Exertion Control

by
Travis Taylor

EE 464
Advisor:
Professor Vladimir Prodanov

Senior Project
Electrical Engineering Department
California Polytechnic State University
San Luis Obispo
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Abstract

Current wearable fitness devices give the user after-the-fact fitness data, but little real-time feedback. Exertion Control, a new wearable device, continuously measures the user's heart rate, creates a heart rate target, and helps the user reach it. This project completes the senior design and master's thesis requirements and contains two milestones. The senior design product continuously measures the wearer's heart rate and logs it with a user-friendly interface. This data models the heart's exertion response and recovery response. The master's thesis device refines the closed control loop with the user to give them a workout optimized to fit their needs.

Thesis Statement:

During running or other physical exertion, optimal exertion gives the runner the most efficient cardio or strengthening workout. A phase locked loop formed by a wearable device and the user's cardiac response allows them to optimize their workout by controlling their exertion level.

Chapter 1: Introduction and Background

With more adults in the US using electronic devices to track their fitness, the development of smartphone apps, smartwatches, and wearable fitness trackers has significantly increased in the past three years. In a study of 1,262 US adult consumers (who regularly use a computer) performed by Rocket Fuel in December 2014, 31% used electronics to track their fitness and health: 16% used a wearable device and 29% used an app or website to track health and fitness [1]. While these consumers still represent a niche market, this niche's considerable size and rapid growth promise a strong market opportunity. In the current field of wearable fitness technology, there exist numerous devices such as smartwatches and activity monitors that record the heart rate and other exercise statistics such as running speed and blood glucose levels. Some companies, such as Athos, even produce fitness clothing with built-in sensors that monitor muscle strain [2]. With consumers funding the development of such technology, there exists room for further development in fitness and health monitoring.In 2014, Samsung, Lenovo, and LG led smartwatch sales, with Samsung alone generating $300M in sales revenue [3]. From Q2 2014 to Q2 2015, the smartwatch market share grew by almost 460%, with Apple growing from 0% vendor market share to an estimated 75.5% after the release of the Apple Watch [4]. This sudden shift in vendor marker share shows that the smartwatch market remains volatile, with the potential for large success. Because of this potential, a new type of fitness device could achieve abrupt success if marketed properly. In the wearable device market, two divisions dominate: smartwatches and fitness trackers. Smartwatches operate primarily to extend the functionality of a smartphone onto the wrist, where fitness apps constitute one of many features. Consumers buy smartwatches with fitness capabilities in mind, but not as a priority. The fitness tracker division aims to monitor fitness with minimal hardware, using a smartphone or computer application to record and communicate the information to the user. Consumers buy fitness trackers with the primary purpose of improving fitness. As the technologies progress, the line between these two divisions fades, with more devices providing both types of functionality.

Exertion Control aims to fill a subspace of this smartwatch market that remains unfilled: a fitness device that gives the user coaching feedback in real time based on heart rate recovery research. Some smartphone apps, such as Samsung's S Health, aim to provide some of this functionality by tracking running speed with GPS and telling the user to speed up or slow down, but this remains cumbersome and imprecise. Research on heart rate recovery has progressed over the past few decades, but has not yet found its way into fitness devices. A device that uses this research not only has potential market success, but potential to improve the understanding of fitness and hear rate recovery. A related research project at the University of Madrid describes the cardiovascular system's response to exertion using mathematics, and relates exertion level with blood oxygen and glucose levels and heart rate [5]. Other research in the field of sports science analyses the use of heart rate monitoring to improve training results, such as running coach Roy Benson's book *Heart Rate Training* [6]. Exertion Control provides a method of furthering this research, and could apply to the study of medical conditions through heart monitoring.

Chapter 2: Customer Needs Assessment, Requirements, and Specifications

Customer Needs Assessment

Exertion Control targets runners who want to improve their fitness. To determine customer needs, I considered the functions that I would want a wearable fitness device to perform. I do not currently own a fitness tracker because they lack the functionality I desire. I need a device that monitors my exertion level while I'm running and tells me in real time how fast I should run to get the best workout. It shouldn't distract me from running, but should enhance my workout by keeping me focused. It should be easy to use, take very little time to set up before a run, and not require any adjustments while I run. Its feedback should be accurate enough that I can trust the device to give me the best workout. I also need a device that withstands sweat, dirt, and concussive impacts.

Requirements and Specifications

The marketing requirements for Exertion Control appear at the bottom of Table 2.1 and encompass the critical selling points that allow this product to succeed. They come from the customer needs described above, and consider the selling points that make popular smartwatches appealing. The Apple Watch promises "important information and essential functions" at the raise of a wrist in a sleek and beautiful accessory [7]. Considering the Apple Watch's abrupt success, Exertion Control should capture these selling points by having an appealing and comfortable design and offer easy-to-use functionality. Like the Apple Watch's competitors, the device must offer unique functionality at a competitive price.

The engineering specifications, also shown in Table 2.1, connect the marketing requirements with the product definition by detailing technical aspects of the device. The performance specifications indicate the overall functionality that the device must provide. The hardware specifications define the physical design needs, and the user interface specifications describe the necessary interaction with the user. Table 2.2 shows a timeline of the deliverables needed to satisfy the Senior Design requirements of Cal Poly, ABET, and the EE department [8].

The thesis part of this project uses the heart rate measurements to measure heart rate recovery (HRR) and heart rate variability (HRV) to model the user's level of fitness. The fitness model then creates the best workout for the user.

Table 1: Exertion Control Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
Performance		
2	Measures heart rates between 30 bpm and 200 bpm with: a) 90% accuracy* in 10 heart beats b) 70% accuracy* in 2 heart beats *Accuracy as compared with a manual pulse-and-stopwatch measurement over 15 seconds	To give the use accurate feedback, the device must accurately and quickly measure their heart rate. Having two measurements allows for the best modeling: the first measurement comes quickly to provide live feedback and the second comes more accurately to improve the model. Most similar products avoid these specifications, but a user would expect accurate measurement.
2	Measures step frequency with 95% accuracy in 5 steps	The device must measure the user’s running pace accurately to tell them how fast to run.
4	Has a rechargeable battery with a 24-hour or longer life.	This provides for a full day of use, allowing the user to wear the device all day and charge it overnight.
1, 2	Measures heart rate recovery (HRR) and heart rate variability (HRV) to model the user’s fitness level	The device must create a fitness model without asking the user to perform measurement or calculations.
1, 2, 4	Gives live haptic exertion feedback to the user during exercise via rhythmic vibration pulses	The feedback must happen non-visually so that the user can exercise without distraction.
Hardware		
3, 4	Has a body casing that does not exceed 2”h x 1.75”w x 0.5”d in size	This size and weight mirrors current smart watches such as the Apple Watch [9], Samsung Gear 2 [10], and LG G watch R [11], and should fit most users comfortably. The user should have have the option of replacing the strap with a standard strap. The display must have enough size and detail to display text clearly.
3, 4	Has an adjustable wrist strap that attaches to the body with 20 mm spring pins	
3, 4	Body weight does not exceed 100 g	
3, 4	Has a display with a size of at least 1.2” diagonal with a pixel density of at least 200 ppi	
4	Does not expose the user to electrical shocks, has no sharp edges, and does not restrict blood flow	The device must be safe to wear.
5	Has a production cost < $50	Based on a production cost estimate of 33%-50% of sales cost, this would match competing devices with a sales price of $100-150.
4	Has water and dust resistance equivalent to IP67 rating or better (no dust ingress, water resistant to 1 m for 30 minutes)	The device must resist sweat and dirt for its intended use.

Table 1 (Cont.): Exertion Control Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
Hardware (Cont.)		
4	Has self-contained user input hardware that allows the user to: - Navigate menus on the display - Turn the display on/off - Power the device on/off	The body of the device must contain the user input method to allow the device to operate as a stand-alone device. The hardware should allow for easy and intuitive use.
1, 4	Has a user-removable battery and microSD card	A removable battery and microSD card leads to longer product life, which improves sustainability. A microSD card represents a standardized and well-supported storage device that can interface with computers and swap out if needed.
1, 4	Has a micro USB port for charging and data transfer.	Using a micro USB charging port improves sustainability and ease of use by eliminating proprietary connectors, and allowing the device to charge from computer USB ports or wall adapters.
User Interface		
1, 2	Is configurable in < 30 seconds before each run for a competent adult	A fitness device should not distract from exercise, but improve it. Less interaction with the device during exercise provides a better user experience.
1, 2	Does not require user input or visual focus during exercise	
1, 4	At the end of the run, it displays the following stats: - Number of steps taken - Average HR - Peak HR	These statistics give the user a brief overview of their run.
Marketing Requirements 1. Easy to use 2. Effective at giving the user the best workout 3. Comfortable to wear 4. Visually and functionally appealing as an accessory 5. Affordable and competitive in price		

Table 2: Exertion Control Deliverables

Delivery Date	Deliverable Description
2/15/16	Design Review
3/10/16	EE 461 Demo
3/10/16	EE 461 Report
6/5/16	EE 462 Demo
6/5/16	ABET Sr. Project Analysis
6/5/16	Sr. Project Expo Poster
6/5/16	EE 462 Report

Chapter 3: Design

Functional Decomposition: Level 0

The level 0 decomposition of Exertion Control shows its inputs and outputs, as defined by the engineering specifications in Chapter 2. As shown in Figure 3.1, the device receives electricity, running motion, a human heart pulse, and user input. It outputs live exertion feedback during a run, and displays an exercise log and summary at the end of a run. Table 3.1 describes Exertion Control's level 0 functionality.

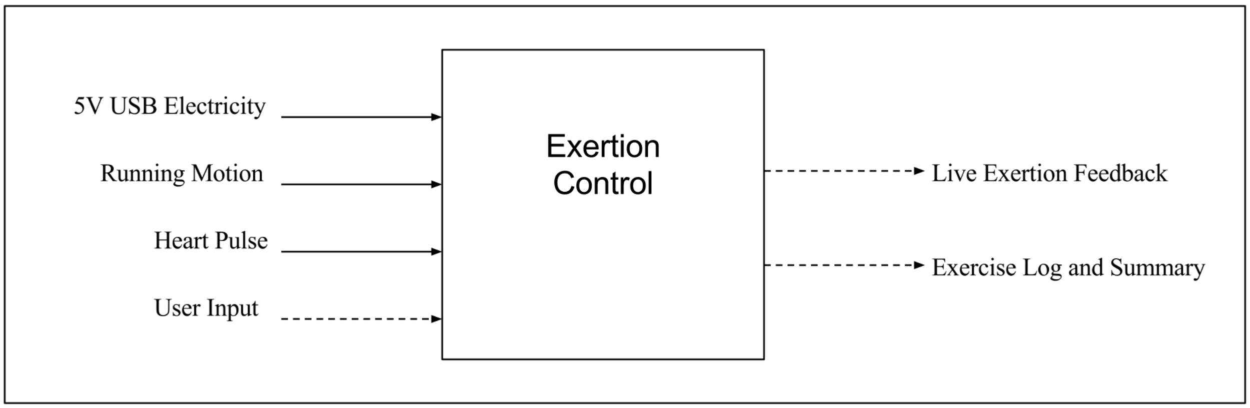

Figure 1: Exertion Control Level 0 Block Diagram

Table 3: Exertion Control Level 0 Functionality

Inputs	- User Input (Running plan details and start signal through button presses) - User's Heart Pulse - User's Running Motion - 5V DC Power from USB while charging
Outputs	- Live haptic exertion feedback that tells the user how fast to run via short pulses of vibration - Exercise summary and stats after the run
Functionality	The device measures the user's heart rate and steps taken and forms an exertion model. The device calculates how fast the user should run to get the best workout. It then gives them non-visual feedback that tells them how fast to run. After the run, it compiles and displays an exercise summary with statistics.

Functional Decomposition: Level 1

Level 1 decomposition shows the inputs, outputs, and functionality of each subsystem of Exertion Control. I chose a microcontroller unit (MCU) as the center of the device because of its digital processing power, connectivity options, low power consumption, and low cost [12]. The other system blocks act as peripherals to the MCU, with the battery and regulator supplying power to all the active components. I chose a haptic engine as the feedback method because of the advantages described by Immersion [13]. Figure 3.2 shows the level 1 block diagram, and Table 3.2 describes the functionality of each block.

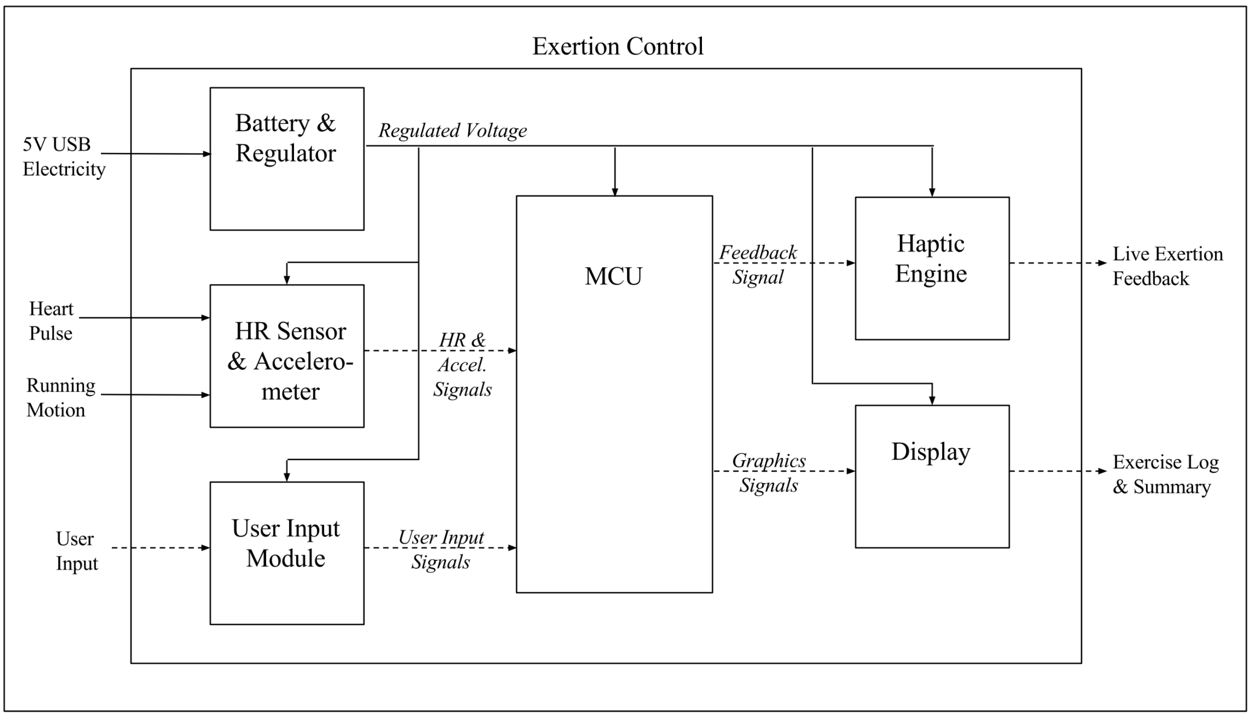

Figure 2: Exertion Control Level 1 Block Diagram

Table 4: Exertion Control Level 1 Functionality

Battery & Regulator	Inputs	- 5V, 1A DC electricity from a USB supply
	Outputs	- 3.3V regulated electricity
	Functionality	When the device connects to a USB charger, the battery charges. When the device operates, the regulator outputs a regulated voltage to power the other components in the device
HR Sensor & Accelerometer	Inputs	- Heart pulse, which changes the reflectivity of the skin - Running motion (movement of the arm)
	Outputs	- Heart rate voltage waveform - 3 axis acceleration signals
	Functionality	The heart rate sensor measures the reflectivity of the skin and converts it to a voltage signal. The accelerometer converts 3 axis motion and converts it into voltage signals.
User Input Module	Inputs	- User input for: navigating menus, turning the display on/off, and powering the device on/off.
	Outputs	- User input voltage signals
	Functionality	The user input module converts user input into voltage signals that the MCU can interpret.
MCU	Inputs	- Heart rate voltage waveform - 3 axis acceleration voltage signals - User input voltage signals
	Outputs	- Exertion feedback voltage signal - Graphics voltage signals
	Functionality	Before a run, the MCU collects user input through the user input signals. While the user runs, the MCU gathers signals from the sensors, computes heart rate, step rate, and HRV, and models HRR. From these variables, the MCU calculates the ideal running rate for the user and outputs it to the haptic engine. After the run, the MCU compiles stats from the run and shows them on the display.
Haptic Engine	Inputs	- Exertion feedback voltage signal
	Outputs	- Haptic exertion feedback vibration pulses
	Functionality	The haptic engine turns the feedback voltage signal into a string of short vibration pulses..
Display	Inputs	- Graphics voltage signals
	Outputs	- Visual exercise log and summary
	Functionality	The display turns voltage control signals into their visual representation. It displays an exercise log and summary after each run and menus during setup.

Chapter 4: Development, Construction and Testing

Development

With the design requirements and specifications described in the previous chapter, I chose parts and designed a printed circuit board in Eagle, shown in Appendices C and D. The board design centers on the ATMega328P microcontroller and was influenced by the Arduino Pro Mini and Sparkfun's FTDI breakout board designs [14, 15]. My board holds the least amount of components for a MCU to operate and link with a computer via serial port. The board also holds a battery charge controller and an LDO to handle power management. The SI1143 and IR LEDs on the bottom of the board handle heart rate sensing by measuring the IR reflectance of the skin. A microSD card slot is included to hold log data. I abandoned the accelerometer IC during board routing, as it took too much space and was not essential to the main functionality.

I wrote the microcontroller code using the Arduino IDE, using the SI1114 library and sample programs written by GitHub contributor ModernDevice, which controls the HR sensor through I2C protocol [16]. I initially used Adafruit's OLED driver library [17], but when the display and HR sensor interfered with each other, I abandoned the display. The basic function of the code is to measure IR reflectance, extract HR, process the signal through a phase locked loop (PLL) to adjust running tempo. This code, in tandem with the human body, forms a phase locked loop, as shown in Figure 3. The phase frequency detector (PFD) and loop filter are built into the code, while the controlled oscillator is the human heart. Appendices E and F show a program flow diagram and a program listing to describe the code in more detail.

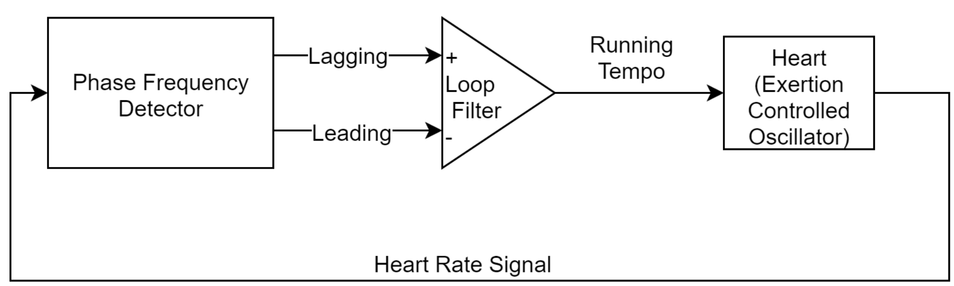

Figure 3: Phase Locked Loop Diagram

The heart rate sensor measures the IR reflectance of the skin, which varies slightly with each heartbeat due to the capillaries filling with blood, which absorbs IR light. Figure 4 shows a sample of data from the IR reflectance sensor. The blue trace in the top plot is the raw data, and the orange is the data passed through a low pass integrator and is effectively a moving average. Hear rate is extracted by comparing these two signals to form a binary signal, shown by the blue trace in the bottom plot. The processed HR and reference HR signals are passed into the phase frequency detector, whose outputs are shown by the gray and yellow traces. In this sample, the measured HR is faster than the reference, so the "leading" output of the PDF pulses high, while the "lagging" output remains low.

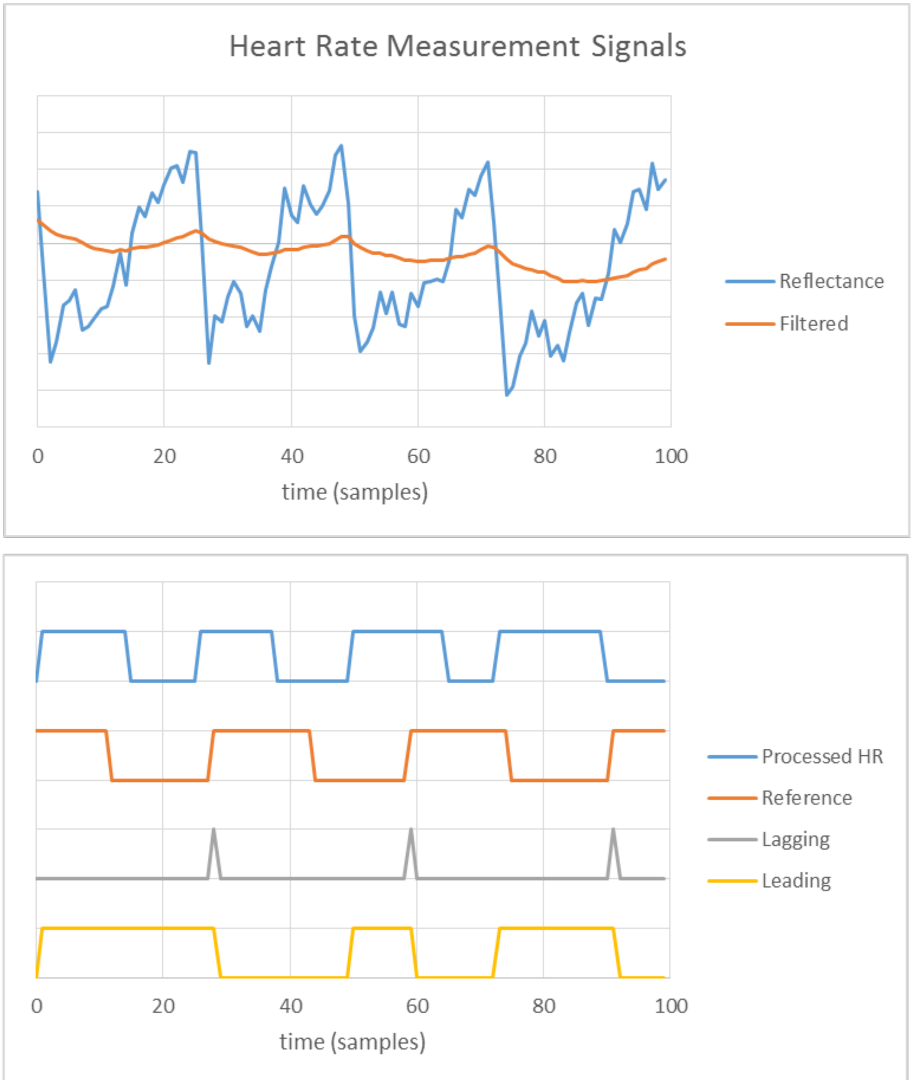

Figure 4: Sensor Data and Heart Rate Signals

Construction and Troubleshooting

After ordering parts from Digikey, Mouser, Ebay, and other vendors, having the PCB fabricated by OSHPark, and a solder stencil made by OSHStencils, I was ready to populate the board. With solder paste stenciled onto the pads, I placed the components and used a reflow oven to solder them into place.

Next was a long process of troubleshooting the board until all of the components worked properly. Below is a list of problems I encountered, their causes, and their solutions.

1. Arduino IDE fails to upload code to the board.
    a. Cause: The factory-default ATMega328P chip did not have a bootloader, which is required to transfer code into the program memory.
    b. Solution: I replaced the chip with one from an Arduino Uno board.
2. IR reflectance sensor doesn't give readings when the OLED display is on.
    a. Cause: Adafruit's OLED driver assumed sole use of the I2C bus, which interferes with the sensor's communications.
    b. Solution: After attempting to limit the OLED's use of the I2C bus, I decided that the bus could not carry communications for both devices, so I abandoned the OLED display.
3. IR reflectance sensor is only making ambient light measurements, not reflectance measurements.
    a. Cause: in a design mistake, I had configured the IR LEDs as if the SI1143 used high-side drivers, where they actually used low-side drivers.
    b. Solution: Hand-edit the PCB to configure the IR LEDs as low-side driven.
4. Battery is not charging.
    a. Cause: In a design mistake, I forgot to connect the battery charge controller's power pin to the 5V USB bus.
    b. Solution: Solder a small wire where the trace should have been.
5. Battery is charging too slowly.
    a. Cause: The resistance that sets the charge current was too large.
    b. Solution: Lower the resistance by adding a resistor in parallel.
6. Vibration motor is buzzing when it shouldn't be.
    a. Cause: When the MCU pin that drives the load switch is configured as an input, the drive pin is left floating.
    b. Solution: Add a pull-down resistor to the drive pin.
7. microSD card is not functioning.
    a. Cause: When designing the board, the pin-out diagram of the microSD card I followed was incorrect.
    b. Solution: Hand-edit the traces to correct the pin connections.

Testing

The troubleshooting procedures described above were a large part of testing. Once everything worked correctly, testing consisted of several closed-loop tests to measure device performance. Following this were several open-loop tests that measured heart rate recovery. Below are some sample data for each type of test.

Figure 5 shows data from a closed-loop test where the reference HR is stepped 120BPM to 140BPM. The oscillating tempo and actual HR signals indicate that the loop is unstable. This is due to the delayed response of heart rate to changes in exertion, which causes the tempo to overshoot the correct value. The open-loop test in Figure 6 measures heart rate recovery, which must be modeled in order to produce a more stable loop. The figure also includes three modeling functions that are potential fits: Gaussian, delayed exponential, and second order exponential [18]. Adding proportional and derivative control to the loop to fit the HRR model will stabilize the loop.

Figure 5: Closed Loop Step Response Test

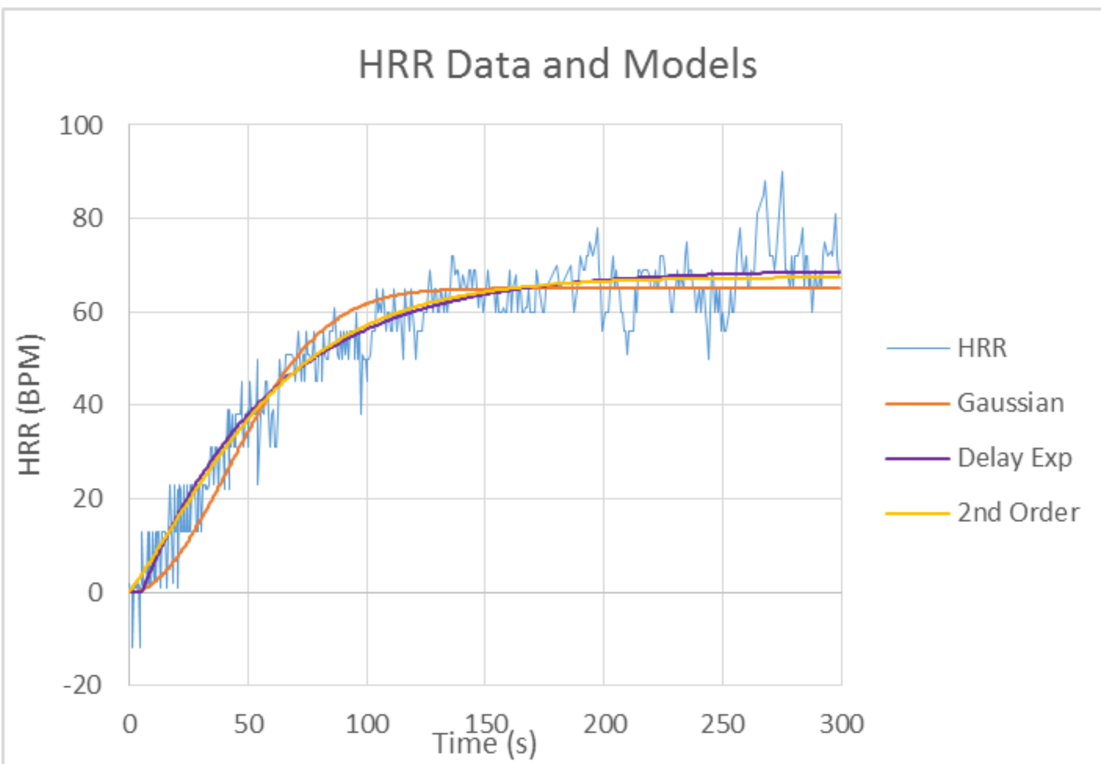

Figure 6: Heart Rate Recovery Test

Chapter 5: Conclusions

The test data shows that Exertion Control achieved its primary goal: to control the user's heart rate by adjusting their running tempo. However, the control loop needs refinement for the device to have accurate and stable performance. I will refine this performance in my thesis work.

Because of the large amount of time spent troubleshooting the device, many of the extra features stated in Chapter 2 were not accomplished, such as an enclosure, a user interface, and a display. In the planning phase, I did not foresee the delays due to troubleshooting mistakes, but time allocated for a second design iteration filled that gap. In a second iteration of the design, I may add a second MCU to handle the user interface, and move the FTDI interface and battery charger to a separate board to reduce size.

References

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[2] Athos (2013-2015), *Athos - Wearable Fitness Technology* [Online]. Avaliable: https://www.liveathos.com

[3] Statista (2015). *Smartwatch Sales Revenue Worldwide 2014* [Online]. Available: http://www.statista.com/statistics/422185/smartwatch-sales-worldwide-companies/

[4] Joe Rossignol (July 22, 2015), "Apple Watch Capture Estimated 75% Smartwatch Market Share in Launch Quarter," in *MacRumors* [Online]. Available: http://www.macrumors.com/2015/07/22/apple-watch-75-market-share-launch-qtr/

[5] James Robert Stirling, et. al., "A Model of Heart Rate Kinetics in Response to Exercise," in *Journal of Nonlinear Mathematical Physics* [Online], vol. 15, suppl. 3, pp 426-436, 2008. Available: http://oa.upm.es/2532/1/INVE_MEM_2008_56669.pdf

This journal article presents a mathematical model of the heart rate's response to exercise intensity at a given fitness level. This model helps to form a fitness model of the user. Both the authors and the publisher of this article give it high credibility. The authors teach at the Polytechnic University of Madrid in Physical Activity and Sport Sciences. The article appears in a peer-reviewed journal with 15 citations.

[6] Roy Benson and Declan Connolly, *Heart Rate Training* [Print]. Champaign, IL: Human Kinetics, 2011.

This book talks in depth about optimizing training for different sports by taking heart rate into account. It claims that monitoring heart rate assists in modeling a workout and explains how to apply heart rate measurements to exercise. Both of the authors bring credibility through experience. Roy Benson, a professional runner, has success as a running coach and exercise scientist. He owns Running Ltd, which partners with and consults for Nike and Polar. He has published works in several popular running magazines and wrote a booklet that sold more than 200,000 copies. Declan Connolly, an exercise physiologist, consults for many professional sports leagues (NFL, NHL, U.S. Rowing, U.S. Skiing) and the International Olympics Committee. He has over 300 publications in scientific journals. These credentials give a very compelling argument for the credibility of this book.

[7] Apple (2015), "Apple Watch" on *Apple* [Online]. Available: http://www.apple.com/watch/

[8] Electrical Engineering Dept, Cal Poly San Luis Obispo (Sep 2011), *Senior Project Handbook* [Online]. Available: http://www.ee.calpoly.edu/media/uploads/Senior_Project_Handbook2011-2012-10-19-2011Update.pdf

[9] Apple (Sep 17, 2015), "Apple Watch - Technical Specifications" on *Apple Support* [Online]. Available: https://support.apple.com/kb/SP717?locale=en_US

[10] Phil Nickinson (Feb 22, 2014), "Samsung Gear 2 Specs" on *Android Central* [Online]. Available: http://www.androidcentral.com/samsung-gear-2-specs

[11] Phil Nickinson (Aug 27, 2015), "LG G Watch R Specs" on *Android Central* [Online]. Available: http://www.androidcentral.com/lg-g-watch-r-specs

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[13] Immersion Corp. (2010), "The Value of Haptics" on *Immersion* [Online]. Available: http://www.immersion.com/docs/Value-of-Haptics_Jun10-v2.pdf

[14] Sparkfun, "Arduino Pro Mini 328 – 3.3V/8MHz" [Online]. Available: https://www.sparkfun.com/products/11114

[15] SparkFun, "SparkFun FTDI basic breakout – 3.3V" [Online]. Available: https://www.sparkfun.com/products/9873

[16] ModernDevice, "SI_Pulse_Prox_Sensors" on *GitHub* [Online]. Available: https://github.com/moderndevice/SI1143_Pulse_Prox_Sensors

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[18] V. Prodanov. (2016, May 5). *Modeling Heart Rate Recovery: Finding Good Curve-fitting Function* [Unpublished].

[19] Kickstarter (2015), “Kickstarter Basics” on *Kickstarter* [Online]. Available: https://www.kickstarter.com/help/faq/kickstarter+basics

[20] Heiko Schwarzburger (Feb. 2010), “The Trouble with Silicon” in *PV Magazine* [Online]. Available: http://www.pv-magazine.com/archive/articles/beitrag/the-trouble-with-silicon-_100001055/86/?#axzz3s4wmNhUU

[21] BlueSkyModel (2015), “1 Kilowatt-Hour” on *BlueSkyModel* [Online]. Available: http://blueskymodel.org/kilowatt-hour

[22] China Water Risk (July 13, 2015), “8 Things Your Should Know About Water & Semiconductors” on *China Water Risk* [Online]. Available: http://chinawaterrisk.org/resources/analysis-reviews/8-things-you-should-know-about-water-and-semiconductors/

[23] World Health Organization (2015), “Electronic Waste” in *Children’s Environmental Health* [Online]. Available: http://www.who.int/ceh/risks/ewaste/en/

The following references are not used in this report, but were part of my literature search.

[24] Mukhopadhyay, S.C., "Wearable Sensors for Human Activity Monitoring: A Review," in *Sensors Journal, IEEE* [Online], vol.15, no.3, pp.1321-1330, March 2015. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6974987&isnumber=6982245

Section III explains sensors used to monitor human activities, mostly for medical applications. It gives a generalized system architecture and explains which types of sensors apply to these uses. The author, a university professor in EE, specializes in sensors. He has written hundreds of technical articles and several books, which go through peer review before publication. This gives the source credibility because, as an IEEE journal article, it underwent peer review.

[25] Health Informatic--Personal Health Device Communication Part 10441: Device Specialization--Cardiovascular Fitness and Activity Monitor," in *IEEE Std 11073-10441-2013 (Revision of IEEE Std 11073-10441-2008)* [Online], vol., no., pp.1-108, March 29 2013. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6491411&isnumber=6491410

This standard defines how cardiovascular fitness data transfers between devices (e.g. a fitness device and a smartphone). If I decide to interface my device with a smartphone app, I need to use this standard. The Personal Health Devices Working Group, which consists of a large number of professional engineers, wrote and reviewed this standard. As an IEEE standard, its writers and editors took great care, and it has high credibility.

[26] Venkatraman, et. al., “Wearable Heart Rate Monitor,” U.S. Patent 8 998 815 [Online], April 7, 2015. Available:

http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PALL&p=1&u=%2Fnetahtml%2FPTO%2Fsrchnum.htm&r=1&f=G&l=50&s1=8998815.PN.&OS=PN/8998815&RS=PN/8998815

Fitbit, Inc., a successful wearable fitness company, owns this patent. The patent describes a sensor and processor system that measures heartbeat waveform and motion. The system then removes the periodic motion from the periodic heartbeat waveform to measure heart rate. My project needs to use a system that provides the same functionality. Fitbit's strong reputation in the wearable fitness device market gives this patent credibility, because current products (which have market success) likely use this method.

[27] Stephen J. Merrill and John R. Cochran, "Markov Chain Methods in the Analysis of Heart Rate Variability," in *Nonlinear Dynamics and Time Series: Building a Bridge between the Natural and Statistical Sciences* [Print], Coleen D. Cutler and Daniel T. Kaplan, Ed. Providence, RI: American Mathematical Society, 1997, pp. 241-252.

This book section presents a mathematical study of HRV (Heart Rate Variability) and explains what different measurements mean with respect to a person's health. This helps if I use HRV as a factor in the human fitness model. Stephen J Merrill, an applied mathematics professor, has 52 publications and 248 citations. This article has only two citations: one in an IEEE article and the other in a conference paper, both on cardiovascular statistics. These credentials give credit to the validity of his mathematical models, while the accompanying claims have less authority.

[28] Tiago Monte. (2015, July 1). "FitBit Surge Teardown" on *iFixit* [Online]. Available: https://www.ifixit.com/Teardown/FitBit+Surge+Teardown/42344

This source shows a teardown of a FitBit Surge, a current fitness smartwatch. This device provides much of the same functions as my project, so I can use this as a reference for my design (rather than reinvent the wheel). This teardown has authority because it simply reports the contents and layout the device. Because photos support everything the authors wrote, the content creates its own credibility.

[29] STMicroelectronics. (2009, October 5). *LIS331HH* [Online]. Available: http://www.st.com/web/en/resource/technical/document/datasheet/CD00250937.pdf

I can use the LIS331, a 3-axis accelerometer, in pedometer application to measure running motion. It has a small package size, low power consumption, and has several interfacing variants using either digital or analog signals. This datasheet gives a thorough and seemingly accurate description of the product. STMicroelectronics, the largest semiconductor chip maker in Europe, has the highest authority to document its own products.

[30] Fredric Paul. (2014, Jan. 8). *What's the Market Size for Wearables? Bigger Than You Think, says CES Expert* [Online]. Available: http://www.broadcom.com/blog/ces/whats-the-market-size-for-wearables-bigger-than-you-think-says-ces-expert/

This blog article explains the growing market in wearable fitness technology, and maps out the types of people planning or planning to buy dedicated fitness devices. This article helps define my target customer, which shapes my design process. The author, an award-winning writer, editor, and content strategist, has works in a handful of popular technology magazines like CNET, Omni, and MIT Technology Review. This article, published on Broadcom's blog, aims to bring recognition to Broadcom's connectivity products, which gives the article an advertisement bias. Also, the statistics used in the article have no citations, leaving their credibility to rest solely on the author's reputation.

[31] Valentina Palladino. (2015, June 22). *Who Has the Most Accurate Heart Rate Monitor?* [Online]. Available: http://www.tomsguide.com/us/heart-rate-monitor,review-2885.html

This buying guide article presents a pseudo-scientific comparison of six popular wearable devices that measure heart rate. This information helped me to determine my heart rate accuracy specifications, and provides me with a procedure for testing it. The author has no credentials that make this article trustworthy. The content includes a transparent description of the procedures used in this study that give the results credit, but not to the scientific standard. Therefore, I can only trust the results presented to ballpark accuracy.

Appendix A: Senior Project Analysis

This analysis of Exertion Control as a senior project considers the impacts of developing and manufacturing it as a commercial product. It analyzes the scope of the project, economic and environmental viability, and ethical issues related to the project. Since many points of analysis assume a commercial scale of production, this analysis assumes that a start-up company designs and supports the device, and a third-party company manufactures it.

1. Summary of Functional Requirements

Exertion Control, a fitness device worn on the wrist, targets runners who want to improve their fitness. They need a device that monitors their exertion level and adjusts their running speed to give the best workout. They need the device to fit comfortably, configure easily, not distract from running, and have an easy to use interface. The device should appeal visually and withstand sweat, water, and dirt. Exertion Control fulfills these needs by modeling the user's fitness through HRR and HRV measurements and calculating the optimal level of exertion. It measures and logs heart rate, and forms a profile of the user's fitness, which the device uses to give the user live feedback during exercise.

2. Primary Constraints

The largest challenges of this project come from creating a novel, portable consumer device. The engineering specifications in Chapter 2 serve as the constraining factors. To have success, the device must provide unique exertion modeling capabilities in a compact and appealing wearable chassis and its battery must last all day. Because of these constraints, sensor measurements, processing, and feedback must all perform accurately with low power consumption. Fitting the system into a water-resistant and dust-proof enclosure small enough to wear on the wrist presents another challenge. Time and expertise also limit the scope of this project. A device that interfaces with smartphones may attract more consumers, but would require wireless connectivity and mobile app development.

3. Economic Impacts

This project initially requires my time and expertise to develop the product, and the time and expertise of Professor Prodanov to advise me. With an estimated development and test time of 382 hours at $30/hour, my time costs $11,460, for which I pay (see time estimates in Chapter 4). The estimated cost of parts used in development totals to $116 (see Table 4.2), which the EE department reimburses. Past the initial development, a small team of engineers brings the device to manufacturing and initial release. I estimate that with three engineers working full time, the time to release takes one year, which totals to $180k in salaries. I estimate requiring an additional $10k to bring the product to release. This brings the initial cost to $202k, which could find funding through a start-up support company such as Kickstarter. Kiskstarter enforces all-or-nothing funding goals and with a 5% fee plus a 3% payment processing fee [19].

Manufactured capital and natural capital falls mostly to the third party company that manufactures the devices. This includes the labor hours needed to manufacture, package and distribute the devices. The natural capital consists the materials needed to produce a plastic chassis, a PCB with ICs and discrete passive components, and batteries. This includes silicon, lithium, petroleum products, resins, metals, and other chemicals used in manufacture, such as etching compounds, photo-resist, and water. Silicon is naturally abundant in the form of sand

(SiO_2), but takes a large amount of energy to convert to its crystalline form. According to PV Magazine, a furnace must heat the sand to above 2000˚C to remove the oxygen [20]. Due to manufacturing inefficiencies, the materials, chemicals, and energy needed to fabricate integrated circuits, PCBs, and plastics exceed the materials contained in the final product.

Based on the development costs of $202k, and assuming a manufacturing cost of $50/unit and a sale price of $150/unit, 2,016 sold units generate enough profit to break even. Additional units sold provide profits of $100/unit, less the costs of maintaining the product, which depends on unit sold per amount of time. The maintenance costs derive from upgrading the product and supporting the product over its lifetime of at least 2 years.

4. Manufacturing Impacts

In the first year of sales, the start-up could manufacture and sell an estimated 20K units, an optimistic and challenging estimate. As the company grows, this number could increase up to 100K units per year. At a manufacturing cost of $50/unit and a sales price of $150/unit, the profit equals $100/unit. This equals $10M/year in profits.

With a fixed development cost of $202K, and a unit profit of $100, the break even point is 2,016 sold units. The cost estimate to the user, after initial $100 purchase and assuming daily use, comes to:

$$Cost/year = \frac{1\ battery\ charge}{1\ day} * \frac{0.78Wh}{1\ battery\ charge} * \frac{\$0.15}{1kWh} * \frac{1kWh}{1000Wh} * \frac{365\ days}{year} = \$0.043/year$$

5. Environmental

The largest environmental impacts come from manufacturing, as the device only consumes an estimated 285Wh/year, which has an environmental impact of adding about 0.322lb/year of carbon dioxide to the atmosphere [21]:

$$Energy\ consumption = \frac{1\ battery\ charge}{1\ day} * \frac{0.78Wh}{1\ battery\ charge} * \frac{365\ days}{year} = 285\frac{Wh}{Year}$$

$$CO_2\ production = \frac{285Wh}{year} * \frac{1kWh}{1000Wh} * \frac{1.13\ lb\ CO_2}{1kWh} = .322\ \frac{lb\ CO_2}{Year}$$

The manufacturing impact includes the extraction process of silicon, petroleum, and metals such as gold, copper, and lithium, as well as the human and thermal energy needed to process these materials, as discussed in the Economic Impacts section. These processes harm the environments from which the materials come, as well as the global atmospheric composition due to carbon emissions of manufacturing. The packaging, distribution, and retail of this product also contribute to carbon emissions. The mining processes lead to shrinking natural habitat and heightened pollution, which may harm local species. IC production also requires a lot of electricity and a large amount of water, about 4.8 million gallons per day for a large fab (average 3,600 gallons per wafer of ICs at 40K wafers/month) [22]. The power and water consumption of a large fab equals that of a small city, which places high demand on water and fossil fuels.

6. Manufacturability

This product shares the same manufacturing challenges as most high-quality portable consumer electronics devices. This device contains a multilayer printed circuit board and a water-resistant and dust-proof enclosure. Both of these components presents its own challenges in both design and manufacturing. Because of the size limitation of the PCB, it must contain small and close-together traces and components. This requires high precision and quality control in the manufacturing of the board, and high precision when populating the board. Manufacturing the enclosure also requires precision, as the device has ports and buttons that need IP67 rated seals. Imprecise manufacturing of the enclosure could compromise the seal, which would lead to a catastrophic failure of the device. These high-precision requirements pose manufacturing challenges, which cost money to overcome (more expensive machinery and more extensive quality control).

7. Sustainability

As with other consumer electronics, this product faces the risk of becoming obsolete before the end of its lifetime. Wearable technology progresses at a fast rate, and better products, including next generations of Exertion Control, likely make this first design obsolete in a few years. To extend the usable lifetime of the product, the design can include upgradable software and a user-replaceable battery, which makes waterproofing more difficult. This product adds to the depletion of the resources used in electronics and to the amount of electronic waste produced by consumer products. This creates environmental sustainability problems at both the beginning and end of its life. At the beginning, it uses rare materials with difficult extraction processes (lithium, gold, copper), whose mining processes often create toxic byproducts. The manufacturing process also consumes energy, releases air pollution (and possibly water pollution), and creates material waste. At the end of it life, the product must either be reused, recycled, or disposed of. Reusing the device's components is the most sustainable option, but creates the challenge of integrating old parts into new products. Recycling the materials in the device, while more sustainable than disposing of them, still has sustainability problems. According to the World Health Organization, recycling techniques used in developing countries release toxic substances into the environment that threaten the health of humans and wildlife in those areas [23].

8. Ethical

The following analyses attempt to answer the follow question with a certain ethical framework: "Is it ethical to design, manufacture, and sell Exertion Control?"

IEEE Code of Ethics:

1. This device aims to improve the health of the user through fitness. At this the device poses no threat to personal or public safety. If any risks surface, the start-up must warn the customer or alter or cancel the product.
2. This device does not create any apparent conflicts of interest.
3. The device documentation must clearly share relevant data to the user.
4. I must reject bribery if it arises.
5. The device documentation must properly instruct users of its intended use. I see no apparent misuses of the device.
6. If I lack necessary training needed to complete this project safely, I must take it or find assistance from someone with proper training.
7. I must accept criticism from my peers and advisor, and give credit where deserved.
8. This device does not pose any discrimination threats.
9. This product has no malicious intent to harm.

Based on the IEEE code of ethics criteria, the design, manufacture, and sale of Exertion Control is ethical.

Ethical Principlism:

This product, if manufactured in an ethical manner, poses little threat to the autonomy or justice of its users. The monitoring and recording of personal health data poses a small autonomy concern. If the device, containing information about its owner, falls into the wrong hands, it could be used against the owner. However, the benefit of using this data constructively outweighs this small risk. On the flip side, this data could promote justice. In several court cases involving health insurance claims, the plaintiff presented Fitbit data as evidence of a physical injury. This data may also apply to cases involving heart conditions. The manufacture of the device poses another threat to autonomy and justice. If the manufacture of this product oppresses workers by exploiting cheap labor, it shares the responsibility of violating acceptable human work and living conditions. The device has no malicious intent, and I do not see any potential ways that the device could aid evil intentions. On the contrary, the device aims to benefit its users by helping them improve fitness and possibly monitoring their health, which could save their life. Based on these principals, the design, manufacture, and sale of Exertion Control is ethical so long as the product uses ethical manufacturing.

9. Health and Safety
As stated in the previous section, the product aims to improve the health of the user. If manufactured ethically, it should not harm any workers involved in its production. The design of the device ensures that it does not expose the user to electrical shock, sharp edges, or blood flow constriction. On a practical level, the device poses no more threat than a wrist watch. The user interface also promotes safety: it requires no visual attention while running, which alleviates the risks of the user running blindly into an obstacle or traffic or tripping over unseen obstacles. The user's health and fitness should benefit from using this device and, if I add a health monitoring feature, the device may save them from heart disease via early detection.

10. Social and Political
I do not foresee any political ramifications of this product, though it may have social implications due to its nature. As with other emerging wearable technology, the early users may bear a stigma, similar to the stigma adopted by the early users of Google Glass and Apple Watch. But as seen with these other technologies, these stigmas quickly die out as the product gains popularity and acceptance.

The stakeholders of this product are its users, the employees of the start-up company, and the workers involved in its manufacturing, and the competing companies. The users of the product gain positively by having a new tool to improve their fitness. The start-up employees benefit financially and professionally if the product succeeds in the market. The impact to the manufacturing workers, as stated in the ethics section, depends on the conditions at the company of manufacture. If manufactured in the U.S., minimum wage and work regulations protect the workers at the cost of a higher manufacturing price. If manufactured in a third-world country with lower wages and nonexistent work regulations, the workers may face inequity. As an emerging company, the start-up has the power to influence the working and living conditions of electronics manufacturing workers globally. With this power comes the responsibility of making ethical design and manufacturing choices. The start-up should also take the social responsibility to market the product accurately and inform the user of the product's abilities and limitations. The marketing of the product influences the use of the product, and should not mislead or deceive consumers to get more revenue. If the product does well in the market, it could have the indirect impact of decreasing competing companies' profits. This could provoke more innovation and better products in the long run, but it could also cause budget cuts to take away jobs. However, for the jobs lost in these competing companies, the success at the start-up would require it to hire more employees.

11. Development
The development of this product uses tools and skills already learned during my time at Cal Poly. To create the body of the device, I will need manufacturing skills, such as machining or 3D

printing. In addition, it required me to research heart rate kinetics, fitness, and measurement methods, as shown in the References section of this report. Among other things, I learned how the heart rate responds to changes in exertion level [5], how heart rate can be used to improve exercise [6], and the method Fitbit uses to measure heart rate [23]. I also learned about codes and standards used in short-range wireless communication [21], ethical concerns with technology, and the marker situation for wearable devices [26, 27]. In the thesis research portion of this project, I must learn analysis techniques from the field of kinesiology to understand and model HRR and HRV.

Appendix B: Schedule and Time Estimates

Table 5: Schedule and Time Estimates

Task Description	**Dates**	**Hours**
EE 460 project planning	Sep. – Dec. 2015	44
Parts search	1/13/16 – 1/23/16	9
Circuit design: schematic design	1/20/15 – 1/21/15	5
Circuit design: PCB routing, place PCB order	1/25/16 – 2/6/16	5.5
Populated first board, ordered additional parts	2/23/16 – 2/29/16	4.5
Troubleshooted board design, ordered more parts	3/4/16 – 4/1/16	7.25
Populated second board and performed corrections	4/8/16	5.25
Coded Arduino sketch	1/30/16 – 5/6/16	27.5
Testing and data analysis	5/6/16 – 5/20/16	21
Documentation	1/13/16 – 6/3/16	15
Total		**156.5**

Appendix C: Parts List and Costs

Table 6: Parts List and Costs

Description	Ref	Value	Package	Manufacturer	Part #	Quantity	Price/Unit
Microprocessor	U1	ATMEGA328P	TQFP32-08	Atmel	ATMEGA328P-AUR	1	3.70
LDO	U2	LP38691	TD03B	Texas Instruments	LP38691DTX-3.3/NOPB	1	1.53
FTDI Bridge	U3	FT323RLSSOP	SSOP28D8	FTDI Chip	FT323RLSSOP	1	5.44
Battery Charger	U5	BQ24093	SOP50P	Texas Instruments	BQ24093DGQT	1	1.41
Load Switch	U6	TPS22860	DBV0006A_N	Texas Instruments	TPS22860DBVR	1	0.72
microUSB Connector	USB	USB-MICROB	USB-MICROB	Amphenol FCI	10118192-0001LF	1	0.46
IR Sensor	IC1	SI1143	QFN-10	Silicon Labs	Si1143-A11-GMR	1	4.39
microSD Slot	J1	HIROSE_DM3CS-SF		Hirose Electric Co Ltd	DM3CS-SF	1	1.66
Resonator	Y1	8.00 MHz	RES-SMD	Murata Electronics	CSTCR8M00G53-R0	1	0.41
Capacitor	C1, C2, C6, C8	0.1 uF	0402	Murata Electronics	GRM155R71 C104KA88D	4	0.10
Capacitor	C3	22 uF	0402	Samsung Electro-Mechanics	CL05A226 MQ5QUNC	1	0.87
Capacitor	C4, C5, C9	1 uF	0402	Murata Electronics	GRM155R61 A105KE15D	3	0.1
Capacitor	C7	10 uF	0402	Samsung Electro-Mechanics	CL05A106 MP5NUNC	1	0.65
IR LED	D1, D2	SFH4056	SMD	OSRAM Opto Semiconductors Inc.	SFH 4056	2	0.95
Green LED	D3	Green	0603	Lite-On Inc.	LTST-S270KGKT	1	0.27
Resistor	R1, R3, R8	4.7 kΩ	0402	Panasonic Electric Components	ERJ-2GEJ472X	3	0.10
Resistor	R2	10 kΩ	0402		ERJ-2GEJ103X	1	0.10
Resistor	R4	1.5 kΩ	0402		ERJ-2RKF1501X	1	0.10
Resistor	R5	30 Ω	0402		ERJ-2GEJ330X	1	0.10
Resistor	R6	2.2 kΩ	0402		ERJ-2GEJ222X	1	0.10
Resistor	R7	100 kΩ	0402		ERJ-2GEJ104X	1	0.10
Vibration Motor		3V 10mm				1	2.00
Battery		500mHh		Shida	702540HP	1	3.08
PCB				OSH Park		1	3.55
Total							**33.54**

Appendix D: Schematic and PCB Layout

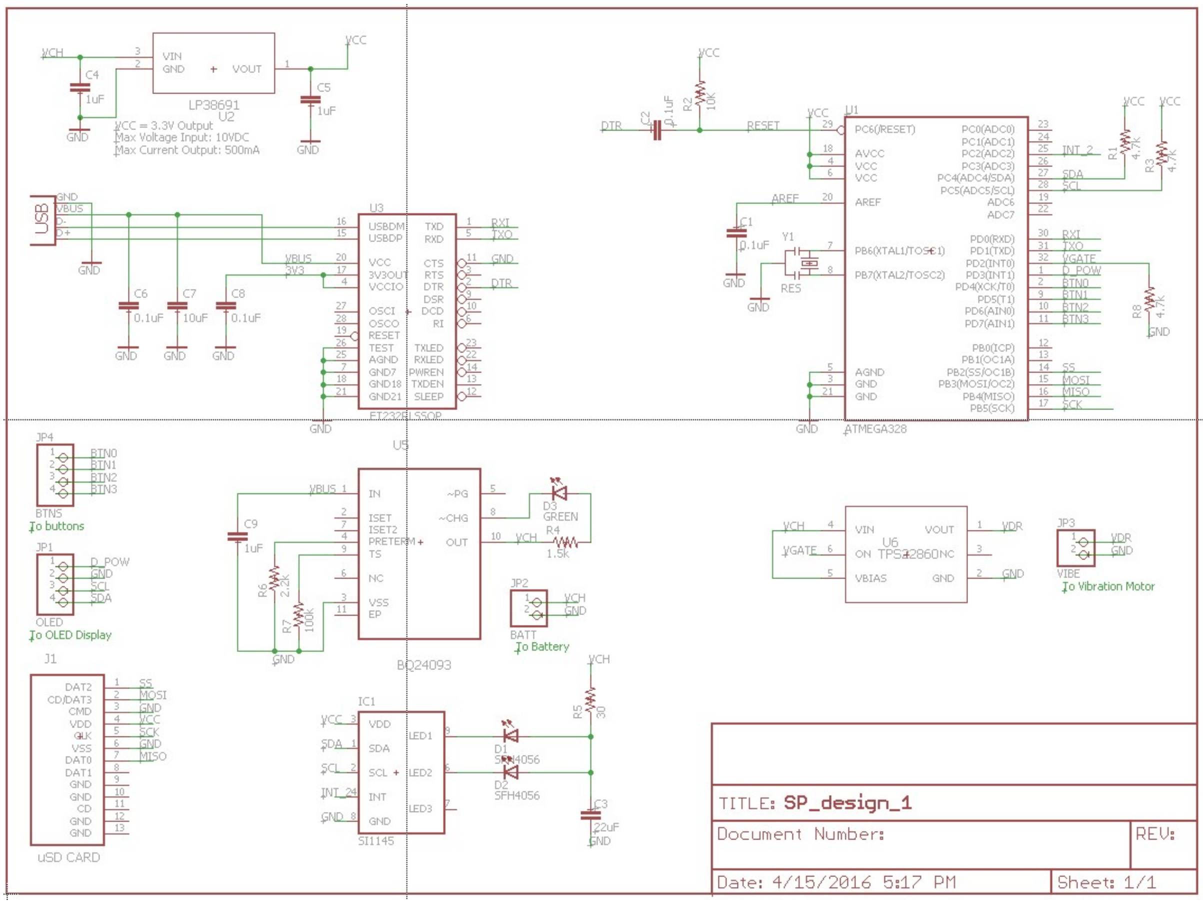

Figure 7: Schematic

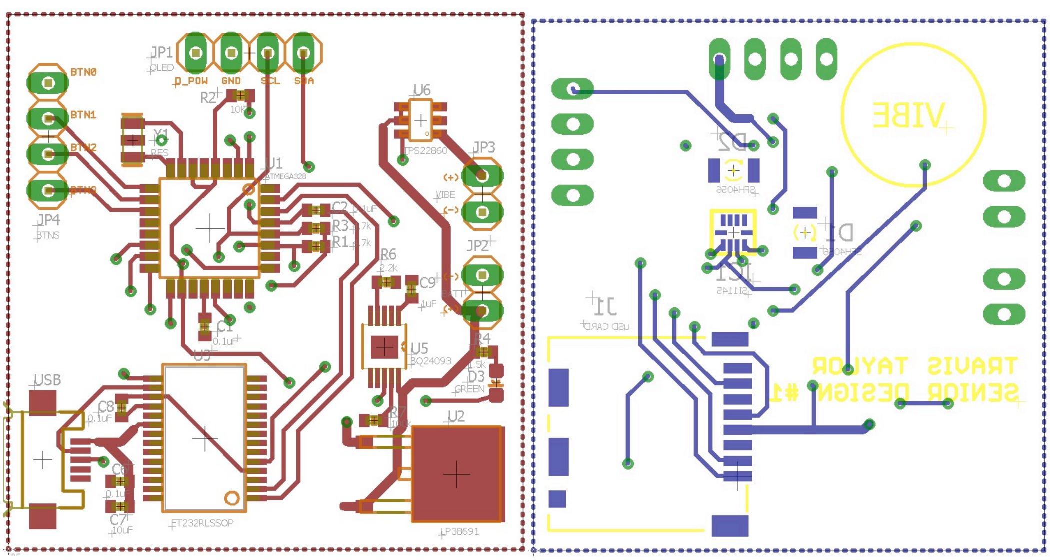

Figure 8: PCB Layout

Appendix E: Program Flow Diagram

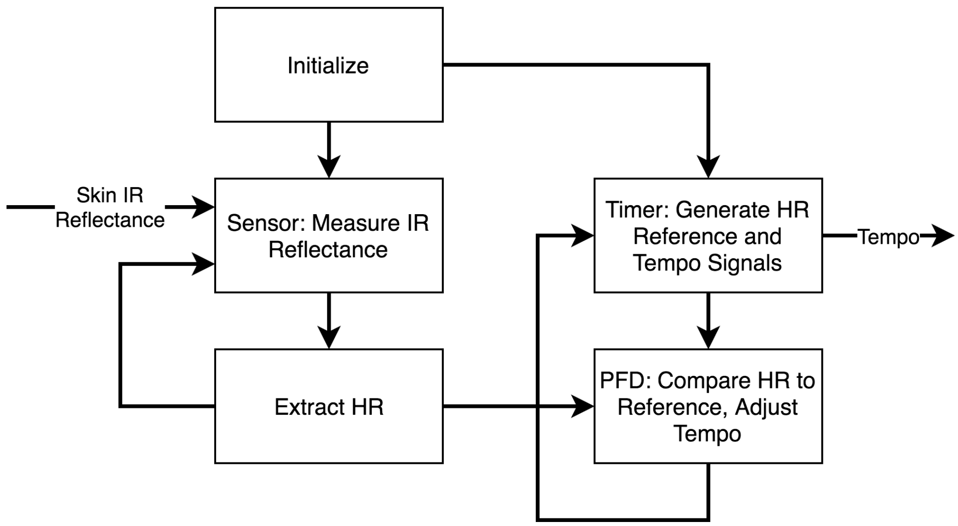

Figure 9: Program Flow Diagram