to minimize user burden during extended use. Materials in contact with the skin must be flexible and skin-safe to prevent irritation during prolonged wear in high-temperature conditions.

III. ARCHITECTURE AND/OR PRINCIPLE OF OPERATION

The system is designed as a multi-layered safety platform for real-time worker health monitoring in physically demanding outdoor environments. Outdoor laborers face compounding risks from heat stroke and overexertion, and existing solutions either rely on periodic manual check-ins or require constant network connectivity to function. This device addresses both shortcomings by performing all critical processing on-board and using Bluetooth Low Energy to relay information to a companion smartphone app only when a connection is available. The result is a wearable that can operate autonomously and notify nearby crew members of an emergency even in areas with limited infrastructure.

At a high level, data flows from the sensor layer through an on-device processing and risk scoring pipeline, which feeds a tiered alert system that drives both local feedback on the device and remote crew notifications through the app. This pipeline was designed around two core priorities: reliable offline operation and minimization of false alerts that could erode worker trust in the system over time. Every architectural decision in the firmware and hardware traces back to one or both of these goals.

The sensor layer captures heart rate via optical photoplethysmography and environmental and skin temperature through a dual-sensor configuration. The distinction between skin and ambient temperature is particularly important for outdoor workers, where ambient conditions vary widely and a raw skin temperature reading alone would be unreliable without environmental context. Battery telemetry is also monitored continuously to ensure the system can warn of low power conditions before they affect operation.

Raw sensor data is ingested by a dedicated sensor interface layer responsible for hardware communication, input validation, and calibration. This layer ensures that corrupted or out-of-range samples are flagged before they can propagate into the risk scoring logic downstream. High-frequency sampling combined with DMA-based data transfer ensures signal integrity by preventing interrupt-driven CPU activity from introducing gaps or artifacts into the data stream.

Processed data is passed to the state manager, which implements the core decision logic of the system as a four-state finite state machine progressing through OK, WARNING, CRITICAL, and EMERGENCY. Transitions between states are governed by configurable vital thresholds, and the tiered structure was a deliberate design choice to reduce alert fatigue. Rather than triggering a notification on

any threshold crossing, the system requires vitals to persistently exceed a given level before escalating, and will de-escalate if readings recover. This behavior mirrors clinical triage logic and is intended to make alerts actionable rather than disruptive. A physical emergency button provides a manual override that immediately forces a transition to the EMERGENCY state, giving workers a direct means of calling for help independent of the automated monitoring pipeline.

When an alert is warranted, two parallel output pathways are activated. The local alerts module provides immediate on-body notification to the wearer through haptic and audible feedback. Simultaneously, the BLE stack transmits updated vital data and alert state to the companion smartphone app, which displays real-time metrics and pushes notifications to a pre-configured crew contact list. The use of a contact list rather than GPS-based location sharing was a conscious scope decision made during design evolution, as it achieves the crew notification goal with substantially lower power overhead.

Power management is treated as a first-class concern throughout the system rather than an afterthought. The power module coordinates sleep state transitions for the MCU, keeping the processor in a low-power mode between active sensing intervals and transmissions. This duty cycling strategy is the primary mechanism by which the system meets its 12-hour battery life target. The firmware runs on Zephyr RTOS, with all sensing, state management, alerting, and power logic implemented as discrete modules that interface through well-defined APIs and leverage the kernel's scheduling and peripheral access primitives.

A commercial deployment of this device would demand an enclosure engineered for the realities of outdoor industrial work. Materials such as TPU, which is commonly used in ruggedized wearables for its flexibility and resistance to impact, moisture, and temperature extremes, would be appropriate candidates for a production design. However, the scope of this project is focused on validating the electronics and firmware as a proof of concept rather than on mechanical or manufacturing design. As such, we aim to create the prototype enclosure as a hand-sewn fabric armband intended to hold the PCB comfortably against the arm during testing. This approach prioritizes wearability sufficient for demonstration and functional validation while acknowledging that enclosure design would be a necessary area of further development before any commercial application.

VITABAND – SYSTEM BLOCK DIAGRAM

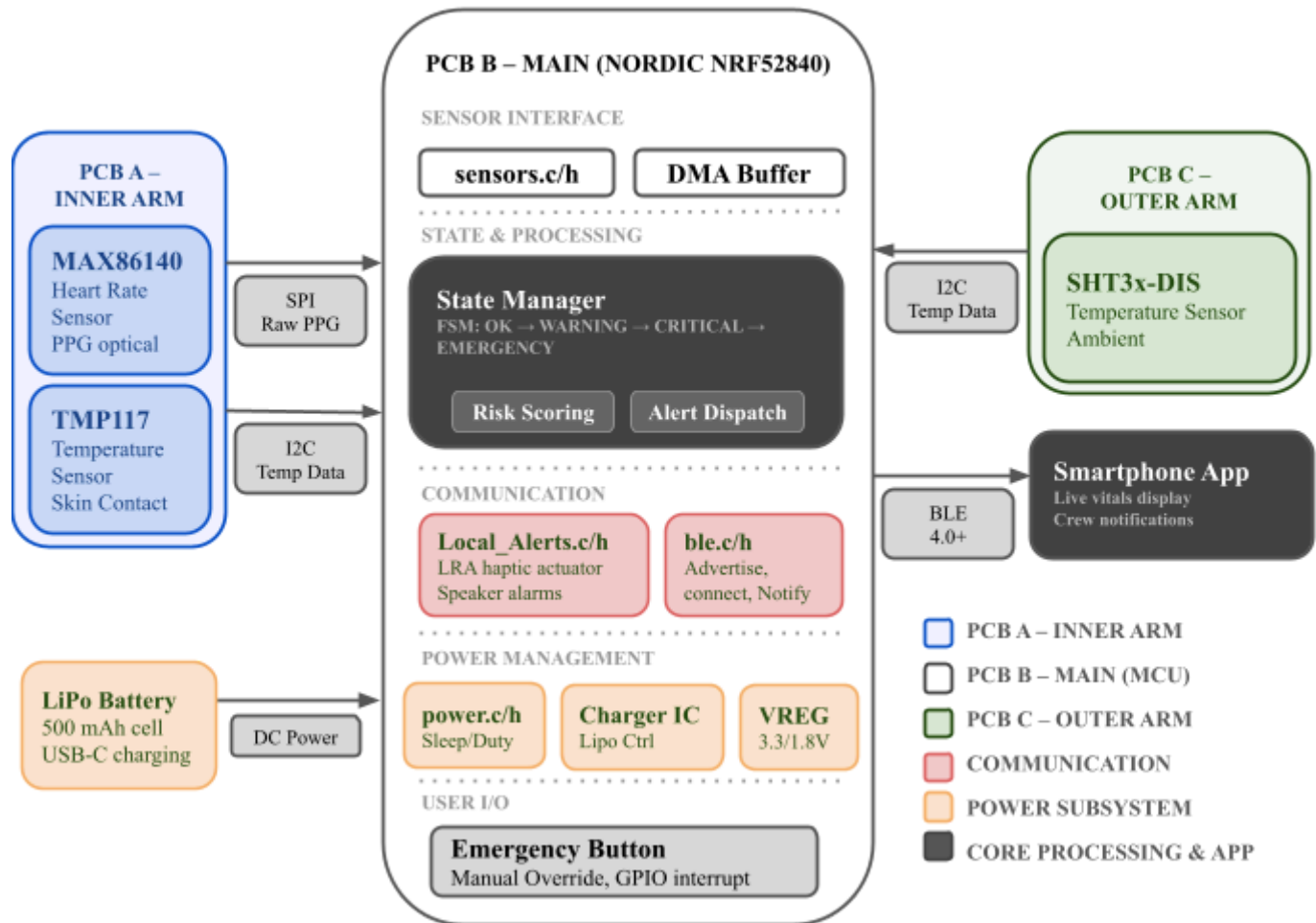


Fig. 1. System Block Diagram

IV. DESIGN REQUIREMENTS

The use-case requirements place concrete demands on four subsystems: power management, heart rate sensing, temperature sensing, and wireless communication. Each of which must meet quantitative specifications derived from the demands of a full outdoor work shift.

The 12-hour battery life requirement sets a hard upper bound on average system current. With a 500 mAh battery, sustaining 12 hours of operation requires $I_{avg} \leq 500 \text{ mAh} / 12 \text{ hr} \approx 41.6 \text{ mA}$. This constraint drives the duty cycling strategy in the power module, where the MCU is held in sleep mode between active tasks to minimize idle current draw.

Accurate heart rate monitoring requires PPG sampling at a minimum of 100 Hz to capture sufficient waveform resolution. A bandpass filter spanning 0.7-3.5 Hz isolates the physiological signal and rejects motion artifacts, and DMA-based data transfer prevents interrupt activity from corrupting the sample stream. The HR output updates at 1 Hz using a 5–10 second estimation window, with a target dropped sample rate below 0.1%.

Temperature accuracy requirements differ between the two sensors. The skin sensor must achieve $\pm 0.5^\circ\text{C}$ accuracy over 30–42°C, while the ambient sensor must achieve $\pm 1.0^\circ\text{C}$ over the Pittsburgh operating range. Beyond sensor selection, these specs impose thermal placement constraints: the skin sensor must maintain direct contact with the body, and the ambient sensor must be isolated and vented to prevent body heat bias. Calibration in the sensor interface layer corrects for residual offset.

The BLE subsystem must maintain a packet success rate of at least 95% at 10 meters and deliver data to the app within 10 seconds. Antenna edge placement with a proper keepout region and impedance matching between the antenna and the Nordic SoC are required to meet this reliability target across the expected operating range.

V. DESIGN TRADE STUDIES -SHARIA

1. Battery Life and Average System Current

The Vitaband use-case requires continuous operation for a full work shift without recharging. The target of 12 hours sets a hard ceiling on the average system current I_{avg} . Given a 500 mAh LiPo cell, the battery-life equation is

$$T_{life} = C_{battery} / I_{avg} \quad (1)$$

where T_{life} is battery life in hours, $C_{battery}$ is the cell capacity in mAh, and I_{avg} is the average system current in mA. Substituting the 12-hour requirement:

$$12 \leq 500 / I_{avg} \Rightarrow I_{avg} \leq 41.6 \text{ mA} \quad (2)$$

(2) defines the primary power budget for the entire system. Every component and duty-cycle decision is evaluated against this constraint. The MCU choice is the dominant contributor: the Nordic nRF52840 draws 5–10 mA during active BLE advertisement, whereas the ESP32-C3 alternative draws 50–120 mA under the same conditions, exceeding the 41.6 mA budget on its own. The Nordic therefore satisfies (2) while leaving headroom for sensors and the charging IC.

2. PCB Architecture: Multi-Board vs. Single-Board

A single four-layer board large enough to house all components would place the charger IC, buck-boost converter, and vibration motor (all high-frequency switching sources) in the same ground plane as the PPG photodiode, which detects microvolt-level optical signals. Simulations and established EMI guidelines require switching regulators to be placed more than 15 mm from sensitive analog circuitry; on a wrist-band form factor, this separation cannot be achieved on one board.

The design therefore partitions the system into three smaller PCBs connected by a flexible flat cable (FPC):

- Sensor PCB: MAX86141 PPG optical block, TMP117 skin temperature sensor, and associated analog front end. Only the photodiode window, LEDs, and skin temperature probe contact the skin; all supporting circuitry is on the back face of the board.
- Ambient/Button PCB: SHT31 humidity and ambient temperature sensor thermally isolated and vented away from body heat, plus the manual emergency-override button facing outward.
- Main PCB: nRF52840 (via MDBT50Q-1MV2 module), vibration motor driver, speaker, MCP73831 charger IC, buck-boost and LDO regulators.

The FPC connector is chosen over a soldered wire harness or board-to-board headers because FPC offers a lower fatigue risk under repeated bending, a smaller bend radius, and reduced weight, all critical for a wearable worn for an entire shift.

3. PCB Layer Stack-Up

A four-layer stack-up is used on the Main PCB to satisfy simultaneous requirements for signal integrity, power distribution, and EMI suppression:

1. Layer 1 (Top): Signal routing and sensitive analog components. Analog signals are kept short and guarded.
2. Layer 2: Solid ground pour providing a low-impedance return path and shielding for Layer 1 signals.
3. Layer 3: Power plane distributing regulated voltages with minimal resistive drop.
4. Layer 4 (Bottom): Digital routing and noisier switching components, thermally coupled to the power plane above for heat spreading.

This arrangement minimises crosstalk between the digital and analog domains by interposing a continuous ground plane and a dedicated power plane between them.

4. RF Design: Module Selection and BLE Link Budget

To maintain a BLE packet success rate $\geq 95\%$ at 10 m, the antenna must deliver sufficient effective isotropic radiated power and must be impedance-matched to the nRF52840 RF port. Custom antenna traces on a small PCB require controlled impedance simulation and an RF keepout region and were judged to be too risky given our schedule. Instead, we chose the Raytac MDBT50Q-1MV2 module; it integrates a 2.4 GHz antenna, a calibrated matching network, a crystal oscillator, and RF shielding in a compact certified footprint. This trades a small increase in module cost for:

- Elimination of RF trace design and antenna keepout layout risk

- Pre-certified BLE compliance, reducing regulatory testing burden
- Reduced EMI debugging time and more predictable BLE range

The BLE link margin at 10 m in an open environment is estimated as:

$$\text{Margin} = P_{\text{TX}} - PL(10\text{m}) - P_{\text{RX,min}} \quad (3)$$

where $P_{\text{TX}} = 0$ dBm (nRF52840 default), $PL(10\text{m}) \approx 60$ dB (Friis free-space, 2.4 GHz), and $P_{\text{RX,min}} = -93$ dBm (nRF52840 BLE 1 Mbps sensitivity). This gives a margin of +33 dB, well above the ~10 dB required for $\geq 95\%$ packet success in a non-obstructed environment, validating the antenna approach.

5. PPG Signal Integrity and Noise Isolation

The MAX86141 PPG front end resolves optical signals at the photodiode in the microvolt range. The primary noise sources coupling into this path are: (a) switching regulator harmonics, (b) digital clock edges on I²C/SPI lines, and (c) power-supply ripple. The following design rules are applied to reduce coupled noise below the ADC LSB level:

- Switching regulators placed >15 mm from the Sensor PCB and located on the Main PCB.
- Decoupling capacitors placed within 2 mm of all VDD pins.
- Separate analog and digital ground regions stitched at a single point to prevent digital return currents from flowing through the analog ground.
- Guard traces around photodiode signal lines on the Sensor PCB.
- Switching regulator frequency chosen outside the 0.7–3.5 Hz heart-rate band to prevent aliasing artefacts into the PPG signal band.

These measures directly support the heart-rate accuracy design requirement (mean absolute error ≤ 5 bpm) by ensuring that the hardware noise floor does not dominate over physiological signal variation.

6. Component Selection Trade-Off Summary

Table I summarises the primary component selections and the alternatives considered. Each choice is governed by the power budget in (2), the accuracy requirements, or the form-factor constraints derived from the use case.

Table I. Component Trade-Off Summary

Subsystem	Chosen Part	Alternative	Metrics Compared	Decision Rationale
MCU + BLE	nRF52840 (MDBT50Q)	ESP32-C3	Sleep current, BLE current, footprint, RF risk	5–10 mA BLE vs. 50–120 mA; smaller footprint; integrated module eliminates antenna design risk

PPG	MAX86141	MAX30102	Motion artifact rejection, power modes, accuracy	Medical-grade filtering and better motion rejection; meets ≤ 5 bpm accuracy requirement
Skin Temp	TMP117	MAX30205	Accuracy, drift, power, range	$\pm 0.1^\circ\text{C}$ accuracy, lower quiescent current, wider range usable for ambient sensing too
Ambient Temp / Humidity	SHT31	TMP117	Humidity support, power, I ² C integration	Combined temp + humidity enables PSI heat index; TMP117 cannot measure humidity
LiPo Charger	MCP73831	BQ24074	Complexity, board area, features	Simple single-cell charger is sufficient; BQ24074 power-path adds unnecessary complexity

Only components with major impacts on battery life, sensing accuracy, RF reliability, or mechanical integration are included in the trade study table; passives were selected to meet interface and filtering requirements.

VI. SYSTEM IMPLEMENTATION

The system is realized as a wearable armband built around a three-part custom PCB architecture, designed to both house the MCU and intentionally position the sensors for accurate physiological measurements. The hardware, firmware, and companion smartphone app each constitute a distinct implementation layer, and together they form the complete end-to-end pipeline described in the architecture section. The following subsections detail the implementation of each layer in turn.

At a high level, the wearable continuously reads the wearer's heart rate and skin and ambient temperatures, evaluates those readings against health thresholds, and responds by alerting the wearer directly on the device and relaying the information to a smartphone over Bluetooth. A physical emergency button gives the wearer a manual way to trigger an alert at any time. The entire system runs off a small rechargeable battery, with the electronics managed to extend life across a full work shift.

A. PCB Implementation

The Vitaband hardware is split across three physically separate PCBs — a Main PCB, a Sensor PCB, and an Ambient/Button PCB — connected by flexible flat cables (FPC). This partitioning was necessary because a single board large enough to house all components would either be too large to wear comfortably or would force high-noise switching components to sit adjacent to the microvolt-level PPG optical front end. By separating them, we can guarantee more than 15 mm of physical distance between the switching regulators and the sensitive analog circuitry, and we can ensure that only the components that need to touch skin actually do.

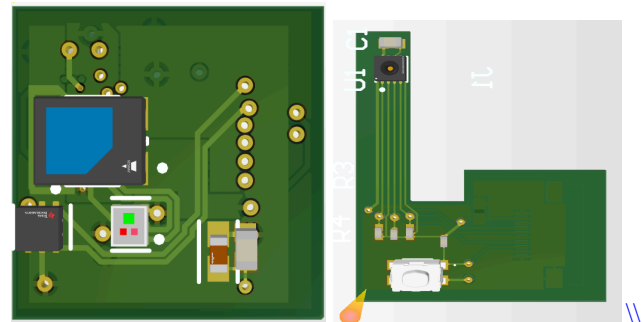
The Main PCB is the computational and power hub of the system. It houses the nRF52840 via the Raytac MDBT50Q-1MV2 module, which integrates the antenna, matching network, crystal, and RF shielding in a single certified footprint — this saved us from having to design and tune a custom antenna trace. The power subsystem sits on this board as well. The MCP73831 LiPo charger handles USB-C input and charges the 500 mAh cell at a rate set by a single resistor — we used a 200 k Ω resistor on the PROG pin, which sets the charge current to 100 mA, a conservative rate that reduces heat during charging while worn. The LiPo cell output ranges from 3.0 V at low charge to 4.2 V at full charge, which means we can't power the nRF52840 or sensors directly from it without risking undervoltage dropouts at low battery or overvoltage damage at full charge. We use a TPS63031 buck-boost to solve this — it regulates the entire 3.0–4.2 V input range to a stable 3.3 V regardless of battery state of charge, which is the supply voltage the nRF52840, digital peripherals, and most of the board logic expect. The 3.3 V rail also powers the SHT31, the level shifters, and the FPC signal lines.

The analog front end requires separate treatment. The MAX86141 has a dedicated analog supply pin (VDDA) rated for 1.7–2.0 V, so powering it from 3.3 V would exceed its absolute maximum rating. More importantly, keeping the analog supply separate from the 3.3 V digital rail means that switching noise from the nRF52840, I²C transactions, and other digital activity doesn't couple directly into the analog front end and corrupt the PPG signal. We use a TPS7A2018 LDO to drop the 3.3 V rail down to a clean, regulated 1.8 V for the analog supply. We chose an LDO rather than another switching regulator here deliberately — LDOs have no switching frequency and therefore introduce no additional high-frequency ripple onto the supply, which is exactly what we need for a rail whose entire purpose is to be quiet. The TPS7A2018 specifically has very low output noise spectral density and high power supply rejection ratio (PSRR), which further attenuates any residual ripple coming in from the 3.3 V rail before it reaches the MAX86141. The 1.8 V rail also powers the TMP117, which operates down to 1.7 V and benefits from the same noise isolation. The vibration motor driver, piezo buzzer, and the two FPC connectors routing out to the other boards also live on the Main PCB, along with SWD debug pads and labeled test points on all major power rails for bringup.

The Sensor PCB is the only board in direct skin contact. The MAX86141 PPG sensor and TMP117 skin temperature sensor are both mounted on the skin-facing side, with the MAX86141 optical aperture and the TMP117 thermal pad exposed directly to the wrist. All supporting analog circuitry is on the back face. To protect the microvolt-level PPG signal, we use a dedicated analog ground region beneath the MAX86141, stitched to the digital ground at a single point, with guard traces around the photodiode signal lines and all decoupling capacitors placed within 2 mm of their respective VDD pins. The FPC connector is placed at the far edge of the board to maximize separation between the analog front end and the digital lines on the cable.

The Ambient/Button PCB handles the two functions that need to be physically isolated from the rest of the system. The SHT31 combined temperature and humidity sensor is mounted through a vented aperture in the enclosure, positioned away from the LDO and other heat sources, with minimal copper pour around it to reduce thermal conduction from the board itself — this is necessary to get accurate ambient readings rather than reading the device's own waste heat. The emergency override button is mounted on the outward-facing side of this board, accessible through a cutout in the enclosure, and connects to a GPIO interrupt on the nRF52840 with hardware debounce via a pull-up resistor and bypass capacitor.

All three boards are connected via ZIF FPC connectors. We chose FPC over a soldered wire harness because it handles repeated bending without fatigue failure, folds flat within the enclosure, and keeps weight and thickness to a minimum. Each cable carries I²C, the 3.3 V and 1.8 V supply rails, and the analog ground reference, with signal lines on the outer layers and a ground layer between them for shielding.



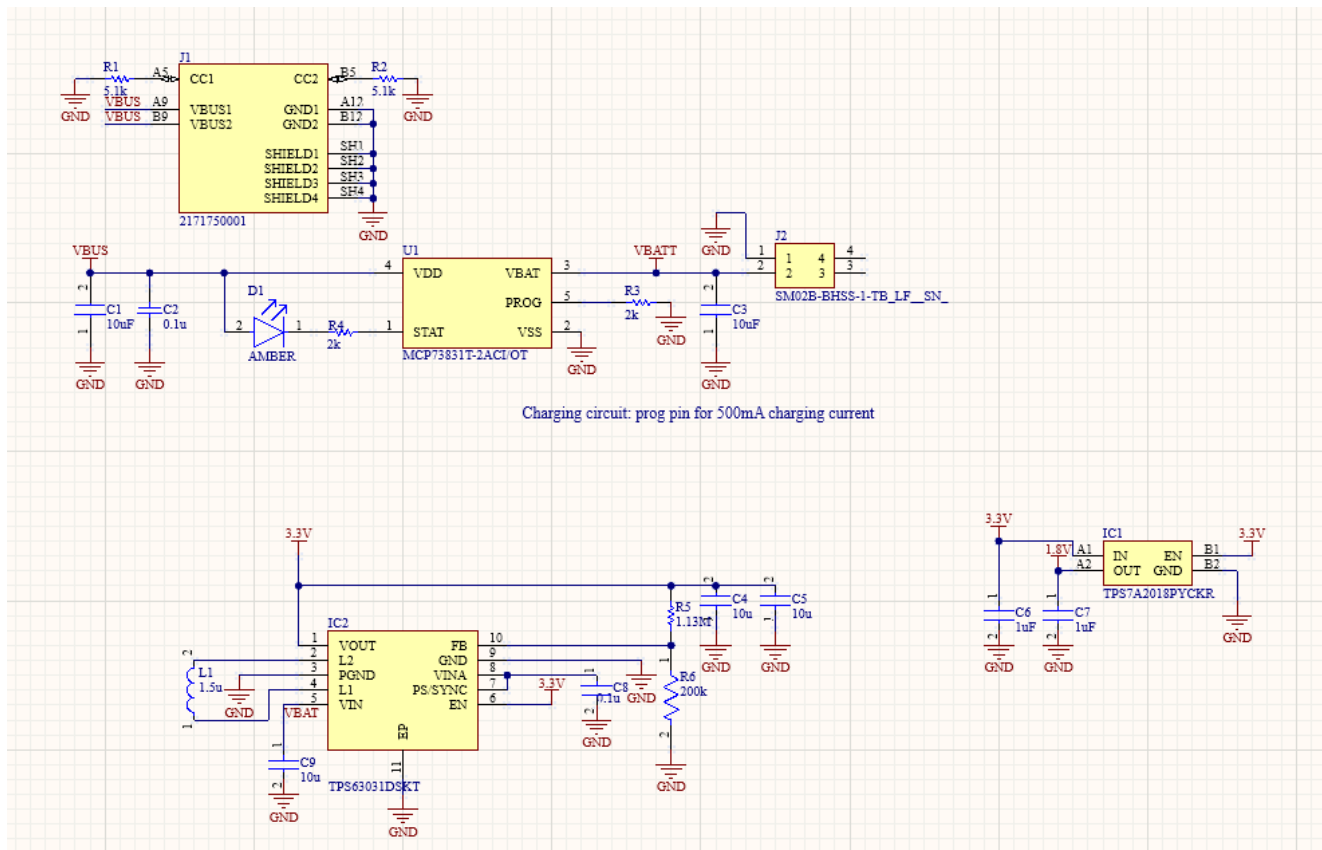
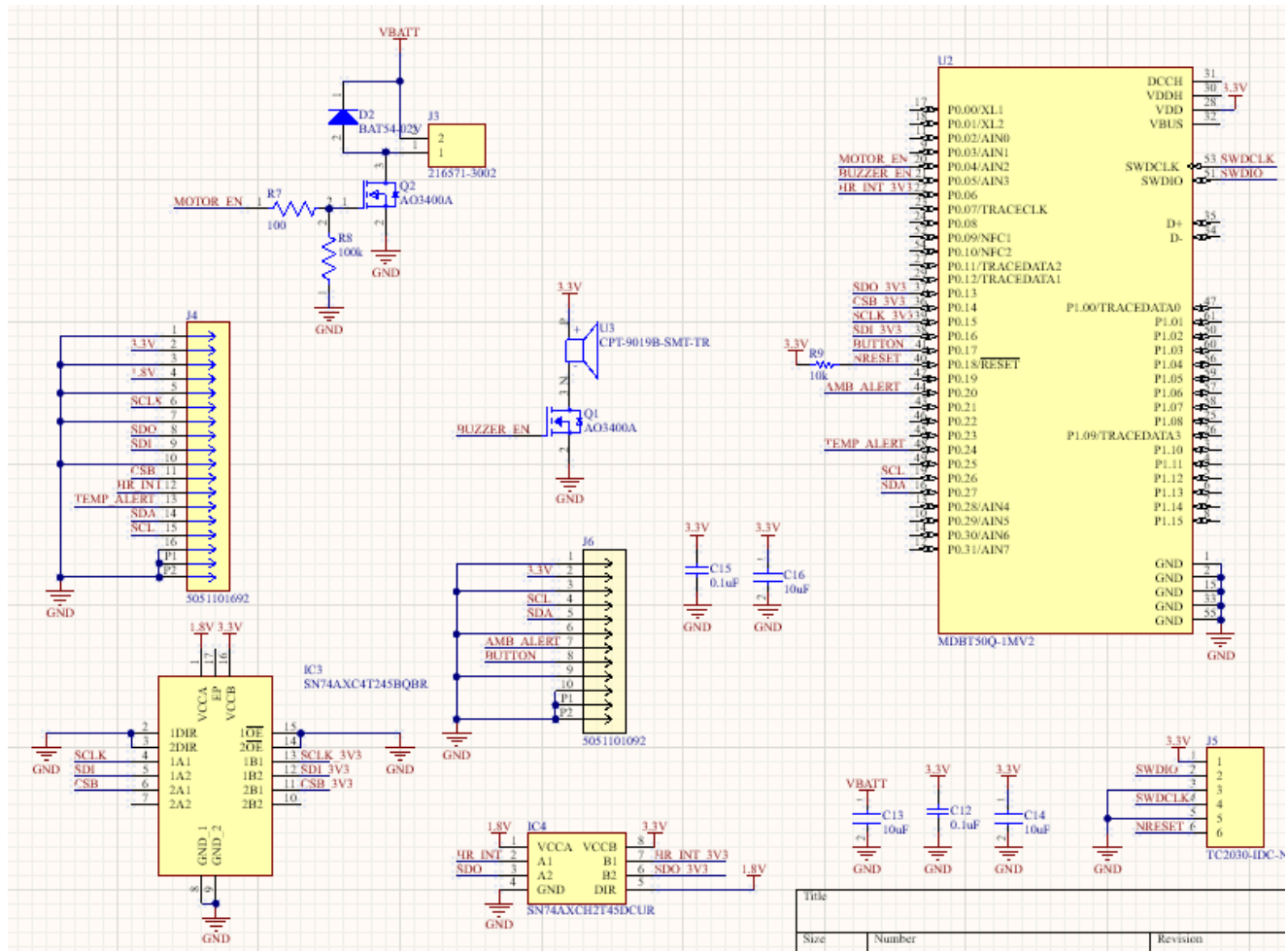


Fig 1. Shows some of the layout (sensor circuitry) and schematics (mcu and power management)

B. Firmware Implementation

The firmware is built on the Nordic SDK with Zephyr RTOS, using the peripheral_hr Bluetooth template as the foundation for BLE connectivity. It is organized into a set of discrete modules, each responsible for a distinct aspect of system behavior. The sensor interface layer (sensors.c/h) handles reading, validating, and calibrating data from the MAX86140 heart rate sensor over SPI, dual temperature sensors (TMP117 & SHT3x-DIS) over I2C, and battery readings from the ASR00035 via ADC. A state manager (state_manager.c/h) implements a four-state machine that transitions between OK, WARNING, CRITICAL, and EMERGENCY states based on configurable vital thresholds. Local alerting is handled by local_alerts.c/h, which drives a linear resonant actuator and speaker for on-device feedback, while power.c/h manages sleep modes and battery optimization. The BLE stack, initialized through the peripheral_hr template, manages advertisement, connection, and notification to the companion smartphone app. All custom modules interface through well-defined AP24Is, with Zephyr's kernel primitives used for task scheduling and peripheral access where applicable.

The firmware performs real-time physiological computation at a rate of 1 Hz. Core body temperature is estimated using a linear physiological model that combines arm temperature and heart rate dynamics:

$$T_c(t) = T_{c,0} + BT(T_{arm}(t) - T_{arm,0}) + B_H(HR(t) - HR_0)$$

where

$T_{c,0}$, $T_{arm,0}$ and HR_0 represent calibrated baseline values captured during device initialization, and B_T and B_H are empirically selected gain coefficients. Baseline values and precomputed constants are stored at calibration to reduce runtime computation. To ensure numerical stability under transient sensor noise, computed core temperature values are bounded within physiologically realistic limits prior to further processing.

The Physiological Strain Index (PSI) is computed using the standard normalized formulation:

$$PSI(t) = 5 * (T_c(t) - T_{c,0}) / (39.5 - T_{c,0}) + 5 * (HR(t) - HR_0) / (180 - HR_0)$$

This produces a bounded strain metric in the range [0, 10]. Denominator terms are precomputed at calibration to avoid repeated division operations, and the resulting PSI value is clamped to the valid interval to prevent overflow or instability caused by anomalous sensor readings.

Risk classification is implemented within state_manager.c/h as a time-qualified finite state machine evaluated once per second. Rather than transitioning based on instantaneous PSI values, the firmware requires sustained threshold violations to reject transient fluctuations and reduce alert chatter. The four operational states are OK, WARNING, CRITICAL, and EMERGENCY. They are defined as following:

OK → WARNING if $PSI \geq 3$ for 30s

OK → CRITICAL if $PSI \geq 7$ for 10s

WARNING → CRITICAL if $PSI \geq 7$ for 10s

CRITICAL → WARNING if $PSI \geq 6.5$ for 15s

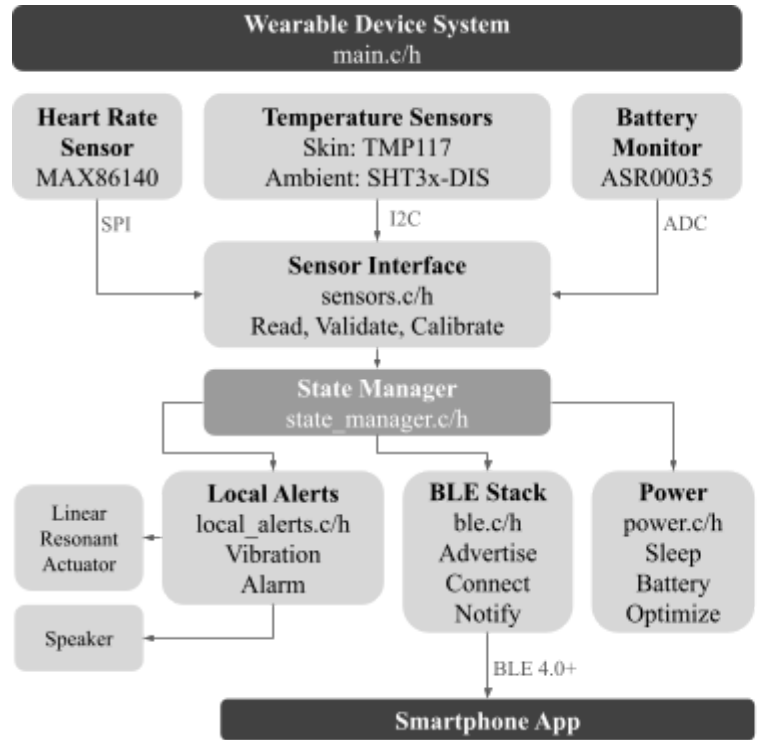
WARNING → OK if $PSI \geq 2.5$ for 30s

EMERGENCY → WARNING if $PSI \geq 3$ for 30s

EMERGENCY → CRITICAL if $PSI \geq 7$ for 10s

When a state transition occurs, the firmware immediately invokes the local alert subsystem and updates the corresponding BLE characteristic to notify the companion mobile application. Because risk computation and state evaluation occur entirely on-device, alert generation remains functional even if BLE connectivity is temporarily interrupted.

Together, the physiological estimation pipeline, finite state machine, and event-triggered alert integration form a robust embedded control layer that translates continuous sensor measurements into actionable safety states.



C. Application Implementation

The VitaBand system includes an iOS mobile application and a BLE interface that together, enable real-time visualization, alert propagation, and data logging. The physical band operates as the BLE peripheral, while the smartphone acts as the central device. Communication is implemented using a custom GATT service derived from the Nordic SDK's peripheral_hr template and extended to support the physiological data specific to VitaBand. The standard heart rate framework was modified to include additional

characteristics for skin temperature, ambient temperature, battery level, computed core temperature, Physiological Strain Index (PSI), and the risk score. BLE connection parameters are tuned to balance responsiveness and power consumption, with connection intervals configured in the 50–100ms range to reduce average current draw while maintaining reliable notification delivery.

To minimize radio airtime and support the 12-hour battery requirement, physiological data is encoded in a binary format prior to transmission. Heart rate and temperature values are transmitted as scaled 16-bit integers, while PSI and system state are encoded using fixed-width integer representations. This encoding reduces packet length and limits transmission time, directly contributing to power efficiency. Once a connection is established, the BLE stack handles advertising, service discovery, characteristic subscription, and notification updates automatically.

The VitaBand mobile application is developed in Swift using Apple's CoreBluetooth framework. The application manages the complete BLE lifecycle, including scanning for peripherals advertising the VitaBand service UUID, establishing a connection, enabling notifications, and continuously receiving physiological updates. Incoming characteristic data is processed within CoreBluetooth delegate callbacks, where raw byte arrays are decoded and scaled into physical units, before being forwarded to the application's data model for display and storage.

The application architecture is organized into three primary layers: a BLE manager layer responsible for connection management and communication, a data model layer responsible for storing current and historical physiological values, and a user interface layer responsible for presenting real-time metrics and risk status. Risk levels are displayed and color coded to ensure rapid interpretation by users and supervisors. When a WARNING, CRITICAL or EMERGENCY state is received, the application generates immediate visual and haptic alerts to reinforce on-device notifications and ensure timely intervention.

VII. TEST, VERIFICATION AND VALIDATION

PCB Bringup and Verification

Hardware testing proceeds in stages, starting at the subsystem level before any firmware is involved and building up to full system validation.

The first stage is power rail verification. With no firmware loaded, we will probe all supply rails under no-load and then loaded conditions — 3.3 V at the TPS63031 output and 1.8 V at the TPS7A2018 output — and verify they are within $\pm 2\%$ of their target voltages across the full LiPo input range of 3.0–4.2 V. We will also verify that the MCP73831 enters constant-current and then constant-voltage charge phases correctly and that the charge current measured at the battery connector matches the 100 mA target set by the 200 k Ω PROG resistor within $\pm 10\%$. If either rail is out of tolerance we will check the feedback resistor network first, then look for solder bridges or cold joints on the fine-pitch packages.

The second stage is analog supply noise measurement. Because the 1.8 V LDO rail feeds directly into the MAX86141 VDDA pin, its noise floor matters. We will use an oscilloscope in AC-coupled mode to measure ripple on the 1.8 V rail while the nRF52840 is active and transmitting BLE packets — the worst-case digital noise condition. The pass criterion is less than 10 mV peak-to-peak ripple, which keeps supply-induced noise well below the MAX86141's LSB equivalent input referred noise. If ripple exceeds this we will add additional bulk capacitance at the LDO output and re-measure.

The third stage is I²C bus verification. We will use a logic analyzer on the SDA and SCL lines to confirm that the MAX86141, TMP117, and SHT31 all ACK their I²C addresses correctly after power-on, that signal rise times are within the 1 μ s limit for standard-mode I²C given our 4.7 k Ω pull-up resistors and estimated bus capacitance, and that there are no collisions or glitches during concurrent transactions. This directly validates the pull-up resistor selection and confirms all three sensors are populated and functional before any higher-level firmware is tested.

The fourth stage is PPG optical verification. With the MAX86141 configured and the SFH 7016 emitter and VEMD5080X01 photodiode installed, we will place the Sensor PCB against the skin and capture the raw ADC output over SPI. A valid PPG waveform should show a clear periodic signal at the heart rate frequency with a signal-to-noise ratio sufficient to resolve the AC component — typically around 0.5–2% of the DC baseline for a wrist-worn device. If the signal is absent or buried in noise we will check the transimpedance amplifier gain settings in the MAX86141 registers, inspect the guard traces for continuity, and verify single-point ground stitching between the analog and digital ground regions.

The final hardware stage is FPC interconnect verification. After assembling all three boards with their FPC cables, we will perform a continuity check on every signal line across both connectors and then repeat the I²C ACK test with the full assembly to confirm that the inter-board connections introduce no signal integrity degradation. We will also flex the FPC through its expected range of motion ten times and re-run continuity to confirm no cracked traces at the connector terminations.

Sensor Accuracy and Signal Integrity

HR output will be compared against a commercially available pulse oximeter (likely an Apple Watch) worn simultaneously on the same subject. Testing will be conducted across a range of activity levels — at rest, walking, and light exertion — to validate that motion artifact rejection keeps the HR estimate within a clinically acceptable margin. This test directly verifies the HR accuracy design requirement and validates that the system can reliably detect overexertion conditions as required by the use case.

Temperature accuracy will be verified by placing the device alongside a calibrated reference thermometer in a controlled environment. The skin sensor will be tested against the

reference while held against the wrist across the 30–42°C physiological range, and the ambient sensor will be evaluated across the Pittsburgh operating temperature range. Readings from both sensors will be logged over I2C and compared against the reference, with the goal of confirming $\pm 0.5^\circ\text{C}$ and $\pm 1.0^\circ\text{C}$ accuracy respectively. Correct thermal isolation of the ambient sensor will also be assessed by comparing its reading against the skin sensor while the device is worn, with an expected differential that reflects ambient rather than body temperature.

State Machine and Alert Behavior

The state manager will be verified by injecting mock vital readings directly into the firmware via a test bench and confirming that state transitions occur at the correct thresholds. Each transition will be exercised in isolation: OK to WARNING, WARNING to CRITICAL, CRITICAL to EMERGENCY, and all de-escalation paths. The emergency button override will be tested by asserting a GPIO interrupt and confirming an immediate transition to EMERGENCY regardless of the current state. These tests verify that the alert dispatch logic behaves deterministically and that the tiered structure reduces false escalations, directly supporting the use-case requirement of reducing alert fatigue.

BLE Connectivity

BLE reliability will be tested by establishing a connection between the device and the companion smartphone app and measuring packet success rate at incremental distances up to and beyond 10 meters in a representative indoor environment. The Nordic nRF Connect app will be used to monitor connection parameters and detect dropped packets.

Battery Life

Average system current will be measured using a bench power supply with current monitoring in place of the battery, with the device running its normal sensing and transmission loop. The measured average current will be compared against the ≤ 41.6 mA design requirement derived from the 12-hour, 500 mAh constraint. If the average current exceeds this threshold, sleep interval tuning and peripheral duty cycling in power.c/h will be adjusted iteratively until the target is met. A full runtime test will then be performed on battery to confirm 12 hours of continuous operation, validating the use-case requirement for a full outdoor work shift.

Schedule (Firmware)

The firmware development schedule is structured around three remaining phases leading the interim demonstration. The foundational work is complete: the Nordic SDK and Zephyr RTOS environment are configured, SPI and I2C drivers for the MAX86140 and MAX30205 are written, and the core state machine is implemented.

The current phase, running through March, focuses on integration and signal processing: connecting sensor outputs to the state manager, implementing the HR estimation algorithm, completing the DMA-based sample pipeline, and bringing up BLE notifications using the peripheral_hr template provided by the SDK. The following phase, spanning

late March through early April, covers power management implementation, full system integration across all three PCBs, and execution of the test and verification procedures described in this section.

VIII. PROJECT MANAGEMENT

A. Schedule

Refer to fig. 1 at the end of this document.

B. Team Member Responsibilities

Sharia will work on PCB design across all three boards, schematic capture, layout, design rule checks, and bring-up, and will take primary ownership of hardware-level testing and debugging once boards are fabricated, including power rail validation, sensor bring-up, and BLE link verification. Emily leads firmware development, covering MCU initialization, sensor drivers, the BLE stack, the PSI risk scoring logic, and the alert state machine. Vidhi leads smartphone app development, including BLE pairing, real-time data display, the tiered notification system, and the cloud relay integration. Responsibilities overlap during integration: Sharia will support Emily on hardware-firmware debugging, particularly for sensor interface issues and signal integrity problems that require both PCB and firmware context to diagnose. All three members share responsibility for integration testing, final validation, and the design document.

C. Bill of Materials and Budget

See Table II at the end of the document.

D. TechSpark Use Plan

We plan to use the TechSpark PCB fabrication facilities to assemble and reflow our custom-designed printed circuit boards, including use of the electronics benches and reflow oven for surface-mount soldering and debugging. Additionally, we may use TechSpark's 3D printing and sewing resources to prototype and refine the wearable enclosure, with material selection based on comfort, durability, and skin-contact requirements.

E. Risk Mitigation Plans

The primary technical risk in our design arises from limited prior experience with the Nordic nRF52840 microcontroller and several of the selected sensors, as this is our first time working within the Nordic BLE ecosystem and integrating these specific medical-grade components. The main risk is ensuring reliable sensor communication, accurate data computation, and stable wireless transmission without data loss or timing errors. To mitigate this risk, we purchased a Nordic development kit to test individual subsystems prior to committing to our custom PCB, allowing us to validate BLE connectivity, firmware configuration, and basic peripheral interfaces in a controlled environment. We will further reduce risk by validating each subsystem independently, first confirming proper I2C communication and raw data acquisition from sensors, then verifying BLE advertising and

packet transmission using Nordic SDK example projects, before incrementally integrating sensing, processing, and communication modules to minimize system-level failures and schedule delays.

IX. RELATED WORK

The problem of physiological monitoring for worker safety has attracted solutions across a broad spectrum, from general-purpose consumer wearables to purpose-built industrial devices. Understanding where existing products fall short helps motivate the specific design decisions made in this project.

Consumer smartwatches such as the Apple Watch and Samsung Galaxy Watch represent the most widely deployed wearables with heart rate and temperature sensing capabilities. These devices use PPG-based optical sensors and communicate over Bluetooth to companion apps, which is architecturally similar to this project. However, they are designed around personal health and fitness use cases rather than occupational safety. Their alert systems are not designed for tiered, threshold-based escalation in hazardous environments, they lack any crew notification infrastructure, and they offer no physical emergency override. Battery life is also a limiting factor, with most flagship smartwatches targeting roughly 18–36 hours under normal consumer use rather than the sustained high-frequency sampling demands of an industrial monitoring context.

SlateSafety's BAND V2 is the closest commercial analog to this project. It is a connected worker IoT device that functions as an early warning system for heat strain and overexertion, measuring heart rate, core body temperature, and exertion in real time. It is purpose-built for industrial deployment and has seen real-world use in settings such as the U.S. Department of Energy's Hanford Site. However, it is a commercial product with cloud-dependent infrastructure, meaning data is routed through external servers for processing and storage. This project diverges by performing all risk scoring on-device, eliminating the dependency on network connectivity and addressing data privacy concerns that may arise in certain employment contexts.

On the research side, NIH-sponsored work has explored lightweight biopatches worn on the chest that measure skin temperature, hydration, and vital signs, with the goal of feeding data into AI algorithms that can predict heat illness before it occurs. NBC News While promising, these systems are not yet commercially available and depend on significant backend computation. This project's on-device state machine approach sacrifices predictive sophistication in favor of real-time determinism and offline reliability, which better suits the MVP goals and resource constraints of an embedded prototype.

Across all of these comparisons, the distinguishing characteristics of this design are its fully on-device processing pipeline, its tiered alert state machine, its dual skin-and-ambient temperature configuration for improved

thermal accuracy, and its manual emergency override. Such features together address gaps left by both consumer wearables, existing industrial solutions, and research efforts.

X. SUMMARY

VitaBand is a wearable, upper-arm physiological monitoring system designed to reduce the risk of heat-related illness and fall-related injury in outdoor workers. The system uses the users' heart rate, skin temperature, and the ambient temperature to alert the user when they are at risk of heat exhaustion. By continuously estimating physiological strain and issuing timely alerts, the design provides workers with actionable feedback and enables them to make data-driven safety decisions. Our stakeholders include workers, site managers, and employers. They will be impacted by early detection of dangerous conditions, reduced medical incidents, and enhanced compliance with occupational safety protocols.

GLOSSARY OF ACRONYMS

BLE - Bluetooth Low Energy
MQTT – Message Queuing Telemetry Transport
OBD – On-Board Diagnostics
RPI – Raspberry Pi

REFERENCES

- [1] A. Tin, "Experimental sensors aim to detect early signs of heatstroke and warn farmworkers," *NBC News*, Jul. 2024. [Online]. Available: <https://www.nbcnews.com/health/health-news/biosensors-aim-detect-heatstroke-warn-workers-rcna168881>
- [2] Apple Inc., "Introduction to Core Bluetooth," Apple Developer Documentation, 2015. [Online]. Available: https://developer.apple.com/library/archive/documentation/NetworkingInternetWeb/Conceptual/CoreBluetooth_concepts/AboutCoreBluetooth/Introduction.html
- [3] C. D. Ashley, T. E. Bernard, and V. Caravello, "Predicting compensable versus uncompensable heat stress from physiological strain index," *Med. Sci. Sports Exerc.*, vol. 36, no. 5, May 2004. [Online]. Available: <https://stacks.cdc.gov/view/cdc/199900>
- [4] SlateSafety, "BAND V2," [slatesafety.com](https://www.slatesafety.com). [Online]. Available: <https://www.slatesafety.com>

AI Usage (for writing the report): Claude Sonnet 4.6

AI Usage (for writing the report): ChatGPT 5.2

Table II: Bill of Materials

#	Description	Value / Notes	Qty	Manufacturer	Manufacturer Part Number	Supplier	Supplier Part Number	Unit Price (USD)	Subtotal (USD)
16	Capacitor, 10 μ F, 16V, X5R, 0805	Bulk / Input Cap	1	Samsung Electro-Mechanics	CL21A106KOQNNNE	Mouser	187-CL21A106KOQNNNE	\$0.100	\$0.10
17	Capacitor, 10 μ F, 25V, X7S, 0805	High-Voltage Bulk Cap	1	TDK	C2012X7S1E106K125AC	Mouser	810-C2012X7S1EK125AC	\$0.540	\$0.54
Resistors									
18	Resistor, 100 Ω , 1%, 0.1W, 0603	Current Limiting / Pull	1	Yageo	AC0603FR-13100RL	Newark	AC0603FR-13100RL	\$0.003	\$0.00
19	Resistor, 2 k Ω , 1%, 0.1W, 0603	I2C Pull-up / Bias	2	Yageo	RC0603FR-072KL	Farnell	3495801	\$0.007	\$0.01
20	Resistor, 4.7 k Ω , 1%, 0.1W, 0402	I2C Pull-up	4	Yageo	RC0402FR-0747KL	Mouser	603-RC0402FR-0747KL	\$0.004	\$0.02
21	Resistor, 5.1 k Ω , 1%, 0.1W, 0603	I2C / USB Pull-up	2	Yageo	RC0603FR-075K1L	Mouser	603-RC0603FR-075K1L	\$0.007	\$0.01
22	Resistor, 10 k Ω , 1%, 0.1W, 0402	Pull-up / Pull-down	3	Yageo	RC0402FR-0710KL	Mouser	603-RC0402FR-0710KL	\$0.012	\$0.04
23	Resistor, 100 k Ω , 1%, 0.1W, 0402	Pull-up / Bias	1	Yageo	RC0402FR-07100KL	Farnell	9239472	\$0.004	\$0.00
24	Resistor, 100 k Ω , 1%, 0.25W, 0603	Voltage Divider / Bias	1	Yageo	SR0603FR-7T100KL	Mouser	603-SR0603FR-7T100KL	\$0.130	\$0.13
25	Resistor, 200 k Ω , 1%, 0.1W, 0603	Charge Rate Set (MCP73831)	1	Yageo	AC0603FR-13200KL	Arrow	AC0603FR-13200KL	\$0.003	\$0.00
26	Resistor, 1 M Ω , 1%, 0.1W, 0603	High-Value Bias / Filter	1	Vishay	CRCW06031M13FKEA	Mouser	71-CRCW06031M13FKEA	\$0.100	\$0.10
Inductors									
27	Inductor, 1.5 μ H, $\pm$ 30%, 1.8 A, SMD 3015	Buck-Boost Power Inductor	1	Taiyo Yuden	NRS3015T1R5NNGH	Mouser	963-NRS3015T1R5NNGH	\$0.380	\$0.38
Discrete Semiconductors									
28	LED, Orange, Clear, 0402 SMD	Status Indicator LED	1	Lite-On	LTST-C190KFCT	Mouser	859-LTST-C190KFCT	\$0.170	\$0.17
29	LED/Emitter, Multi-Chip IR/Green/Red, SMD	PPG Optical Emitter (530/655/940 nm)	1	Osram Opto	SFH 7016	Mouser	720-SFH7016	\$1.590	\$1.59

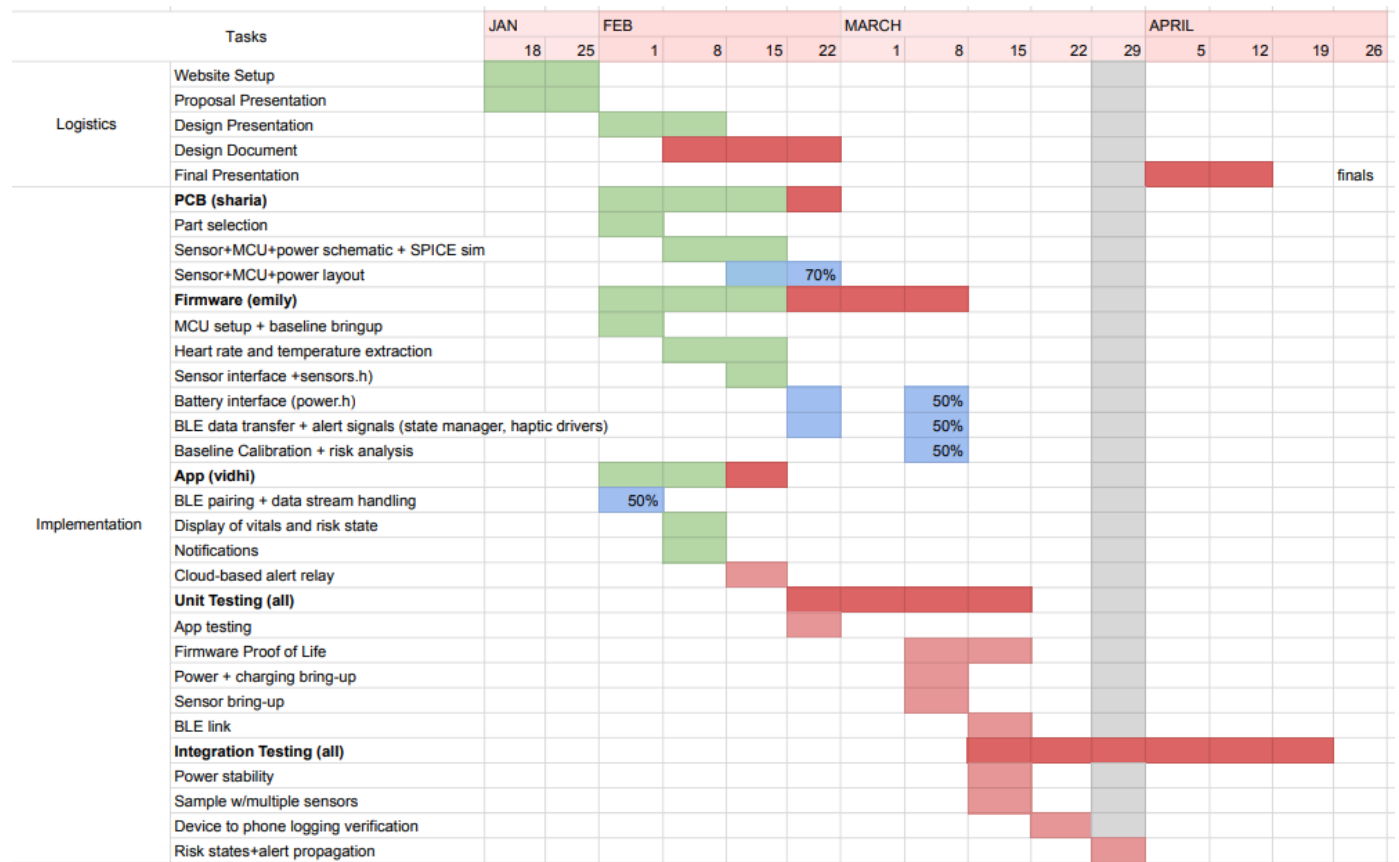


Fig. 2: Gantt chart showing responsibilities and status of completion