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TOWARDS SYSTEMS ON CLOTH: THE DESIGN, MANUFACTURING, AND VALIDATION OF OPEN-SOURCE EMBROIDERED RESISTORS

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TOWARDS SYSTEMS ON CLOTH: THE DESIGN, MANUFACTURING, AND VALIDATION OF OPEN-SOURCE EMBROIDERED RESISTORS

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Definitions

Wearables / Smart Devices – Any type of wearable electronic device that assists a user.

E-textiles – Electronic devices or components that are made with conductive fabric materials. Also referred to as "smart textiles" or "textile electronics".

Systems on Cloth – Electronic systems integrated into fabrics, often manufactured with inkjet printing or embroidery. A type of E-textile.

E-broidery – Embroidery with conductive thread for creating flexible electronic devices.

List of Abbreviations

RFGT – Resistor File Generation Tool

.exp – file format for embroidery machines

.dst – file format for embroidery machines

ECG – Electrocardiogram. Heart rate monitor that uses light waves to measure pulse.

GSR – Galvanic skin response. Measures changes in sweat gland activity to detect stress levels or emotional state.

PCB – Printed circuit board. Method of creating circuitry for most electronic devices.

SoCl – Systems on Cloth. Electronic devices integrated into fabrics, often made with inkjet printing or embroidery.

BOM – Bill of Materials.

Abstract

This thesis is focused on advancing embroidered wearable electronics and textile electronics by creating open-source flexible resistors. Advancements in textile electronics could usher a new generation of smart devices that are entirely flexible. Current systems on cloth primarily use rigid components, which limits the flexibility and comfort of using the fabric devices. To advance this field, I propose a novel method of creating flexible electrical resistors with embroidery. To realize this technology, I created an open-source tool to create embroidery files for machine fabrication. This thesis details the methods and tools created for resistor fabrication. The resistors were tested to cover a range of conditions wearable electronic devices may be subjected to, then tested in an applied setting by being used in a touch sensing device. It is concluded that the embroidered resistors are a viable technology and warrant continued study, development, and use.

1 Introduction

1.1 General Background & Motivation for this Research

The use of wearable electronics is growing rapidly, with over 60.5 million users in the United States alone [1]. Devices include smart watches, smart garments, smart glasses, smart shoes, and more. Some examples of these wearable devices are shown in **Figure 1.1**.

Figure 1.1: Examples of common wearable devices [2], [3], [4], [5], [6]

The most common of the wearable electronic devices is a smart watch [7]. Common examples include the Apple Watch and the Fitbit. These devices are very popular for their ability to pair with smartphones, collect health data, and record activity levels.

The limitation of smart watch technology is that these devices are rigid and are size limited. As technology develops and the capabilities of wearable electronics increase, it is expected that devices will be incorporated into clothing [8]. Incorporating devices into clothing presents great opportunities for health monitoring, activity monitoring, communication, user convenience, and fashion [9].

Current electronic devices are often rigid, bulky, and not durable enough to be worn through daily activities and washed [8]. Incorporating these electronic devices into fabrics necessitates that all aspects of the devices be flexible and durable [10].

Embroidery is an emerging manufacturing technique for creating wearable electronics on fabrics or e-textiles. Embroidery machines can be programmed to create any circuitry on chosen fabrics using conductive thread or yarn. These conductive circuits are fully flexible and can be readily integrated into clothing [11]. See **Figure 1.2** for a depiction of how the embroidery machines can create circuits and aesthetic patterns. These embroidered circuits create the base framework for electronic devices to be made around.

Figure 1.2: Embroidery machine in operation [12]. This manufacturing process can be used to create electronic circuits and aesthetic designs.

The goal in utilizing embroidery machines to create wearable electronics is to increase device wearability, improve user comfort, and increase potential device applications. The embroidered conductive thread can be used to create the circuits and components, which removes the need for rigid PCBs and other obtrusive parts present in current devices. The embroidered thread is flexible and integrates seamlessly (pardon the pun) into any fabric.

In current embroidered wearable devices, conventional rigid resistors need to be used, among other rigid electrical components. These resistors are soldered onto the embroidered threads to complete the circuits. This process of adding rigid resistors limits the desirability of embroidered wearable devices, as it adds complexity to the manufacturing process and decreases the comfortability of the devices. Adding complexity to the manufacturing process leads to increased time, increased cost, increased Bill of Materials (BOM), and difficulty managing quality control. The rigid resistors decrease the comfortability of the devices because they impede flexibility and they protrude beyond the surface of the fabric. **Figure 1.3** shows a depiction of the rigid resistors soldered onto the embroidered circuit.

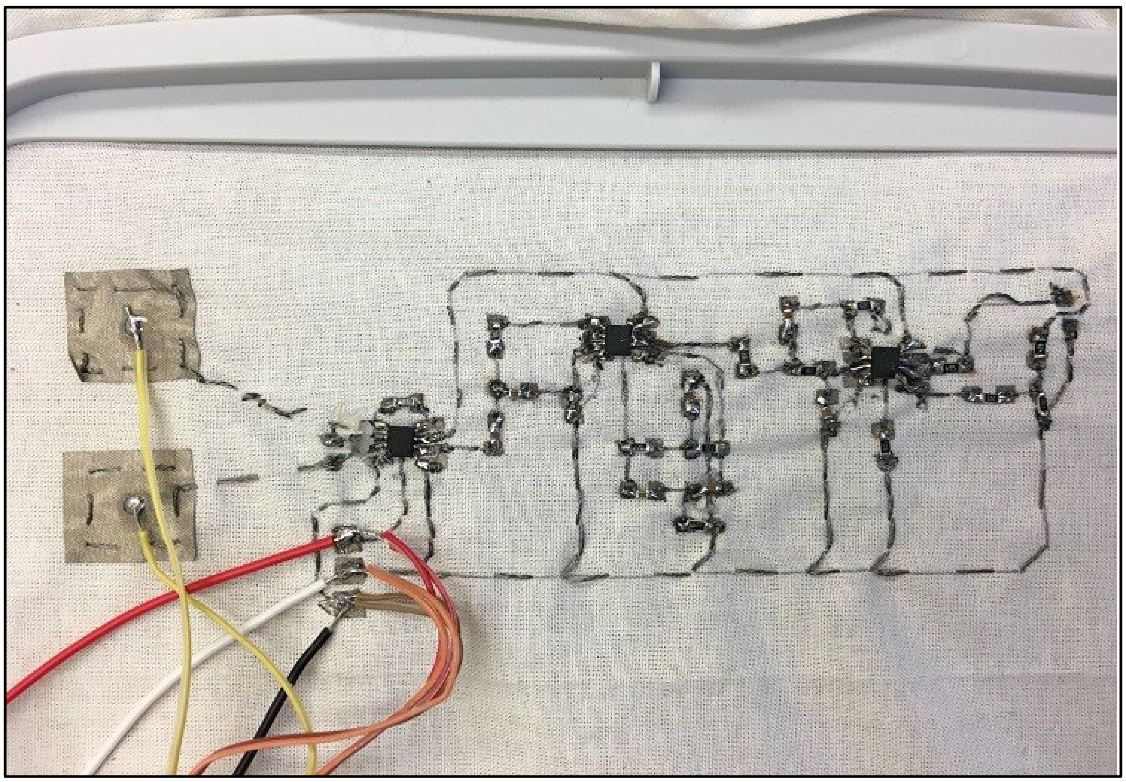

Figure 1.3: Wearable ECG detector with rigid resistors. Each rigid resistor needs to be soldered on and limits the flexibility of the device.

Embroidery is a promising method of creating flexible resistors because any conductive thread that could be used already has a resistance to electrical current flow. This electrical resistance is linearly related to the length of the thread being used. This resistance is a factor of the conductive material used, thread thickness, and weave methods. Each commercial thread has a unit resistance provided by the supplier. With conductive thread selection and control of the length of thread used, an embroidery machine could be used to create resistors to replace conventional rigid resistors.

Therefore, the goal of this study is to develop embroidered flexible resistors. This development is a significant step for establishing the platform technology for embroidered wearable electronics towards designing fully flexible systems on cloth. Together with my research group, we are seeking to realize all of the technologies to enable fully flexible systems on cloth with embroidery. We are seeking to create this technology with an automatic design-to-manufacturing translation with a cloud manufacturing tool. This study is a key technology which builds upon previous work in my research group to develop cloud manufacturing for embroidered wearable electronics by creating embroidered electrical circuits.

To achieve the goal of creating embroidered flexible resistors, there are two major technical challenges: 1) Develop robust techniques for manufacturing passive flexible resistors for embroidered wearable electronics; and 2) develop an open-source design-to-manufacturing translation tools to enable cloud manufacturing.

1.2 State of the Art and Current Limitations

Wearable electronic devices provide excellent capabilities for user needs in a variety of applications. The advances of textile manufacturing techniques provide the opportunity to create a new generation of wearable electronics. These devices would be created entirely on cloth. The embroidery manufacturing technique places design patterns into fabric substrates. By using conductive materials, this manufacturing technique can be used to create electronic devices and components.

Embroidered electronics have currently be used to create circuitry, keypads, integrated wiring, wireless inductive charging, and antennas for wireless communication [11], [13], [14]. All of these systems have been made by sewing conductive materials into a base substrate to create electrical flow paths in specific patterns or layouts. In embroidered circuits, the conductive thread allows current flow in specified paths connecting components and power sources to control the devices. Wireless charging and antennas are made with specific layouts of conductive thread that create electric fields from current flow patterns.

Embroidered resistors do not yet exist. Other flexible resistors have been experimentally made with 3D printing and with conductive woven fabrics [15], [16], [17]. The benefit of embroidery over these methods is that embroidery can permeate a pre-existing cloth. This differs from 3D printing as printing only allows conductive material to be deposited on one side of the fabric substrate. Woven fabrics are rather a method of creating new fabrics entirely. This is important because embroidery grants the ability to add electronics to pre-existing cloth such as a uniform or purse etc. This increases the utility and versatility of the technology and potentially decreases user costs.

To design embroidered resistors, a design-to-manufacturing translation tool is needed to create embroidery files for the resistor fabrication. It is desired for the tool to be open-source to enable widespread user access, to enable integration into my research group's cloud manufacturing site, and to promote development by the open-source community. The benefits of making this tool open-source are described in more detail in Chapter 2.5.

In summary, there are two technical limitations for achieving fully embroidered electronics on cloth: 1) embroidered resistors do not yet exist, and 2) the design tool to fabricate the resistors is lacking. Therefore, in this thesis, my research focuses are to develop embroidered resistors and their associated open-source design-to-manufacturing translation tool for creating embroidery machine files.

1.3 Proposed Approaches

The overall goal of my research is to advance textile wearable electronic devices by presenting open-source flexible embroidered resistors.

To demonstrate this technology is viable, a manufacturing method needed to be developed, prototype resistors needed to be made, and the resistors needed to be tested to verify performance.

To make this technology open-source and approachable, I needed to create tools for this device that would be free for anyone to use and easy for others to understand. I needed to use open-source coding platforms and create clear documentation.

To accomplish these tasks, this study investigates the embroidery process and machine use, sources conductive threads, creates an open-source tool to generate embroidery machine files, creates and documents the manufacturing process for, and develops testing criteria to prove the resistors perform well enough to replace conventional rigid resistors.

The design criteria for the embroidered resistors were the following:

- Create scalable resistors between 1 and 100 kΩ.
- Manufacturable with less than one bobbin of thread.
- The resistor area is always less than 7 by 7 centimeters.
- The design of the resistor minimizes the area of fabric.
- No short circuits occur in the pattern in its manufacture or as the fabric articulates.
- The fabric retains flexibility such that it can still be folded.

The design criteria for the embroidery file creation tool were the following:

- Use an open-source coding platform to create the program.
- Post the program to an open-source repository.
- Create clear documentation on how to use the program.
- Create clear documentation on how to write embroidery files.

1.4 Potential Future Applications of E-textiles and Embroidered Electronics

E-textiles present a huge opportunity for the development of smart wearable devices. The ability to add electronics to clothing or other fabrics would create opportunities for new functionalities and applications. The development of flexible electronic components may help realize these future devices. The following list provides examples of the potential future applications enabled by e-textiles or embroidered electronics.

- **Health monitoring and well-being management for in-hospital and out-of-hospital settings** – Flexible textile devices present the ability to incorporate devices into bed sheets or clothing that a patient already wears and is comfortable with. This removes the need for external wires and improves patient comfort.
- **Rehabilitation** – Provide sensing and communicating garments that provide patients with constant coaching and assistance without the cost and inconvenience of frequent doctor visits.
- **Driver state monitoring** – Steering wheels, seats, and seatbelts could have sensors integrated into them to detect if the driver is falling asleep or becomes distracted.
- **Smart uniforms for military applications, first responders, etc.** – Uniforms could detect injuries, send information between personnel automatically, and provide hands-free instructions.
- **Daily assistive technologies –** Daily clothing featuring assistive soft robotics, consumer electronic technologies, and more.
- **Family tracking –** Children's clothing that alerts the parents if the child gets lost, needs help, or is in distress.
- **Fashion design –** Clothing or fabrics that utilize electronics for style and self-expression.

1.5 Organization of this Thesis

Broken down into a little more detail, the chapters of this thesis are laid out below.

Chapter 2 provides more detail into the current state-of-the-art technologies and background information that relates to this research. It provides more detail into the embroidery manufacturing method used in this thesis, then discusses notable developments in textile wearable electronic devices and textile electronic components. These research areas have enabled the development of my embroidered electronic resistors. They have created systems and supporting technology that could benefit from flexible resistors, and could come together to create the smart devices of the future.

Chapter 3 documents the creation of the Resistor File Generation Tool (RFGT) for embroidery file generation. It provides documentation on how to use the tool as a user and as a developer. It also provides links to open-source sites where the tool and documentation are housed. These pages will continue to be updated by myself and other users as problems are found or improvements are made.

Chapter 4 provides information on the manufacturing process to create the textile resistors. Conductive materials are compared and a thread is selected for use. The properties of the thread are discussed. Pitfalls and remedies are presented along the manufacturing process, including issues with the conductive thread and the embroidery machine. The chapter is concluded with a demonstration of a post-processing step to improve resistor accuracy via the creation of manual short circuits across conductive tines.

Chapter 5 delves into the testing methodology and results. A variety of tests were designed to verify that the resistors perform well enough to replace conventional resistors.

Chapter 6 documents the testing of the flexible resistors in a touch sensing device. The chapter also documents the manufacturing method for creating the touch sensing device, which is a flexible device built into the cloth with embroidery. The use of an embroidered device with embroidered componentry is intended to demonstrate the capabilities of the manufacturing technique.

Chapter 7 provides concluding statements, a discussion of the work presented in this paper, and proposed future works for myself, my research group, and others in this field.

2 Background and Literature Review

2.1 Overview

This chapter aims to presents a comprehensive review of the state-of-the-art technologies relating to this research project into flexible embroidered resistors. The literature review in this chapter aims to summarize the existing comparable technologies, explain the motivation, and provide the necessary background for this study. Some of the mentioned literature and innovations helped lay the foundation for embroidered electronics, some illustrated the need for flexible electronic components, and some have helped direct the methodology used for system design and testing. The organization is as follows: Chapter 2.1 is the overview of this chapter including the broad background of wearable electronics; Chapter 2.2 explains the background enabling our embroidered electronics technology; Chapter 2.3 reviews the state-of-the-art textile electronics; Chapter 2.4 reviews the current advances of textile electronic components enabling textile electronics; Chapter 2.5 introduces the background of open-source software.

While this thesis is focused on the development of embroidered electrical resistors and their fabrication, there are some other key innovations and techniques that are necessary for creating fully flexible e-textiles and embroidered electronics as a whole. It is important to review related studies to understand the state of the art of wearable devices and embroidered electronics which is the key background of this thesis work. Future wearable electronic devices will likely be made with a wide assortment of technologies, materials, and manufacturing methods. For example, conventional rigid electronic devices like smartphones and smart watches are built with a variety of technologies, materials, and manufacturing methods such as LED screens, casted plastic or metal housing, PCBs, soldered connections, and more. Embroidered wearable electronics are still in the emerging stage and do not have as wide of a range of components and applications as conventional electronics, but some of the technologies in this chapter will likely be significant steps for future flexible systems.

To clarify the vision, a brief review of the major types of wearable devices is provided before discussing the advances in embroidered electronics. This provides a background on the types of technology that are driving the popularity of wearable electronic devices and demonstrates the current capabilities and functions of rigid wearable electronic devices.

2.1.1 Review of the Major Types of Wearable Devices

Wearable electronic devices, or wearables, are systems that are worn on a person's body or clothing. They can be referred to as smart devices. Wearables assist the user with tasks, track and transmit personal data, can be used for fashion, and more [18]. One out of every three citizens in the US wears some type of smart device [19].

The prevalence of employer wellness programs has aided the widespread adoption of fitness tracking wearable devices [20]. These programs give out fitness tracking wearable devices as rewards and incentives, and further incentivize the use of these devices to track healthy lifestyles. Employees upload their daily activity levels and step counts so that they can collect points, compete in wellness competitions, and receive further awards from the companies. Employers are incentivized to run these wellness programs because having healthier employees creates a more productive workforce and decreases the cost of employer-provided health care [21].

Smart watches and wristband fitness trackers dominate the current market for wearables. Smartwatches account for 58% of devices sold worldwide, and wristband fitness trackers take up the next 37% [7]. This popularity stems from the devices being reasonably affordable, easy to wear, easy to use, and have a wide range of capabilities. Watches have always been mechanical or digital, so adding better technology and more features to watches has been a natural progression.

Watches and wrist-based devices capabilities are largely based on smartphone connectivity and health monitoring [19]. Smartphone connectivity allows users to view and send text messages, make phone calls, play music, view weather forecasts, and more. Health monitoring features include sleep quality tracking, activity tracking, step counters, heart rate (ECG) monitors, blood oxygen sensing, and more. The user interface is primarily through buttons around the watch or through a touchscreen.

Smart footwear has gained commercial traction with sensing shoe insoles geared towards athletics, health, and comfort [5]. This technology includes shoes that collect and analyze data from running gait and technique during workouts to improve form and avoid injury. There are products designed towards collecting data on walking strides to improve rehabilitation during injury or surgery recovery. Other products geared towards comfort include temperature regulating and self-tightening shoes.

Smart rings present much of the health tracking capabilities of smart watches but present an advantage in being smaller and less obtrusive to wear [22]. They are largely geared towards sleep, activity, and health data collecting. They also can feature touchless payment tech, and the ability to wirelessly unlock a phone, car, or computer for convenience and ease of access.

Smart eyewear is currently considered an emerging technology, without extensive commercial use but growing capabilities and expected future success [23]. Some glasses feature sound technology that transmits sound by vibration into the user's bones touching the glasses' sidearms. Others include cameras and speakers, augmented reality capabilities, and personal assistant capabilities.

Smart clothing may not have gained traction in the consumer market yet, but its capabilities are increasing. There are clothing options to track activity and health data, detect UV exposure, give feedback on body movement during physical activity, and interface with a cell phone [24]. These smart garments are made in jackets, pants, shirts, socks, and more. The capabilities and popularity of smart clothing will likely increase dramatically as textile electronic technology improves. Textile technology currently trails behind conventional rigid technology.

This is not an exhaustive list of available wearable technologies, but is intended to be a brief overview of the most popular and prevalent technologies, and how they are being used. These technologies and applications present opportunities for improvement by being made as fully flexible systems on cloth.

2.2 Manufacturing Methods for Textile Electronics

Most of the development of flexible textile electronics are in the areas of sewing, inkjet printing, embroidery, knitting, and woven conductive fabrics [8]. Each technique is a method to bind conductive materials to flexible fabrics, allowing current to flow in specified areas or to create desired properties like electrical shielding. This thesis focuses on the embroidery method so it is the manufacturing technique explained in most detail in this review.

None of these technologies were initially created for electronic device manufacturing. They are either staples in the fabric, clothing, and fashion industries for creating functional or stylish garments. The desire to create flexible electronic devices is leading these manufacturing methods to be used for new purposes.

Embroidery was initially used for adding patterns and designs to clothing with thread or yarn [25]. Long before the process became digitized, embroidery was done by hand stitching. Later with the invention of sewing machines, embroidery hoops were manually manipulated by the user to trace patterns with the machine stitching. The process began to be automated in the industrial revolution and has continually been improved to bring us to the fully digital systems used today. Perhaps the next big step in their development will be the mass-production of smart garments.

2.2.1 Embroidery method for e-textiles

Embroidery machines utilize the technology of sewing machines, and primarily differ by their addition of a “hoop” and hoop control mechanism. **Figure 2.1** compares a typical sewing machine, a typical embroidery machine, and an industrial embroidery machine. The embroidery hoop holds the base fabric flat and tightly in place, so it can be manipulated to create patterns across it with thread. The hoop is controlled to move in the x and y directions. Embroidery files that tell the machine how to trace desired patterns stitch by stitch. Embroidery files contain a list of stitches for the machine to create in order, specifying the movement needed between each stitch.

Figure 2.1: Comparing a sewing machine (a), embroidery machine (b), and an industrial embroidery machine (c) [26],[27],[28]

To create stitches, a spool of thread is housed both above and below the base fabric. With each stitch, the threads are interlocked with the mechanism shown in **Figure 2.2**.

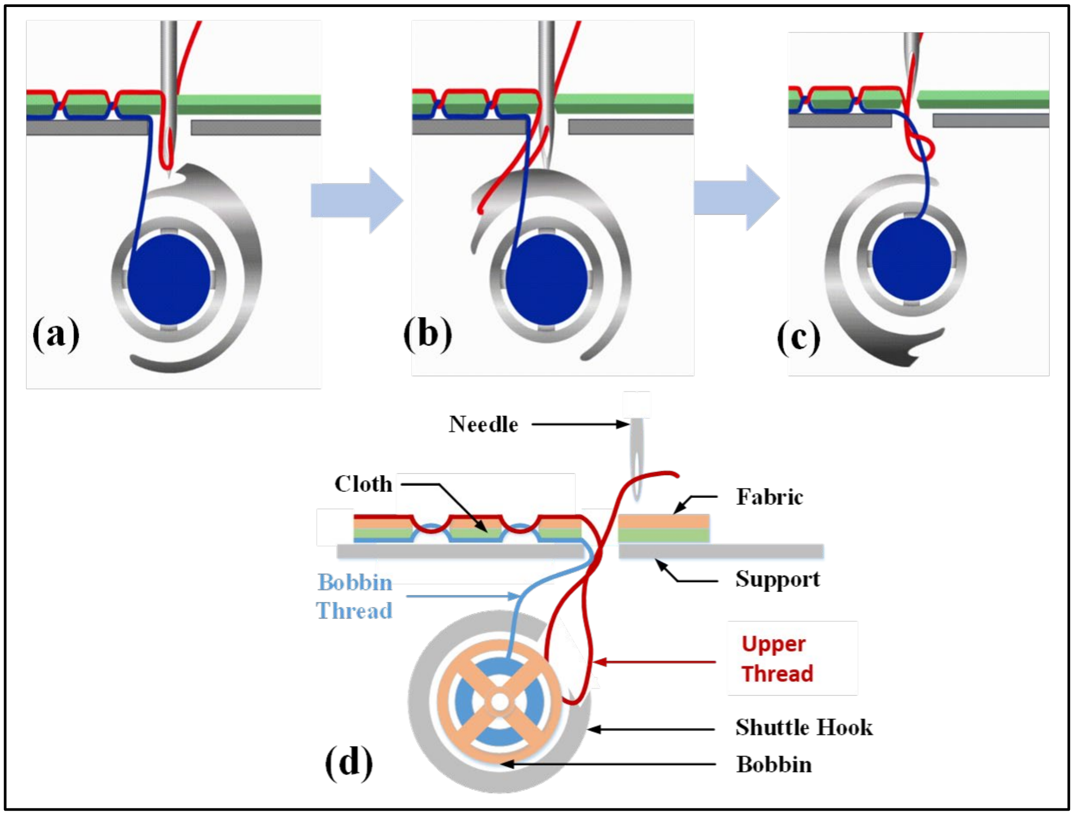

Figure 2.2: Embroidery mechanism sketch. Modified from [29].

To utilize an embroidery machine for e-textiles, the upper and/or lower (bobbin) thread can be replaced with a conductive thread. The properties of the embroidered systems can be controlled by the physical pattern and the conductive properties of the thread being used.

Embroidery in e-textiles has been studied as a method to create electrical contacts, electrical flow paths, and circuitry. Specific applications are discussed in more detail in Chapters 2.3 and 2.4.

2.2.2 Connection Methods for Electrical Contacts

While discussing e-textile manufacturing methods, it is important to discuss connection methods to create electrical contact between components of a device. Because this thesis focuses on resistors which are components that function when connected to a device to enable current through it, it is important to discuss the methods of creating the electrical contact.

Creating electrical contact between textile components can be done with hand stitching, embroidery, conductive epoxy glues, soldering, and other methods. Each poses benefits and costs to compare. The best method may depend on materials used, technologies available to the user, target device use, and production size.

Hand stitching requires the least amount of technology and preparation but can be time-consuming. That lends it well to prototypes and low volume production. The downsides are that the electrical connection can be weak, and the process can be tedious. The connection may be weak if insufficient threads are used to create a large surface area between both terminals being connected. The connection may also be weak if there isn't enough force applied during sewing to keep the thread pressed against the terminals being joined. Creating enough quality stitches to ensure a strong connection can be time-consuming.

Embroidery creates a strong connection, can be done quickly, and can be automated. The downsides are that embroidery machines are expensive for individual creators or low-volume production. Also, if a connection is misaligned, it is impossible to undo and the system being created may need to be discarded.

Conductive epoxy glues can be convenient and require no machinery. Downsides are potentially weak connections and poor durability. When subjected to mechanical stresses or water exposure like many garments regularly experience, glued contacts can separate.

Soldered connections can be effective for combining rigid conventional electronic components to textile or embroidered circuitry. The major downside of this method is difficulty in bonding to the textile part. Conductive pads may need to be connected to the textile part before soldering. Liquid or paste flux may need to be used to increase contact with the textile part and avoid burning the fabric.

He et al compared the connection methods of embroidery, epoxy, and 3D printing for microchip attachment. They found that all three methods performed well for peak range testing, immersion testing, and bending testing. Under a stretching test, the embroidered connection performed well and the other two failed.

Torsten Linz studied the performance of embroidered connections in great detail, comparing thread types and observing test results under different environments [30]. He verified embroidery to be an effective contact method. He also provided information on specific weaknesses of the method and measures to improve the process. Those details are outside of the scope of this thesis but will be important for ensuring quality contacts in the future development of textile devices.

2.3 Textile Wearable Electronic Devices

The pioneering paper in this field is "E-broidery: Design and fabrication of textile-based computing" by Post et al [11]. This article documents the creation of a fabric keyboard, light-up dress, musical jacket with embroidered control keypad, musical ball, electronic tablecloth, and radio communicator. Each device uses embroidery for a key mechanism. The fabric keyboard, which is in turn redesigned and used in the jacket and radio, is made with embroidery. The buttons for the keypads are embroidered pads, with their conductive thread leading back to the control or transmitting mechanism of the device. This article specifically mentions that rigid resistors may eventually be replaced, but for their devices, rigid resistors were soldered on when needed and the process for doing so was documented.

Chang et al demonstrated the ability to use 3D printing in creating circuits, transistors, capacitors, and resistors [16]. Utilizing this technology, they were able to create fully flexible gain amplifiers and a digital to analog converter. With this technology, they have the tools and framework to build a variety of new devices.

Wicaksono et al created a textile conformable suit with sensing capabilities for health monitoring and wireless transmission [31]. This garment resembles a snugly-fitting knit sweater and all of the electronics are completely hidden inside the fabric. This study is notable for the number of body metrics the device is able to track, all in one garment that does not visually appear to be electronic. The device can track body temperature, movement, heartbeat, and respiration. This garment was made using woven conductive materials and by housing non-textile flexible electronic components between layers of fabric. This garment is shown in **Figure 2.3**.

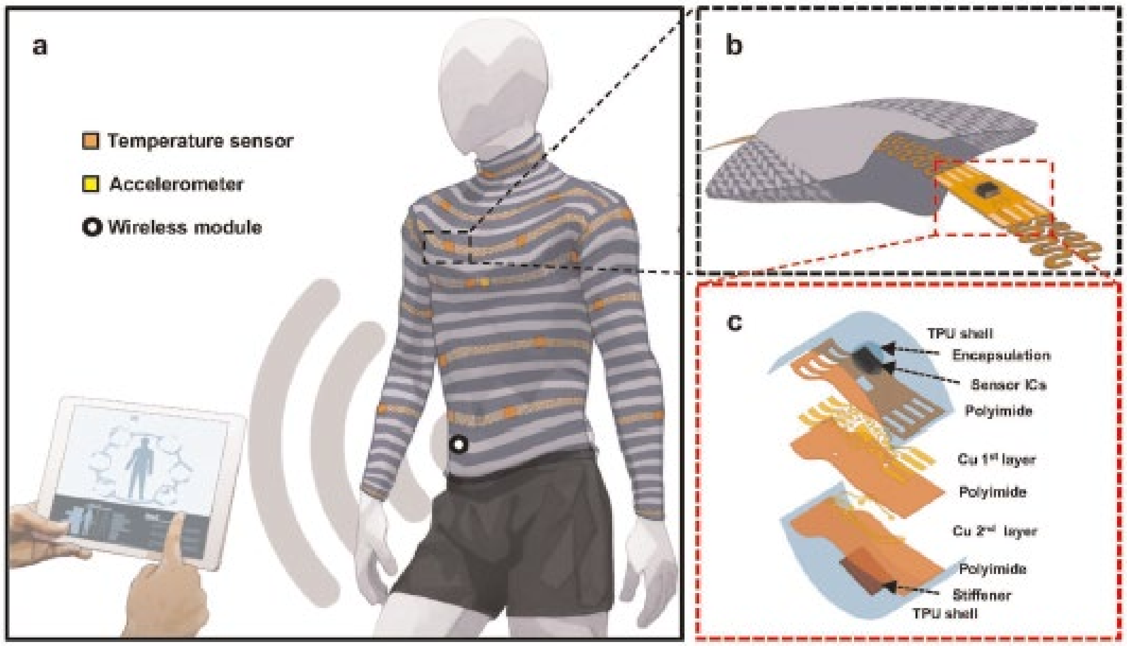

Figure 2.3: Wicaksono et al's physio sensing suit [31]

2.4 Textile Electronic Components

Monica et al were able to create high resistance resistors with inkjet printing of graphene on flexible substrates [15]. They suggest that their component will work well in high power circuits and could be used as a heating element for wearable electronics in harsh environments.

As previously mentioned, Chang et al were able to create transistors, capacitors, resistors, and inductors by 3D printing on flexible substrates [16]. This was accomplished to allow them to create fully flexible systems with their range of components.

Sun et al developed textile coils for wireless charging capabilities [13]. They compared the performance of embroidery, laser-cut fabric, and screen-printing manufacturing methods. While they found benefits to laser cutting and screen printing, they determined embroidery to be the most effective solution for wireless charging. They conclude that their component can be embedded in future wearable electronic devices to enable wireless electric charging.

Alonso-Gonzalez et al developed a slot antenna for wireless communication with a combination of woven materials and embroidery [14]. With this method, the authors were able to create a fully flexible antenna with multilayer conductive fabric using embroidery to create desired electrical connections between the conductive layers.

Zhao et al created conductive woven fabrics with the ability to control electrical resistance by altering their weaving methods [17]. By changing the weave structure, weave density, and arrangement of conductive versus nonconductive yarns, they were able to control the resistive properties of their fabric.

2.5 Benefits of Open-Source Development

To enable embroidery machine use, a key technology for embroidered electronics is the design-to-translation tool, which creates embroidery machine files for pattern generation. In my research group's previous work, we developed a public cloud manufacturing network and created functionality to convert PCB designs to embroidery files. In this thesis research project, a focus is to design an open-source tool for developing embroidered resistors that is compatible with our cloud manufacturing network.

In this thesis research project, I am utilizing open-source programs, and in turn, I am creating an open-source tool intended for public use and development in my research group's cloud manufacturing network. Open-source development poses many benefits for accelerated tech advancement and ease of access to users. Thus, this sub-chapter provides the background of open-source development.

Some of those benefits include transparency, reliability, documentation, free software cost, and development speed [32]. Most of these benefits come from the fact that anyone can use and develop open-source software so with more people developing projects, there is more documentation, a faster rate of improvement, errors in code are often found and corrected by other developers, and the code is always visible and can be checked for transparency and reliability concerns.

There are many prime examples of open-source software being highly effective. Mozilla Firefox, LibreOffice, GIMP, VLC Media Player, Linux, Python, and more have created powerful and trusted software [33].

Starting an open-source tool provides the opportunity to connect with other developers and receive extra help in creating, refining, and adding functionality to the tool, package, program, or software.

Open-source technology is generally free by definition, but plenty of opportunities still exist to make profit and find funding. Some examples include donations, paid customer support and/or services, verified and trustworthy hardware manufacturing to support the software, paid server hosting, and more [34].

3 Creation of a Resistor File Generation Tool (RFGT)

3.1 Overview

To successfully design embroidered resistors and enable their fabrication method, I created an open-source resistor file generation tool (RFGT) which is presented in detail in this chapter.

To create embroidered designs, an embroidery machine needs files containing instructions for how to trace the desired patterns. These files contain a sequence of movements that the needle follows. With each movement, the file specifies whether to make a normal stitch, change threads, jump stitch (movement with no stitch), or pause/stop.

This file is read by the machine in the same way that a “gcode” file is used by a 3D printer. The primary difference is that everything is created on one layer of fabric and lines created can stack over each other countless times as a pattern might need, where most 3D printers create a 2-dimensional layer of a uniform thickness. The embroidery machine can create a more complex layer than a 3D printer but is limited to only making one layer.

The process of resistor creation presented in this research begins with the machine creating a start terminal, then creating a path for current to flow through, then creates an end terminal. The length of the electrical current flow path dictates the resistance of the component. The longer the path, the higher the resistance.

The main elements of the RFGT are the calculations for thread length, creating the physical layout of the pattern or current flow path, and laying down the sequence of stitches to trace the pattern.

To understand the fundamentals of how to use conductive materials to control the resistance of the embroidered resistors, a background is provided on resistance to current flow.

3.1.1 Unit Resistance of Conductive Materials

Conductive materials all have a resistance to current. At the base level, this resistance is determined by the length, cross-sectional area, and material properties of the conductive material. The conductive material properties are represented as resistivity which is measured in Ohms times meters. Resistivity charts are widely available to compare conductive materials [35]. The direct calculation for resistance of a specified conductive object can be achieved by $R = \rho \cdot \frac{L}{A}$, where R is the total resistance, ρ is the resistivity of the material, L is the length of conductive material, and A is the cross-sectional area.

Using this calculation, one can make a resistor to the desired value with the right length of conductive material. For example, if the resistivity and cross-sectional area are known, and with the desired resistance, these values can be used to quickly solve for the length of wire or other conductive material needed to provide the desired resistance using the equation above.

Conductive threads and yarns are often sold with a specified unit resistance, which is measured and provided by the manufacturer. In some conductive threads and yarns, there may be a combination of materials interwound with each other, or a conductive material coated over a base thread making it difficult to calculate resistivity and conductive area in the cross section. With the unit resistance provided, a user can divide their target resistance by unit resistance of supplied material to get their required length of material.

3.2 Pattern Design

Thread length is the first calculation in the process of mapping the resistor because it controls the resistance of the component. The program divides the target resistance by the unit resistance of the selected thread which provides the required thread length. The thread length is then fed into the pattern generation calculations.

The RFGT calculates thread length by dividing the target resistance by thread unit length. In the following equation, L is the total Length, R is the target resistance, and R_u is the thread's unit resistance.

$$L = \frac{R}{R_u} \quad (1)$$

The pattern layout created for the RFGT was a set of repeating columns, with the outermost columns having their outer thread pass back along the bottom towards the middle and ending in adjacent terminal modes, as shown in **Figure 3.1**.

This pattern was selected for its scalability, constant and minimal gaps between thread lines, and symmetry. Experimentation showed that having linear columns only for the current flow path allowed for the tightest spacing between lines without contact between lines. Contact between lines creates a short circuit which decreases the resistance of the component from its target value. With a set value for allowable gap length between lines, that parameter can be held constant while the resistor is scaled as needed for any target resistance.

Large and scalable terminal pads were added to the RFGT so the resistors can be easily integrated into embroidered circuits. These pads allow for conductive threads to be sewn between the terminal pads on the resistor to terminal pads on the embroidered circuit and have maximal electrical contact. Having a strong contact between resistor and circuit ensures connection durability and consistency in current flow between the resistor and the circuit. These terminal pads are shown at the bottom of the resistor in **Figure 3.1**. A demonstration of connecting the terminal pads to a circuit is given in Chapter 4.5.3.

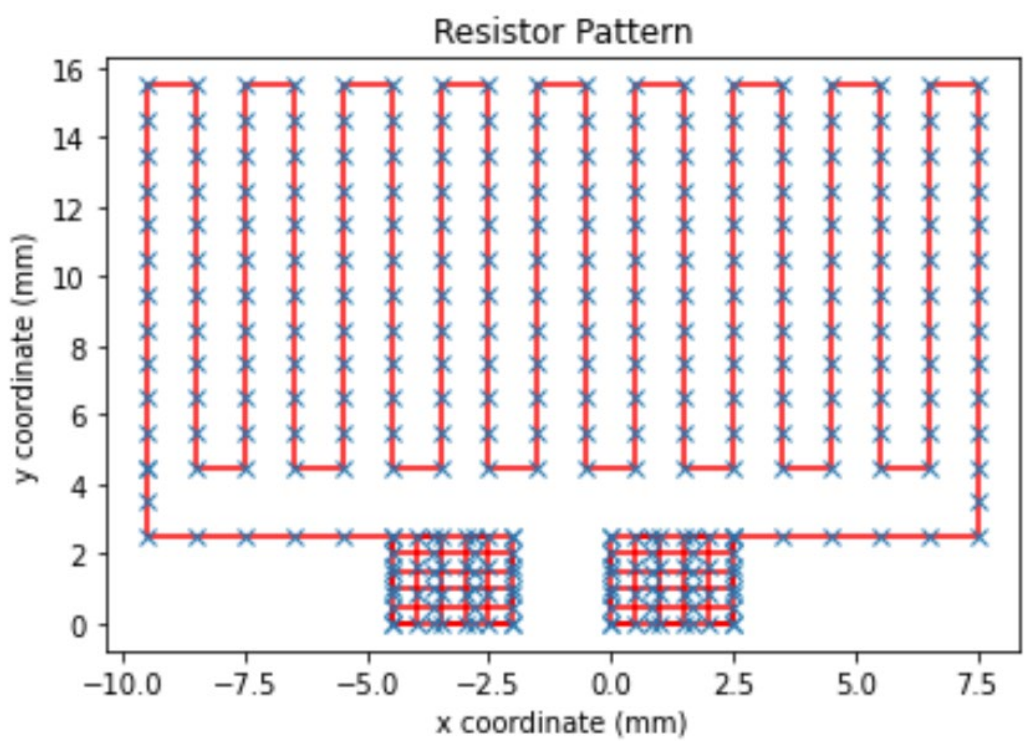

Figure 3.1: Depiction of the resistor design pattern with stitch locations.

Scalability of the design by the RFGT is required for the creation of resistors between 1 and 100 kΩ. To increase resistance, the quantity and length of the columns are increased by the RFGT to use a longer amount of thread.

Having constant and minimal gaps between the tines in the flow path allows the program to fit as much thread as possible in a small area. Adequate gaps must be maintained to avoid the creation of short circuits. Short circuits are formed when the thread has an unwanted point of contact and the current is able to skip a section of the intended flow path. Fine tuning of the gap length needs to be done by trial and error. Different embroidery machines, needles, and selected threads will alter the stitch spacing and parameters needed. An explanation of the parameters used in this project is provided in Chapter 3.2.

The symmetrical pattern ensures that the resistor does not create any inductance to current flow. Each line in this resistor pattern has a line opposite to it with current flowing in the opposite direction. No significant fields should be created by the resistors and there should be minimal effect of external magnetic fields on the resistance of the resistors.

The pattern is created from the input variables fed into Equation 2. Parameters used in the equations are shown in an example resistor in **Figure 3.2**.

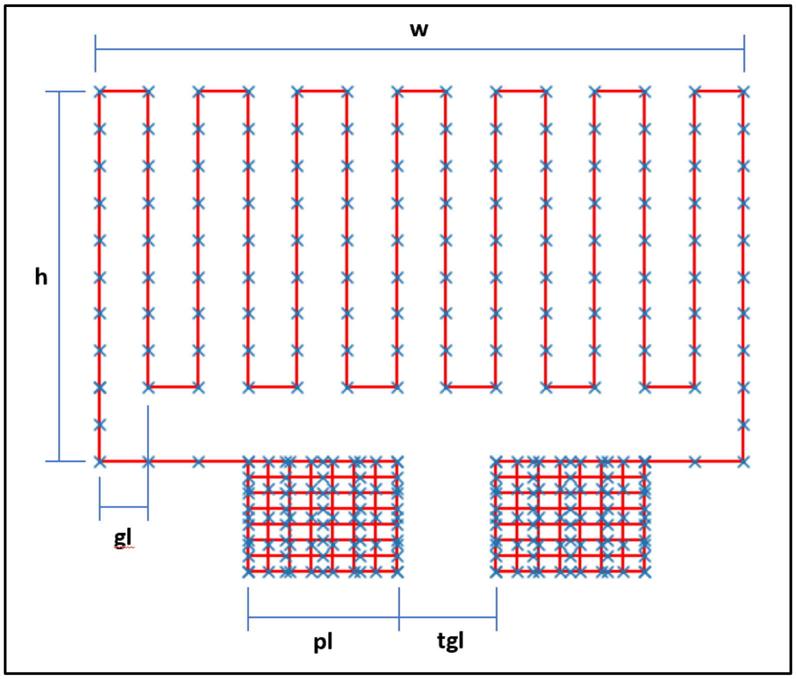

Figure 3.2: Parameters of resistor pattern. These parameters are the key measurements used by the RFGT in creating the resistor pattern and embroidery trace.

$$w = {(-3 * gl + \sqrt{gl^2 + 4 * gl * tgl + 4 * L * gl})}/{2} \tag{2}$$

In Equation 2, *w, gl*, *tgl*, and *tpl* are the distancing measures shown in Figure 3.2.

Equation 2 was derived from Equation 3, which describes how the pattern uses the overall length of the thread. Equation 4 relates the width of the tine area to the length of the tines so that the resistors have a consistent shape, and reduces the variables in Equation 2.

$$L = w * 2 - tgl + h * \left(\frac{w}{gl} + 1\right) + 2 * gl \tag{3}$$

$$h = w \cdot \frac{2}{3} \tag{4}$$

3.3 Writing to embroidery machine readable files

3.3.1 Background

The RFGT writes directly to the .exp file format, then converts to other file types as desired by the user. This process was selected because the .exp file format was the most logical and straightforward embroidery type. Using the coding language Python 3.8 and the IDE Spyder, I created files for pattern creation, customization, and .exp file writing. Using the existing open-source python library, pyembroidery [36], I added the functionality to convert to any major embroidery file type.

Through my research and experimentation, I selected the .exp file format because it is the most straightforward of the embroidery formats. Many of the other file formats were intentionally created to be difficult to write to or decode manually, intending their file format to stay exclusive to their own machines [37]. This may have been partly motivated by embroidery companies wanting to sell their own embroidery file software or that of a partner company. Or to avoid individual users making their own potentially files and blaming the machine manufacturers for machine malfunction or bad print quality. Another suggested reason for the differences in file types is so that users will be more likely to keep using the company of their previous machine so they never need to convert old files.

There is limited public information on all of the embroidery file types, including .exp. Of the limited documentation, some of it is incomplete or inaccurate. The documentation online has come from individuals posting their findings from self-experimentation. For example, the biggest writeups on the .dst file format contradict each other in some of their descriptions and explanations. These can be seen at [38], [39], and [40].

The most accurate information on all file formats that I have found is contained in the source code of the pyembroidery python library [36]. However, the documentation for this library is focused on how to interface with the library for its basic functions. There is limited written documentation on the intricacies of embroidery file writing to any of its supported embroidery file types. Without a good understanding of python coding and lots of time to unravel the methodology, the library works as a "black box", meaning it works well but users are not expected to open the box and understand how it functions inside. It also means that users will not be able to easily troubleshoot the tool when it malfunctions when used for an unusual task or operation. Even without the pyembroidery library source code documentation, the package is a very effective tool for file reading or conversion from an existing embroidery file.

With this understanding of embroidery file formats, it was concluded that the most effective method of file creation would be to create a .exp embroidery file, then to convert it with the pyembroidery library to other file types as required for the machine being used.

3.3.2 Creating EXP Files

To create .exp files I started by reading the limited available documentation and experimented with example stitch operations [41], [39]. While creating my file writing code in python, I created documentation on writing to .exp file format. This writeup should help others to quickly and easily be able to write their own embroidery files for other applications. This writeup is posted on the open-source webpage https://www.appropedia.org/EXP_Embroidery_File_Format, and provided below.

Background / Framework for EXP File Format

.exp files are embroidery files designed for use with Melco or Bravo systems.

These files are written in binary code. The code is written in sets of 8 bits. A bit is the binary number 0 or 1. These sets of 8 bits are called bytes. These bytes contain the information for each stitch operation. There are 256 possible combinations of bits to make a byte. These bytes represent numbers ranging from 0 to 255. Each of these numbers signifies a command to the embroidery machine.

Bytes are written to the file in pairs of 2. These pairs are usually the commands for a movement in the x (left/right) and y (up/down) directions. The first byte is the movement command for x and the second byte is for y.

The minimum resolution of a stitch movement in the .exp file format is 0.1mm. As the movements are all based upon this resolution, it is most convenient to consider 0.1mm as the base unit of measurement when working with data to be written to embroidery.

The maximum movement in one stitch command is 12.7mm. Any desired movement larger than this length between stitches must be created with one or more “jump” movements, explained below.

Movement / Stitch Commands

A movement of 0 in x or y is represented by the byte value 0.

A positive movement in x or y in mm*10^-1 is represented by the same byte value. For example, a movement of +0.3mm is represented by the byte value 3, a movement of +7.1mm is represented by the byte value of 71, etc.

A negative movement in x or y in mm*10^-1 is represented by the movement's absolute value subtracted from 256. For example, a movement of -0.3mm is represented by the byte value 253 (256-3), a movement of -7.1mm is represented by the byte value of 185 (256-71), etc.

Special operations are also given as a set of 2 bytes. These special operations include “change color / stop”, “jump”, and “end / cut thread”. These special operations always start with 128 as the first byte, and the second byte signifies which of the special operations to take.

- “Change color / stop” tells the machine to pause so that the operator can change colors of the embroidery thread or adjust machine settings as desired midway through a print.
  - *Byte representation - (128,1)** *followed by movement command (0,0) if no jump is desired with the command. Followed with another command of (0,0) to signify to create a stitch at this point to start the next commands from.
- “Jump” signifies that the following set of x and y movement commands should not receive a stitch. This lets the machine put larger spacing between stitches or allows separate objects to be made without stitching the fabric between.
  - *Byte representation - (128,4)** *followed by the (x,y) coordinate command for the intended jump. String together the jump command and jump coordinate command in succession to travel a further distance without intermediate stitches. Upon completion of the jump or series of jumps, use coordinate stitch command (0,0) for creating the origin for the next stitch operation.

- “End / cut thread” signifies that the thread should be cut. It can be used when finishing a part of an embroidery process and/or at the end of the file. used It is recommended to always end a file with this command. It gives a clean cut at the end of the embroidery process to avoid having any loose threads.
  - *Byte representation - (128,128)** *followed with a (0,0) command.

Command		**Byte Representation**
Movements (x or y)	0 mm	0 (x,y)
	(+) 0.1 to 12.7mm	1 to 127 (x,y)
	(-) 0.1 to 12.7mm	255 to 129 (x,y)
Special Operations *followed with a (0,0) command	Change color / stop	128,1 *
	Jump	128,4 *
	End / cut thread	128,128 *

Figure 3.3: Stitch Commands

EXP File Writing

The .exp file starts at the coordinate center (0,0) and then lists the commands to trace the stitch pattern. Unless a special operation is read, the machine will follow the instructions for the (x, y) movement and create a normal stitch. When the machine comes to a special operation command, it will complete the following movement command after the special operation byte set then comply with the special operation.

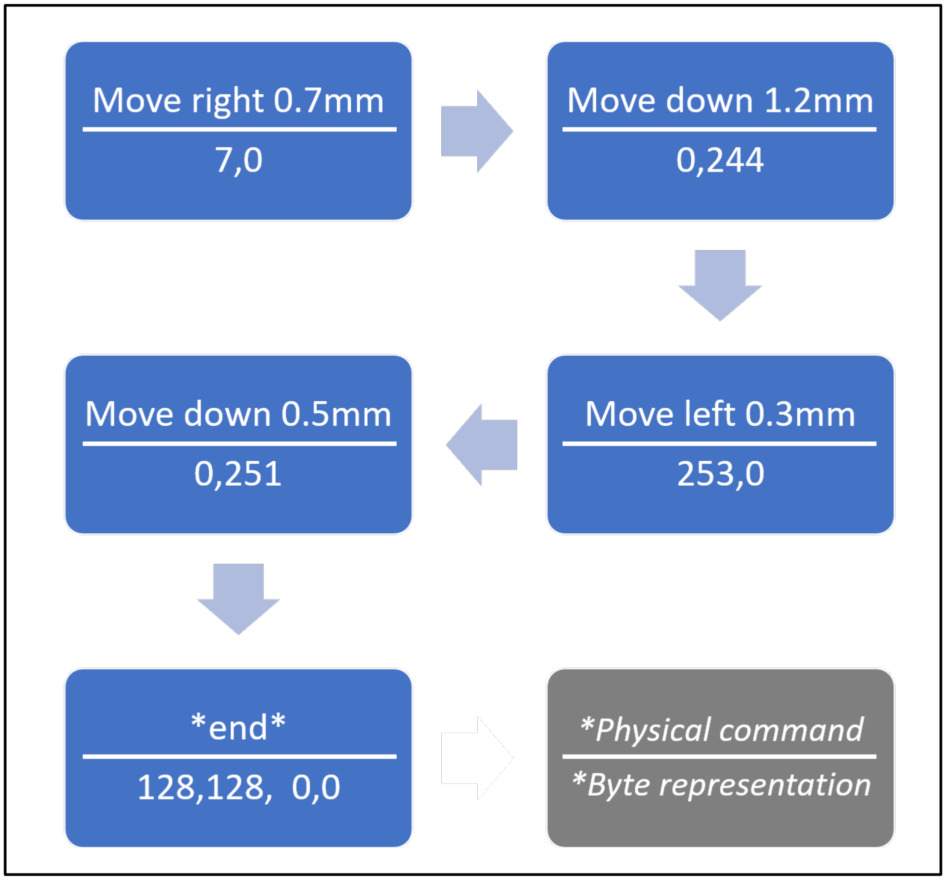

Figure 3.4: Series of stitches example

Converted to binary this series of stitches would be written as a continuous string like:

chr(7), chr(0), chr(0), chr(244), chr(253), chr(0), chr(0), chr(251), chr(128), chr(128), chr(0), chr(0)

^as a reminder, the "chr(0), chr(0)" is listed after the "cut/end" command because the special command needs to be followed by a double zero

EXP File Encoding

One important note with writing .exp files is that the encoding language used for writing the data to the file can cause many glitches. If the languages "ASCII" or "UTF-8" are used, the file will be completely botched. Using Python 3.8 to write the .exp files, the best results came from the encoding language "latin-1". Even with this language, there are some glitches, most notably with the number 10. Using the command 10 causes a movement and stitch of (+1.3, +1.0) mm for (x, y) in one-byte command if given in the place of x. It then resets its reading of bytes as pairs of two. So, the following y command is then read as an x and that bias continues for the rest of the file. If 10 is received as a y command, two stitches are created from the command. The first is a (0, +1.3) mm movement and stitch, the second is a (+1.0,0) mm movement and stitch. The stitches that follow these stitches will also be completely different than the commands given, even if the commands normally work completely fine. Usually with a large jump in an unwanted direction. In conclusion, always use the encoding language "latin-1" when writing files with Python and do not write the command 10.

3.3.3 Framework/workflow of the RFGT

The RFGT begins with receiving the input information from the user on desired resistance, unit resistance of the thread used, and adjustment parameters. With the input information, the RFGT uses the calculations explained in Chapter 3.2 to prepare for the process of tracing out the resistor.

The RFGT begins mapping out the resistor with the first conductive terminal pad. It then traces the flow path of the resistor. The RFGT concludes by laying out the concluding terminal pad. Every step in this process is controlled by the input adjustment parameters for desired pad size, pad thread density, stitch length, gap length, and the gap between terminal pads.

Along the continuous path to creating the resistor, the x and y coordinates of each stitch are saved in succession. Because the .exp file format runs on the change in coordinates between each stitch, the lists of stitch coordinates are converted into the lists (dx, dy) or change in x and change in y.

The (dx, dy) lists are prepared to be written to the .exp file with a series of manipulations. The (dx, dy) units are scaled to the base unit size of the .exp file and rounded to the minimum movement size the file can write. The lists are then converted to the byte representation for each stitch operation. The bytes are recorded as a continuous string, then encoded to the .exp file.

The .exp file is then converted to the embroidery file type of choice with the use of the open-source python package “pyembroidery” [36]. The package is used to load the commands of the .exp file and convert it to the target file type.

The location the file was written to is printed to the user so they can easily find and use it. The name is also printed for clarity.

The generated resistor is plotted in python so the user can visually check to make sure no errors occurred and that the resistor is a reasonable size.

The RFGT is organized into 4 files. The “main” file contains the input parameters, size equations, the call functions to the other files, the file conversion operation, and the output plot of the resistor. The file “pads” is called by the main file and receives pad length and stitch density information and outputs the list of stitch coordinates for the right and left terminal pads as called upon. The “stitch_gen” file is called by the main file and receives stitch parameters and resistor size information then traces the electrical flow path of the resistor and returns the list of coordinates for the stitches. The “exp_generation” file is called by the main file and receives the lists for change in x and y (dx, dy) for the entire stitching operation. It manipulates the data, creates the .exp file, and writes in the stitch operations.

3.4 Open-Source Contribution

To promote the development of this technology, I made the RFGT fully open-source so that any user can download and use the files for free. They can create their own resistors without needing to buy expensive software. They will also have easy access to the code so they can to further improve upon the RFGT or add functionalities outside the scope of this project.

I built the RFGT to run on the coding language Python with version 3.8. I created and use the tool with the IDE “Spyder”, though other users could use their python IDE of choice. Both the base language of Python and the IDE is free and open-source. I chose python as the coding language for this project because it is powerful, easy to learn, features a lot of capabilities, and is very popular [42]. Because of its popularity, the documentation is excellent. I was able to piece together advice and examples on how to make my project work from people using similar techniques on different applications. Because python can be used for web-based applications, I will be able to add this to the cloud-based manufacturing page my research group is building. The popularity of python also suggests that future developers or users of the RFGT are more likely to be comfortable with using and modifying the tool.

The RFGT is available for free download on the platform GitHub because other users can easily download, use, modify, and update the tool. With GitHub, users can “push” their updates to the RFGT back to the main folder online so that the tool is constantly being refined and updated. This makes it likely that the tool will stay relevant and beneficial. If it stayed fixed it would more quickly become outdated or rendered obsolete.

I created detailed documentation for the RFGT listed it on the open-source website, Appropedia, linked below. With the written instruction, explanations, and images on the page, it should be reasonably easy for users to understand how to use, interface with, and understand the working mechanisms of the tool. Because this website is open-source and the page is open-edit, other users can add contributions as they find new insights, create new tips, or modify the RFGT.

I created detailed documentation on the EXP file writing process on a separate page also on Appropedia, linked below. I created this webpage as a stand-alone writeup so that other users have an easier time applying it to other technologies or purposes. Both pages link to each other for clarity, so that readers can understand the entire process I used to create a Python tool to write embroidery files.

3.4.1 RFGT Download and Documentation Links

RFGT download:

https://github.com/srschrock/embroidered_resistor_generation

Instructions for RFGT use:

https://www.appropedia.org/Embroidered_Electrical_Resistor_Generation

Instructions for .exp file writing:

https://www.appropedia.org/EXP_Embroidery_File_Format

4 Manufacturing Methods

4.1 Overview

This chapter describes the manufacturing methods used to create the embroidered resistors. That begins with a description of the material selection process and which thread was selected. Then a description of its properties is given along with a discussion of the difficulties the threads posed. A description of the use of the embroidery machine for this specific application is given. Manufacturing problems encountered and the methods to avoid them are explained. The process of connecting the resistors to an embroidered circuit is presented. And concluding this chapter is the final manufacturing step to perform quality control on the manufactured resistors.

Note that I am using the Memory Craft 400e embroidery machine for all of my work. I am using a cotton base material in my embroidery hoop. I am using the Janome SQ20B embroidery hoop. I am not using a fabric stabilizer. I am using polyester sewing thread 125 dtex 2 ply. I am placing the conductive threads in the bobbin of the machine.

4.2 Material Comparison

The criteria for thread selection were extensive to make effective scalable resistors. The threads needed to be flexible such that the embroidered system would retain the flexibility of the base fabric that the embroidery is created upon. The threads needed to be strong enough to withstand the embroidery machine manufacturing process. The threads needed to have a diameter between standard sewing thread size 3 and 12 for suitable performance in the embroidery machine. To keep the surface area size of the resistors small, the unit resistance of the thread needed to be between 1kΩ/m and 100kΩ/m.

A wide variety of stainless steel and silver-coated nylon threads were investigated. All of the stainless-steel threads proved to have too low of a unit resistance to be used in embroidered resistors. Silver-coated nylon threads were better suited to use in resistor fabrication, as they have a wider range of unit resistances. See Table 1.1 for a list of the threads tested and their properties.

Table 4.1. COMPARISON OF CONDUCTIVE THREADS/YARNS.

Material	**Resistance (kΩ/m)**	**Works in embroidery machine?**	**Observed Thread Characteristics**
44/12 Ag coated PA +113/32 PET	~ 25 to 100	Yes	Excellent resistance. Works well for resistors between 1 kΩ and 150 kΩ.
78/18 Ag coated PA	~0.91	Yes	Resistance is slightly too low. Works well for resistors between 100 and 1000 Ω.
44/12 Ag coated PA	~6.1	Yes	Suitable resistance, discontinued by the producer.
44/10 Ag coated PA	~1.6	No - too thin	Good resistance, but too thin and weak for embroidery machine use.
Sparkfun 10867 Stainless-Steel	~0.059	Yes	Too low of resistance. Stiffer than normal sewing thread.
Sparkfun 13814 Stainless-Steel	~0.019	Yes	Too low of resistance. Stiffer than normal sewing thread.
Adafruit 603 Stainless-Steel	~0.046	Yes	Too low of resistance. Stiffer than normal sewing thread.
117/17 dtex 2 ply Ag-coated PA	~0.13	No - too thin	Too low of resistance
235/36 (4 Ply) Ag coated PA	~0.025	No - too thick	Too low of resistance

Material	Resistance (kΩ/m)	Works in embroidery machine?	Observed Thread Characteristics
235/36 dtex z turns Ag coated Nylon	~30.3	Yes	Too low of resistance
TPU coated AG coated PA by Shieldex (dtex properties not provided)	~0.05	No - too thick	The TPU coating made the thread much too thick for the embroidery machine.

*All of the silver-coated nylon threads in this table were sourced from V Technical Textiles. Some other companies make silver-coated nylon threads, but none made high enough resistances for use making the resistors targeted in this study. Some samples of stainless-steel thread were included to show that the material currently cannot be used for this application. The unit resistance for the stainless-steel threads was too low to be used in resistors over ~ 200 Ω.

44/12 Ag coated PA +113/32 PET was selected as the best performing thread for resistor manufacturing. A more detailed analysis of this thread is presented in Chapter 4.3, Properties of Selected Thread.

While 44/12 Ag coated PA +113/32 PET is the thread in main focus for the rest of this thesis, it should be noted that for creation of resistors less between 100 Ω and 1 kΩ, 78/18 silver-coated nylon performs better. Using 44/12+113/32PET for such small resistors causes the pattern to become too small. The relative resolution of the stitches to the resistor is not fine enough to provide accurate resistance. This is shown in **Figure 4.1**, where the RFGT is used to attempt creating a 750 Ω resistor with 44/12+113/32 PET.

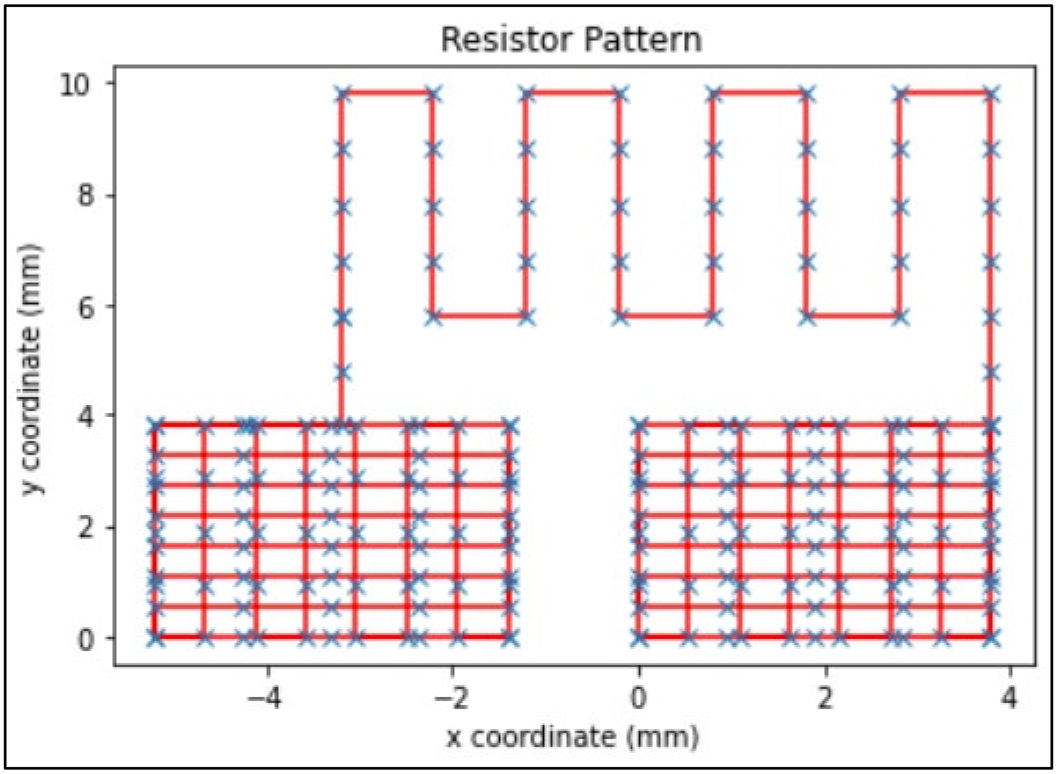

Figure 4.1: A resistor created with improper thread. The unit resistance of this thread was too low for the target resistance.

Stainless steel threads showed promise in the fabrication of resistors under 100Ω. However, those results are not included in this thesis because the range was outside of the focus of this research project. A quick note from my experimentation with stainless steel threads found that they were generally stiffer than sewing threads. This occasionally caused the sewing needle to break. It also caused embroidered patterns with sharp corners to be rounded when using stainless steel.

In the future implementation of this manufacturing method, it would be extremely useful to have a selection of conductive threads with matching mechanical properties and a range of unit resistances. The resistances would ideally cover a range of at least 0.05 to 200 kΩ/m with regular intervals of unit resistance throughout the range. This could allow a range of resistors to be made between approximately 10 Ω to 250 kΩ or more.

4.3 Properties of Selected Thread

44/12 Ag coated PA +113/32 PET is composed of silver-coated nylon (44/12 dtex Ag coated PA) and polyester (113/32 dtex PET). These two threads are interwound to make a 2-ply thread, as shown in **Figure 4.2**. A cross section of the silver coating over the nylon base thread is shown in **Figure 4.3**.

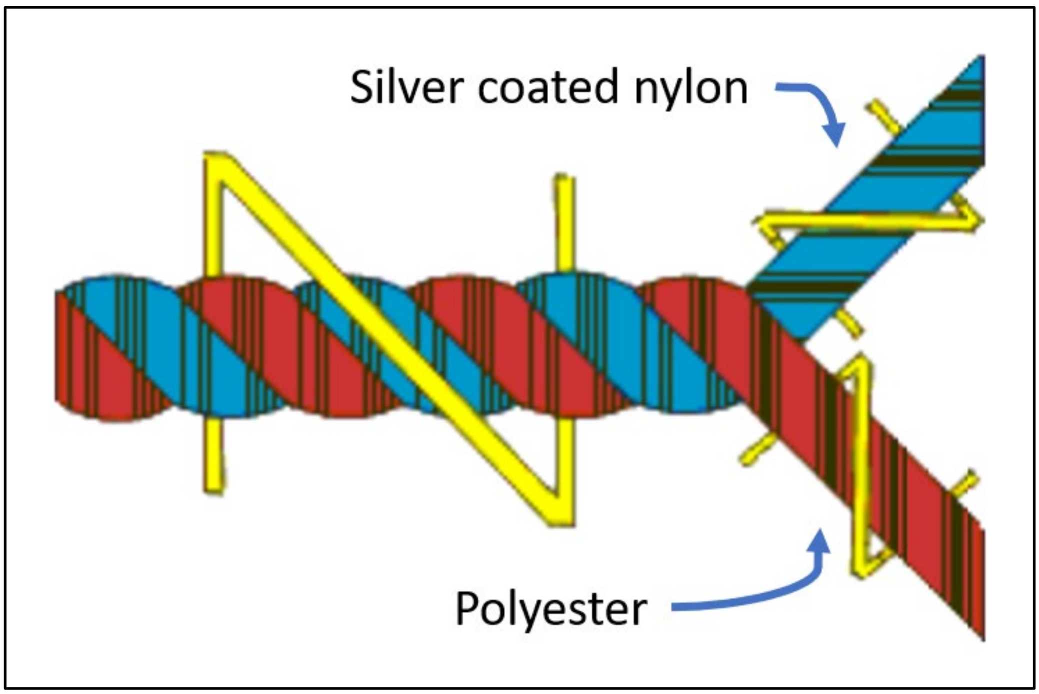

Figure 4.2: Composition of 44/12 + 113/32 PET thread [43]

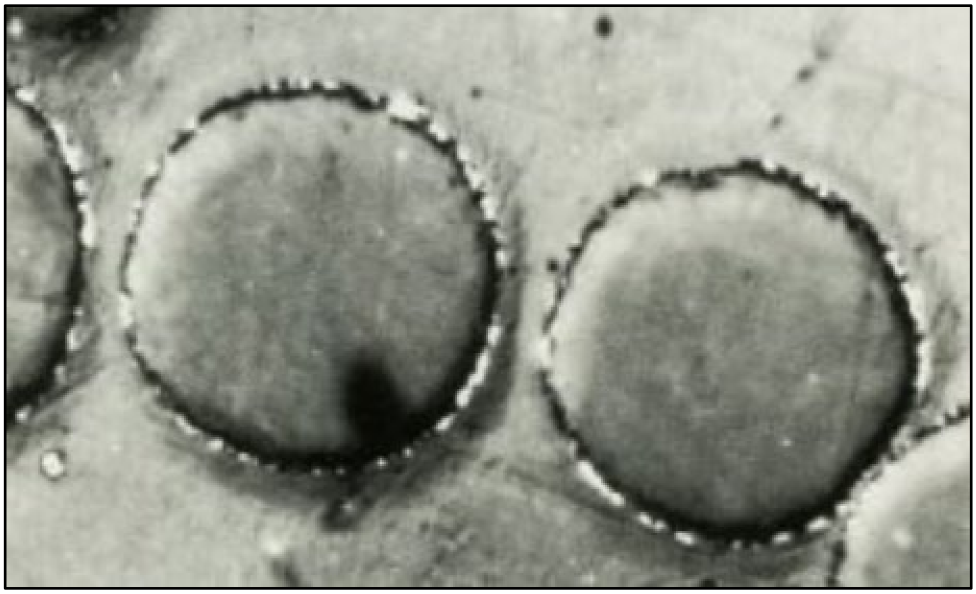

Figure 4.3: Cross section of the silver coating over nylon base for 44/12 + 113/32 PET thread [43]

The combination of a silver-coated nylon thread and a polyester thread allows this thread to have a very high resistance (low conductivity) while still having a thick enough thread to perform well in the embroidery process.

4.4 Thread Issues

Throughout the process of creating prototype resistors, inconsistent resistances between batches of silver-coated thread made accurate manufacturing more difficult. The resistance of each batch had to be measured before it was used and the specific value measured needed to be entered into the RFGT. This added complexity and time to the manufacturing process.

With the 5 batches of 44/12 + 113/32 PET thread I used in prototype testing, I had a range of unit resistances from 25kΩ/m to 100kΩ/m, which is far outside the specified tolerance provided by the manufacturer, Shieldex. Their spec sheet lists the tolerance for silver coating on the nylon base as “Yield: 58,000 M/100g +/- 5%” [43]. Furthermore, their spec sheet lists their resistance as being “< 300 Ω/cm”, or under 30 kΩ/m and I observed 3 of 5 batches being over 30 kΩ/m. One with a unit resistance of 70 kΩ.m, 90 kΩ/m, and 100 kΩ/m. These observations are given visually in **Figure 4.4**.

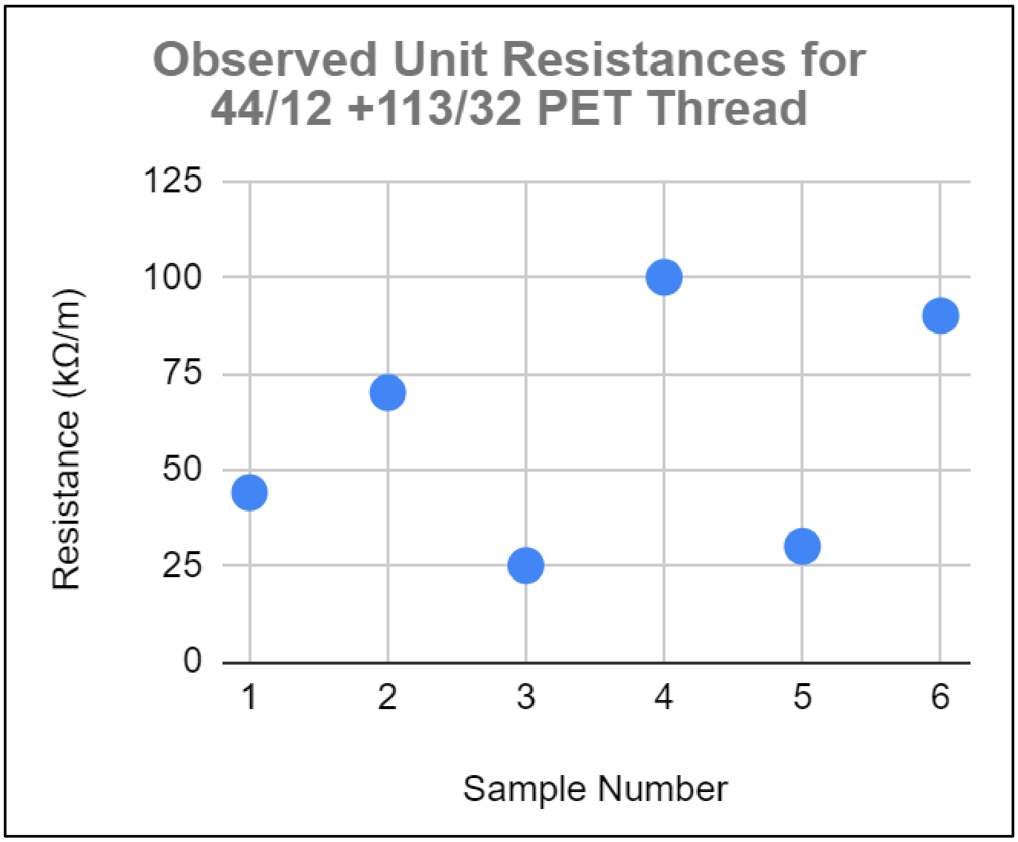

Figure 4.4: Inconsistencies in the unit resistance between batches of the silver-coated nylon thread 44/12 + 113/32 PET.

Another issue faced with the conductive thread was high levels of inconsistency with resistors created even within the same batch of silver-coated thread. With an identical manufacturing process for each prototype and the same wind of thread, the resistance between each resistor was inconsistent. This was recorded and discussed in more detail in Chapter 5.5.

Lastly, after completing some prototype resistors it was observed that some of the resistors had disconnects in the conductive material and did not allow any current to flow. While this was rare and did not occur during any formal recorded testing, it pointed to another possible issue with the silver-coated thread to watch out for.

In the future development of embroidered electronic devices, it may be beneficial to create conductive threads "in house" so that the process of making the threads is better understood and threads can be developed specifically tailored to these applications. This was considered outside of the scope of this project, but is noted for discussion.

4.5 Manufacturing Process

4.5.1 Using the RFGT to Create Resistor Files (Instruction Manual)

I wrote the following manual for public instructions on utilizing the RFGT. It is the process that has been validated in this study to create the embroidered resistors in this project. The instruction manual is listed below and can be seen on its original page at:

https://www.appropedia.org/Embroidered_Electrical_Resistor_Generation

The details can be found below:

The RFGT is a Python package, so downloading Python is required. The tool utilizes the python libraries, numpy, math, matplotlib, and pyembroidery. The tool was made in Python version 3.8.

To use this package, download it from https://github.com/srschrock/embroidered_resistor_generation. Open the file "main.py" with any python interpreter (I use Spyder or PyCharm). In "main.py", all inputs are listed near the top.

Enter your desired resistance, and the unit resistance of the conductive thread you are using. Note that this tool is designed for the conductive thread to be placed in the bobbin thread with normal sewing thread to be used as the upper thread, so make sure your machine is set up accordingly.

Customize further parameters as needed including the stitch length, the gap length between lines, the width of terminal pads, the density of stitches in terminal pads, and the gap length between terminal pads.

Specify which output file type you need for your embroidery machine.

Run the program (main.py) with your desired inputs, and the embroidery file will be created in your working directory.

Check the generated plot to view your creation. The stitch path is shown in a red line, and the individual stitches are shown in blue "x" over the path line.

Specifically for my materials and machine, I used the following settings in the RFGT. I set my stitch length and gap length to be 0.9mm. I set my gap length between terminals as 1.8mm. I set my terminal size to 3.8mm with a thread density of 4 rows (per pad per direction). For my Janome Memory Craft 400e embroidery machine I wrote to .dst embroidery files. Each time I started a new batch of conductive threads, I measured the unit resistance of the thread and updated the value in the RFGT.

4.5.2 Using the embroidery machine

I wound my conductive thread to my embroidery machine bobbin. I kept polyester sewing thread as the upper thread. I set my base material, cotton fabric, tightly in my embroidery hoop and attached it to my embroidery machine. I uploaded my embroidery file from the RFGT to my embroidery machine via a USB flash drive. I hit start on the embroidery machine, and a resistor would be made.

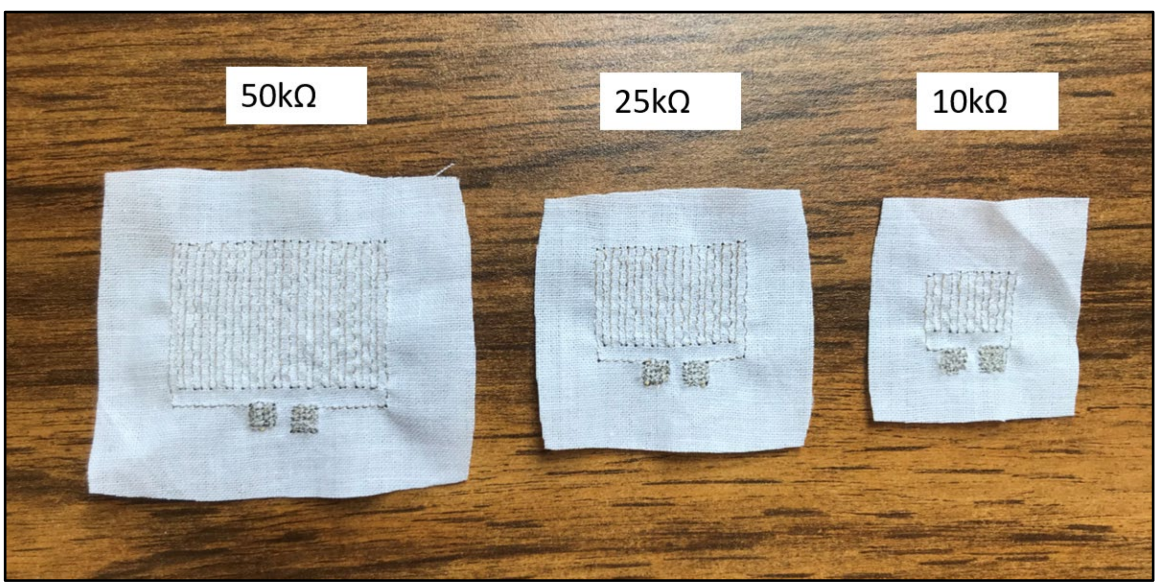

Figure 4.5: Embroidered resistors in 50, 25, and 10 kΩ strength.

4.5.3 Connection Method

To add the flexible resistors to textile devices, the component was laid over the base circuit, creating a multi-layered circuit board. The terminal pads were aligned between the resistor and the circuit, and the terminal pads were sewn to their match with conductive thread as shown in **Figure 4.6**.

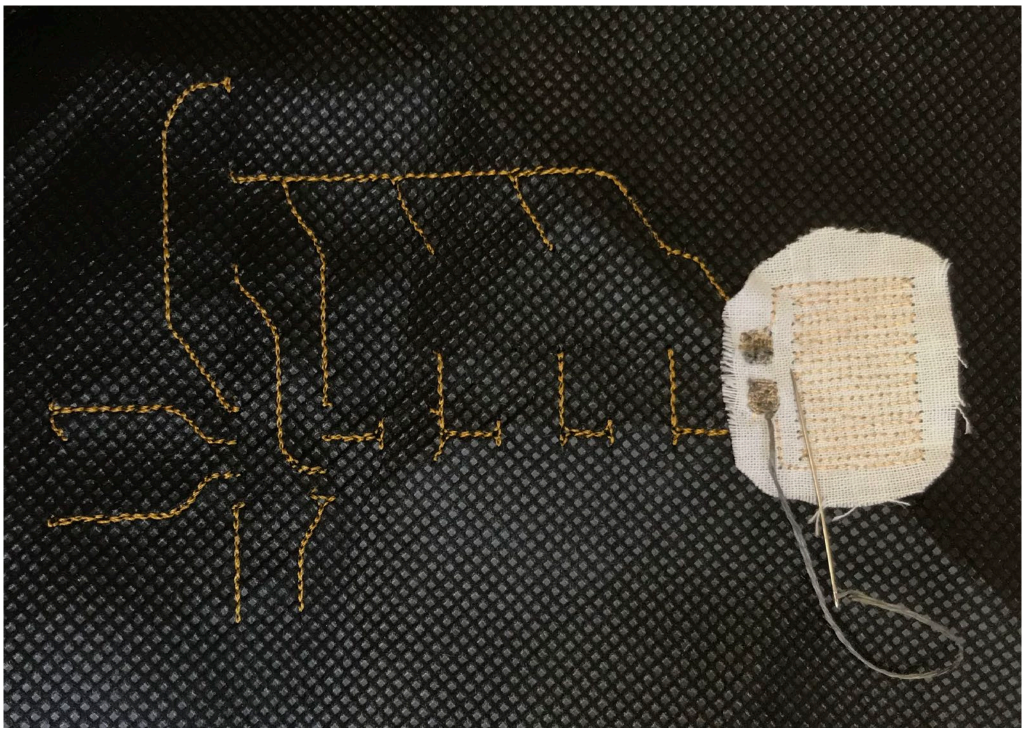

Figure 4.6: A resistor attached to an embroidered circuit via hand sewing.

This process can be done with any conductive thread. This process can also be done with the embroidery machine by overlaying the parts in the embroidery hoop and using a conductive pad file to create a robust connection very quickly.

Using sewing or embroidery as a connection method is valuable because it simplifies the overall manufacturing process for textile electronic systems. Soldering to these flexible systems was immensely difficult. Usual outcomes were burned conductive threads or weak connections that would break when the device articulated.

As discussed in Chapter 2.2.2, sewed connections present strong durability. Hand sewing as used in this study is effective for small production levels and prototypes, and embroidery is well suited to larger production levels.

Producing these resistors and flexible textile systems in a larger scale would warrant the automation of an embroidered connection process. This process can be used to connect multiple layers of embroidery, creating a multi-layered fabric electronic device.

The printing of all the desired resistors directly in place in a circuit likely cannot be done in a one-step procedure until the generated resistors become more consistent and reliable. As discussed in Chapter 4.4, the current best-performing thread presents an issue for resistance consistency. The current method for mitigating this is discussed in Chapter 4.7. While this method can reliably create resistors to specification, it does not completely prevent failed resistors. Therefore, the process will need to be improved before a full set of resistors can be printed in a single layer in a one-step operation.

4.6 Manufacturing Process Problems

Throughout creating prototypes, problems included fabric slipping around in the embroidery hoop, cloth getting pulled into the embroidery machine, and short circuits created in the resistors.

To avoid short circuit in the resistors, the spacing of the gaps between columns and terminal pads needed to be sufficiently large while still using minimal fabric surface area. Short circuits, as shown in **Figure 4.7**, cause reduced resistances as the current can take the shortest path and skip some thread sections. This was a serious problem to avoid.

Optimal spacing and stitch parameters were dependent upon a variety of factors, and needed to be found with trial and error. The main factors were the embroidery machine being used, fabric qualities, needle size, and selected thread.

I found 0.9mm to be a good size for stitch length and gap length, with tight spacing for the resistor with no observed short circuits during the fabrication of hundreds of prototype resistors during my tests. I was using a cotton base material, Janome Polyester Embroidery Thread No. 2 (125dtex x2 ply) as the upper thread, 44/12 + 113/32 PET as the bobbin thread, Janome Memory Craft 400e embroidery machine, and a size 11 sewing needle.

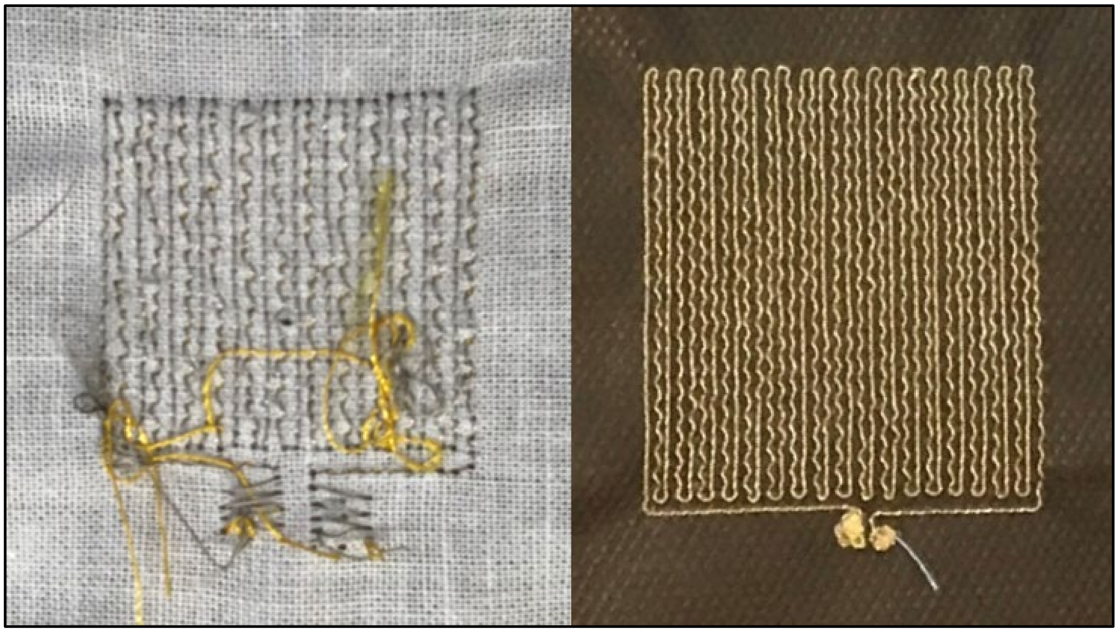

Figure 4.7: A comparison between a faulty Resistor with a short circuit (left) and a resistor with proper spaces (right).

The forces on the cloth from the needle and taught thread caused the cloth to move around in the hoop. Tightening the hoop to maximum hand tightening did not provide a strong enough hold on the cloth. While the hoop is able to sufficiently hold the corners, the cloth is not held tightly on the sides between the corners. As the embroidery machine would run, the cloth would be pulled side to side which caused frequent short circuits. This problem was remedied by placing safety pins on the cloth after pulling the cloth tight, as shown in **Figure 4.8**.

Figure 4.8: Use of safety pins to prevent fabric movement within embroidery hoop.

Cloth could occasionally be pulled into the embroidery machine by the needle, causing destruction of the cloth and risking damage to the embroidery machine. Ensuring that the cloth was held by the hoop in high tension and using safety pins reduced the risk of this. To avoid this risk, it is important to use cloth without any defects or loose threads. It was observed that thin or loosely knit cloths were more likely to be sucked into the machine. It was important to watch the machine during operation so the process could be aborted in case the fabric is pulled into the machine.

4.7 Manual Short Circuit Method for Quality Control

To improve resistor accuracy, a finishing manufacturing step is presented to improve previously made parts. Manually creating a short circuit across flow path columns reduces the resistance of the resistors by creating a shorter pathway for the electricity to travel. By adding short circuit pads as needed, the resistance of any resistor can be reduced until the resistor reaches its target.

This process is done by taking a conductive piece of material and pressing it down to connect a small area of the resistor's conductive columns. I used a flexible copper pad to ensure good contact with the conductive thread in the columns. To find the area that needs to be short circuited, I started in an upper corner and bridged as many columns as possible without passing the resistance target. With the number of columns found, I then slid the pad downwards on the columns to fine-tune the resistance. This process allows to reduce resistance in smaller increments than bridging columns. See **Figure 4.9**a for a depiction of this process.

With a target area to short circuit, the resistor was brought back to the embroidery machine and a conductive pad was sewn to create the short circuit. **Figure 4.9**b shows a resistor with short circuits applied to connect tines.

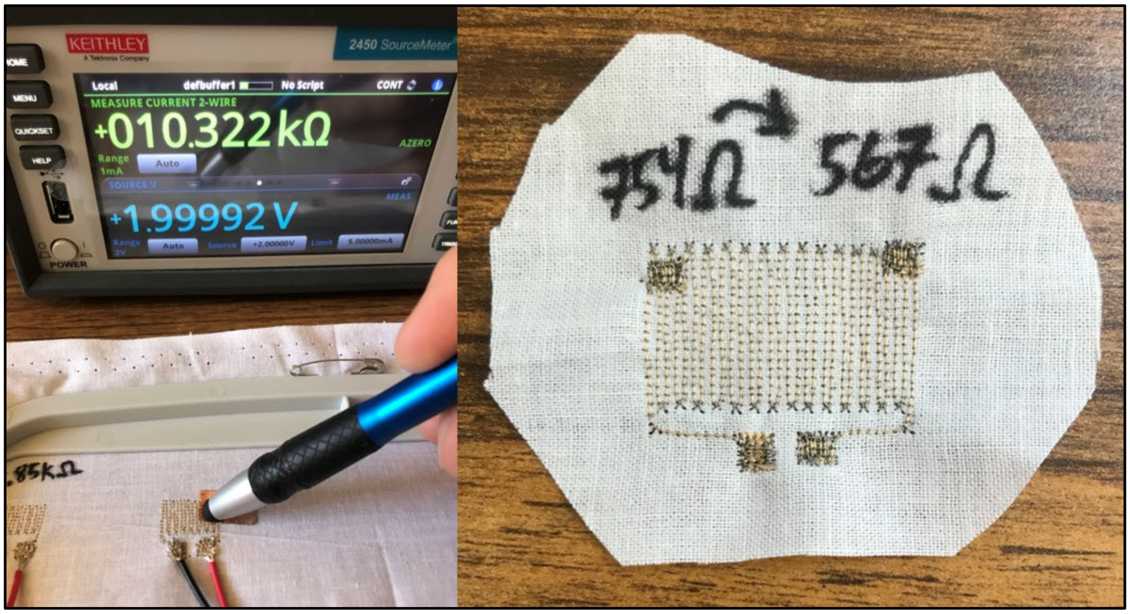

Figure 4.9: Experimental setup. (a) Measuring where to create a short circuit (left) and (b) a resistor after having short circuits created (right).

Oftentimes this short circuit procedure needed to be done multiple times in succession to achieve target resistance. If the addition of one pad did not reduce the resistance enough to hit the target, the process would be repeated as needed. **Figure 4.10** shows an example where four short circuit pads were added to reduce resistance down to the specified target.

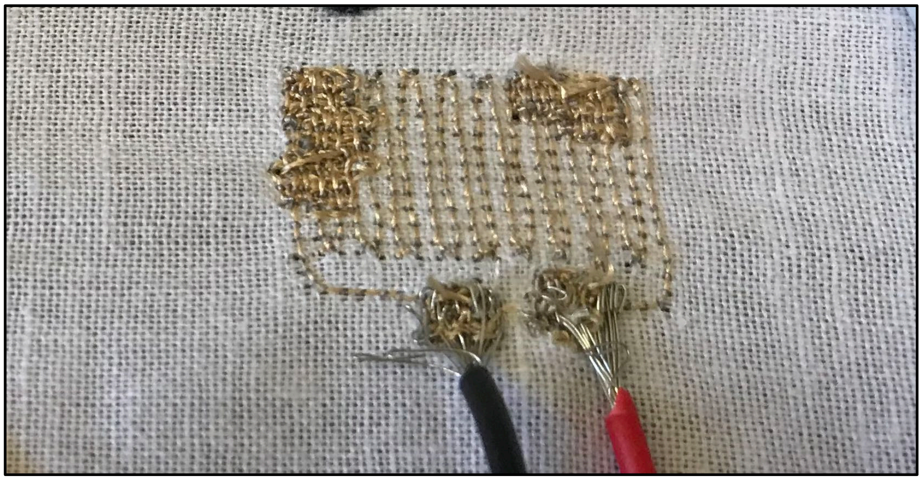

Figure 4.10: Resistor with 4 short circuit pads added to achieve target resistance.

Small pads are used in the short circuit process because decreasing the resistance by small increments decreased the risk of passing the target value. Creating the entire short circuit in one pad increased the risk of bridging too many columns and passing the target. This process of short circuiting cannot be undone, so if the target is missed the resistor either needs to be used for a lower value resistor or thrown away. Creating the short circuit in increments improves final accuracy and reduces the chance of passing the target resistance.

For minimal work in the short circuit process, it was beneficial to print extra resistors for each desired value. For example, if I needed 3 resistors at 10kOhms, I would print 5 or 6. The resistors that were below target by more than tolerance allows would be discarded or saved to use as a smaller resistor. Resistors that fell inside the tolerance bounds would be left unaltered. Any resistors remaining above the chosen tolerance bound would be short-circuited to decrease resistance to specification.

The results to validate this quality control process are shown in more detail in Chapter 5.5.

5 Testing and Validation

5.1 Overview

To validate the resistor effectiveness, this chapter shows the detailed validation results after manufacturing and during use. This was accomplished by conducting a varied bend test, a repeated bend test, a stretch test, a VI (voltage to current) test, and a manufacturing consistency test.

The goal of these tests is to validate that the resistors perform well under a range of conditions they will be subjected to when they are used in wearable devices. When a device is worn as part of a shirt or any other garment, it will be subjected to stretching, bending, folding, and water exposure. The resistors are tested under this whole range of conditions to verify both that their performance is consistent and that the resistors are durable enough to withstand daily use. The experiments are designed to cover these conditions.

These tests are meant to be a preliminary set to demonstrate the resistors warrant further study and development. The testing does not perfectly isolate all variables, and does not contain a huge quantity of data. In future development of the resistors, it would be useful to run these tests under a wider range of conditions, with different silver-coated thread types, different conductive materials used, and testing of the conductive threads both before and after the embroidery process.

For all of the following tests, the conductive thread 44/12 + 113/32 PET was used, which is made by ShieldEx. This thread was described in more detail in Chapter 4.3. This conductive thread was wound in the bobbin, and Polyester Embroidery Thread 125 dtex by 2 ply was used as the upper thread.

5.2 VI Test

To verify that the resistors will perform consistently over a range of voltages, a VI (Voltage against Current) test was performed. In this test, the current was measured as the resistors were subjected to voltages between 0.5 and 5 Volts. The plot shows a perfectly linear relationship between current and voltage, confirming that the resistance stays constant as voltage or current changes. These results are shown in **Figure 5.1**.

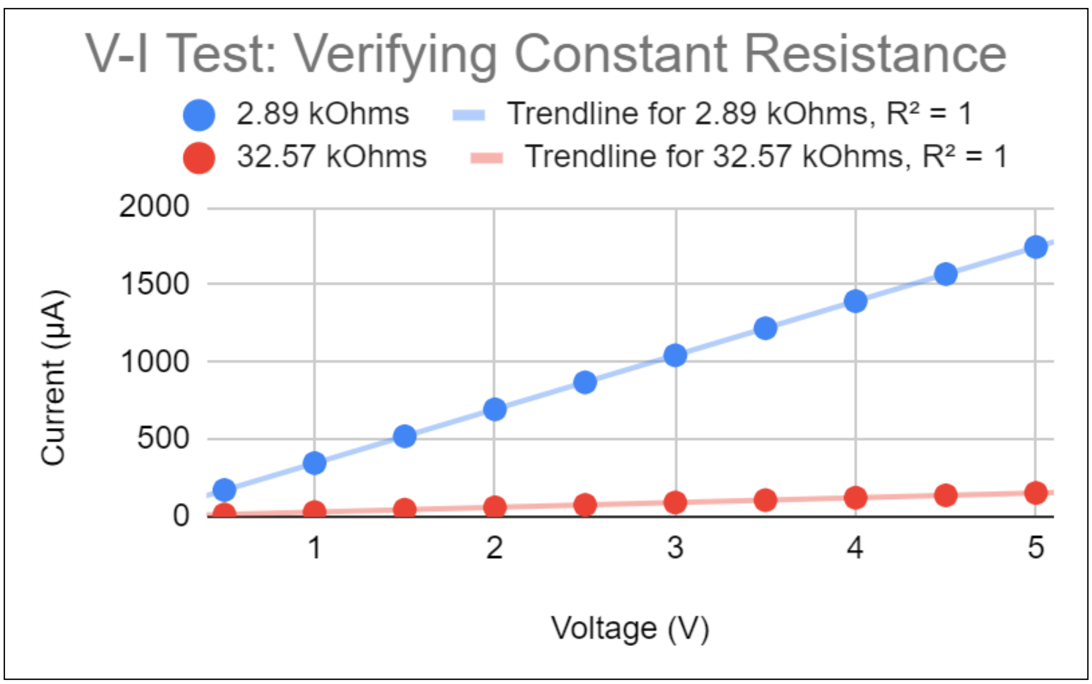

Figure 5.1: A VI (voltage-current) test

This test was performed with fresh and unperturbed resistors. They had not been exposed to water, and had not been stretched or bent before the test.

5.3 Bend Tests

To verify that the resistors perform consistently as they are being worn or used, a varied bend consistency test was conducted. In this test, the resistors were measured when lying flat, bent to a 24mm diameter, 9.5mm diameter, and folded. The results of this test are shown in **Figure 5.2**. The resistances shown in this plot show slight variations in the 38 kΩ resistor and nearly no variation in the 10 kΩ resistor, indicating that the resistors will perform consistently when subjected to a range of bends as the fabric they are bound to articulate.

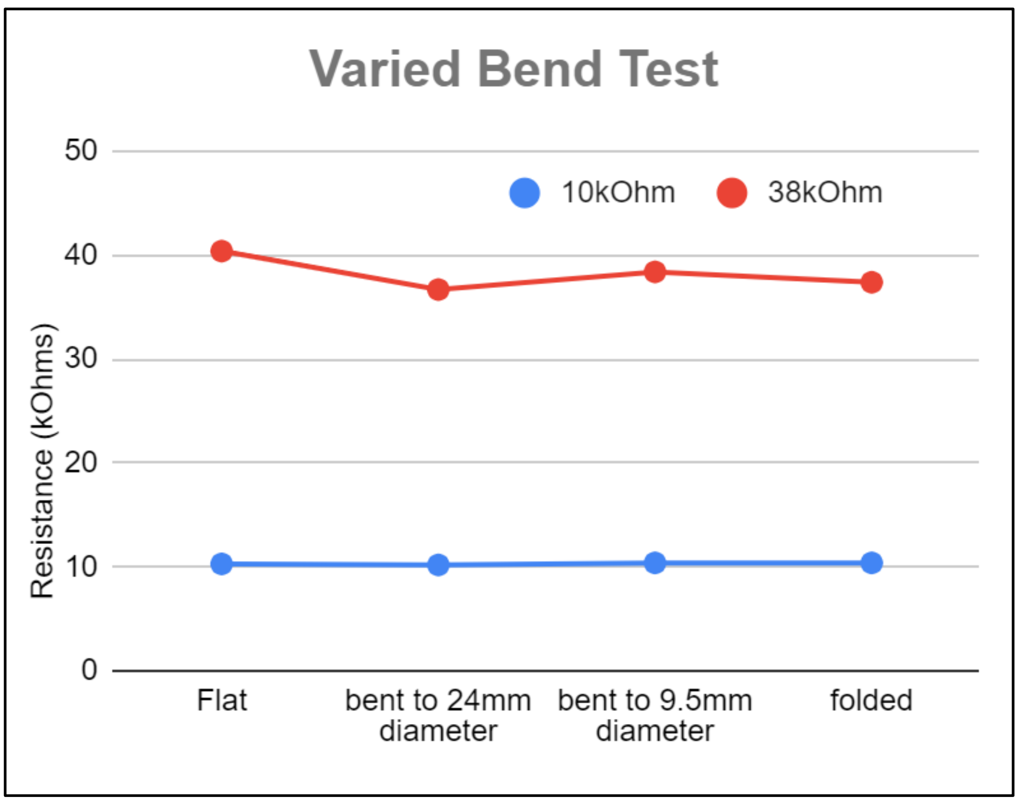

Figure 5.2: Varied bend consistency test

To verify that the resistors will perform consistently throughout daily wear and time, a repeated bend consistency test was performed. In this test, the resistors were measured when laid flat, and were repeatedly folded and unfolded with a measurement taken after each cycle. The results of this test are shown in **Figure 5.3**, which shows a slight variation in the 38 kΩ resistor and nearly none in the 10 kΩ resistor. This test was conducted with the resistors folded diagonally as shown in **Figure 5.4**.

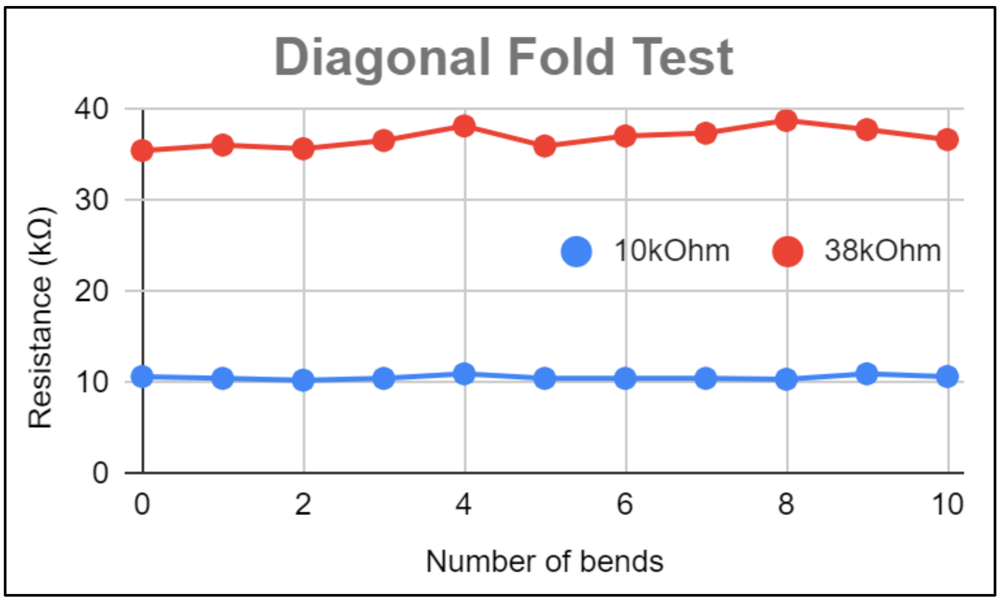

Figure 5.3: Diagonal fold test

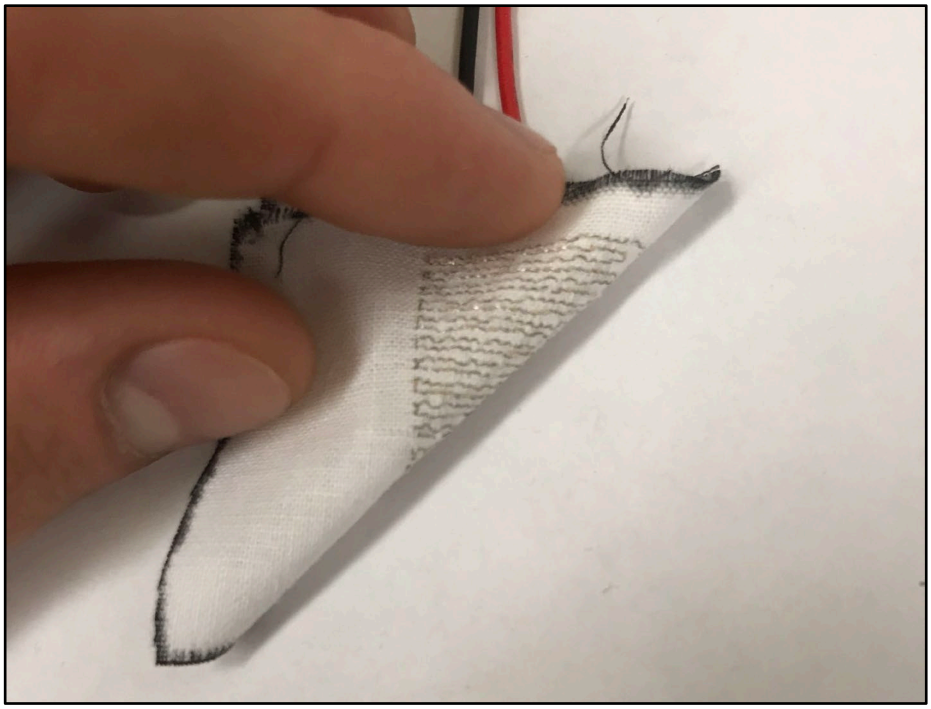

Figure 5.4: Diagonal fold method used for testing.

Another repeated fold test was performed to independently study the effects of folding the resistor perpendicular and parallel to the flow path tines. Folding the resistors perpendicular to the flow path tines causes significantly more conductive threads to be bent than parallel. This test is intended to illustrate the effect directionality has on resistance.

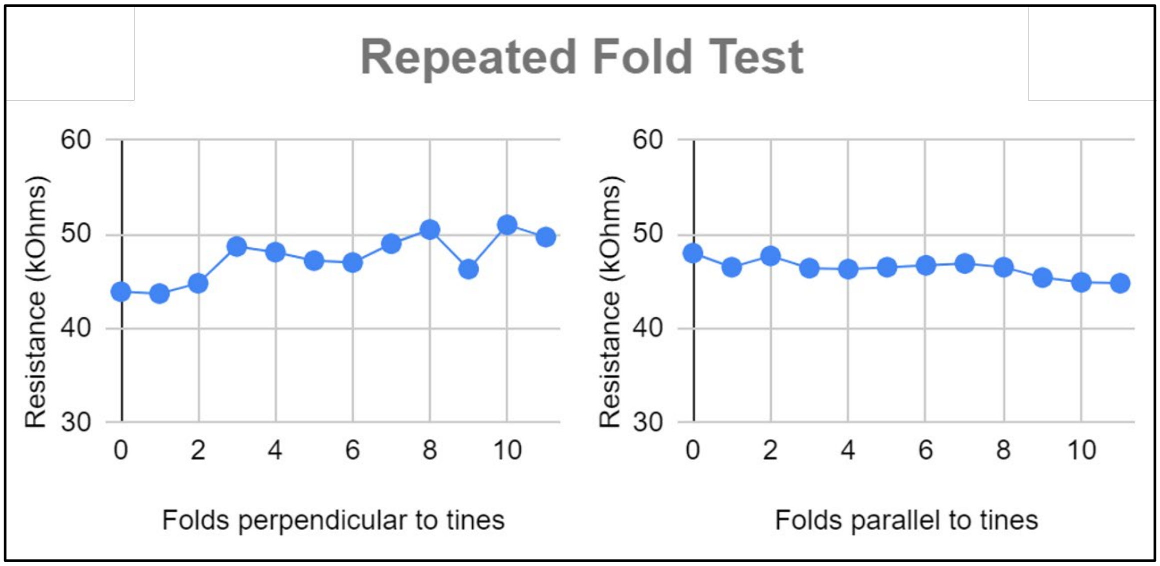

Figure 5.5: Repeated fold test to compare the effect of perpendicular and parallel folding on resistance.

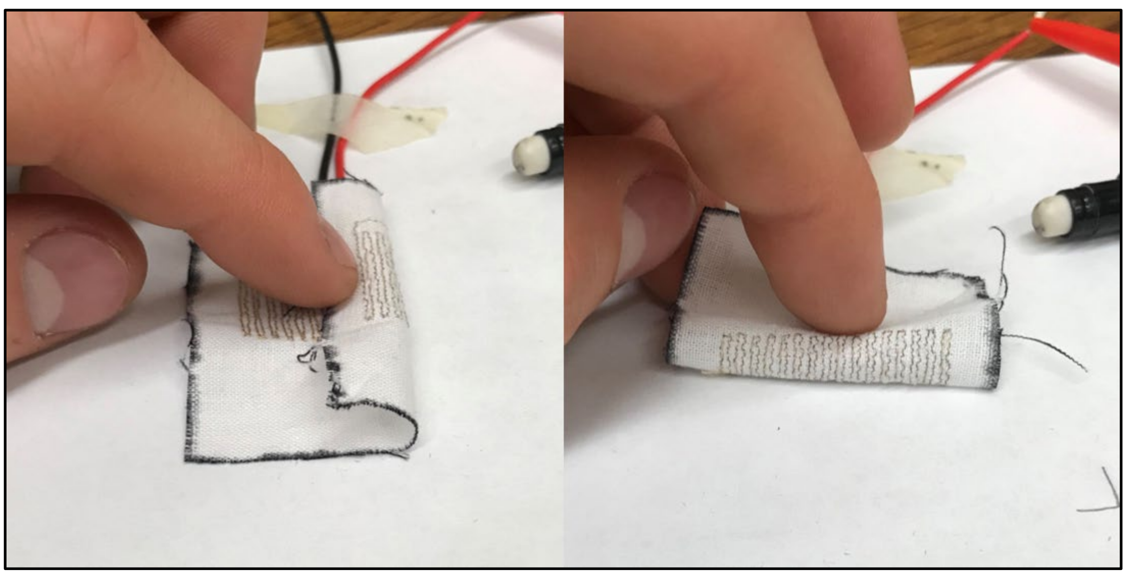

Figure 5.6 a & b: Folding the resistor parallel to (left) and perpendicular to (right) the embroidered conductive flow path tines.

These observed variations in resistance due to folding suggest that the resistors may not be the most accurate for applications where the garment is used in harsh environments, on flimsy garments, or in high precision devices. More study is needed into the effects of base fabric on bending performance.

Additionally, more study may be needed into the durability of the silver coating of the conductive thread. It is suspected that with the super thin coating of silver, when the thread bends or is unbent that the thickness of the coating changes as the soft metal is deformed. Or that micro-cracks may be formed on the outside edge of the thread as it is bent, and when it returns to its previous state the crack may come back into contact or might not. Study under a microscope is needed to investigate.

One possible method to mitigate the effects of mechanical stress on these resistors from stretching or bending could be to make the tines with a zig-zag stitch pattern instead of straight lines. This would allow the base fabric to stretch and articulate without imparting as much stress in the conductive thread. This method of zig-zag stitching is used when sewing elastic or stretchy materials with stiffer sewing thread. In this application, it is usually intended to avoid the base material from losing its stretchability from the stiffer sewing thread used.

5.4 Water Exposure / Washability Test

The performance of the resistor when subjected to water exposure is important because in the daily use of an item of clothing or garment, the cloth can get wet from the rain, a spilled drink, or regular washing. It is important to understand how the resistor performs both as it is wet and after it dries out again.

The results of this test showed that water drastically affects the performance of the component. **Figure 5.7** shows how the resistances of two samples change with exposure to water. When submerged in water, the current was able to short circuit the entire resistor and the resistance was dramatically decreased. It is important to note after the resistors have fully dried to their original, the resistance has been significantly increased and the resistors would not perform consistently with use before water exposure.

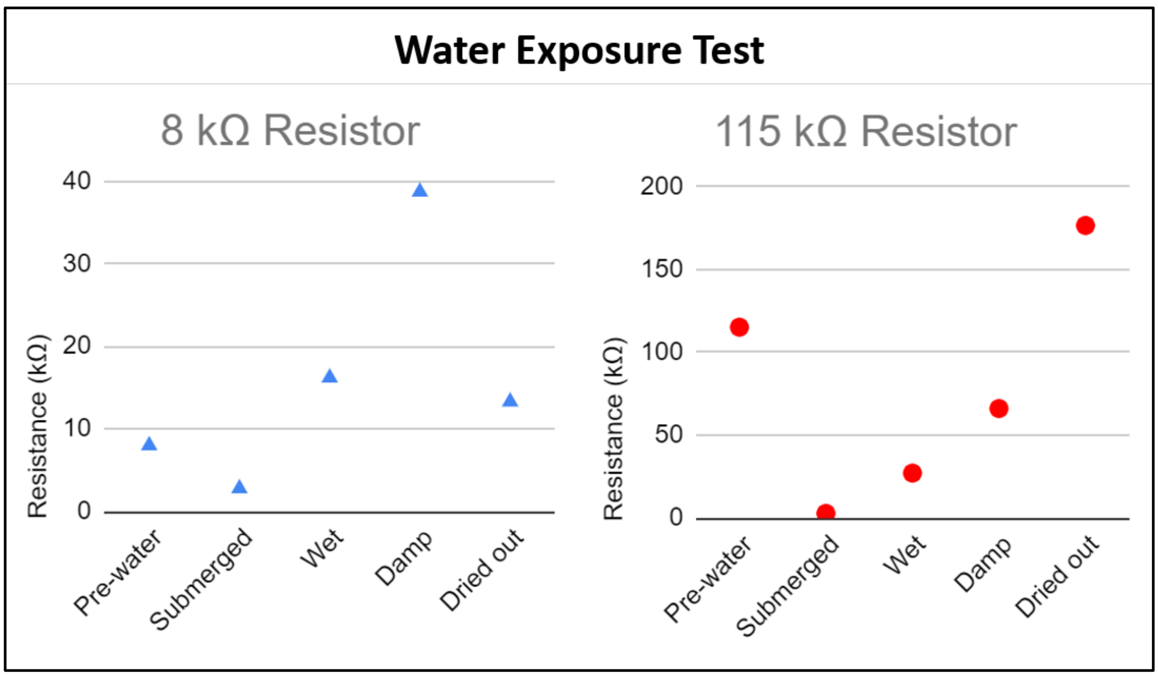

Figure 5.7: Water exposure test

These results suggest that a waterproofing measure will be required before these components can be used in consumer devices. Further study will be required into potential solutions for flexible and waterproof films and to verify these films do not adversely affect the electrical properties of the electrical devices they are protecting. Any study in this area will also likely benefit the e-textile research field in its entirety.

This test was performed with filtered drinking water from the Michigan Technological University campus. The water was not specifically measured for acidity, particulate matter, water hardness, and other water quality measures. It was assumed that if the water was rated safe for human consumption on the university campus, that the water quality should be reasonably representative and reproducible. As the resistors are future developed, a more detailed study of their performance with water exposure would be beneficial.

Torsten Linz provides a more detailed testing analysis of the performance of Shieldex silver threads over multiple wash cycles, which found that the resistance of the threads would decrease after the first couple of washes, then after approximately 5 washes, the resistance would continuously increase [30]. This differs from my testing results which found the resistance to rise after one washing. These differences could be due to any number of factors, including different embroidery machine use, different base material, and different models of Shieldex thread. Regardless of the differences we found, both results indicate that the thread should be used in safer environments if unprotected, and needs to be protected when subjected to harsh environments like washing.

5.5 Batch Accuracy Testing

In the manufacturing consistency test, 6 resistors were made with the same embroidery file for a specific target resistance. These trials were compared against each other to demonstrate consistency, and compared to the target to demonstrate accuracy. **Figure 5.8** shows that the resistors are reasonably consistent and accurate, but not enough to achieve tolerances of normal rigid resistors.

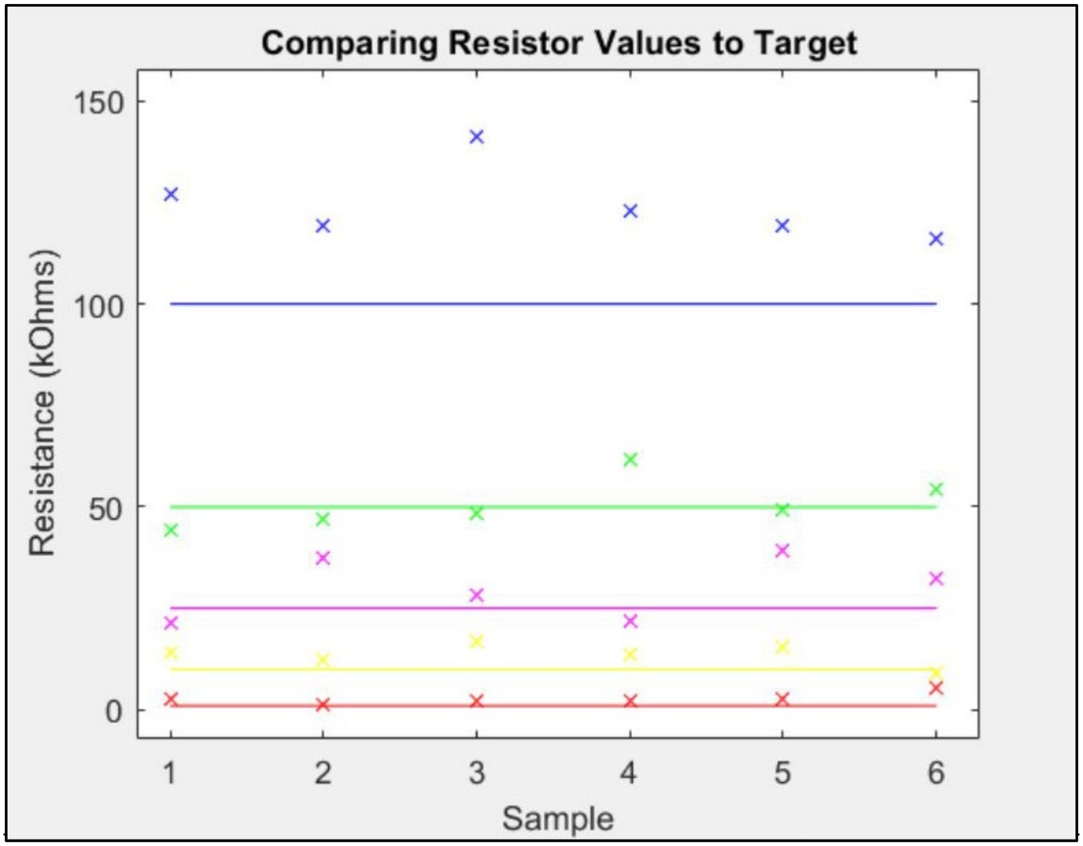

Figure 5.8: Batch Accuracy test to compare target and achieved resistances for 6 different strength resistors.

The manufacturing methods remain identical for each of the 6 resistors, so it is suspected that the variance comes from varying silver coating thickness of the thread. From the spec sheet, the thread coating process has a tolerance of +/-5% but I suspect the variance to be higher in the batches I have used. Torsten Linz suspected the same when studying Shieldex thread as a method of creating embroidered electrical contacts [30].

To make the resistors viable, they were altered with the quality control operation documented in Chapter 4.7. The results of this method are demonstrated in **Figure 5.9**. With this method, resistors could reliably be made inside the tolerance bounds for target resistance. In this sample, resistors 1 and 5 had an initial resistance below the acceptable tolerance bounds. These two resistors could either be discarded or could be saved to use in a smaller resistor. Both could very easily be altered to make 10 or 15 kΩ resistors.

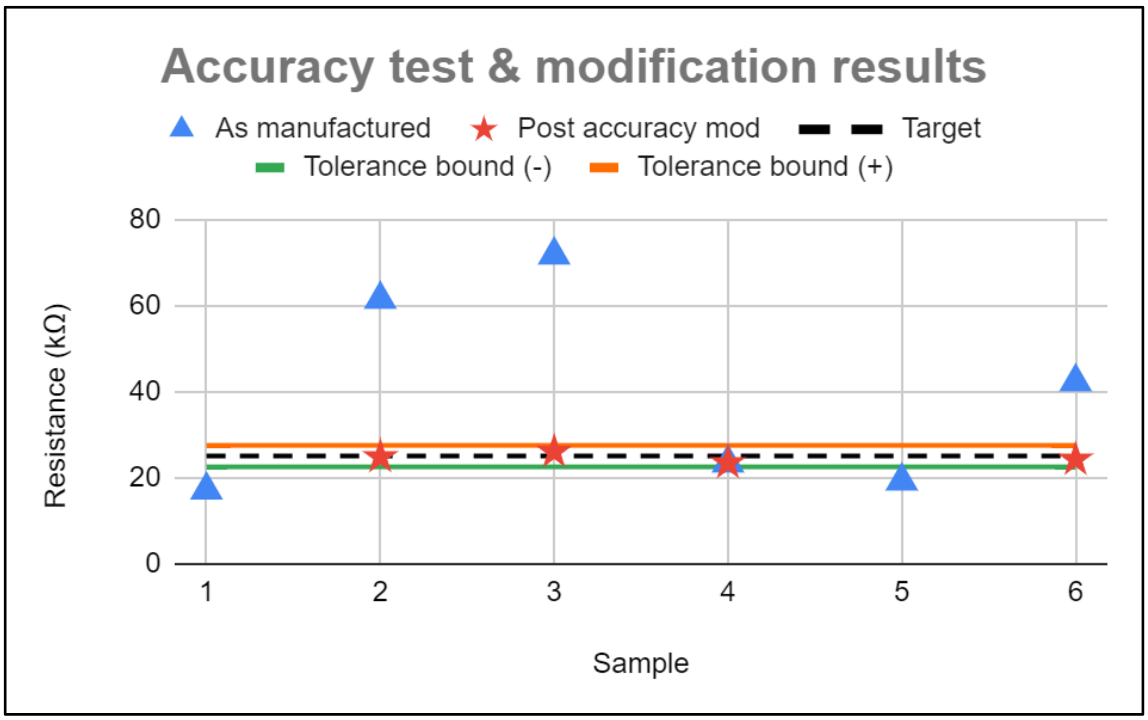

Figure 5.9: Batch accuracy test and the modification results.

6 Embroidered Resistors in a Touch Sensing System

6.1 Motivation and Overview

This chapter compares the performance of a textile device with embroidered resistors against its performance with conventional rigid resistors. This is intended to be a nearly all-encompassing test to validate that embroidered resistors are viable to replace conventional resistors.

This test subjects the resistors to a dynamic range of electrical conditions. The contacts between the resistors and the circuit are also put to the test.

To test the resistors, they will be used for finger touch sensing. Detecting finger touches is an important use of systems on cloth because it is a primary method of interfacing with most devices. Beyond controlling devices, my research group is developing soft and flexible end effectors for robotics. These end effectors will need flexible systems to detect contact has been achieved with their targets. Another target use for fabric systems to detect touch is in the steering wheel of a car to ensure the driver keeps their hands on the wheel, and alert them in the case of falling asleep or to keep their focus on the road.

To detect finger contact, an ECG device made by embroidery was repurposed. This ECG device initially operated with rigid resistors. To test the device with flexible resistor technology, the rigid resistor controlling the gain of the amplifier was replaced with an embroidered model.

Demonstrating that an embroidered device and embroidered resistors work well together is an important demonstration of the capabilities of e-broidery as a manufacturing technique for e-textiles.

6.2 Manufacturing Methods

The touch sensing system was created with a combination of an embroidered base circuit and conventional electronic components.

6.2.1 Embroidery File Creation from PCB Layout

The creation of the embroidery file for the base circuit was accomplished with the software package embroiderSoCl, developed for conversion of PCB layouts to embroidered patterns. This is a package being developed by my research team to become an open-source cloud manufacturing webpage. It can be used on the site http://socl.me.mtu.edu/en-US/index.html.

Using this package, the PCB layout image was uploaded and an embroidery file was created. This tool accomplishes this conversion by binarizing the PCB image, skeletonizing the image, then saving the pixels of each body as a list. The lists are traced one at a time, with the coordinates recorded along the path for stitches to be created by the embroidery machine. A depiction of this process is given in **Figure 6.1**. With the methodology documented in Chapter 3.3, the coordinates are converted into the embroidery format and written to an embroidery file.

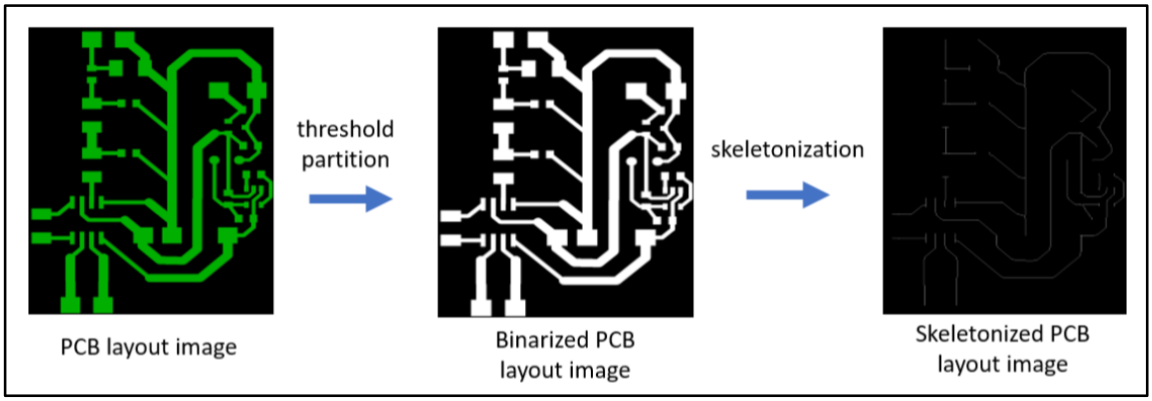

Figure 6.1: PCB to embroidery file conversion methodology.

6.2.2 Creation of the Touch Sensing model

To create the physical model, the base material was placed in the embroidery hoop, the bobbin was wound with conductive thread, a polyester non-conductive thread was used on top, and the embroidery file was uploaded to the machine.

Conductive pads were added to the base cloth to increase electrical contact and ease of connecting with non-fabric components. The pads used in this study were stainless-steel cloth with an adhesive backing. To create the pads, an entire layer of the conductive cloth was placed over the base cotton cloth and adhered to. The outline for the conductive pads was traced, and the extra fabric was cut away. The pads were placed to match the locations of the end terminals in the circuit and adhered to the base cloth. This process is shown in steps (a) through (c) in **Figure 6.2**.

With the placement of the pads aligned with the starting point for the embroidery machine, the machine was run. The embroidery machine sewed the conductive thread to integrate it into the base cloth. This process is shown in part (d) of **Figure 6.2**.

The rigid electrical components such as the gain amplifier, resistors, and capacitors were soldered onto the circuit. This process is shown in part (e) of **Figure 6.2**. After verifying that the prototype system worked as intended, a flexible embroidered resistor replaced a rigid resistor for testing.

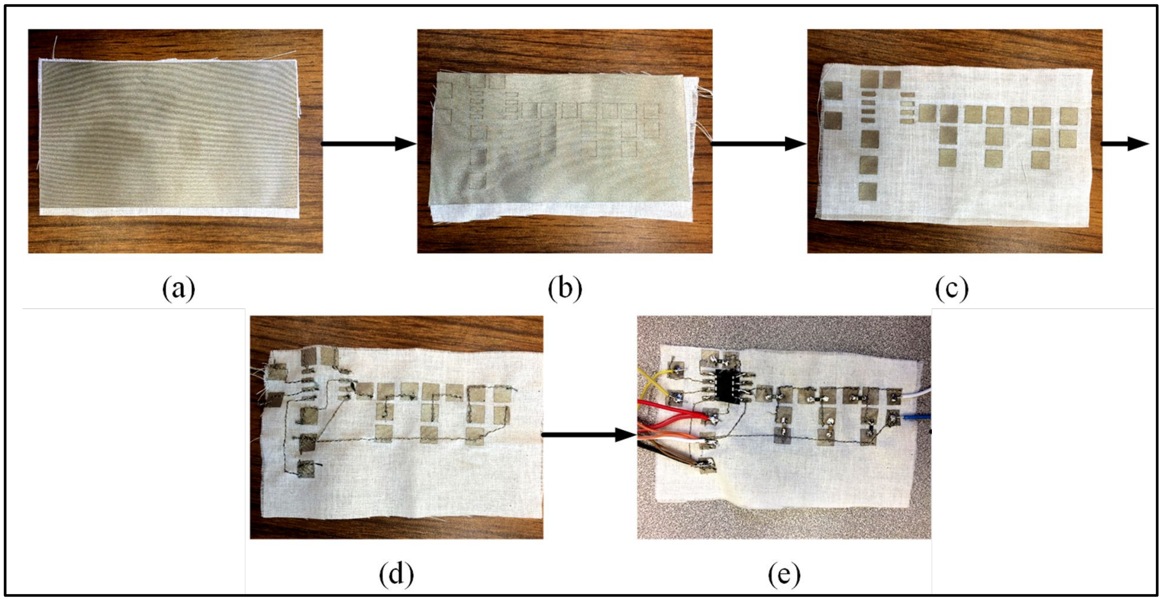

Figure 6.2: Manufacturing process for creating the touch sensing model with embroidery.

To complete the prototype touch sensing model, the external components were added to the circuit. Those components included two battery packs and two dry contact electrodes for biopotential monitoring. The schematic for the prototype system is given in **Figure 6.3**.

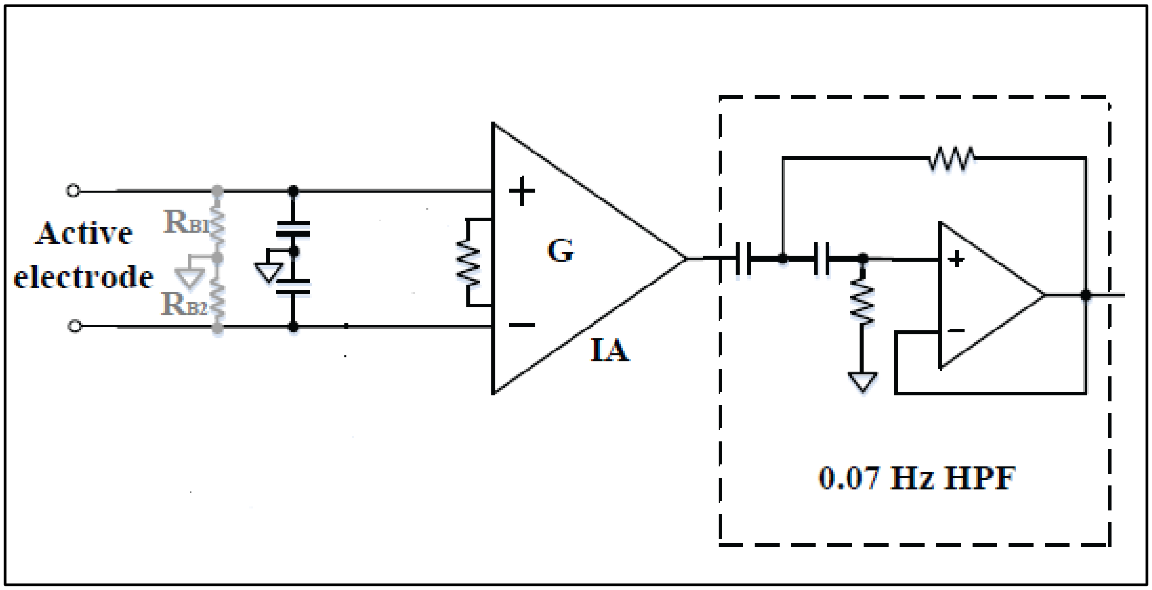

Figure 6.3: Schematic of the touch sensing device.

6.3 Touch Sensing Test

To prepare the touch sensing device for testing, the resistor across the gain amplifier was replaced with an embroidered resistor. The hand stitching process was used to create the electrical contact between the embroidered resistor and embroidered circuit. The completed system is shown in **Figure 6.4**.

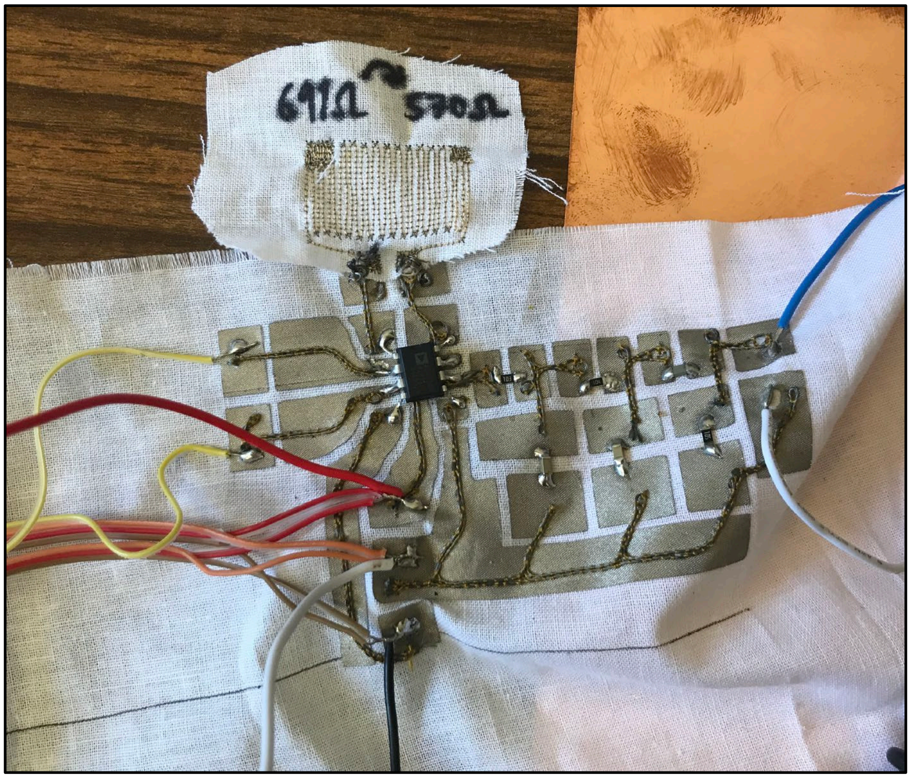

Figure 6.4: Touch sensing device with a flexible resistor attached.

It should be noted that because this resistor has a strength of less than 1 kΩ, the conductive thread 78/18 Ag-coated nylon was used, also from Shieldex as shown in Table 4.1. The manufacturing method used to create this resistor, aside from the different thread, was identical to the process detailed in Chapter 4.

Because this touch sensing system is a prototype and does not have a protective covering layer to provide shielding from electrical noise, the device was covered by a copper tent and sat on top of a layer of copper tape on the table, shown in **Figure 6.5**.

Figure 6.5: Copper tent to provide shielding for the prototype device.

Leads to a data acquisition system (DAQ) were attached to the circuit. With the DAQ running, I repeatedly touched and released contact with the electrode and my finger. The data recorded are shown in **Figure 6.6**.

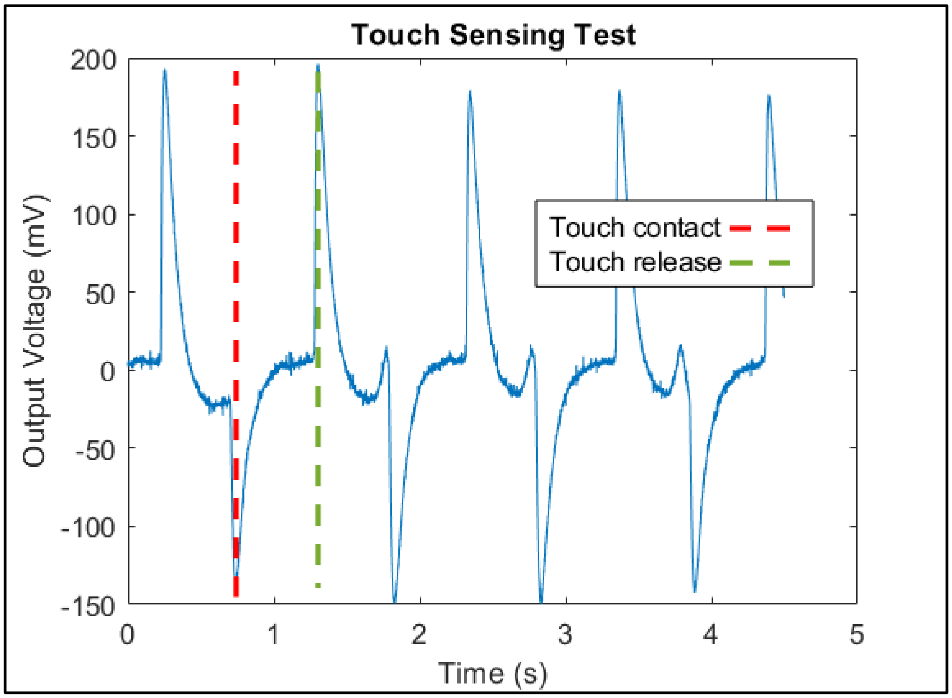

Figure 6.6: Touch sensing test results.

These results demonstrated a very clear signal of when touch contact was made and released from the electrode. The clear signal read by the touch sensing device demonstrates that there is good contact between the resistor and the circuit, and that the resistor performs as intended. The results of this applied device test suggest that the flexible resistor technology is a viable method for further development, study, and application.

7 Conclusion

7.1 Conclusion

A novel method for creating flexible resistors is demonstrated using embroidery, with the intent of being used in wearable electronic devices. This method is effective in creating resistors between 1 and 100 kΩ with the conductive thread "44/12 +113/32 PET". Using this method, resistors can also be made in higher or lower resistances with higher or lower unit resistance threads.

A resistor file generation tool (RFGT) was built and demonstrated for the creation of .exp files for running embroidery machines. The RFGT runs calculations for input thread type and target resistance and generates the pattern and operating code the embroidery machine will use.

Conductive threads were compared and the currently available thread with the best performance for creating 1 to 100 kΩ resistors was selected. That thread was 44/12 Ag coated nylon + 113/32PET (polyester) which is a combination of the two thread types interwound to make a two-ply thread with high electrical resistance.

The manufacturing process for creating embroidered resistors was demonstrated, along with common problems and methods to avoid them. RFGT parameter selection methods are explained.

It was shown that the generated resistors had wide variability in measured resistances directly after manufacturing, so a secondary operation was proposed and demonstrated to ensure accuracy. This method was completed by manually creating a short circuit across electrical flow path tines to decrease resistance down to the target value.

The resistors were tested in a variety of methods to ensure that they could withstand the conditions expected in textile wearable electronic devices.

An applied test was run which placed an embroidered resistor in a textile electrical device for detecting touch contact. The procedure for creating the device and completing the test was documented. The results of the test were shown, and it was concluded that flexible resistors are a viable technology.

7.2 Discussion

With the processes documented in this thesis, the resistors and main circuitry could be entirely fabricated and combined in a multi-step embroidery operation. Together with the touch buttons and wireless charging systems developed by other researchers, e-broidery is becoming a valuable tool for creating wearable electronics and e-textiles.

To continue the growth and development of e-broidery, I recommend further study into conductive materials to provide a greater range of resistances and improved resistance consistency. It may be beneficial as a manufacturer of embroidered electronic devices to look into creating the conductive materials “in house”. By doing this, there can be better clarity on quality control, and the conductive threads can be made with properties specifically tailored to each application of the embroidered electronics.

A more detailed and robust testing study of embroidered electronics may help to better understand how the conductive threads are affected by the embroidery process, how bending and stretching affect performance and durability, how the embroidered components react to water, and how to protect from water. While these conditions were tested in Chapter 5, they could be expanded upon to provide more detailed performance information. The tests in this thesis were intended to give initial validation of embroidered resistors and show that they warrant further development and study.

A potential method to decrease the effects of stretching or bending on the electrical properties of an embroidered component may be to incorporate a zig-zag stitch pattern in the place of linear lines. This method is used often when hemming or adding seams to clothes with high stretchability such as some polyesters and spandex, which allows a stiff and durable sewing thread to be used while not limiting the stretch of the fabric. Specifically in improving these resistors, the vertical lines that comprise the tines for electrical flow could be made into lines of small zig-zags. This would likely increase the space of fabric the resistor would need to cover, but may improve electrical consistency by reducing the variable strains the thread is subjected to.

In recreating or building upon this work, it is important to experiment with the specific embroidery machine, materials used, and other process steps. Different machines work differently from each other, different file formats may not convert between each other as well as others when given specific unusual commands, and different materials change the properties and performances of embroidered products.

One potential shortfall of embroidery as a manufacturing process is that it is currently not able to achieve ultra-fine resolution so it cannot be used to create super intricate electronic components. Study into scaling down the embroidery machines may be beneficial towards creating flexible electronics on a microscale or nanoscale.

With a more advanced circuit generation program and a thread with a higher unit resistance, circuits and all required resistors could potentially be made in one layer and with only one manufacturing step. Or they could be made in a multilayer process and joined together, which would contain the device to a smaller surface area.

The use of the silver-coating process for conductive thread in this thesis presents benefits and costs. First and foremost, silver presents an increased material cost. Silver is a “precious metal” and can be significantly more expensive than other conductive materials. It is the most thermally and electrically conductive metal [44]. Silver is generally regarded as safe, but in high exposures, some people can contract a rare disease called “argyria” which turns their skin permanently blue but poses no other side effects [44]. Study into other methods of fabricating high resistance embroider-able thread may be beneficial.

7.3 Future Work

This research group plans to continue the development of flexible electrical components, starting with capacitors and transistors. They also plan to develop an embroidered sensor to detect touch and touch pressure with a resistive network of embroidered thread.

This research group is working to develop a website around embroidered technology. This site will contain a robust library of embroidered wearable electronic devices. Users could use this library to download the files to create their own devices from a verified library. They could also upload and share their own designs to build upon the site. This site would connect consumers, designers, and manufacturers all towards creating more designs and applications. It could create a community and an economy around the technology.

The website currently hosts the program for PCB to embroidered circuit conversion, the file to embroider an ECG device circuit, a GSR device circuit, and embroidery testing files. It will soon host the embroidered resistor program as well. As more devices are developed by the research group they will be added to the website.

The long-term goal of this research group is to implement their developments in textile electronic devices to control and interface with robotic systems. We are also developing soft robotics in an effort to increase user safety. With textile electronic devices and soft robotics, the interactions between humans and robots could become closer and more natural.

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