Machine Shop Buddy Verification System

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Contents

Acronyms & Pre-Requisite Information

- ADC - analog-to-digital converter
- CC/CV - constant current/constant voltage
- CCM - continuous conduction mode
- DRS - Division of Research Safety
- ECE - Electrical and Computer Engineering
- ESR - equivalent series resistance
- HR - heart rate
- PWM - pulse width modulation
- PCB - printed circuit board
- RSSI - received signal strength identifier
- SoC - System on Chip
- UVLO - under-voltage lockout

1 Introduction

Working in a machine shop alone is dangerous and the Machine Shop Buddy System sets out to guarantee at least two individuals are in the machine shop for the equipment to operate. Machinists must constantly pay attention to ensure that they are not misusing a machine in a dangerous way. Accidents in college machine shops are especially dangerous. Students are often allowed to work odd hours and a second person is not always in the room to help in an emergency.

Some accidents have even resulted in death. In 2011, a Yale student died working late one night on a lathe [1]. Her hair was out and got caught in the spinning mechanism. She was suffocated by her own hair and died. No one was nearby to power down the machine or call for help.

This semester our goal is to create a two-factor system that will attempt to enforce a buddy system. We will use heart rate monitoring to ensure two unique users are present and a trilateration system to ensure the heart rate monitors are each being worn by a person in the machine shop and not a person in a room next door.

We selected this project to help make university machine shops safer. There is a need for this type of system in a machine shop here at the University of Illinois. The system we create could also be adapted and used by many machine shops around the country. According to the Bureau of Labor Statistics, the Fabricated Metal Product Manufacturing industry had 34 fatalities in 2014 [2]. We envision our system being used to help reduce this number and ensure a safer working environment for machinists.

2 Design

Our system can be broken out into four physical systems: a main hub, a heart rate (HR) band, trilateration receivers, and a user feedback system.

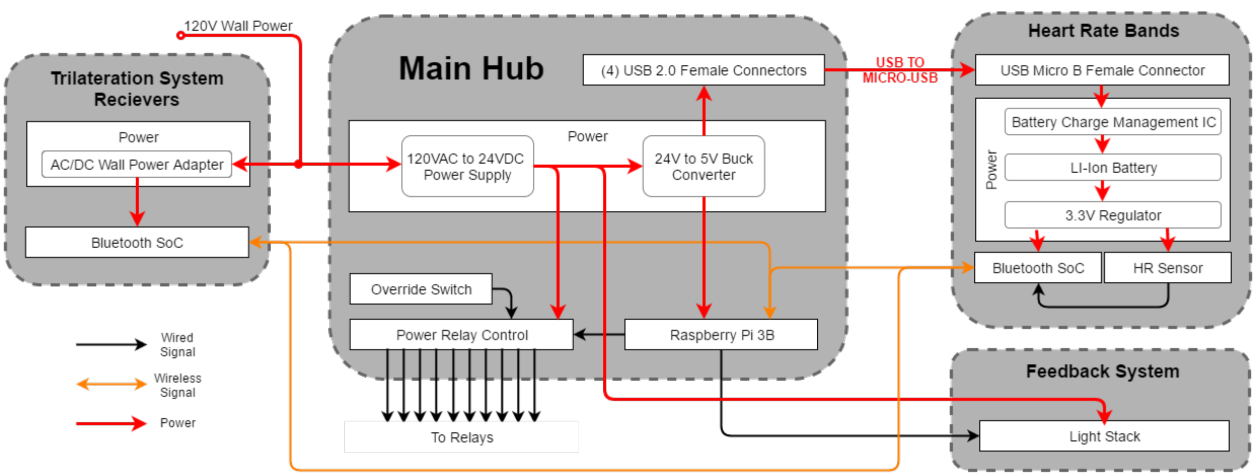

Figure 1: Block Diagram for Machine Shop Buddy System

3 Block Description

3.1 Main Hub

The main hub is the centerpiece of the Machine Shop Buddy System. It takes in signal strength data from the trilateration beacons and heart rate data from the heart rate bands, and outputs signals which control power relays to the machinery in the room as well as signals that control the feedback lights and power for four USB HR band charging stations. The main hub can be further broken down into three parts: a power module, power relay control, and the Raspberry Pi 3 processor with Bluetooth.

3.1.1 Power Module

Input: 115/230VAC from wall outlet
Output: 24-27.2VDC adjustable voltage range to power relays, +5V±5% to Raspberry Pi and four (4) USB 2.0 charging stations

The power module is responsible for properly and efficiently converting AC wall power to the various DC outputs. These outputs take on two voltages: 24-27.2VDC and 5VDC. Table 1 shows the power load of the main hub. Power requirements of the load were taken into consideration in the output power column and power losses due to inefficiencies were accounted for in the dissipated power column. Total power is the sum of the two columns. The power supply was oversized by 20% as a safety factor for the main hub.

Table 1: Power Requirements of Main Hub

Load	**Feeds**	**Output Voltage**	**Output Power**	**Eff.**	**Dissipated Power**	**Total Power**
LM2678T-5.0/NOPB Voltage Regulator	Raspberry Pi, HR band Charging Station	5V	25W	86.5%	3.9W	28.9W
Power Relay Control w/FDN359BN Logic Level MOSFET	All Relay Outputs	27.2V (max)	90W	95%	4.7W	94.7W
					Total Load	123.6W
					Safety Factor	x1.2
				Required	Power Supply	148.3W

The LS150-24 was selected for the main hub power supply. The power supply can accept 115V or 230V AC power from a wall outlet and convert it to 24-27.2VDC with a max current of 6.5A and max wattage of 150W. It has over-current protection for any currents over 110%, or 7.15A @ 24V [3]. This protection to the system is important for the main hub in case one of the 24V switch terminals from the power relay control were shorted.

The LM2678 5V switched voltage regulator is used to efficiently step down the 24-27.2VDC to 5VDC. The chip holds an input voltage range of 8-40V, built-in thermal protection, and current limiting. It manages the power to four USB ports for HR band charging and powering the Raspberry Pi. Table 2 shows the pin connections for the LM2678.

The regulator gives suggested component sizes, but essentially acts as the switch for a buck converter with feedback. First, the inductor is sized using equation 1 where f_{SW} is 260kHz for the LM2678, $V_{in} = 27.2V$,

Table 2: LM2678 Voltage Regulator Pin Connections [4]

Pin	**Function**	**Connection**
1	Switch_output, voltage reg. switch output	To bootstrap cap.,head of diode, and 22uH inductor
2	Input, voltage reg. input voltage	To output of ac/dc power supply
3	CB, boost capacitor pin	To boost capacitor
4	GND, ground pin	To PCB ground plane
5	NC, not connected	-
6	FB, feedback loop	To output side of 22uF inductor
7	ON/$\overline{OFF}$, on/off switch for regulator	To resistor voltage divider

$V_{out} = 5V$, D is the duty ratio or 0.184, and ΔI_{Lp-p} is assumed to be about 1/5th of the maximum output current, or $0.2 * 5A = 1A$.

$$V_L = L\frac{dI}{dt} \rightarrow \Delta I_{Lp-p} = \frac{DT(V_{in} - V_{out})}{L} \rightarrow L = \frac{(V_{in} - V_{out})D}{f_{sw}\Delta I_{Lp-p}} \quad (1)$$

This gives an inductor value of 15.625μH. To give some margin and guarantee CCM operation, a 22μH inductor was chosen for this design. CCM is used to maximize charge storage in the inductor. The core must be powdered iron or ferrite material in order to handle the 260kHz frequency.

The output capacitor is used for sizing the voltage ripple on the output signal. ESR and inductor current ripple also impact how great the voltage ripple is. For our design a voltage ripple of $\Delta v = 0.25V$ is desired. The equation below determines the minimum amount of output capacitance required to have this voltage ripple [5].

$$\Delta v = \sqrt{V_{out}^2 \frac{LI_{out,max} + \frac{\Delta I_{Lp-p}}{2}}{C_o}} - V_{out} \rightarrow C_o = \frac{L(I_{out,max} + \frac{\Delta I_{Lp-p}}{2})}{(\Delta v + V_{out})^2 - V_{out}^2} \quad (2)$$

Given $I_{out,max} = 5A$, $\Delta I_{Lp-p} = 1A$, $V_{out} = 5V$, and $L = 22\mu$H, the output capacitance must be greater than 119.8μF. This equation does not take into a account ESR of the capacitor and the added ripple ESR jump causes. A 35V rated 560μF capacitor with low ESR ($\tan\delta = 0.12$) is used on the output [6]. A capacitor sized over 550% of the required capacitance was suggested for the LM2678 to maintain a unity gain bandwidth of less than 1/6th the switching frequency. Keeping unity gain bandwidth below 40kHz will help keep the switching regulator circuit stable [4].

The input capacitor must be rated at least 1.3 times the maximum input voltage (27.2V x 1.3 = 35.4V), and must also be able to handle an RMS current of at least half the maximum value of the output current (2.5A). A 63V rated 1200μF input capacitor was recommended for the LM2678 switch regulator. The capacitance chosen is much higher than the 10-22μH per output ampere required, but it is a capacitor that has proven successful with this converter and meets the RMS current capacity with the ability to handle 2.51A. It too has a low ESR rating with a dissipation factor of only $\tan\delta = 0.09$ [7].

The MBR1045 Schottky diode was chosen for the regulator diode. It has a reverse-repetitive maximum voltage of 45V and a maximum forward current of 10A. Both ratings are enough to handle the maximum input voltage and maximum output current that the diode would see [8].

The circuit schematic for the main hub is shown on Figure 2.

3.1.2 Power Relay Control

Input: 24VDC power, one control signal per power relay output
Output: Ten 24VDC output screw terminals

The Power Relay Control module switches on and off up to ten 24VDC output screw terminals. These screw terminals will allow the user to feed 24VDC to the coil of a relay, power or control, located on each machine. 24VDC is becoming the control system voltage of choice and was chosen for its safety and performance as opposed to higher level control voltages [9].

An adjustable voltage between 24-27.2VDC gets sent in from the power supply. This range of voltages allows the user to account for DC line losses if the 24V signal needs to be sent to equipment located farther away from the main hub. Power goes through the drain to source connections of an N-channel logic-level FDN359BN MOSFET. This is what switches the 24V for the screw terminal. With a 1.8V threshold gate-source voltage, the MOSFET can be controlled by a logic-level 3.3VDC control signal from the Raspberry Pi. Each relay has an individual MOSFET allowing the Raspberry Pi to select which relay outputs are enabled.

The number of power relay circuits was chosen so that each of the seven machines that are in the on-campus machine shop could have their own power relay and to leave room for more machines to be added.

Figure 2 shows the Power Relay Control circuit schematic. The control signal RELAY_X comes from the Raspberry Pi and SCREW_X is the control signal for the given relay. The control signal is output from the Main Hub through a screw terminal.

3.1.3 Raspberry Pi

Input: 5V power, heart rate from each heart rate band, signal strength of heart rate bands
Output: 3.3V control signal to each power relay control, 3.3V control signal to each feedback light control

We chose a Raspberry Pi to ease implementation of features outside the scope of our project. For our project to be used, the machine shop administrators want a card swipe system and a database that lists which machines each user is allowed to use. The Raspberry Pi will make it easy for them to add a card reader via USB and they will be able to implement the database lookup far easier on a full application processor than on an embedded microprocessor.

The Raspberry Pi will receive data via bluetooth from the heart rate bands and the trilateration receivers. The heart rate bands will send their calculated beats per minute. The trilateration receivers will send the signal strength that they measure from each heart rate band. The Raspberry Pi will be programmed to compare the heart rates and signal strength data to determine if the machines should be enabled. It will output one 3.3VDC control signal for each of the machines to the Power Relay Control module. The Raspberry Pi will also output one 3.3VDC control signal for each of the feedback lights.

The Raspberry Pi will be powered by a 5VDC regulator. It will be connected to the Main Hub PCB through

Table 3: Raspberry Pi Pin Connections

Pin	**Function**	**Connection**
2,4	5V, 5 volt power connection	Voltage regulator 5V line
6,9,14,20, 25,30,34,39	GND, ground connection	Ground of PCB
7	RELAY_1	Control pin of power relay 1
13	RELAY_2	Control pin of power relay 2
15	RELAY_3	Control pin of power relay 3
16	RELAY_8	Control pin of power relay 8
18	RELAY_9	Control pin of power relay 9
22	RELAY_10	Control pin of power relay 10
27	RELAY_4	Control pin of power relay 4
28	STATUS_LED	Anode of the status LED
29	RELAY_5	Control pin of power relay 5
31	RELAY_6	Control pin of power relay 6
36	RED_LIGHT	Control pin of red feedback light output
37	RELAY_7	Control pin of power relay 7
38	YELLOW_LIGHT	Control pin of yellow feedback light output
40	GREEN_LIGHT	Control pin of green feedback light output
1,3,5,8,10, 11,12,17,19, 21,23,24,26, 32,33,35	Unused	Break out with through holes on PCB for future expansion

a ribbon cable between the 0.1" headers on the Raspberry Pi and the Main Hub PCB. The pinout of the ribbon cable is shown in Figure 2 and Table 3 gives a pin summary.

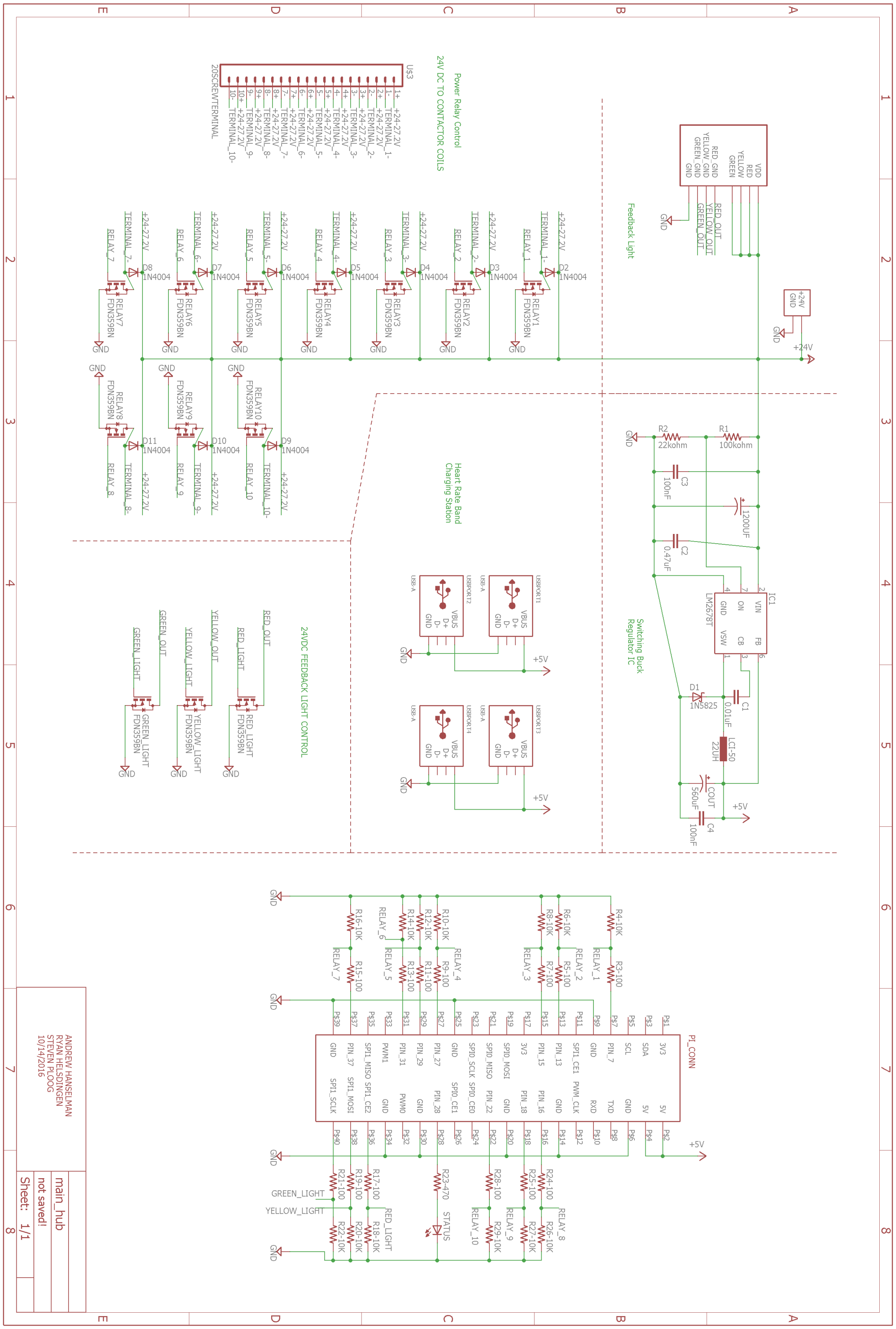

Figure 2: Main Hub Schematic

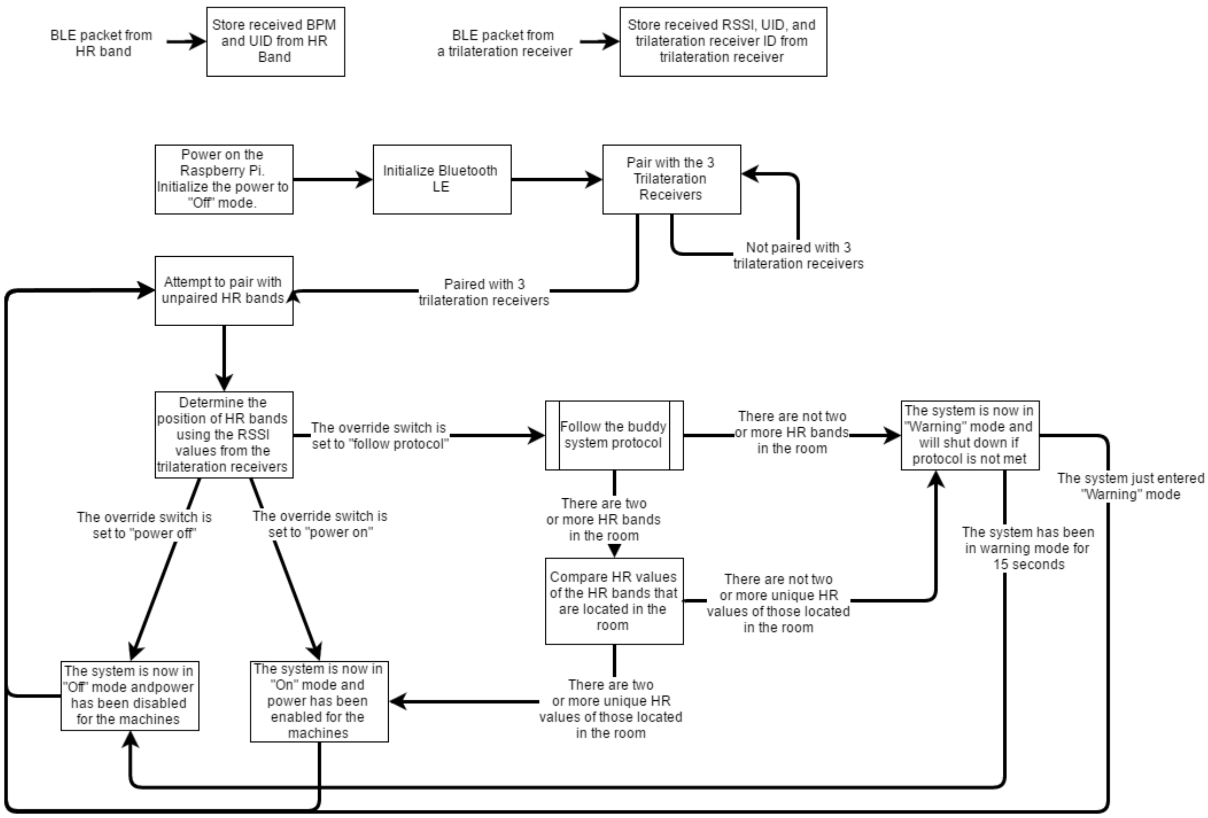

Figure 3: Main Hub Flowchart

3.2 Heart Rate Band

The Heart Rate Band will detect the heart rate of the user. It will also be used to help locate the user within the room, or to determine that they are out of the room. We will use an optical pulse sensor along with a SoC to detect heart rate. The SoC will be equipped with Bluetooth in order to communicate with the Main Hub and with the Trilateration System. The Heart Rate Band can be broken down further into three subsystems: a power module, the Bluetooth enabled SoC and the heart rate sensor.

3.2.1 Power Module

Input: +5V from USB or wireless charging receiver, +3.45-4.20V Rechargeable 500mAh Li-Ion Polymer Battery

Output: +3.3V±2% for nRF51822 Bluetooth SoC and Heart Rate Sensor

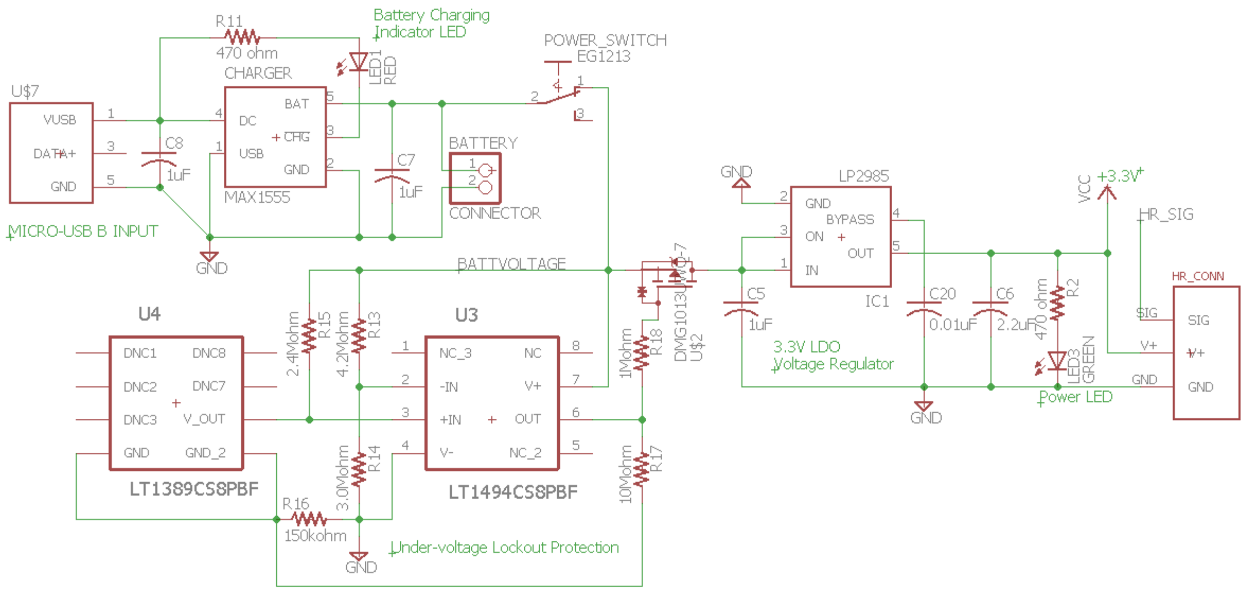

Figure 4: Circuit Schematic of HR Band Power Module

The power module for the HR band is tasked with the responsibility of efficiently powering the nRF51822 and HR sensor while properly charging and discharging the battery.

The 523334 LiPo battery was chosen for several reasons. Lithium-Ion batteries use a simple linear charging process known as constant current/constant voltage (CC/CV). At +3.7V nominal voltage, the battery balances both size and functionality. The 523334 has a high capacity for being slightly larger than a quarter in size. This battery form factor reduces bulk and weight to the wearable while meeting all power requirements of the device.

Table 4: Voltage/Current Limitations for devices used in HR band.

Devices	**Voltage/Current Requirements**
500mAh Lithium-Ion Polymer Battery 523334	Nominal Output Voltage: +3.7V Charging Voltage: +4.20V Charge Current: Max 500 mA
Heart Rate Sensor	Voltage: Max +5V, Min +3V Current: 6mA @ 3.3V
nRF51822 Bluetooth SoC	Voltage: Max +3.6V Min +1.8V Current: 13.88mA
SPDT slide switch	Voltage: Max +500V
MAX1555 LiPo Charger	Input Voltage: Max +7V Min +3.7V Charging Voltage: 4.20±1% Charging Current: Max 340mA
LP2985 +3.3V Regulator	Input Voltage: Max +16V, Min +2.5V Output Voltage: +3.3V±1% Output Current: Max 150mA

Charging the battery requires a constant charge voltage and current of +4.20V @ 1C maximum (1C =

500mA). The MAX1555 Charge Management Controller runs through a CC/CV charge algorithm that provides the battery its charging needs while protecting the battery from overcharge and overheating. This battery allows charging up to 1C, however most manufacturers agree that Li-Ion batteries should not be charged over 0.8C to maintain longevity[3]. The MAX1555 LiPo Charger sends a safe maximum of 340mA or 0.68C to the battery. Table 5 refers to the pin connections of the charge controller chip.

Table 5: MAX1555 Pin Connections [10]

Pin	**Function**	**Connection**
1	USB, USB Port Charger Supply Input	Not Used
2	GND, System Ground Terminal	To Ground Source
3	$\overline{CHG}$, Charge Status Indicator	To Load
4	DC, DC Charger Supply Input	To VUSB on Micro-USB female connector with coupling capacitor to ground
5	BAT, Battery Connection	To positive terminal of battery with coupling capacitor to ground

Two features of the MAX1555 charge controller are used in our design: a charging indicator produced by an active-low open-drain pin out, $\overline{CHG}$, and package thermal limiting. The $\overline{CHG}$ pin toggles between low (L) and high impedance (HI-Z) and follows the outputs in Table 6 for given modes of the charge cycle. A red LED in series with a 470Ω resistor connects the +5V of the DC pin to the $\overline{CHG}$ pin. The charging LED lights up when current going to the battery is over 50mA.

Table 6: Charging Indicator LED.

Charge Cycle	$\overline{CHG}$	**LED**
Precharge	L	ON
Constant Current	L	ON
Constant Voltage (Charge Complete)	HI-Z	OFF
Thermal Limit Reached ($I_{charge} > 50mA$)	L	ON
Thermal Limit Reached ($I_{charge} < 50mA$)	HI-Z	OFF
No Battery Present	HI-Z	OFF
No Input Power Present	HI-Z	OFF

Package thermal limiting protects the battery from overheating throughout its charge cycle. Charging current gets reduced by about 17mA for every degree C above a die temperature of +110 degree C. [10] With no thermal pad on the chip, connecting the ground pin to a large ground plane will help dissipate power from the MAX1555.

Placed between the battery and the load is a UVLO circuit used to protect the Li-Ion battery from depleting its voltage below its minimum allowed 3.0V. Figure 5 shows the circuit used. Our circuit uses an LT1494 op amp as a voltage comparator to determine if the voltage of the battery is below the threshold voltage. The output of the comparator controls the gate of a P-channel MOSFET which manages whether the battery can send power to the load or not. The reference voltage is managed by a high precision, low-power LT1389 chip.

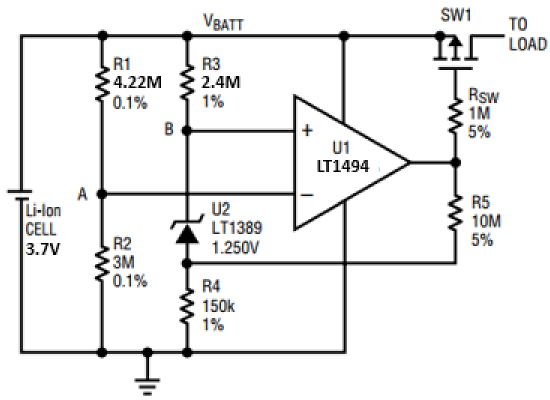

Figure 5: Under-voltage Lockout Circuit [11]

For this battery, a cutoff voltage of 3.3V was decided on since it is higher than the rated 3.0V discharge cutoff of the battery yet lower than the minimum voltage the LDO regulator can accept. Equation 3 uses a voltage divider of R_1 and R_2 to determine the voltage at node A when the battery voltage hits its cutoff, equation 4 verifies the current going through the LT1389 (I) is near its rated 800nA, and equation 5 determines the reference voltage at node B. This voltage should match with the voltage at node A when the battery is at its threshold voltage.

$$V_A = V_{th}\frac{R_2}{R_1 + R_2} \rightarrow V_A = 3.3V\frac{3M\Omega}{3M\Omega + 4.22M\Omega} = 1.371 \tag{3}$$

$$I = \frac{V_t - 1.25V}{R_3 + R_4} \rightarrow I = \frac{3.3V - 1.25V}{2.4M\Omega + 150k\Omega} = 803.9nA \tag{4}$$

$$V_B = 1.25V + IR_4 \rightarrow V_B = 1.25V + (803.9nA)(150k\Omega) = 1.371 \tag{5}$$

The output voltage of the battery charge controller can range with the voltage of the battery. That is, it can go as low as +3.0V and as high as +4.2V. The nRF51822 Bluetooth SoC has a maximum voltage of +3.6V and an absolute maximum voltage of +3.9V. Our design requires a +3.3V regulator in front of the nRF51822 to guarantee voltage protection. The LP2985-N micropower voltage regulator is used for its low dropout voltage (0.15V) and its ability to take in the full range of voltages that the battery may put out between charging and discharging states [12]. To maintain voltage consistency, the HR sensor is also placed passed the +3.3V regulator in parallel with the Bluetooth SoC. A green LED with a forward voltage of 2.1V is also placed to signal power. At 3.3V with a 240 ohm resistor in series, the LED draws 5mA of load current while on.

Regulating at a higher voltage benefits the HR sensor which returns a better signal at +3.3V compared to a +3.0V input. However, a drawback of the LDO regulator is the +3.45V input (3.3 + dropout voltage) required for it to output useful power. The battery is useless when its voltage drops below that threshold. According to the battery's 0.2C discharge curve in Figure 6, the battery voltage is deemed useless when about 5% of its capacity remains.

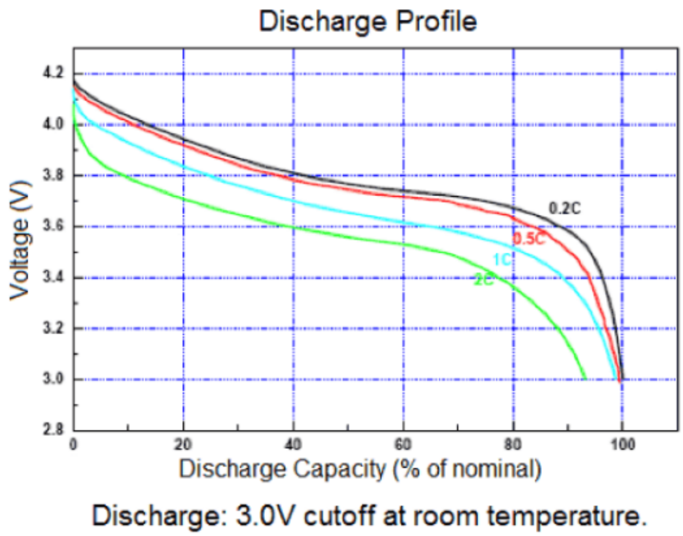

Figure 6: 523334 Battery Discharge Curve

Table 7 shows a summary of the loads in the HR band.

Table 7: Power Management for HR band battery.

Device	**Voltage**	**Current**	
		Active	**Quiescent**
nRF51822 Bluetooth SoC	+3.3V	13.88mA	0.6μA
Heart Rate Sensor	+3.3V	6mA	0mA
MAX1555 Battery Chargers	+4.2V	5μA	5μA
LP2985N-3.3 LDO Regulator	+3.3V	0.6mA	5μA
LED (1)	2.2V	5mA	0mA
	Total	25.485mA	10.6μA

Battery	**Capacity**
523334 Lithium-Ion Polymer	500mAh

The battery has a nominal capacity of 500mAh, 475mAh (95%) of which is usable. We can solve for the minimum amount of time our battery will be able to run off of a full charge.

$$t_{batt} = \frac{capacity}{i_{max}} = \frac{475mAh}{25.485mA} \approx 18.64hours \tag{6}$$

This calculation assumes the battery is deemed too low voltage when the capacity remaining is about 5% and no degradation has occurred. It also assumes that the load has no additional losses and is running at maximum power for the full time. A slide switch is added between the battery and input of the LDO regulator to prevent quiescent currents from draining the battery when not in use.

3.2.2 Bluetooth SoC

Input: 3.3V power, Heart Rate Sensor signal
Output: Status LED control signal, heart rate data

Our Bluetooth SoC is a Nordic Semiconductor nRF51822-QFAA-R7. This SoC has multiple ADC inputs that can be used for the Heart Rate Sensor and digital outputs to control status LEDs. It was chosen for its Bluetooth capabilities and the availability of both standalone packages and development boards. In addition to all this, the ADC inputs are tolerant of 3.6V when the SoC is powered with 3.3V. This was needed to properly interface with the Heart Rate Sensor which will output a 0-3.3V signal when powered by 3.3V.

The SoC will digitally filter the Heart Rate Sensors input signal to detect heart beats. To detect heart beats, we will use two simple moving averages. By comparing a short period moving average and a long period moving average we can detect a beat by looking for areas where the short period moving average has a greater value than the long period moving average. We can calculate the simple moving average with equation 7, where p is the number of samples per period, i is the current sample and s is the list of samples.

Moving Average:

$$\sum_{n=1}^{p} \frac{s[i-n]}{p} \tag{7}$$

Sampling every 25ms and using a short period moving average of 250ms with a long period moving average of 1s we were able to obtain the result shown in Figure 6 [13]. The square wave represents the detected beats. By counting the number of rising edges we can count the number of beats.

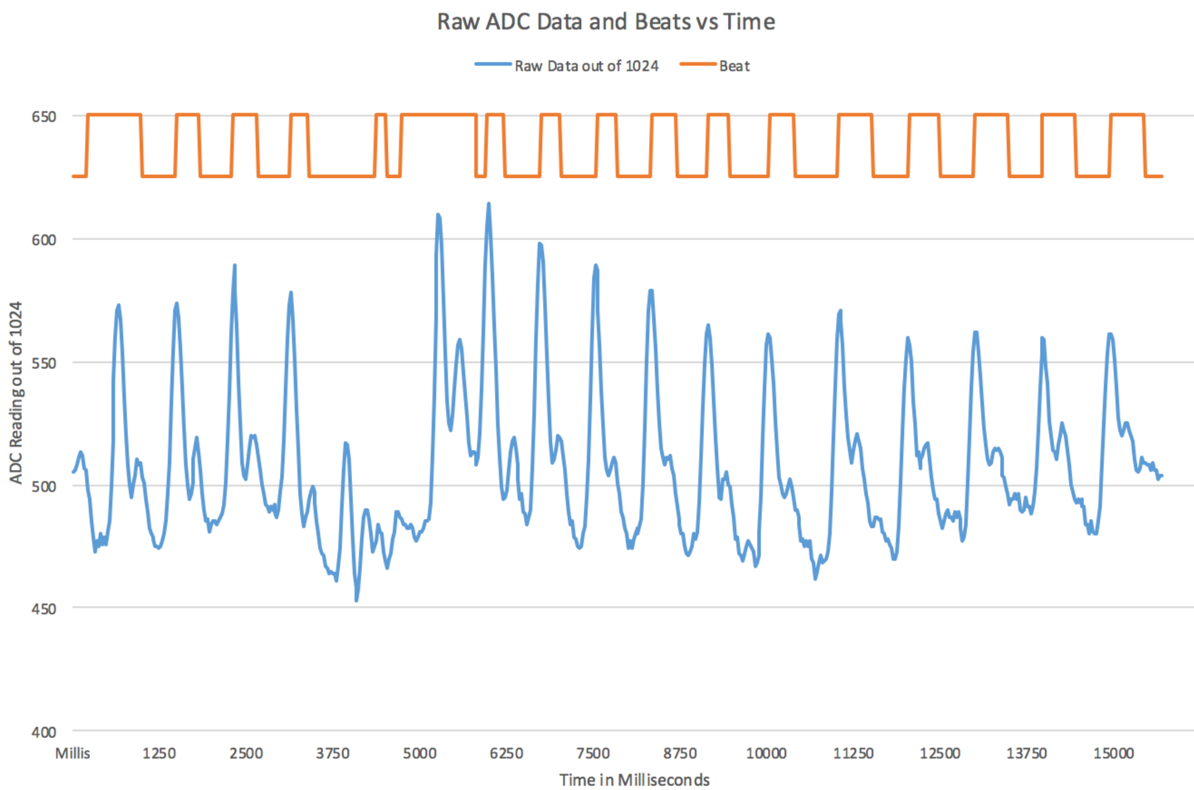

Figure 7: Beat Detection Plot

The SoC will keep a count of recent beats and use that count to determine heart rate which it will then report to the Main Hub via Bluetooth. The SoC will also control a status LED that turns on when it is connected to the Main Hub and blinks when disconnected from the Main Hub.

Shown below are the pin summary for the SoC in Table 8 and the Bluetooth SoC system schematic in Figure 7.

Table 8: nRF51822 Bluetooth SoC Pin Connections [14]

Pin	Function	Connection
1,12	VDD, 3.3V input	Output of voltage regulator
2	DCC, power supply for radio	Pins 35 and 36
7	HR_SIG, input from HR sensor	Signal pin of heart rate sensor
13,33,34	VSS, ground connection	Ground plane of PCB
14	STATUS_LED, control the status LED driver	Control pin of LED driver
23	SWDIO, debug/programming IO	Break out to through hole
24	SWDCLK, debug/programming	Break out to through hole
29	DEC2, power supply decoupling	Through capacitor to ground plane
30	VDD_PA, power supply for on chip power amp	Antenna balun
31	ANT1, differential antenna connection	Antenna balun
32	ANT2, differential antenna connection	Antenna balun
35,36	AVDD, power supply for radio	Pin 2
37	XC1, input for 16MHz crystal	Crystal
38	XC2, output for 16MHz crystal	Crystal
39	DEC1, power supply decoupling	Ground plane through capacitor
49	DIE_PAD, ground connection	Ground plane
3-6,8-11,15-22,25-28,40-48	Unused	Breakout to through holes for future expansion

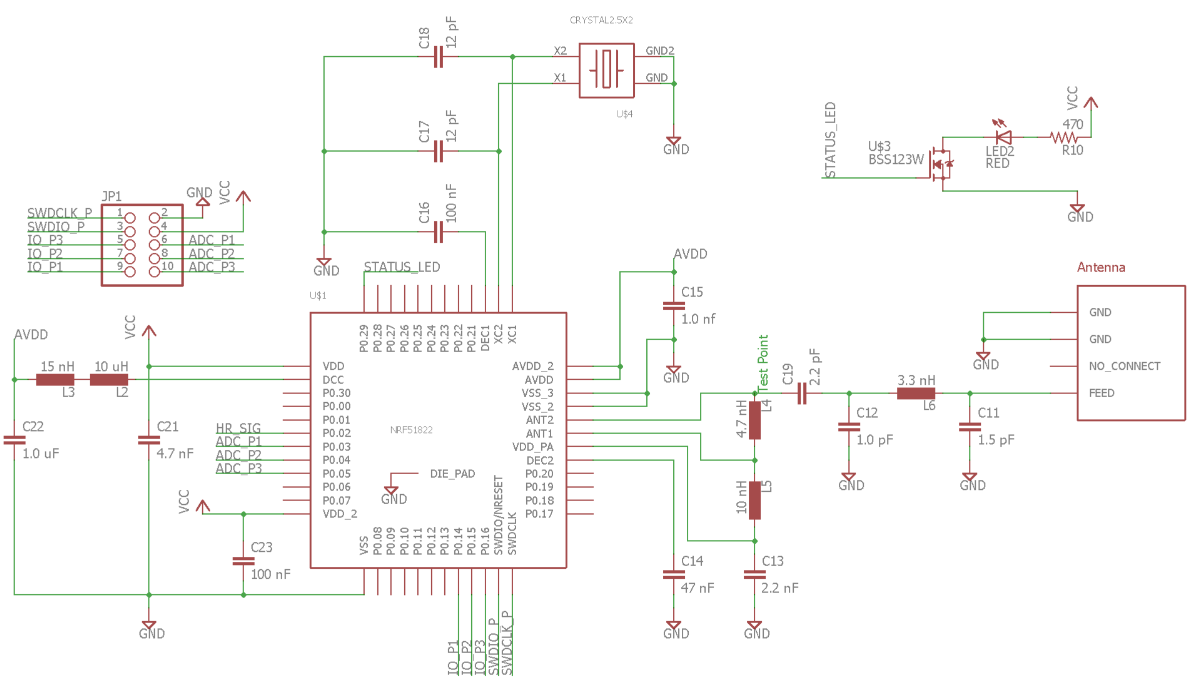

Figure 8: Bluetooth SoC Schematic [14]

3.2.3 Heart Rate Sensor

Input: 3.3V power
Output: Heart rate signal

The Heart Rate Sensor optically detects heart rate. It requires power input between 3V and 5V. We chose to power it with 3.3V as we had a 3.3V supply available and the absolute max the ADC on our SoC will tolerate is 3.6V. The sensor outputs between 0 and 3.3V on its signal line when powered with 3.3V. The output signal is connected to the ADC on the SoC.

Shown in Table 9 is the pin summary for the Heart Rate Sensor. Figures 8 and 9 show the flow diagrams for the HR band.

Table 9: Heart Rate Sensor Pin Connections

Pin	**Function**	**Connection**
1	VCC, power input	Output of the voltage regulator
2	SIG, signal	ADC input of the SoC
3	GND, ground	Ground plane of the PCB

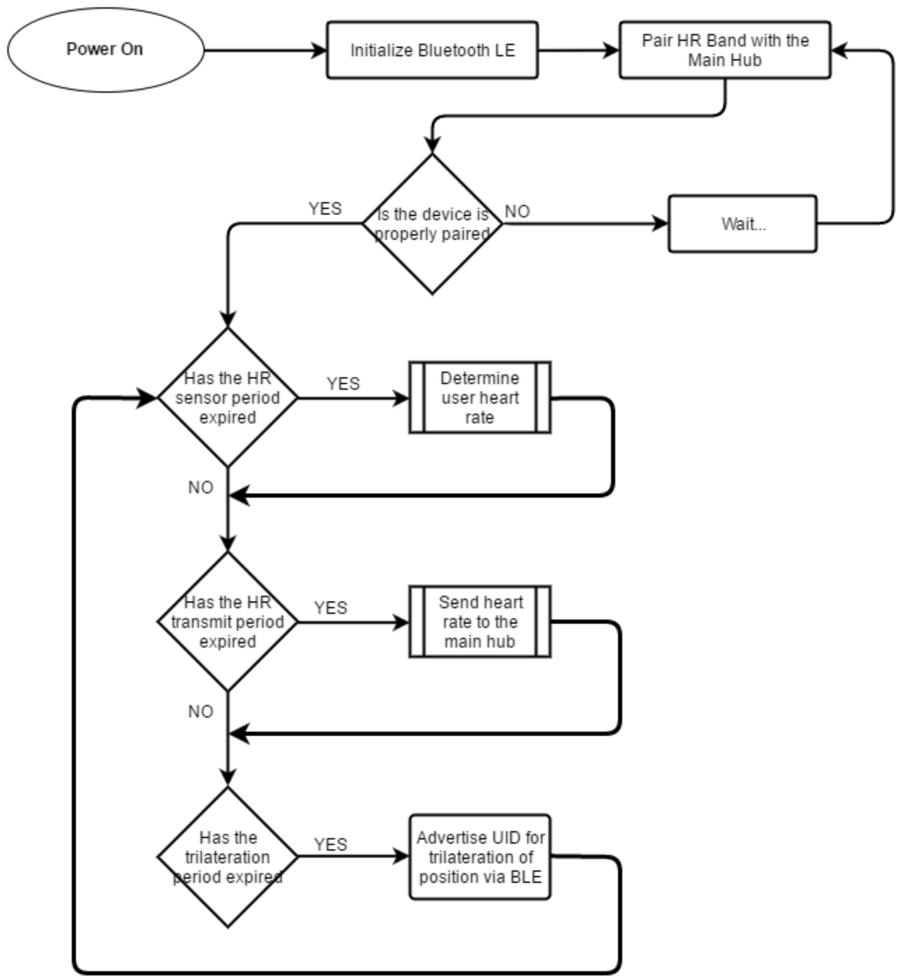

Figure 9: HR Band Flow Chart

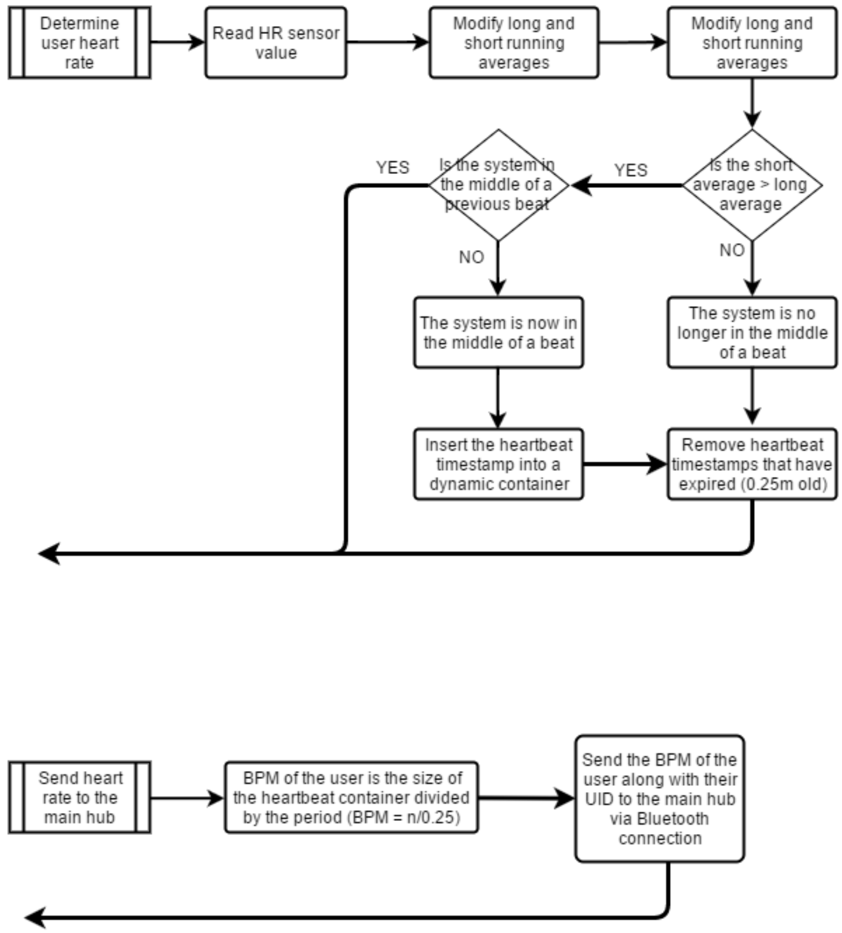

Figure 10: HR Band Flow Chart

3.3 Trilateration Beacon

Input: 5VDC power, Bluetooth signal
Output: Bluetooth signal

The Trilateration Beacons listens for Bluetooth data from the Heart Rate Bands and sends the Received Signal Strength Indication (RSSI) of the data received to the Main Hub to determine the location of a given Heart Rate Band. The system requires three Trilateration Beacons around the room to work properly. To calculate position, the RSSI will be used to calculate a rough distance from each Trilateration Beacon. The system can calculate three radii, one from each Trilateration Beacon. The location of the Heart Rate Band will be where all three radii intersect. Figure 11 shows an example of this.

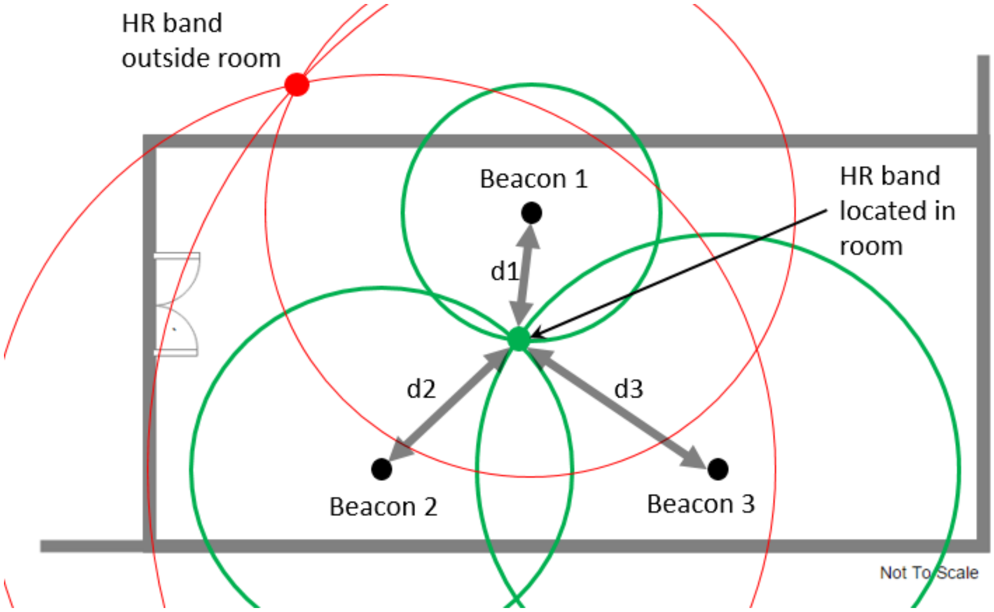

Figure 11: Trilateration Example

Each Trilateration Beacon will use one Red Bear Labs BLE Nano development board along with a 120VAC to 5VDC power supply. We chose the development board for its relatively low cost and because it uses the same SoC we will use on the Heart Rate Band. Figure 12 shows the schematic for the Trilateration Beacon. Figure 13 shows the Trilateration Beacon flow chart.

Table 10: Red Bear Labs BLE Nano Pin Connections

Pin	Function	Connection
5,7	GND, ground	To ground pin of USB
6	Vin, input power	To 5V from USB port
1,2,3,4, 8,9,10,11, 12	Unused	Break out to through holes for future expansion

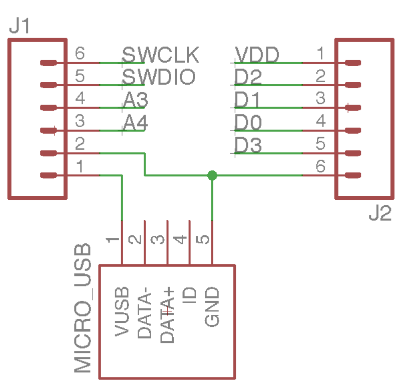

Figure 12: Trilateration Beacon Schematic

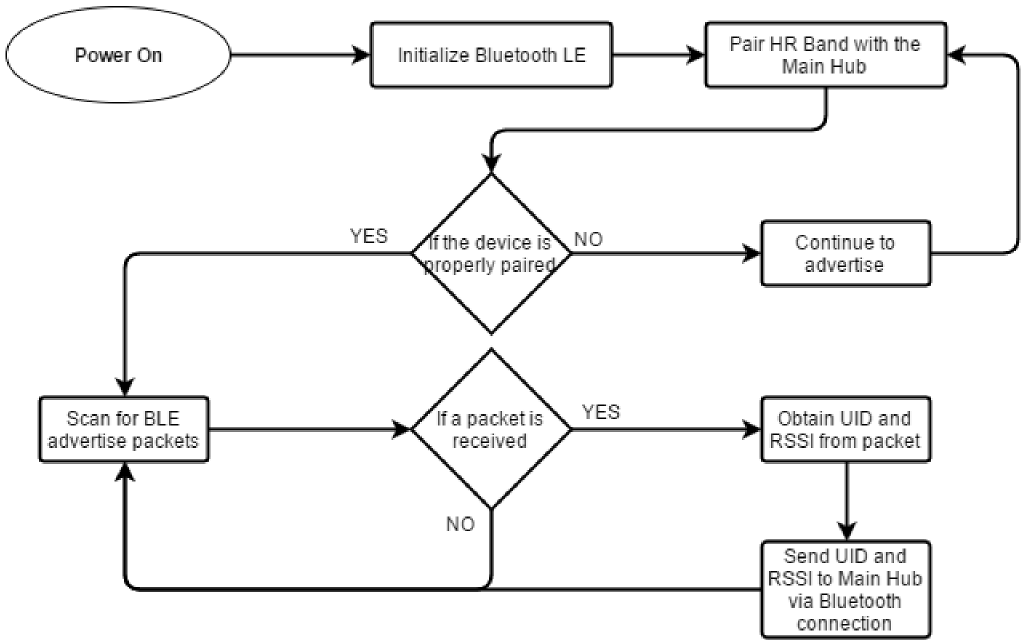

Figure 13: Trilateration Beacon Flow Chart

3.4 Feedback Light

Input: 24V power, one control signal for each of the three lights
Output: Colored light

An industrial style light keeps users informed of the state of the system. The Feedback Light will take in 24VDC to power and three lights. A green light indicates machines can be turned on. A yellow light is a warning that the machines will turn off in 15 seconds. A red light indicates that the machines will not power on.

Figure 14: Feedback Light

A schematic for the Feedback Light control is shown in Figure 2. The control signals {COLOR}_LIGHT are from the Raspberry Pi and the outputs will have connectors to attach between the Main Hub and the Feedback Light.

4 Tolerance Analysis

A critical component of this system is determining the location of the active heart rate bands. The layout of the machine shop is well known. The width of the walls in the room are measured to be approximately 0.2 meters thick. Figure 15 shows where these walls are located in the machine shop.

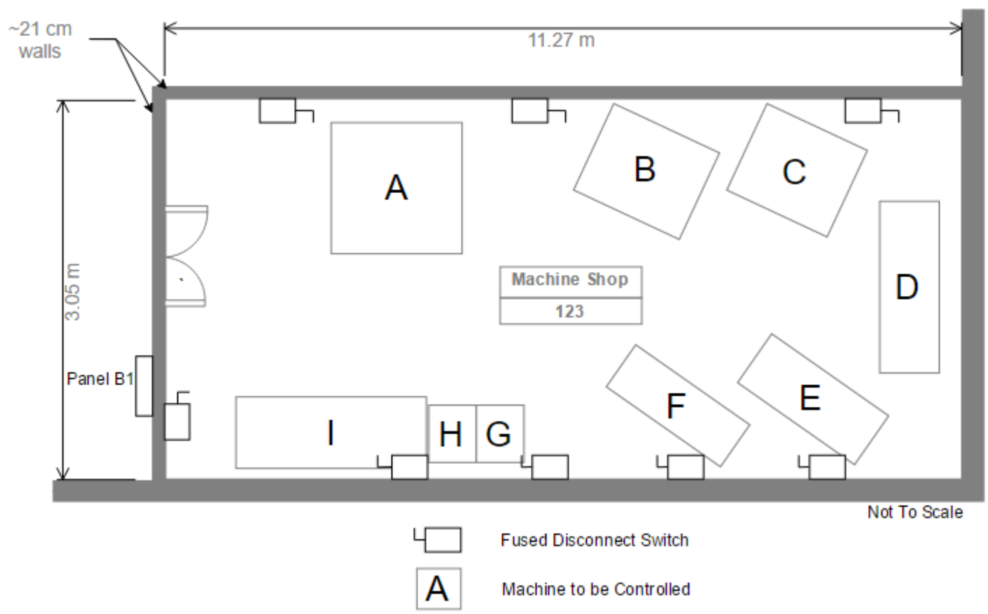

Figure 15: ESPL Machine Shop Floorplan

In order for the trilateration system to effectively determine that an active heart rate band is in the room or outside of the room, the location of the active heart rate band determined by the trilateration system must have an positional error less than the thickness of the walls. To ensure that the trilateration system has the resolution to provide accurate measurements, we will perform a varying distance test. By placing a transmitter at a set point and varying a receivers distance between 0 and 10 meters, it is possible to plot the signal strength at a receiver throughout this range. The results in a preliminary component test can be seen in figures 16 and 17.

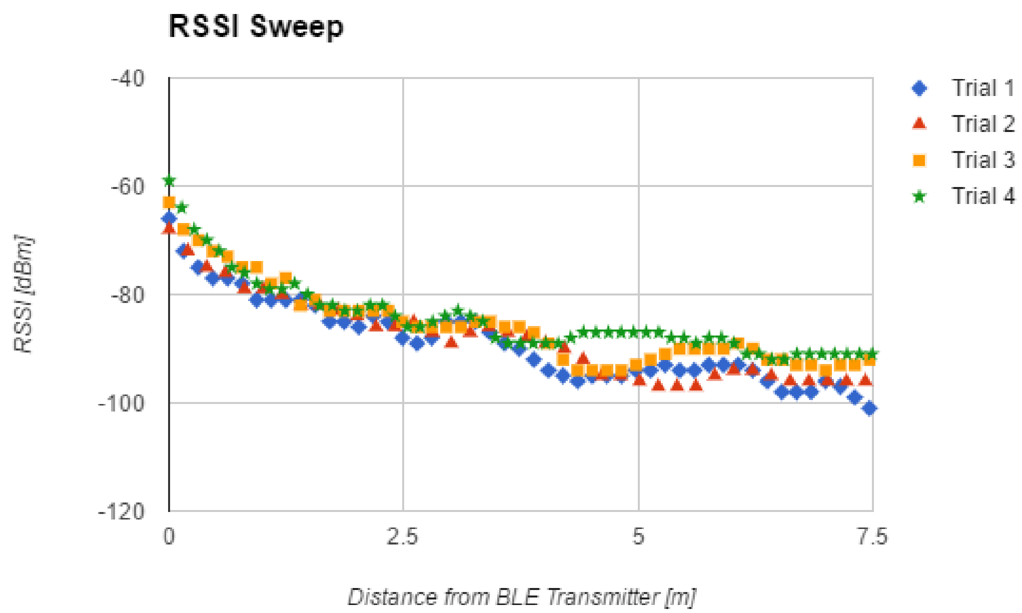

Figure 16: RSSI Sweep Data

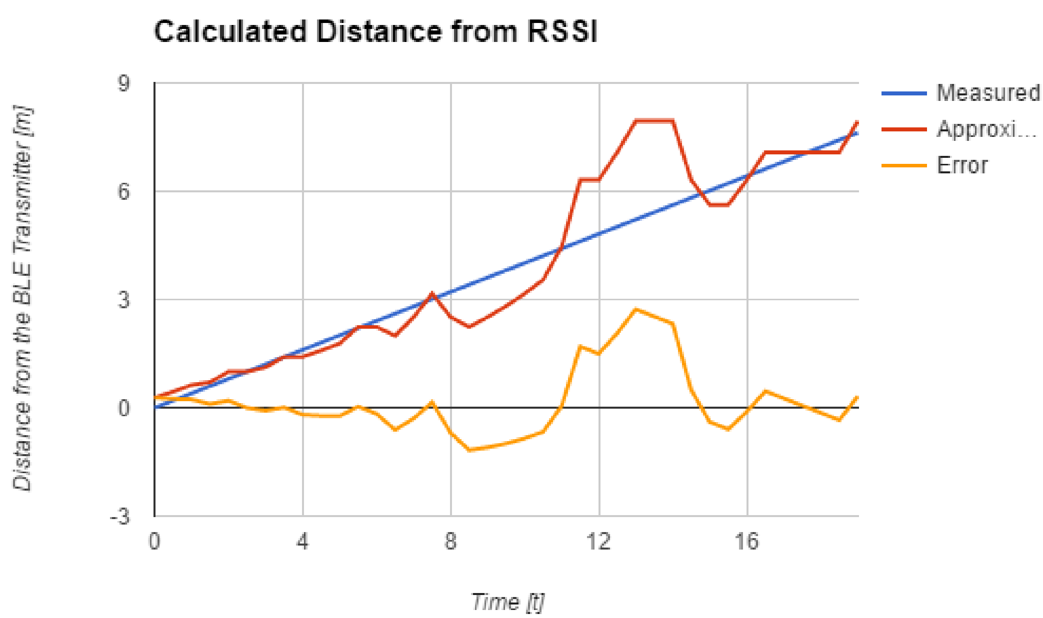

Figure 17: RSSI Distance Test Results

The approximated distance was determined by assuming the fall off of the signal strength followed the inverse square law. This was calibrated using a RSSI measurement at 1 meter, allowing some terms to cancel in a simplification of the equations.

$$I = k\frac{P}{r^2} \rightarrow \frac{I_1}{I_2} = \frac{P_1 r_2^2}{P_2 r_1^2} \rightarrow \frac{I_{1m}}{I_2} = \frac{P_{Tx} r_2^2}{P_{Tx} r_1^2} \rightarrow \frac{I_{1m}}{I_2} = \frac{r_2^2}{r_1^2} \tag{8}$$

$$\log(I_{1m}) - \log(I_2) = \log(r_2^2) - \log(r_1^2) \rightarrow (dBm_{1m} - RSSI[dBm])/10 = \log(r_2^2) \tag{9}$$

$$r_2 = \sqrt{10^{(dBm_{1m} - RSSI)/10}} \tag{10}$$

Implementing the above equations in a system allows trilateration to become functional. Though the RSSI values are not perfectly accurate and prone to error introduced by interference in the area.

The nRF51822 has a RSSI resolution of 1dBm. Using an approximate decay of signal strength over distance, 1dBm would have an innate error range similar to Figure 18. It is not difficult to insure that the system has proper resolution when distance is small. The distance uncertainty is also small because the RSSI value falls off quicker. Ensuring proper resolution at large distances is difficult. This resolution even at a large range should be smaller than the tolerance introduced earlier of 0.2 meters.

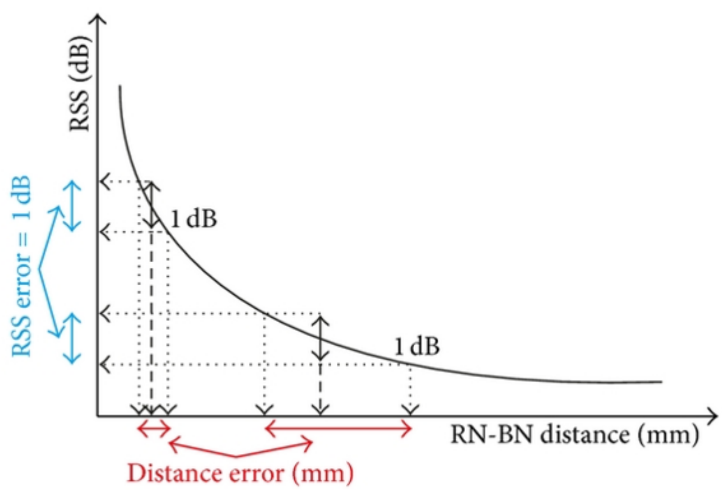

Figure 18: Decay of Signal Strength Over Time [15]

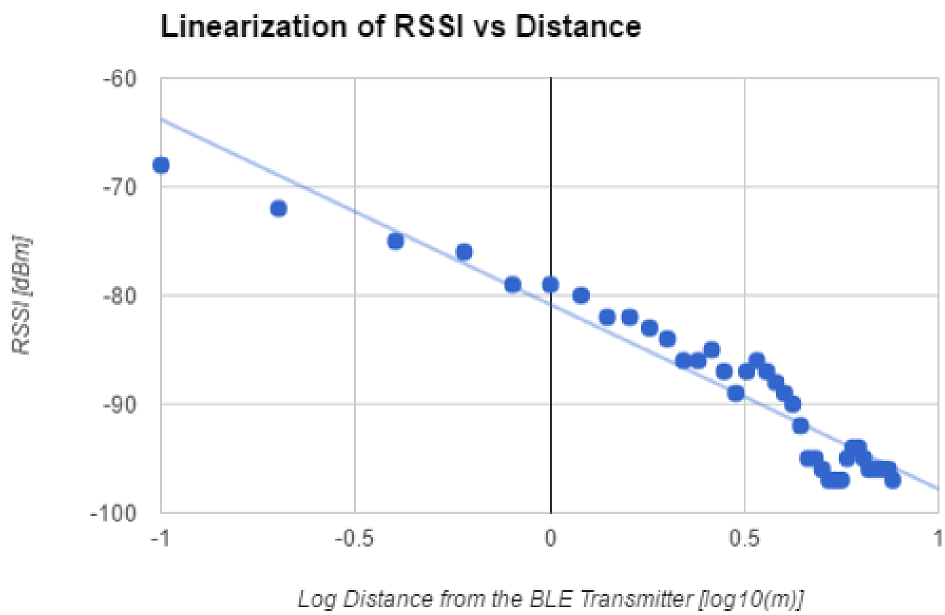

Figure 19: Relationship of RSSI vs. Distance

$$RSSI = -17\log(r) - 80 \rightarrow \frac{RSSI}{dr} = \frac{-17}{r\log(10)} \rightarrow \frac{r}{d(RSSI)} = \frac{-r}{17} \tag{11}$$

A best fit line of the data obtained in trials reveals the relationship between distance from the transmitter and the maximum accuracy of the distance approximation. This shows that the system meets accuracy requirements up to 3.5 meters. At that point, $3.5/17 = 0.2$m/dBm. At larger distances, our system will not be able to meet its required tolerance. As these results were obtained on development device, increasing the transmitting power on the final design will improve the accuracy at greater distances.

5 Requirements and Verification

System	Module	Requirement	Verification	Points
Main Hub	SoC with Bluetooth	Calculate position of HR band to within 20 cm.	1. Place HR band in multiple known locations 2. Calculate position via trilateration 3. Repeat with the antenna rotated 0, 90, 180, 270 about the vertical 4. Repeat with the antenna pointing vertically, rotated 0, 90, 180, 270 degrees about the vertical 5. Compare the actual location to the calculated location	1
		On signals are sent to relay control only when in machines enabled or warning states	With the green or yellow lights on use a voltmeter to check voltages of the relay control signals. The voltage should be 3.3V +- .25V	3
	Manual Override	Enable power to all relays when override is active without damaging control signals to Raspberry Pi.	1. Place 5V across pin 11 of the Raspberry Pi. 2. Using a voltmeter, verify the voltages across pins 7,13,15,16,18,22,27,29,31,37 are all between 2-5V.	3
	Power Module	AC/DC Power Supply outputs voltage between 24-27.2VDC to system with no load and loaded conditions.	Testing with no load: 1. Place voltmeter across DC output pin of power supply source and ground. 2. Plug AC side of power supply into 115V wall receptacle. 3. Verify Voltage is between 24-27VDC. 4. Use turnnob on power supply to verify range of voltage reaches 24V and 27.2V. Testing with load (115-148W): 1. Place 5 ohm power load across DC output pin of power supply source and ground. 2. Repeat steps 2-4 from above.	2
		LM2678 Switched Voltage Converter outputs 5V+0.1V with up to 25W load at an allowed input voltage range of 24-27.2V.	1. Place 1 ohm power load across Feedback Pin 6 of LM2678 and ground. 2. Place voltmeter across the power resistor. 3. Power on input voltage from power supply. 4. Sweep through allowed input voltages verifying output voltage remains between 4.90 and 5.10V.	3
	Relay Control	Relay control sends output 24VDC only in on (green) or warning (yellow) states.	1. Program Raspberry Pi to output on (green) state for 5 seconds, warning (yellow) state for 5 seconds, and halt (red) state for 5 seconds. 2. Place voltmeter across one of the screw terminals. 3. Verify voltage is between 0V and 2V in on and warning states. 4. Verify voltage is 24V +- 1V in halt state.	3
		Relay control outputs 24-27.2VDC with 1/3A current to up to 10 relays for up to an hour.	1. Place 75 ohms power load across each 24V switch terminal (or as many as possible). 2. Turn on power supply to power relay control. 3. Allow Raspberry Pi to turn relays on. 4. Keep relays on for 1 hour. 5. Check temperature with laser thermometer logic-level MOSFET do not exceed 125 C.	3
				18

Table 11: Requirements and Verification Table

System	Module	Requirement	Verification	Points
Heartrate Band (HR band)	HR sensor	Collect heart rate to within 10 BPM	1. Collect heart rate for 30 seconds with HR band and with a commercial device or manually at the same time. 2. HR sensor reading should be within 10 BPM of the other reading	3
	SoC with Bluetooth	Have less than 90% packet loss when transmitting HR data to the Main Hub	1. Pair with Main hub. 2. Use a BLE sniffer to check for retransmitted packets. 3. Retransmitted packets should be less than 90% of total packets.	3
	Power Module	LiPo Battery must not discharge below 3.25V if battery left connected to load.	1. Connect 25mA power load from source of PMOS to ground. 2. Let battery sit for 2 days with power left on. 3. Measure voltage across battery with voltmeter verifying voltage has not dipped below 3.25V	4
		LiPo Battery must have capacity to power HR band for at least 8 hours.	1. Charge battery until voltage across measures 4.2V, 2. Remove power to charging station, 3. Place 25mA power load from source of PMOS to ground 4. Verify low battery indicator is still off after 8 hours	4
		LDO Voltage Regulator outputs safe 3.3V+-2% at 25mA and no load with input voltages 3.3V-4.2V (design limits of battery).	Testing with no load: 1. Disconnect load from output of LP2985N-3.3. 2. Place voltmeter across pin 6 of LP2985N-3.3 and ground. 3. Send 4.2V to pin 2 of LP2985N-3.3. 4. Sweep voltage down to 3.3V verifying voltage reading remains within limits. Testing with 25mA load: 1. Place 25mA load across pin 6 of LP2985N-3.3 and ground. 2. Follow steps 2-4 above.	4
	Status LED	LED flashes quickly when HR band disconnected from Main Hub	Shut down main hub, power on the HR band. Status LED should begin to flash.	1
		LED is solid when HR band connected to the Main Hub	Power on the main hub and the HR band. The status LED should flash and within one minute switch to solid on.	1
				20
Trilateration Receiver	SoC with Bluetooth	Antenna can receive position information from HR Band at 10m	1. Transmit bluetooth advertise packets from a spoofing device at +4dBm 2. Connect the trilateration SoC to a computer. 3. Print RSSI values derived from the packets advertise over UART port on SoC, read from computer. Verify that the RSSI value at 10m is greater than (closer to 0) -92.5dBm.	5
		Antenna can detect the HR band advertise packets such that the approximate slope of the RSSI/distance function is greater than 5dBm/meter throughout the range of 0-10m	1. Transmit bluetooth advertise packets from a spoofing device at +4dBm 2. Sweep the distance range from 0-10m with a BLE sniffer 3. The RSSI value should drop at least than 5 dBm every meter.	2
		Have less than 90% packet loss when transmitting RSSI data to the Main Hub	1. Pair with Main hub. 2. Use a BLE sniffer to check for retransmitted packets. 3. Retransmitted packets should be less than 90% of total packets.	3
	Status LED	The status LED should be lit when the receive has connected to the main hub	Power on the main hub and the trilateration receiver. The status LED should flash and within one minute switch to solid on.	2
				12

Table 12: Requirements and Verification Table - Continued

6 Schedule

No.	Week	Andrew	Ryan	Steven	Team
1	9/12	Finalize project proposal Create list and order microcontroller and bluetooth module candidates	Make final decisions on how to control machines. Build an idea of power requirements for system.	Create list of potential HR sensors Create list of potential microcontroller and bluetooth modules for HR band Order potential components for testing	Complete, edit, and turn in the design proposal by Wednesday.
2	9/19	Test bluetooth modules for HR band Test bluetooth modules for triangulation beacons	Begin design of power module in main hub (rectifier and/or buck converter).	Test HR sensors Select bluetooth/microcontroller for HR band Select Raspberry Pi or similar computer for main hub	Form design matrix of potential parts for determining design specs. Begin design.
3	9/26	PCB design for HR band PCB design for triangulation beacons	Test design on protoboard. Begin design of PCBs for both main hub and HR band in Eagle.	Finish PCB for feedback lights if needed and order Test feedback lights Start PCB for main hub	Make final touches on design for Design Review.
4	10/3	Order PCB for HR band and triangulation beacons Begin programming triangulation beacon bluetooth sync and sniffing functionality	Finalize design of PCBs for both main hub and HR band in Eagle.	Finish design and order PCB for main hub Write interface for main hub power relay control Write interface for main hub feedback system control	Finalize design and prepare for design review. Begin purchasing parts.
5	10/10	Assemble beacon(s) from PCB and components Continue programming/testing triangulation beacon system	Begin soldering stage if possible. Test power connections and reliability.	Test PCB for main hub Finish corrections to PCB for main hub Order revised main hub compute PCB	Revise design based on commments from design review. Begin design.
6	10/17	Assemble HR band(s) from PCB and components Program HR band bluetooth communications	Construct HR band power module prototype. Test functionality of band.	Program HR Band communication Program two person HR accept/reject	Coordinate with Greg size constraints for HR band.
7	10/24	Program main hub bluetooth communications Program main hub for triangulation system computations	Continue with AC/DC bridge rectifier, DC buck converter and power relay control. Test efficiency, input/output power in lab.	Integrate all main hub program interfaces Start test full main hub functionality	Coordinate with Greg size requirements for Main Hub Enclosure (i.e. where holes need to be placed, overall design).
8	10/31	Test and debug triangulation system	Finish all soldering of power parts to PCBs and test functionality, safety, and reliability. Debug if necessary.	Continue test full main hub functionality	Verify with Greg enclosures are properly sized.
9	11/7	Test and debug triangulation system Prepare for final demo and presentation	Test entire product for overall power efficiency. Modify if necessary. Place equipment into their respective enclosures.	Test and debug triangulation system Start planning demo Begin final paper and presentation	Integrate all parts of project together. Place in enclosures if possible.
10	11/14	Test and debug triangulation system Prepare for final demo and presentation	Begin to draft final paper in LaTeX. Continue making build changes if needed.	Finish debugging triangulation system Continue planning demo Finish final paper Continue final presentation	Prepare for demo!
11	11/21	Thanksgiving Break - No School - Eat Turkey			
12	11/28	Finish final presentation	Refine draft final paper in LaTeX. Continue making build changes if needed.	Finish final presentation	Run demos on the final product and verify all goals were met.
13	12/5	Finishing touches on presentation Present	Finalize product and final paper.	Finishing touches on presentation Present	Focus on editing and wrapping up final paper and presentation slides.

Table 13: Team #1 Extended Schedule

7 Cost Analysis

LABOR			
Service	**Hourly Rate**	**Qty.**	**Total**
Computer Engineer I (Andrew Hanselman)	$80.00	225	$18,000.00
Electrical Engineer I (Ryan Helsdingen)	$80.00	225	$18,000.00
Computer Engineer I (Steven Ploog)	$80.00	225	$18,000.00
Labor Sub-Total			**$54,000.00**

Note: The hourly rate includes a 2.5 multiplier.

PARTS				
Part Name	**Distributor**	**Unit Cost**	**Qty.**	**Total**
Raspberry Pi 3B	Amazon	$35.70	1	$35.70
8GB uSD Card	Amazon	$6.99	1	$6.99
LS150-24	Mouser	$37.65	1	$37.65
AC Power Entry Module	Mouser	$0.93	1	$0.93
LM2678T-5.0/NOPB Voltage Reg.	Mouser	$5.82	1	$5.82
FDN359BN Logic Level MOSFET	Mouser	$0.30	13	$3.90
USB 2.0 A female PCB mount	Mouser	$1.36	4	$5.44
Power Pushbutton Switch	Mouser	$5.75	1	$5.75
Other Various Passive Elements (Diodes, Resistors, Capacitors, Inductors)	Mouser	$10.00	1	$10.00
PCBs (Testing and Final Product)	PCB Way	$10.00	5	$50.00
MAIN HUB		**$104.50**	**1**	**$104.50**
nRF51822-QFAA-R7	Mouser	$4.62	1	$4.62
Antenna	Mouser	$1.01	1	$1.01
NPN Transistor	Mouser	$0.48	2	$0.96
LT1389BCS8-1.25V Shunt Voltage Ref.	Linear Tech.	$3.60	1	$3.60
LT1494 High Precision, Low Power Op Amp	Linear Tech.	$2.00	1	$2.00
LED	Mouser	$0.30	3	$0.90
Lithium Ion Polymer Battery 3.7V 500mAh	Mouser	$7.95	1	$7.95
JST-PH 2-pin SMT Right Angle Connect	Mouser	$0.75	1	$0.75
MAX1555 Battery Charger	Mouser	$1.98	1	$1.98
LP2985N-3.3	Mouser	$0.35	1	$0.35
Miniature Slide Switch	Mouser	$0.50	1	$0.50
USB Micro B Connector	Mouser	$1.50	1	$1.50
Crystal SMD 2520 16MHz, 8pF +-40ppm	Mouser	$1.41	1	$1.41
Heart Rate Sensor	Mouser	$6.99	1	$6.99
Other Various Passive Elements (Diodes, Resistors, Capacitors, Inductors)	Mouser	$10.00	1	$10.00
PCBs (Testing and Final Product)	ECE Shop	$4.70	10	$47.00
HR BANDS		**$48.14**	**4**	**$192.56**
Red Bear Labs BLE Nano	Mouser	$17.90	1	$17.90
DC Power Supply	Mouser	$5.00	1	$5.00
Trilateration PCB	Mouser	$8.00	3	$24.00
TRILATERATION BEACONS		**$30.90**	**3**	**$92.70**
Red Bear Labs BLE Nano	Mouser	$32.90	1	$32.90
Industrial Stack Light 24VDC	Amazon	$24.00	1	$24.00
MISCELLANEAOUS		**$32.90**	**1**	**$56.90**
Parts Sub-Total				**$446.66**

GRAND TOTAL	**$54,446.66**

Table 14: Cost Analysis

8 Safety

The ultimate goal of the Machine Shop Buddy System is to address the safety concerns for working alone within a machine shop. In the Fabricated Metal Producation inducstry alone, roughly 30-50 work-related deaths occur each year [2]. Injuries or worse, death, can be prevented in the machine shop with the presence of a second person to aid the individual in trouble or call for help. The Machine Shop Buddy System only allows the operation of powered mechanical tools such as lathes, saws, mills, and CNC machines when two individuals are located within the walls of the machine shop.

Safety should be considered when dealing with electrical appliances. While our main hub design quickly mitigates the danger of 120VAC down to a safer 24VDC with the power supply, 120VAC nonetheless enters the main hub. Do not open the main hub enclosure when it is live.

Safety must also be considered when dealing with a high energy density Li-Ion battery. This type of battery has been known to heat up and potentially explode under improper conditions. The following rules for Li-Ion batteries must be followed:

- Do not short the terminals of the battery.
- Do not discharge the Li-Ion cell below 2.4V.
- Do not continuously charge a fully charged Li-Ion cell.
- Do not charge the Li-Ion cell outside 0-45 degree C ambient temperature range.
- Do not store or discharge the Li-Ion cell outside -20 to +60 degree C temperature range.
- Do not store the Li-Ion cell in high humidity (75%+)
- Do not charge the Li-Ion cell over 1C.

9 Ethical Considerations

The IEEE Code of Ethics is located in IEEE Policies, Section 7 - Professional Activities (Part A - IEEE Policies) and were considered while designing the Machine Shop Buddy System. The sections of the IEEE Code of Ethics [16] relevant to our project are as follows:

Our system attempts to improve the safety of the individuals using the machine shop and so we are making decisions affecting the safety of the public. If our system were to fail then any improvements in safety would be lost. (Section 7.8.1)

To prevent failure, all parts of the project will be tested extensively with extreme conditions (i.e. ware/tear of wearable) so as to meet within working tolerances for all machine shop environments.

Our system attempts to use trilateration to determine that an individual wearing a Heart Rate Band is actually inside of the machine shop. We must not overstate the accuracy of this trilateration system. (Section 7.8.3)

Our system is intended to be used with high power relays. Given our lack of experience with such devices we have chosen not to include them in the scope of our project. (Section 7.8.6)

To overcome potential ethical issues we must prevent users from cheating the system and we must not overstate the capabilities of our trilateration system.

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