Stayin' Alive

School of Engineering and Applied Sciences
Harvard University
33 Oxford Street
Cambridge, MA

Description: A compact medical Tricorder device used to measure major body vital signs.

By: Samuel Becker, Bryan Bu, and Brian Krentz

Class: ES50
Instructors: Marko Loncar & Evelyn Hu

May 2014

ABSTRACT

The Stayin' Alive Tricorder is a portable biomedical device that is used to obtain and output four major body vital measurements: heart rate, blood oxygen saturation, body temperature, and heart electrical activity (an electrocardiogram, or EKG). The device was designed to subsequently print all measurement data, including an electrocardiogram image, with an enclosed thermal printer, instantly providing the user with a physical record of his or her medical data.

This project encapsulates many of the concepts taught in the ES50 curriculum. Basic circuit elements, such as operational amplifiers, bandpass filters, resistors, capacitors, and power sources, are widely used in the project. Other concepts include project development and design, computer coding, human interface, laser cutting, signal processing, data management, and component integration.

INTRODUCTION

Much of the human body is controlled by electricity. This fact makes electrical engineers particularly interested in biomedical devices—and as Greg Charvat mentioned in his guest lecture, perhaps the future of engineering lies in the symbiosis of these fields.

Our health is dependent on the effectiveness of electrical systems within our body--including those that control our heart, our breathing, and our temperature. We can engineer devices that provide a snapshot of what is happening within the body, using that information to analyze one's health. These devices are important for understanding our well-being.

Our electrical engineering project, named the *Vital Signs Tricorder* in homage to the legendary Star Trek medical apparatus, seeks to create a compact, portable electrical device that determines several critical vital signs: heart rate, blood oxygen saturation, body temperature, and heart electrical activity. After measurements, the numerical values of these data, as well as an image of the user's electrocardiogram (EKG), were designed to be printed with a built-in thermal printer for immediate output and recordkeeping.

From vital sign measurements, we can often draw important conclusions about our circulatory, respiratory, and thermoregulatory systems, which together can determine much of our general well-being. This device will facilitate that process in a noninvasive, rapid, and convenient way, and the "health receipt" serves as a creative, novelty, and simple way of preserving and recording data.

This project is motivated by the group's interest in medical technology. Bryan, an emergency medical technician, also sought to create an easy-to-use, low-cost way of measuring vitals for in-field use. Further, the Tricorder was also later proposed as a recommended project by 4Combinator, who became a sponsor of the project.

DESIGN

Box/Enclosure Design

We were fortunate to have the opportunity to use the SEAS Teaching Labs and their design software, laser-cutting equipment, and acrylic materials. We took most of a morning to create a perfectly sized box that could house all of our electronics effectively without any excess space. Trying to make this device portable required us to be very economical in our design. When we went to the lab to use the laser cutter, we had measurements down to the millimeter, and the box was also designed with etchings on the top and sides to provide a professional and pleasing presence.

We designed the enclosure in a sensible and intuitive way. The color-coded EKG chest lead connectors were placed on the front of the device, giving the user easy access to the plugs. The chest leads are also removable, as they can be attached and detached from the female banana plugs on the device. The finger hole, through which the user must insert a finger to determine pulse oximetry, temperature, and heart rate, is also in the front for easy access. The power connector for the printer is located in the back of the device, where a standard 5V, 2A adapter can be connected. The end result is a clutter-free, easy-to-transport device, as unwieldy wires can be removed and easily reconnected.

The top of the box is translucent, allowing the user to look into and observe the inner workings of the device. For decoration, a SEAS logo was engraved on the top surface, while stylized text of “Stayin' Alive” was engraved on a side surface. Our name, course title, course year, and the ubiquitous “Resistance is Futile!” mantra is engraved on the opposite side.

The sides of the box are a dark blue, while the top and bottom of the box are a light orange, giving a pleasant aesthetic quality to the product. Each side was cut separately and later adjoined with a liquid acrylic bonding material through a syringe.

From a more practical aspect, we designed the box so that the top can be removed easily for maintenance, repair, or demonstration access. The top is secured with bolts that run vertically from the bottom of the box, and the structure is locked into place with screw-on nuts.

For images of the final product, please refer to the appendix.

The design process began at the dinner table, where preliminary design discussions began. These brainstorming ideas then took to paper, as we created hand-drawn blueprints of the box. As the project developed further, revisions had to be made to accommodate changes and realizations, and subsequent drawings were made. In all, three versions of hand-drawn blueprints were created during the process.

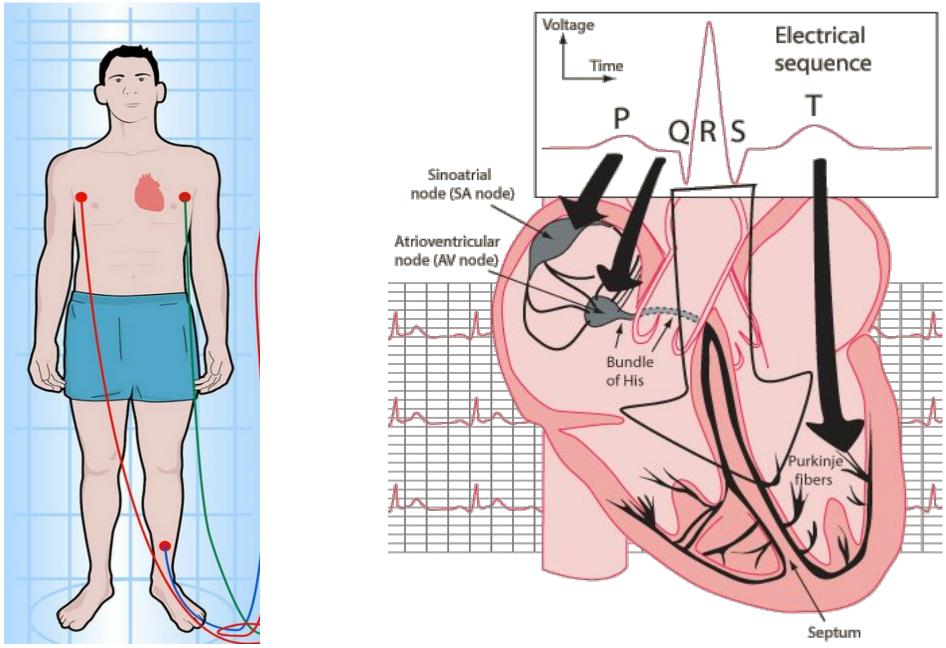
Ultimately, the design was finalized on CorelDraw software, from which the final product was exported to the laser cutter. For the finalized electronic designs, please see the Appendix of this report.

Circuit Design

Three main circuits comprise the physical circuitry of the board. The first, and perhaps most complex, is that of the electrocardiogram.

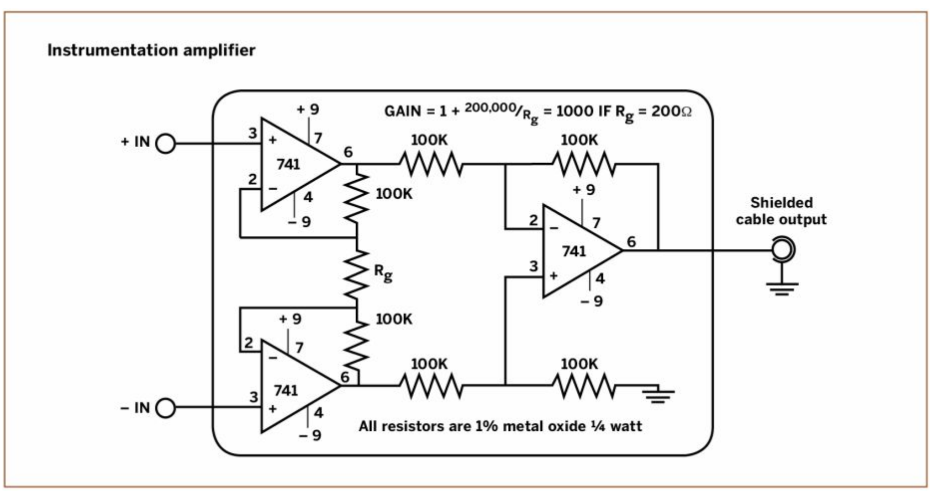
Electrocardiogram

The electrocardiogram works by amplifying the voltage difference between different regions of the chest. The heart is controlled by electrical impulses from the brain, and each impulse travels from the sinoatrial (SA) node of the heart, to the atria, and then lastly to the ventricles. Each part of the wave represents a different part of the heart's contraction cycle. The foot, far away from the heart, serves as the circuit ground, and each measured EKG voltage is compared to the foot voltage.

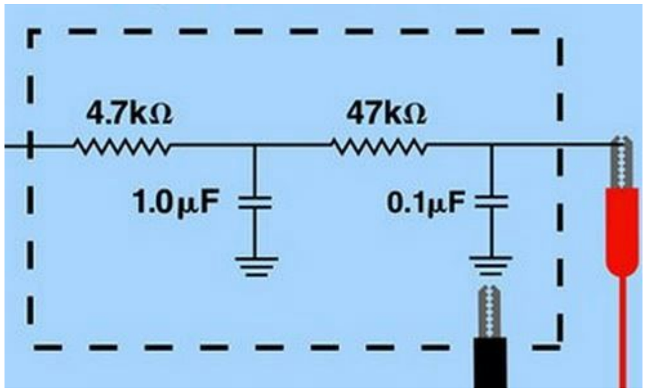


Above: Diagram representing EKG lead placement and image reflecting heart electrical signal graphing

The original circuit design was based on one op-amp, wired to serve as a differential amplifier. However, after seeing that circuit was ineffective, we continued research a better way to amplify the voltage difference between different parts of the chest with respect to a foot ground. After three failed circuit designs, our investigation finally led us to a specific instrumentation amplifier. However, because of the cost and shipping time of an ideal instrumentation amplifier, we decided to use three LM 741 op-amps instead to effectively create an instrumentation amplifier. A schematic of the amplifying circuit, as found on makezine.com and cited in the *References* section, is as follows:

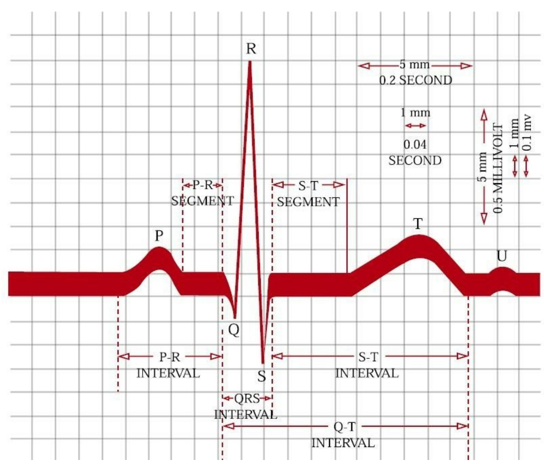


When observing the output on an oscilloscope, we found that the signal was extraordinarily noisy. In order to dampen the high-frequency noise picked up by the amplifiers, a low-pass filter was used. A schematic of this filter, from the same source as above, is shown below:



At first, we noticed that noise still remained, despite the filter in place. However, we further addressed this issue by trying different capacitors, settling ultimately on a 2.2 μF capacitor in place of the 1.0 μF capacitor. Ultimately, the output was a clean, accurate signal that reflected the electrical activity of the heart. The instrumentation amplifier measured the voltage difference between two parts of the chest, which represents the voltage difference between different sides of the heart. The circuit ground was connected to the right ankle, to which all other voltages for the EKG were compared.

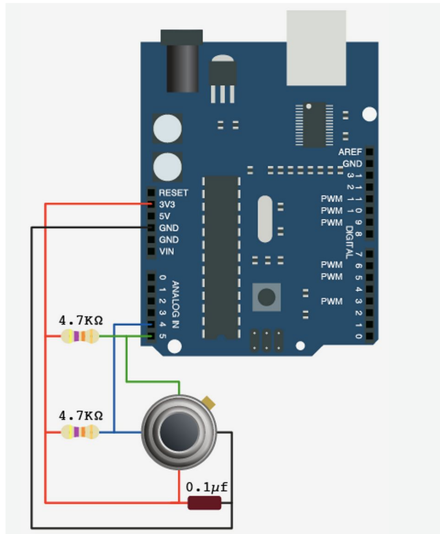
Our EKG oscilloscope output is shown on the left, while a "textbook" EKG is to the right, for comparison::



Comparing the above signal to an ideal EKG, we can see that all elements are present. We were extremely satisfied with the accuracy, clarity, and conformity of the EKG signal. Bryan presented the signal to his paramedic instructor, who was able to effectively interpret the EKG as a healthy waveform.

Temperature Sensor

The second circuit we had was for the temperature sensor. This took in a power source and the temperature sensor converted the IR temperature reading into a signal that could be read and turned into a temperature value by an Arduino Uno. For the code on how this was done, please refer to the submitted files to the course dropbox.



Pulse Oximeter and Heart Rate Sensor

The circuit for the pulse oximeter and heart rate sensor came from hacking a commercial pulse oximeter that we bought. To hack the pulse oximeter, we opened up the casing of the product to get to its inner circuit design. After this, we tested every internal component to find where the signals for the pulse oximeter and heart rate were being sent, so that we could intercept them. We found the heart rate and hooked that up to the Arduino. On one pin, every time there was a beat of the heart, a few voltages would be sent along to the screen. Taking in this input along with the ground for the device, we were able to write an Arduino program that captured this. The information for the pulse oximetry level was never found, but the screen on the device was able to print it out, and the user can see his/her pulse oximetry level through the box's translucent top.

Thermal Printer

The third major component of our tricorder was what made it able to produce a take-away print-out for interested spectators at the Fair—the thermal printer. A thermal printer, most commonly encountered in daily life as the standard for receipt printers, uses a special heat-sensitive paper, which it heats up in specific regions to create black areas on the otherwise white paper (these areas can take the form of text, logos, etc.). The thermal printer we chose to use was available from Adafruit.com and included the handy feature of an Arduino library designed to facilitate the use of the printer.

Above: A print-out from the Adafrut thermal printer.

However, issues with the thermal printer arose when we tried to use it to print large images, like we had hoped to do for the EKG printout. Although the printer can technically (or perhaps allegedly) handle images up to 384 pixels across (the full width of the receipt paper used), in practice, this is not the case. With images larger than approximately 256 pixels across, the printer would become temperamental, and not print the images as desired. We then discovered the further limitation that the largest image that can be printed directly is 256 rows of pixels vertically. Even once we wrote code that we believed would satisfy all of these requirements, and generate an array of hexadecimal values that would code for a bitmap image, our hopes were dashed, and the lack of error messages (it would just not print anything at all) made it all the more difficult to troubleshoot.

PARTS LIST

Description	Vendor	Part Number	Quantity	Unit Price
Thermal Printer	Adafruit http://www.adafruit.com/products/600	600	1 Unit	$61.95
Infrared Thermometer	Sparkfun https://www.sparkfun.com/products/9570	MLX90614	1 Unit	$19.95
EKG Electrodes	Ebay http://www.ebay.com/itm/140645044387?ssPageName=STRK:MEWNX:IT&_trksid=p3984.m1497.l2649	315	2 Packs	$5.45
Pulse Oximeter	Amazon http://www.amazon.com/50-DL-Pulse-Oximeter-Neck-Wrist/dp/B004BJT9OE/ref=sr_1_1?s=hpc&tag=hkc14-20	CMS 50-DL	1 Unit	$17.65
Acrylic Sheet Material	Harvard	N/A	2 Partial Sheets	$10

Nuts, Bolts, and Washers	Dickson Bros.	Various	4 Bolts, 14 Nuts, 8 Washers	$4.50 total
Arduino Uno	Harvard	Uno R3	1	$20
Batteries	Harvard	AAA, 9V	3 AAA, 2 9V	$5 Total
Breadboard, circuit elements, and circuit accessories (resistors, capacitors, op-amps)	Harvard	Various	1 Breadboard 3 Op-amps 15 Resistors 3 Capacitors Assorted Wires	$10 Total
Total Price	N/A	N/A	1 Tricorder unit	$135

PROJECT IMPLEMENTATION

The path to our finalized product took a general route. We first came together and split up the different tasks of researching and building different components. We each researched what parts would be required for all the components and were responsible for making sure those were ordered. After the parts were ordered, we built each component individually. After the parts were made, we came together to design and build the box to house the components. Lastly, we integrated all of the parts together into the box.

Bulleted Steps:

1. Gather necessary components, schematics, and other resources for the individual components
2. Build ECG, temperature sensor (using IR temperature thermometer), heart rate sensor, and pulse oximetry sensor (in our case, those last two went together)
3. Wire thermal printer to the Arduino board and learn how to print from the arduino (Tutorials can be found online. Much more difficulty here than one would anticipate, so do not shirk on getting familiar with how the printer works!)
4. Create box to house all the components (Make it stylish!)
5. Integrate all four components into the box being sure to create space for all the breadboards, printer, batteries, etc.
6. Display final project proudly

General Tips:

- For the temperature sensor: it reads in skin temperature so a little bit of bias will be required to equate it to actual core body temperature
- Using a commercial pulse oximetry sensor is convenient, but know that it will require some time to hack because there are no tutorials available on the subject, despite copious Internet searches.

Most of your time here will be using an oscilloscope to understand the signals within the sensor, and trying to understand different components on the circuit board inside the plastic housing.
- The thermal printer is not friendly. The thermal printer may get angry. The thermal printer does what it wants. Understand these three things and you will be less frustrated. Seriously, although the thermal printer is technically capable of doing certain things, it may just decide not to do them. Or spontaneously change font size and style without any change in code. It is finicky.
- An Arduino has one ground for analog inputs. *This project requires three.* If you want to improve the project then we would recommend finding a way to solve this—perhaps by using multiple Arduinos. Otherwise, understand what information is most crucial to being printed to a thermal printer. For us, the pulse ox and heart rate came on the commercial device and the ECG could be presented on an oscilloscope monitor.

TEAM MANAGEMENT

Specific asks were generally allocated as such, though we often cooperated with each other:

Samuel Becker: Box design and procurement, Arduino coding, Thermal Printer
Brian Krentz: Thermometer, pulse oximeter/heart rate, Arduino coding
Bryan Bu : EKG and signal processing

The team worked well, and the project was completed in a fair and equitable way.

OUTLOOK AND POSSIBLE IMPROVEMENTS

The Arduino code could be improved. The printer would print out inaccurate values for the temperature for the first print-out as it warmed up. We also would love to have had the program to print out the EKG, but we were having trouble getting the thermal printer to print out a picture, as discussed previously. There was also the issue that the Arduino could only handle one of our analog inputs at a time, so finding a solution to this issue would be a great improvement to our project. We would have liked to develop a system with multiple Aruduinos or deeper-level manipulation of one primary Arduino.

ACKNOWLEDGEMENTS:

Of course, we would like to acknowledge Marko Loncar and Evelyn Hu for arming us with the knowledge we needed to complete this project. Their instruction during lectures and guidance during project development gave us an impoprtant electrical engineering toolbox.

We would also like to thank our project TF, Jonathan Budd, who gave us great help during the process. During the construction process, Marko came at a crucial moment to help us troubleshoot the EKG. A handful of TFs and proctors on-site helped us here and there, and they were especially helpful in finding components in the mess of the lab. Furthermore, we would like to thank the staff of the Teaching Labs, and all of our fellow ES50 students this semester for bringing such a great level of energy and enthusiasm to the course.

DISCLAIMER

We release our work.

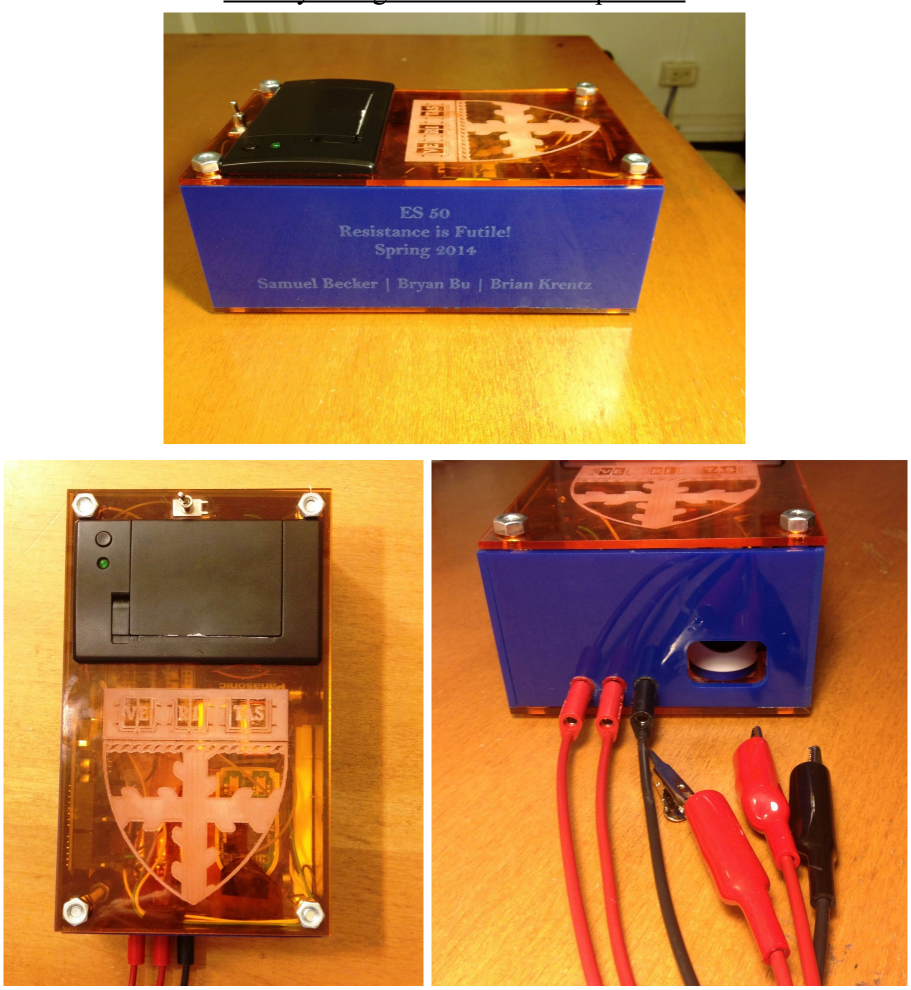
REFERENCES:

- http://makezine.com/magazine/make-11/citizen-science-diy-ecgs/
- http://bildr.org/2011/02/mlx90614-arduino/
- https://learn.adafruit.com/mini-thermal-receipt-printer

APPENDIX

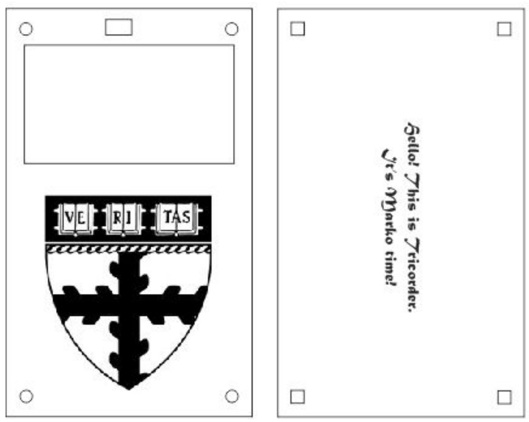
The releveant Arduino code has been submitted via a zip file to the course website.

Gallery: Images of the finished product

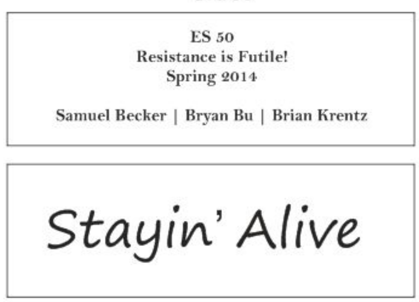


CorelDraw Final Design

Top and Bottom



Sides



Front and Back