# THE ELECTRICAL TESTER: NON-CONTACT VOLTAGE DETECTOR GLOVE WITH MEMORY

By

James Mellott

Isaac Robinson

Eric Monahan

A senior design project submitted in partial fulfillment

of the requirements for the

Bachelor of Science - Electrical and Computer Engineering

Department of Electrical and Computer Engineering

Howard R. Hughes College of Engineering

University of Nevada-Las Vegas

May 2017

Abstract

The risk of electrical shock from working with electrical circuits that could potentially become live is a major concern for both individuals and employers operating in the high voltage A/C electrical field. In the event of an accident, information regarding the details of the accident is critical in preventing future accidents. There are currently no existing detection devices that record any information of the events prior to an accident occurring.

The motivation behind the proposal is to design a glove that can be worn while working on the circuit while simultaneously providing constant monitoring of the surrounding area for an active A/C voltage. On the current market, there are no devices with memory providing passive detection of live A/C circuits. The detection devices currently on the market require active use for immediate detection, but do not continuously record live A/C circuit detection data.

The Electrical Tester offers passive detection to alert the user immediately if they are working in the vicinity of a live circuit that could potentially cause electrical shock. Our design is intended to protect individual users, employers, and employees. To protect the employer, our design implements memory to record the detection of a live circuit as well as offering immediate detection to prevent damage to equipment. The recorded data can be used to provide more information on the events prior to an accident. To protect the user/employee, our design offers passive detection to alert the user immediately if they are working in the vicinity of a live A/C circuit that could potentially cause electrical shock or worse.

Table of Contents

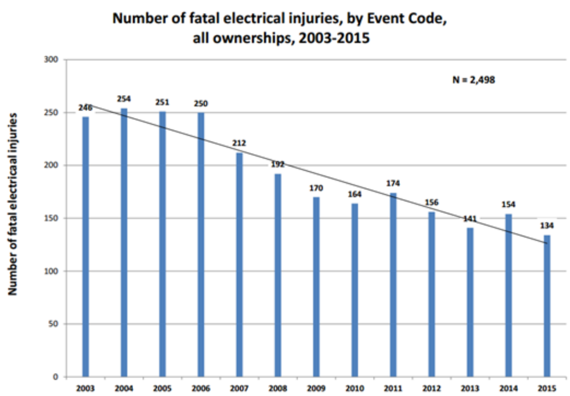
## Introduction

The University of Nevada, Las Vegas EE498 Senior Design project completed is a non-contact voltage detector glove with memory, named the Electrical Tester (ET), to be used by individuals working on electrical circuits where the potential for electrical fault is present. The project involved circuit design, testing, component integration, and fabrication. The completed ET was designed and intended as a safety precaution to help electrical workers detect the presence of energized wires prior to physical contact with the wires. An additional feature of the ET is the capability of storing time stamped data regarding the positive detection of a live circuit. The stored data will be retrieved wirelessly via an Android based application for analysis.

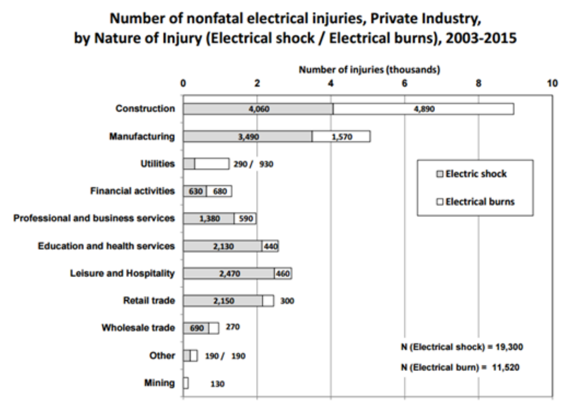
Existing technologies do not incorporate constant monitoring and expose individuals working on A/C circuits to potential electrical shock. These technologies only offer momentary detection meaning the technology is used to detect the presence of an electromagnetic field and then switched off so the individual can use their hands to work as necessary. A safety hazard occurs if a wire becomes 'hot' while work is being performed. The ET aims to remove this hazard and also incorporate data collection that will record when such an event occurs. This concept offers an additional safety net by allowing continuous monitoring while work is performed with data collected for review and accident investigation.

# Motivations

There are several key motivations serving as the impetus for the ET, but none weigh more heavily than increasing the safety of electrical workers. According to data compiled by the Electrical Safety Foundation International using Bureau of Labor statistics, in 2015 there were 134 fatal electrical injuries and 2480 nonfatal electrical injuries across all industries.[1] Due to efforts by employees, employers and government agencies, such as The Occupation Safety and Health Administration, these numbers represent a downward trend, as seen in Figure 1 below.




| Number of electrical fatalities in selected industries, by EVENT, Private Industry, 2003-2015 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Industry Sector | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
| Construction | 132 | 122 | 107 | 126 | 108 | 89 | 89 | 76 | 69 | 66 | 71 | 74 | 81 | 1,210 |
| Professional and business services | 23 | 29 | 39 | 21 | 25 | 27 | 24 | 20 | 23 | 30 | 20 | 19 | 18 | 318 |
| Trade, transportation, and utilities | 17 | 30 | 29 | 32 | 19 | 19 | 18 | 19 | 16 | 16 | 13 | 17 | 9 | 254 |
| Natural resources and mining | 16 | 20 | 27 | 27 | 24 | 13 | 9 | 18 | 24 | 21 | 14 | 16 | 9 | 238 |
| Manufacturing | 22 | 22 | 17 | 14 | 17 | 19 | 15 | 11 | 20 | 11 | 9 | 12 | 7 | 196 |
| Other services | 7 | 6 | 10 | 6 | 5 | 5 | 5 | - | 5 | - | 5 | - | - | 54 |
| Leisure and hospitality | 4 | 3 | 6 | 5 | - | 3 | - | 3 | 4 | - | 3 | 6 | - | 37 |
| Information | 3 | 6 | 4 | 3 | - | - | - | 4 | 3 | 1 | - | - | - | 24 |
| Financial activities | 5 | - | - | 5 | 3 | - | - | 4 | 1 | 3 | - | 3 | - | 24 |
| Total | 246 | 254 | 251 | 250 | 212 | 192 | 170 | 164 | 174 | 156 | 141 | 156 | 134 | 2,500 |




Statistical data compiled by the Electrical Safety Foundation International (ESFI) using data from the BLS CFOI and SOII, 2003-2015

*Figure 1*

However, this downward trend is a small consolation for those individuals impacted by these events. The impact on these individuals is not solely physical, but also psychological and financial with nonfatal injuries resulting in potential loss of income and possibly an inability to continue living as done prior to an event. The ET was conceptualized and proposed as an attempt to help employers and employees drive these statistics to zero. That is the main motivation behind the ET.

## System Overview

The proposed system incorporates a 3.6V battery powered, operational amplifier (op-amp) based, non-contact voltage detection circuit that utilizes a simple wire antenna sewn into a safety glove to detect the presence of electromagnetic fields via induction. An ON-OFF switch will activate the ET. Once activated, if the antenna senses an electromagnetic field, the resulting induced voltage is filtered through an active low-pass filter and then connected to the positive terminal of a non-inverting op-amp with a gain designed to amplify the induced voltage. The amplified signal is routed through a flexible printed circuit board (PCB) to a microcontroller (MCU) to activate light emitting diodes (LED) and a piezoelectric speaker and begin the data collection stage. The PCB will be protected by a 3-D printed box design that will be fixed to a safety glove. Data will be accessible via an antenna on the PCB designed to support Bluetooth Low Energy (BLE) communication to an off-device Android based application (app).

## Design Considerations

This section presents a synopsis of the design considerations for the project with more specific details regarding each part of the project included in later sections of the report. Prior to beginning the design process, team members met to determine mutually agreeable design parameters and constraints for the ET that the team felt were achievable within the time and budget limitations of the project.

The main consideration was the design ergonomics needed to be non-restrictive so an individual would not feel encumbered by the ET and would be willing to wear it. This led to the decision to attach our PCB to a safety glove. The initial safety glove selected was only cut-resistant, but we decided to pursue a safety glove that was also flame resistant due to the potential for burn injuries. The final glove selected was the Ansell PowerFlex 80-813 due to characteristics suitable to the project. Specifically, the glove is cut-resistant, uses a proprietary flame resistant solution and is also arc rated to 8cal/cm^2. An additional benefit was the gloves retail for under $20 per pair, thus helping to keep our budget low.

Next, the PCB design itself was conceptualized to be the size of the average wristwatch to model a device individuals would be used to wearing. The initial idea was to design a flexible PCB, but this was abandoned in favor of a traditional PCB due to the teams collective inexperience with PCB design. The software used for the PCB design was Diptrace, a free design suite selected due to ease of use, familiarity and a broad library of design relevant components. Additional benefits to using Diptrace included having a mentor familiar with the program, a built in design rule check feature and the ability to order PCB's directly from the program.

The last general design consideration discussed was affordability. The group wanted to keep the price of each unit in a reasonable range with the ultimate goal being in the $50 per unit range. If the ET is eventually taken to market, the goal would be to drive this cost down further, but not at the expense of compromising design integrity. The per unit cost will be discussed later in the section on budget.

The remaining design details were all related to the actual circuit design. In brief, the team wanted to meet the following general design criteria:

- Sensitive to AC voltages
- Durable
- Low power with ability to change batteries
- Small PCB to meet wristwatch size ergonomic goal
- Ability to broadcast via bluetooth

The final design met some of the considerations discussed above, however many of these proved to be unattainable for a variety of reasons that will be detailed in future sections with clarification on the potential reasons and suggestions for future versions of the ET.

Non-Contact Voltage Detection Circuit

The non-contact voltage detection circuit design was a basic non-inverting operational amplifier topology. Due to the simplicity of the design and integrated circuit availability, the Texas Instruments LM324-N, a general purpose, low power op-amp was used for the circuit. In future iterations of the design, a variety of different amplifiers will be tested and considered in an effort to reduce PCB size since the LM324-N is quad operational and the design only calls for a single amplifier. The final LT Spice circuit schematic is referenced in Figure 2.

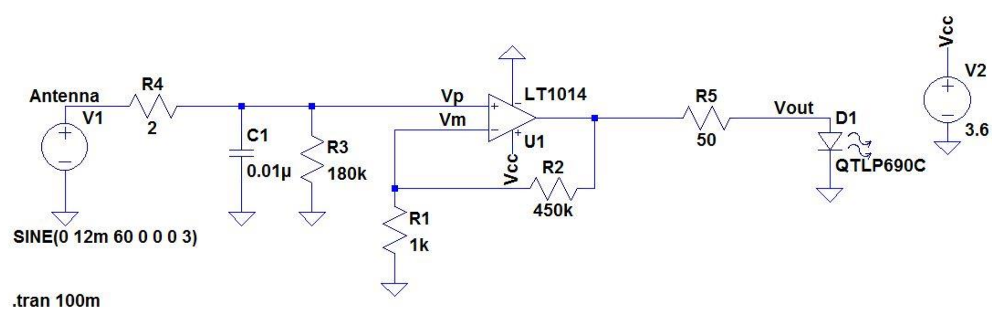



*Figure 2*

The LT Spice circuit uses a 12mV 60Hz sinusoid input to model the induced voltage measured from the antenna during laboratory experiments. The induced voltage is fed through a low-pass filter, $R_4$ and $C_1$, to reduce noise and into the op-amp. The 180kΩ resistor, $R_3$, to ground is used to reduce the offset voltage. The physical antenna is an insulated copper wire that will later be incorporated into the PCB design through an SMA connector. The non-inverting topology has a gain defined by the following

$$\frac{v_{out}}{v_{in}} = 1 + \frac{R_2}{R_1}$$

with a resulting gain of 451 for this design. However, this gain proved to be much larger than necessary for the MCU used, so a variable resistor was added in parallel to $R_2$ to allow adjustment once the design made it to the PCB. Essentially, footprints for both were added to the PCB design to allow testing for optimal sensitivity and then placement of a fixed resistor once the optimal gain is set. The final value for $R_2$ on the PCB was approximately 30kΩ and this provided significant amplification for the induced voltage fed from the antenna. Simulating the circuit resulted in the waveforms displayed in Figure 3.

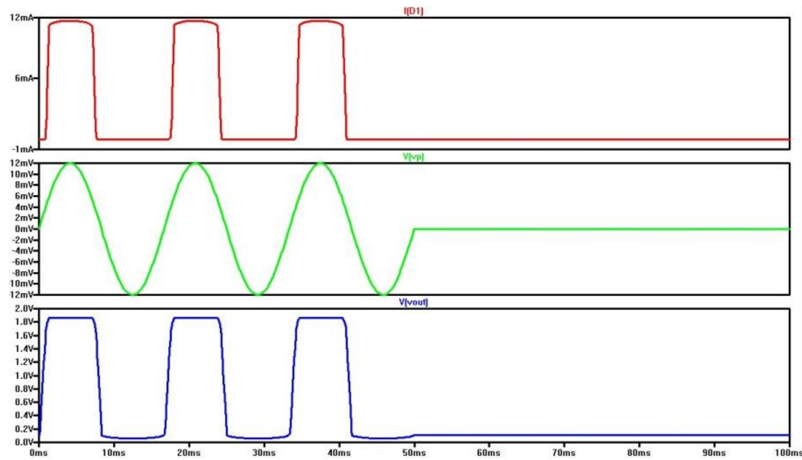



*Figure 3*

The 12mV signal is seen in the middle plot with the output voltage, $V_{out}$ , on the bottom. The LED on the output voltage regulates the voltage and results in the clipping seen at approximately 1.8V, thus verifying the diode is active. As the input voltage drops below 0V the op-amp is limited by the 0V to 3.6V rails and is unable to amplify the negative voltage. The top plot displays the current draw during the amplification at a value of approximately 11.75mA with a power dissipation of approximately 1.26mW.

Experimental testing of the circuit resulted in comparable results to the simulated results discussed above. The circuit was built and tested on a breadboard using identical values as those seen in Figure 2. The oscilloscope image displayed in Figure 4 verifies the induced AC voltage is in fact approximately 12mV as modeled in LT Spice.

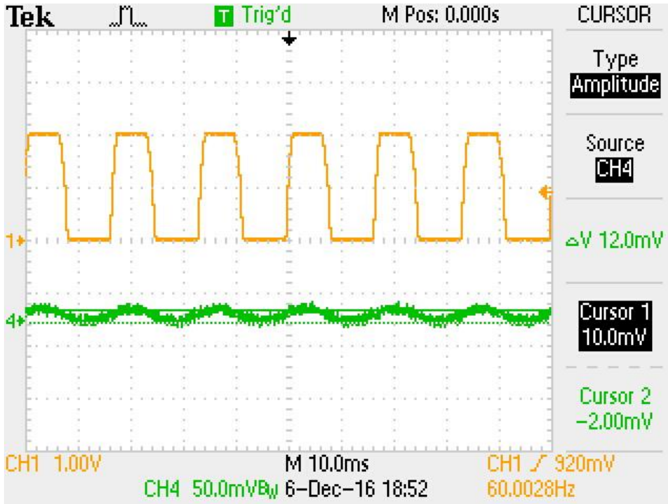



*Figure 4*

The amplified voltage is displayed in Figure 5 below on channel 1. The simulation result clipping at approximately 1.8V closely approximates the experimental results of 2.08V and demonstrates the circuit is functioning as intended.

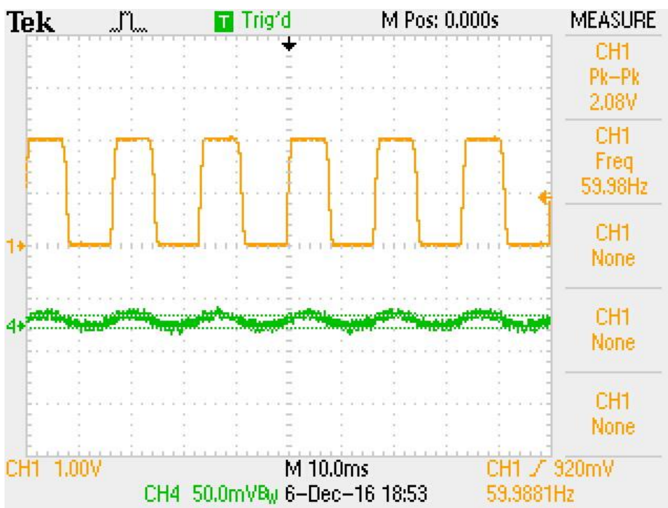



*Figure 5*

Once the analog circuit was determined to be designed and functioning properly, the next step was finding a suitable MCU and testing the analog circuit to see if it communicates with the MCU. This will be detailed in a later section.

## Microcontroller

The MCU selected was the TI - CC2650. This motherboard was selected due to its small form factor, low price and ability to perform BLE communication. The MCU will be powered by the same 3.6V power source connected to the operation amplifier. Moreover, due to the fact that Texas Instruments offers a TI CC2650 Launchpad, Figure 6, prototyping for the CC2650 chip can be done on the fly.

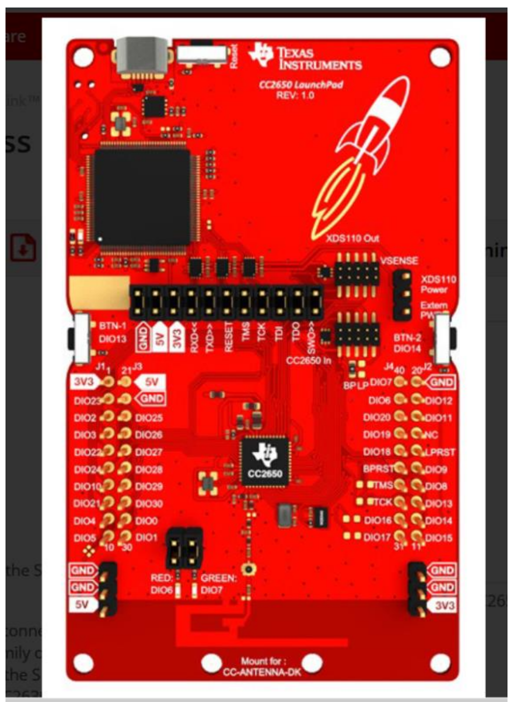



*Figure 6*

This is due to the peripherals offered by the Launchpad on top of the CC2650, including a non-volatile flash memory unit, LEDs, hardware debugger, and a high performance PCB antenna for the Bluetooth LE communications.

## Integrated Development Environment

To perform useful work from an MCU, there must be a way to give it commands to execute and calculate. Useful work from microcontrollers is generally done by generating machine code for the MCU to run from a memory unit. To acquire machine code, one must either have an intense understanding of the MCU at the bit level to create bit level commands, or use an integrated development environment (IDE) with a more human, readable programming language to generate the machine code for the MCU. Texas Instruments provides an IDE for the development of the MCU code called Code Composer Studio. This IDE will not only work for the TI-CC2650 but allows for code to be written for other TI embedded processors. The IDE is feature rich with a C/C++ compiler, debugger, profile build environment and other features that are highly sought after when developing for an MCU.

## Arithmetic Logic Unit, Flash Memory and MCU

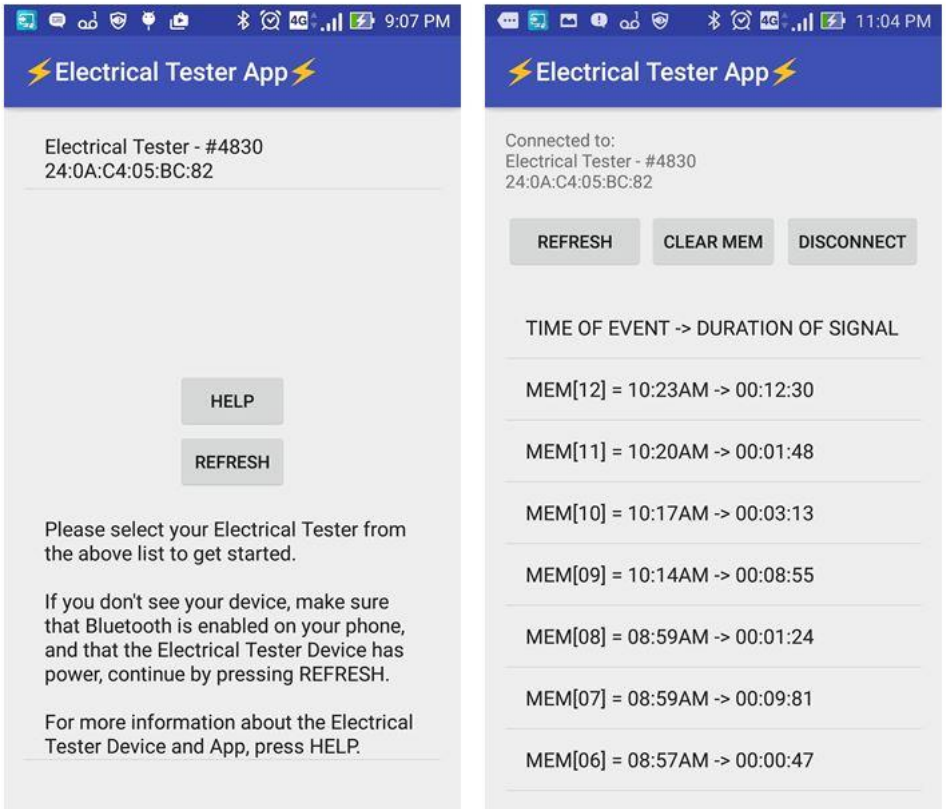
The 3.6V power source for the op-amp and MCU can be considered the VDD of the circuit, an important detail when considering the MCU's Analog to DC (ADC) converter circuit. To prevent damage to the MCU, no digital pin is to input higher then VDD + 0.3 Volts. Considering that the VDD of the amplifier is the same as that of the MCU, the amplifier will at most put out a signal of VDD, thus under the VDD + 0.3 limit of the MCU digital pins. This circuit will be responsible for reading in the inputs from the Non-Contact Voltage Detection Circuit (NCVDC). The digital values read from the ADC will then be processed by the MCU. Due the ADC's ability to read a variety of inputs, there will be a degree of flexibility in the reading of the NCVDC output.

Next, when the output from the ALU detects a signal from the NCVDC indicating an event has occurred, the event data must be stored for future reference. This will be done with an external non-volatile memory unit. The TI-CC2650 Launchpad provides a 1MB serial flash unit to save data onto. The MCU needs to store the time that a voltage has been detected and for how long the voltage was detected. This will be done using some calculations and the on chip crystals oscillators. The goal is to broadcast the event to an external application developed to allow the retrieval of time-stamped data that includes the duration of any events that occur. The development of the application will be discussed in the next section.

## Electrical Tester Application

Adding a memory to the detection device required a way to read the memory from the device. Since there are no physical connections from the final circuit to read the memory, the design for the data transfer included the incorporation of an antenna to broadcast wirelessly. As discussed earlier, the wireless medium selected for communication is Bluetooth, specifically BLE. BLE was a perfect choice for this device due to the fact that BLE devices tend to, as the name implies, not use a lot of power. This characteristic reduced the required power supply, in this case the battery, to something small that will not be heavy or invasive and will contribute to the goal of keeping the overall design small.

Originally, the plan was to create a Windows 8.1/10 application to read the data off the MCU. This turned out to be an issue because Microsoft had not added support to communicate to unpaired devices at the time this project started. Microsoft has stated that due to the popularity of BLE devices they were planning to add support to communicate with unpaired devices, but there has been no further update on this. The TI - CC2650 Launchpad does not allow for pairing, so this idea was ruled out. However, Android smart devices are widely available and do support communication to BLE devices. Thus, an application that was able to communicate with the MCU via BLE was coded using Android Studio. The images displayed in Figure 7 below are Android screenshots of the final version of the application used for the project. All relevant code will be included in the Appendix.




**Android based Electrical Tester App for wireless data transfer**

*Figure 7*

Note the app includes time stamped data and the duration of each event, as intended.

## Analog to Digital Communication

Once an early version of the application was developed, the analog circuit was connected to the TI Launchpad to determine if the analog circuit breadboard prototype and the MCU could communicate with verification determined via the MCU controlling an on board LED. Simply, if an AC voltage was detected by the sensing antenna an induced voltage would be amplified and sent to the MCU and the MCU would activate an LED to alert the user that an AC voltage was detected.

Initial testing resulted in the realization that the amplifier gain was too high, thus making the device overly sensitive. There were two steps the team used for solving this issue. The first step was to decrease the feedback resistor, $R_2$, such that the gain was reduced. This was achieved via a variable resistor with an approximate value of 50kΩ settled on for a suitable degree of sensitivity. Next, to further refine the sensitivity, the MCU was programmed to adjust the threshold voltage that would trigger the LED and memory. This allowed two separate methods for controlling sensitivity.

After making these adjustments, the analog and digital components worked as designed. Upon detection of an AC voltage, the MCU turned on an LED and broadcast to the ET app. An early version of the app indicating a positive AC detection with LED activation is displayed in Figure 8.


*Figure 8*

The net result of the analog to digital testing was successful communication between the three main components of the ET. The analog to digital components communicated and the BLE antenna successfully broadcast event data to the ET app. The next step involved moving from the breadboard to the actual PCB design.

The printed circuit board design presented several challenges for the team due to inexperience with PCB design, as well as challenges in fabricating a working antenna to allow BLE communication. As discussed previously, the software used for the design was Diptrace. The first step involved in the PCB design was creating a schematic. The finished schematic is displayed below. This process included choosing the proper components and their values to allow the circuit to function and included the addition of decoupling circuitry and diode protection. The finished circuit schematic is seen in Figure 9.

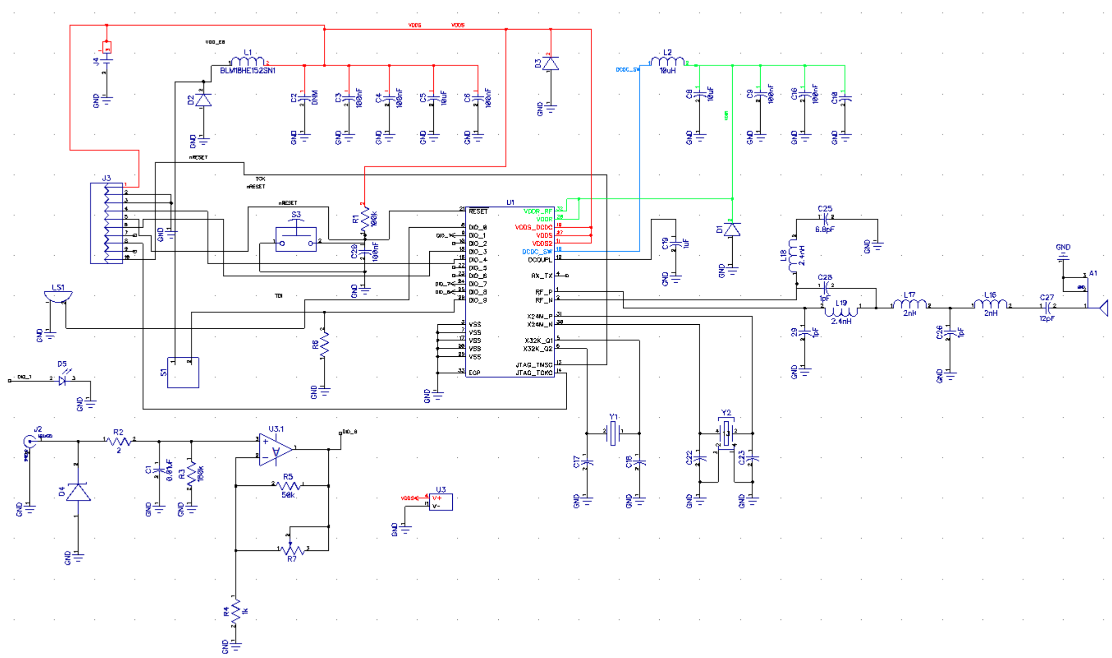
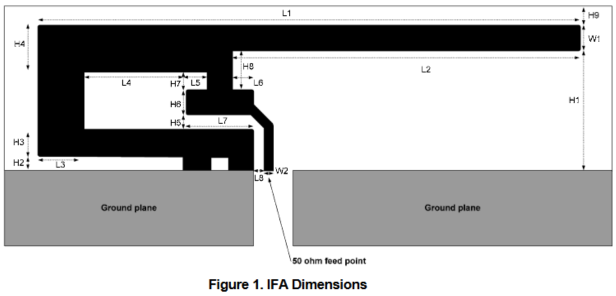


*Figure 9*

Once the schematic was completed, footprints for components not included in the Diptrace library were created. One of the main challenges in transferring from the Launchpad to the PCB was the creation of an antenna. Since antenna design is complex, the team elected to simplify the design process by treating the antenna design as an out of the box component similar to the operational amplifier. To this end, the antenna on the Launchpad was replicated using TI's available antenna specifications, seen in Figure 10 [2] on the left, with the correlating footprint replicated in Diptrace on the right. Additional consideration was given to the impedance matching of the antenna design on the Launchpad such that the PCB reflected similarly.




| | | | |
|---|---|---|---|
| H1 | 5.70 mm | W2 | 0.46 mm |
| H2 | 0.74 mm | L1 | 25.58 mm |
| H3 | 1.29 mm | L2 | 16.40 mm |
| H4 | 2.21 mm | L3 | 2.18 mm |
| H5 | 0.66 mm | L4 | 4.80 mm |
| H6 | 1.21 mm | L5 | 1.00 mm |
| H7 | 0.80 mm | L6 | 1.00 mm |
| H8 | 1.80 mm | L7 | 3.20 mm |
| H9 | 0.61 mm | L8 | 0.45 mm |
| W1 | 1.21 mm | | |

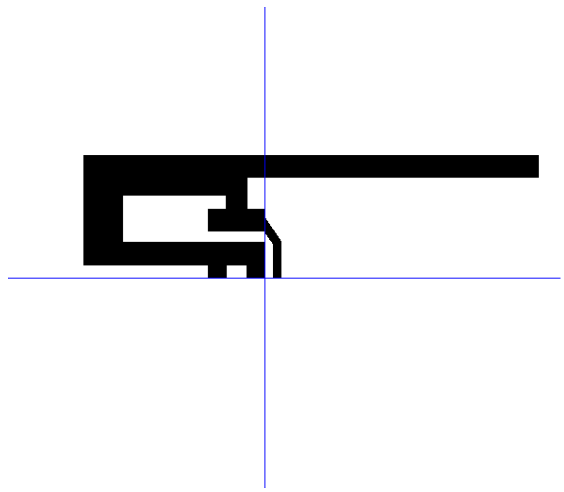


*Figure 10*

After all the footprints were completed, the PCB layout commenced with the final version seen below in Figure 11.

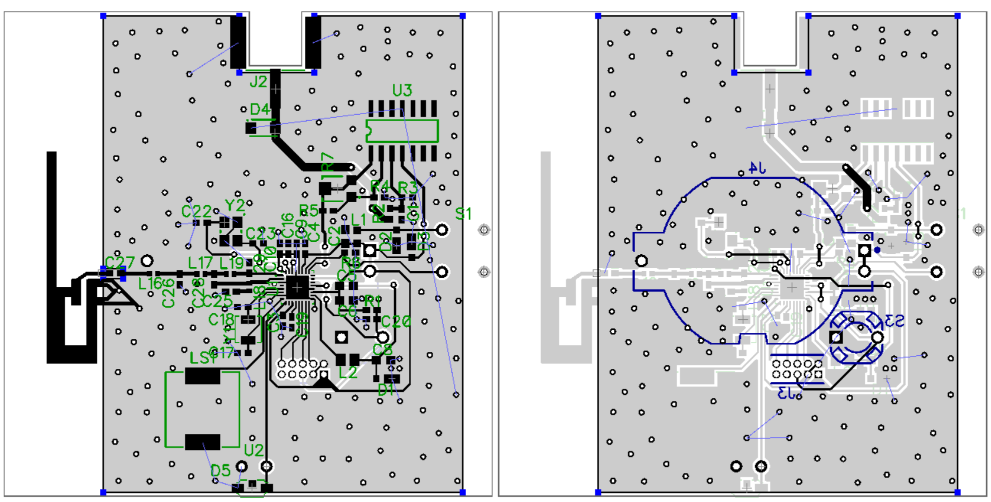



*Figure 11*

The images in Figure 11 show the unpoured version of the PCB with the top layer displayed to the left and the bottom layer to the right.  The learning curve for the PCB design included seven versions of the board with an early version sent for fabrication to Bay Area Circuits with incorrect footprints for several components.  Additional early design errors included improper placement of coupling capacitors and less organized trace routing.  After redesigning to address these issues, a second PCB design was sent for fabrication.

As a contrast, Figure 12 displays the same images with the poured ground plane included.

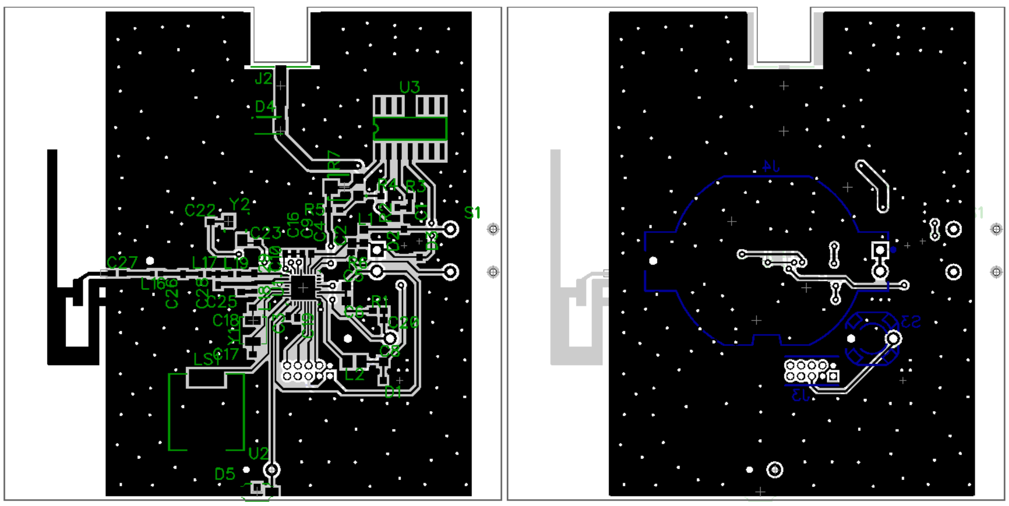



*Figure 11*

The next step after designing and ordering the boards was ordering all the relevant components.  Nearly all the components were surface mount with all components purchased via the internet through either Mouser or DigiKey.  A list of all the components included in the project will be detailed in a later section.  Additionally, the PCB 3-D housing was ordered. The design files are not included in the report as these were created by an outside vendor and considered proprietary.  The only information given to the vendor was the dimensions required for the design.  The housing for the PCB is literally a box with a slide top that allows the PCB battery to be changed and holes for a switch, LED and an antenna.  This concludes the PCB design section.

## Electrical Tester Assembly and Troubleshooting

The last stage of the project involved assembly of all the components to build a functioning prototype. This included organizing all the PCB components to be soldered, sewing the antenna and PCB housing to the safety glove, and testing the ET once assembled.

This stage of the project proved to be the most challenging for the team and provided the most practical engineering experience to date. The soldering process was completed using the reflow station in the UNLV Electrical Engineering laboratory. A total of seven boards were soldered with varying degrees of success and failure. The second board soldered was the board that performed the best, but had several drawbacks. Specifically, the board did not have an ON-OFF switch or piezoelectric speaker because this was a PCB from the first design containing incorrect footprints. The team was unable to complete a functioning board from the PCB's fabricated with the correct footprints.

The second board was selected for the prototype due to time constraints as the project came to the end. The selected board activated an LED, as intended, but even more significantly the ET broadcast event data to the ET application meaning the memory worked. This was a credit to the PCB designed by the team electrical engineers and the app developed by the computer engineer. The board was hot-glued to the 3-D printed housing and the antenna was connected via the SMA connector. The final step of the assembly involved sewing the housing and antenna to the glove for the prototype. The final prototype did not offer ideal mechanical stability, but the team was satisfied with the results for the first version ET prototype. The completion of the assembly allowed the team to compete in and win the Grand Prize in the Fred and Harriet Cox Senior Design Competition for the UNLV Spring 2017 semester featuring 31 different teams from all the UNLV engineering disciplines.

## Future Improvements

The design process resulted in a functioning prototype, however several key improvements are suggested for future versions of The Electrical Tester. These include, but are not limited to the following:

- Reduce power consumption
- Decrease PCB layout area
- Test flexible PCB suitability
- Increase sensitivity range
- Reduce per unit cost
- Improve Glove-PCB integration
- Develop App to be more user friendly

Despite the successful completion of the design, the team members are looking to future versions of the design, as well as areas that were neglected due to time constraints. An area that was neglected during prototyping was testing the ET. The final prototype was completed less than 48 hours prior to the competition. Due to this, the design presented emphasized proof of concept while neglecting actual testing. The team recognizes testing for issues such as false positives and negatives, sensitivity to variations in temperature, durability, and basic circuit testing including power consumption are all required to move the ET into the next stage of development. The team intends to pursue a provisional patent and to continue working on improving the design.

## Budget

The total per unit cost of the ET is estimated at $76 with the project costs totaling approximately $700. These costs can be driven lower if the ET was to be produced on a large scale with savings seen in bulk purchases, reduced layout size and design simplification. An itemized list of all the ET components cross referenced with the PCB schematic is included in Table 1 below. The PCB housing was printed for free, thus this cost is omitted.

| PART | QTY | PRICE | TOTAL |
|---|---|---|---|
| C3 C4 C9 C | 5 | 0.019 | 0.095 |
| C5,C8 | 2 | 0.15 | 0.3 |
| C6 | 1 | 0.019 | 0.019 |
| C14,C27,C | 3 | 0.014 | 0.042 |
| C26,C28,C | 3 | 0.105 | 0.315 |
| C25 | 1 | 0.027 | 0.027 |
| C1 | 1 | 1.5 | 1.5 |
| C19 | 1 | 0.1 | 0.1 |
| D1,D2,D3 | 3 | 0.321 | 0.963 |
| D4 | 1 | 0.47 | 0.47 |
| D5 | 1 | 0.4 | 0.4 |
| FL1 | 1 | 0.21 | 0.21 |
| J2 | 1 | 5.39 | 5.39 |
| J4 | 1 | 0.83 | 0.83 |
| J5 | 1 | 3.11 | 3.11 |
| L2 | 1 | 0.17 | 0.17 |
| L16,L17 | 2 | 0.055 | 0.11 |
| L18,L19 | 2 | 0.139 | 0.278 |
| LM324-N | 1 | 0.368 | 0.368 |
| LS | 1 | 2.09 | 2.09 |
| R1 | 1 | 0.0088 | 0.0088 |
| R2 | 1 | 0.026 | 0.026 |
| R3 | 1 | 0.012 | 0.012 |
| R4 | 1 | 0.012 | 0.012 |
| R5 | 1 | 0.009 | 0.009 |
| R6 | 1 | 0.011 | 0.011 |
| R7 | 1 | 0.28 | 0.28 |
| S1 | 1 | 4.08 | 4.08 |
| S3 | 1 | 0.23 | 0.23 |
| U1 | 1 | 8.95 | 8.95 |
| Y1 | 1 | 0.81 | 0.81 |
| Y2 | 1 | 0.51 | 0.51 |
| GLOVE | 1 | 15.89 | 15.89 |
| BATTERY | 1 | 2.95 | 2.95 |
| PCB FAB | 1 | 25 | 25 |
| | | | 75.5658 |

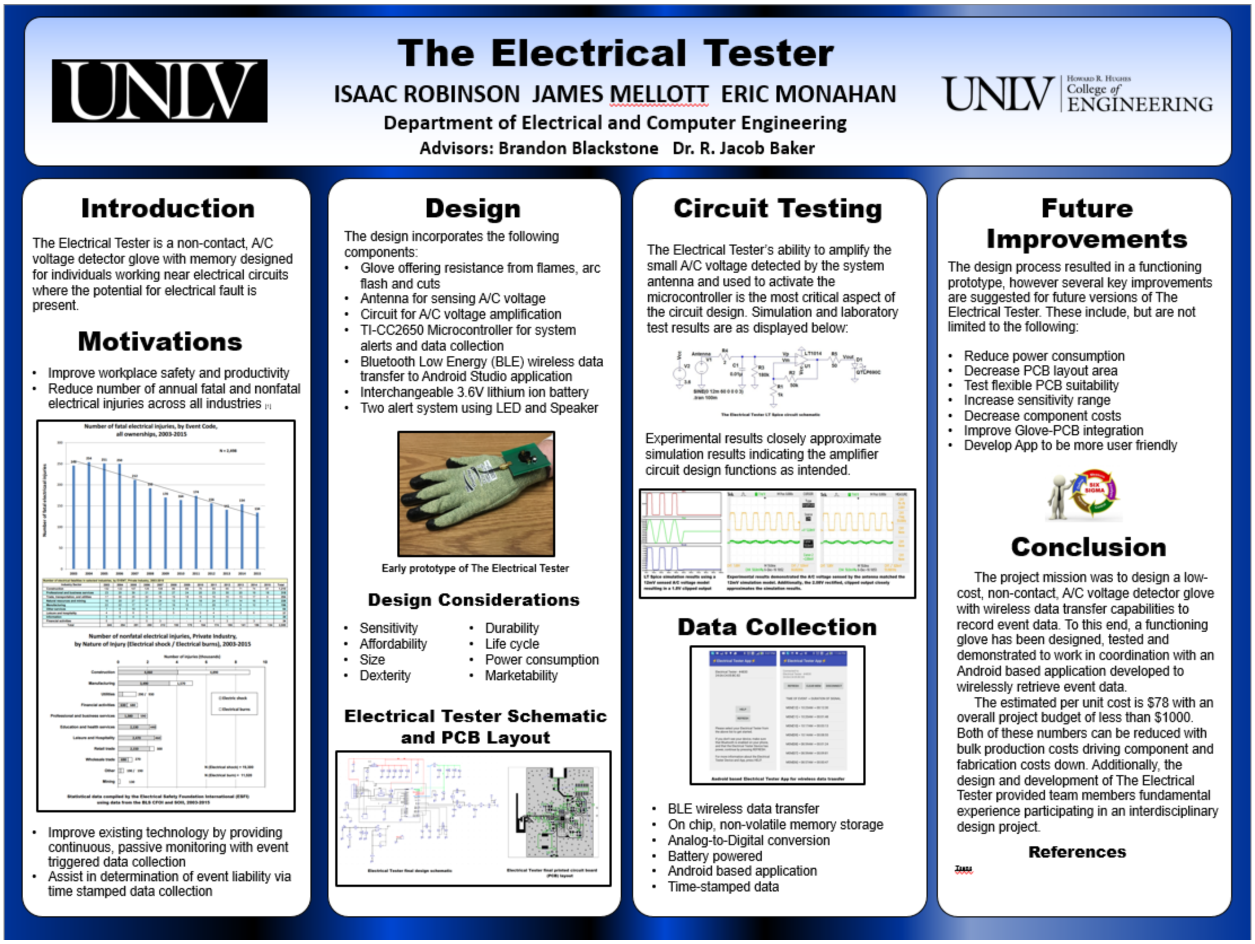
*Table 1*

## Conclusion

The project mission was to design a low-cost, non-contact, A/C voltage detector glove with wireless data transfer capabilities to record event data. To this end, a functioning glove has been designed, tested and demonstrated to work in coordination with an Android based application developed to wirelessly retrieve event data.

The estimated per unit cost is $76 with an overall project budget of less than $1000. Both of these numbers can be reduced with bulk production costs driving component and fabrication costs down. Additionally, the design and development of The Electrical Tester provided team members fundamental experience participating in an interdisciplinary design project.

Appendix A: Project Poster



## References

1. Electrical Safety Foundation International using data from the BLS SOII, 2003-2015, http://www.esfi.org/resource/workplace-fatalities-and-injuries-2003-2015-571
2. http://d3i5bpxkxvwmz.cloudfront.net/articles/2011/09/22/inverted-f-antenna-PCB-1316730420.pdf

NOTE: INTERNET PDF

CODE HAS BEEN REMOVED FROM REPORT TO PREVENT INFRINGEMENT OF PROPRIETARY INFORMATION