INTELLIGENT SELF ADAPTING APPAREL TO ADAPT COMFORT UTILITY

by

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This thesis is dedicated to my great mentor who has shown me the world is a beautiful place.

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LIST OF ABBREVIATIONS

ACS	American Community Survey
ADL	Activities of Daily Living
AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
ASTM	American Society for Testing and Materials
BRFSS	Behavioral Risk Factor Surveillance System
CDC	Center for Disease Control and Prevention
CE	Credibility and Expectancy
CoAP	Constrained Application Protocol
CPS	Current Population Survey
CRS	Comfort Rating Scales
EDL	Eclipse Distribution License
EPL	Eclipse Public License
GUI	Graphic User Interface
IA	Intelligent Agent
IADL	Instrumental Activities of Daily Living
IDE	Integrated Development Environment
IoT	Internet of Things
M2M	Machine To Machine
MDS	Multi Dimensional Scaling
MQTT	Message Queuing Telemetry Transport
OS	Operating System
PEOU	Perceived Ease of Use
PTSD	Post Traumatic Stress Disorder
PU	Perceived Usefulness
RPM	Revolutions Per Minute
SIPP	Survey of Income and Program Participation
WA	Wearability Assessment
WT	Wearable Technology
XMPP	Extensible Messaging and Presence Protocol

ABSTRACT

Enhancing the capability to control a tremendous range of physical actuators and sensors, combined with wireless technology and the Internet of Things (IoT), apparel technologies play a significant role in supporting safe, comfortable and healthy living, observing each customer's conditions. Since apparel technologies have advanced to enable humans to work as a team with the clothing they wear, the interaction between a human and apparel is further enhanced with the introduction of sensors, wireless network, and artificially intelligent techniques. A variety of wearable technologies have been developed and spread to meet the needs of customers, however, some wearable devices are considered as non-practical tech-oriented, not consumer-oriented.

The purpose of this research is to develop an apparel system which integrates intelligent autonomous agents, human-based sensors, wireless network protocol, mobile application management system and a zipper robot. This research is an augmentation to the existing research and literature, which are limited to the zipping and unzipping process without much built in intelligence. This research is to face the challenges of the elderly and people with self-care difficulties. The intent is to provide a scientific path for intelligent zipper robot systems with potential, not only to help people, but also to be commercialized.

The research develops an intelligent system to control of zippers fixed on garments, based on the profile and desire of the human. The theoretical and practical elements of developing small, integrated, intelligent zipper robots that interact with an application by using a lightweight MQTT protocol for application in the daily lives of diverse populations of people with physical challenges. The system functions as intelligent automatized garment to ensure users could positively utilize a zipper robot device to assist in putting on garments which also makes them feel comfortable wearing and interacting with the system. This research is an approach towards the "future of fashion", and the goal is to incentivize and inspire others to develop new instances of wearable robots and sensors that help people with specific needs to live a better life.

CHAPTER 1. INTRODUCTION

The rapid development of wearable technology has transitioned from a conceptualized vision of art and fiction to set of stylized new product ideas for the general public and especially for those with assistive needs. Numerous factors, such as cost reductions in electronic parts, such as sensors, pervasive network access and mobile computing have enabled to development of these technologies, an expanding consumer desire for lifestyle to ensure they remain as fit as possible, and the unmet need for existing solutions in the market to continuously enhance function have resulted in on the explosion of wearable devices. These technologies also play a significant role in enterprise, startup, small business, government policies, and academic topics while creating new research area. As the wearable industry develops, the fact that existing solutions can be used in real life is also being re-examined.

Meanwhile, a zipper is a basic device which is commonly found to join two pieces of fabric or flexible material together, especially on garments such as jackets and dresses in the fashion industry. A zipper is seemingly a device that is simple to use, but those with physical challenges may struggle to put on garments and zip or unzip efficiently and independently. Many people require assistance, from another person, to zip or unzip their clothing and this requires more dependence on others to perform basic functions of their life, which reduces their independence.

According to a report from the Center for Disease Control and Prevention (CDC)'s data from the 2016 Behavioral Risk Factor Surveillance System (BRFSS), self-care (difficulty dressing or bathing) is the one of main issues examined into the first CDC report of the percentage of adults across six disability types, of disability measured, with mobility, cognition, hearing, vision, and independent living [1], [9]. Regarding the United States Census Bureau, disability data originates from the American Community Survey (ACS), the Survey of Income and Program Participation (SIPP), and the Current Population Survey (CPS), and all three surveys ask about six disability types: hearing difficulty, vision difficulty, cognitive difficulty, ambulatory difficulty, independent living difficulty, and self-care difficulty [2]. Independence to dress or undress is commonly considered as essential performance for everybody as it is a basic everyday task in the activities of daily living. It describes whether a person is capable of living independently, requiring assistance or dependent. However, zipping to dress is a difficult task for the people with physical disabilities, elderly, especially when the zipper is located at the back and difficult to reach, for example.

A few novel solutions exist. One good example was created by Adam Whiton at the Massachusetts Institute of Technology, who built the robotic zipper [3]. A second example is Cliff built by Baharom *et al.* [4], [5], [21]. While these are excellent zipper robot designs, these automatized zippers cannot be controlled during operation, efficiently or intelligently.

To further the work, zipper robots must be enhanced with intelligent control. Thus, the goal of this research aims to develop a multi-agent system to control the device, showing the progress of developing zipper design, aimed to assist the zipping and unzipping process for individuals who have problems or difficulties to complete the task. Also, the solution will reduce the negative stigma by working to reduce the size of the current existing solutions, making it portable. Portable robots can be easily placed in a pocket. Improving the aesthetics of the automatized zipper, because the size and appearance are important factors in design and usage of wearable devices, will also be a goal. Furthermore, the system will possess fast and efficient communication using lightweight protocols frequently used in the IoT industry. Finally, the purpose is to create insights to commercialize for people with having difficulties of self-care such as dressing by themselves, enlarging the social engagement of the fashion industry by technology innovation.

1.1 Problem Statement

The problem addressed in this study is that controlling a zipper robot to zip and unzip to dress is a difficult task for people with physical disabilities, elderly, especially when the zipper is located at the back or hard to reach areas by themselves. Current exiting solutions cannot be controlled intelligently once they are in motion. A user can control zipper movement, anywhere between the limits of the zipper device to maximize comfort and functionality. Also, because the size of existing automatic zippers is large, the size will be reduced to comfortably wear them as clothing.

1.2 Significance

To understand the significance of this general problem, the abstract issues of population growth, increasing the population of people with distinct physical challenges, and social and economic challenges.

1.2.1 World Population Growth

In an Aging World: 2015, a demographic reported by W. He, D. Goodkind and P. Kowal, they describe the proportion of world's older population to grow dramatically, given the fact that there were 7.3 billion people worldwide in 2015, an estimated 8.5%, or 617.1 million, are 65 or older, and by the year 2030, there will be at least 1 billion above 65 years old, globally [6].

This represents about to 12.0% of the total global population. Based on these projections, the percentage of people over 65 years old will continue to grow in the next 20 years. By the year 2050, there will be 1.6 billion people over 65 years old worldwide, roughly 16.7% of the total world-wide population of 9.4 billion. This is projected assuming an average annual growth rate of more than 27 million 2015 to 2050, of people over the age of 65 years.

Although external and internal factors coexist for causes of disability, the general incidence of disability is highly associated with age because physical and mental abilities deteriorate and progress as they grow older. Based on the report Americans With Disabilities: 2010 by Brault, at 70.5%, people in the group 80 years and older, were approximately 8 times as likely to have a disability as persons group which are less than 15 years old, at 8.4% [7]. Severe physical challenges requiring the need for other human assistance increased with age. Of individuals, in the 55 to 64 years age range and nearing retirement, constitute approximately 6.0% of those requiring assistance, with one or more Activities of Daily Living (ADL) or Instrumental Activities of Daily Living (IADL) [7]. The percentage of the population requiring assistance in the age group 80 and older, is approximately 5 times as large [7].

Developments and improvements in the medical healthy industry have a huge effect on populations to live longer. To ensure that people have the necessary assistance to maintain a useful, practical, productive and happy lifestyle, as they age, remains a topic of concern. Optimizing and creating assistive tools and technologies for the larger populations of older people can provide a significant incentive for the investment, conceptualization, development and commercialization of devices intended to help older, at risk, populations to cope with various physical challenges.

Emerging Artificial Intelligence (AI) and Internet of Things (IoT) are key technologies to overcome and enhance the services for daily living. Newer technologies can enable transformation to preventive and consumer-oriented care through the daily management of individuals using various information and communication technology. IoT and wearable devices are intended to be for everyday usage for a relatively long periods of time. Data collection and constant communication will be continuously conducted in the everyday progression in the life of a person with challenges. Movement to common platforms and standards rather than a dedicated devices or systems, will be the future direction [8].

1.2.2 Contribution to Social Development: Economic and Social Corporation

According to a report in CDC's Morbidity and Mortality Weekly Report, "1 in 4 of U.S. adults – 61 million Americans – have a disability that impacts major life activities" [9].

The population of people with physical challenges represent a significant part of the U.S. economy, both for contributions to economic conditions and markets, but also for their direct roles in development of government policies and programs. People with specific challenges offer a unique and special skillset to task environment, company culture and augment the overall labor market. In addition, they represent a significant market sector of consumer activity of greater than $200 billion in discretionary spending, innovation and technology-based entrepreneurship [7].

"Federal programs like social security and medicare and more than 60 smaller federal and state programs provide a wide array of income, health care, and other support services to individuals with disabilities across the United States. In 2008, the federal government spent an estimated $357 billion dollars on programs for working-age people with disabilities, representing 12 percent of total federal outlays" [7].

Considering that the study for intelligent garments is about physically handicapped and elderly for future-oriented, it is significant as a valuable study when it broadens the radius of their daily lives. Technical aids are included so that to achieve their own problem-solving skills, advances in technology and science have are necessary to help them. The development of an automated zipper control system can directly benefit a large population of people with physical challenges, giving each person more autonomy, comfort and control.

1.3 Purpose

The purpose of this study is to design and develop an intelligent zipper control system to manage the zipper devices used in clothing such as shirts or dresses for people with physical disabilities. Light networking service use for protocols is also required for control of behavior. Additionally, by designing a miniaturized zipper robot, it helps users to have a positive perception of wearable equipment. This will give a positive effect to their independent living and self care.

1.4 Research Questions

The following research questions are addressed in this study:

(1) Is the prospect of WT (Wearable Technology) research area future-oriented and valuable for business innovation?

(2) How can the WT systems benefit a general population of humans with physical challenges?

(3) Is an intelligently controlled zipper robot viable for automation of apparel for humans?

(4) How will the development and implementation of an intelligent zipper control system improve comfort, usability and autonomous function for people with physical disabilities?

1.5 Definitions

Differences of definitions create inconsistent application in many areas. The area of physical challenges, defined, is no different. A person may be defined as having a challenged under one standard, but not by another. For example, medical models view disability as an extension of a physiological condition requiring treatment or therapy, on the other hands, certain federal programs, "narrowly define disability as the impairment or limitation that leads to the need" [7].

1.5.1 Physical Challenges and Disabilities

The definition and standard to classify what is means to be disabled is critical, meeting those conditions as much as understandable. To meet those standard definitions, the criteria of report by defined CDC's Morbidity and Mortality Weekly Report —, divided into 6 types of disability measured [1]:

(1) Mobility (serious difficulty walking or climbing stairs)

(2) Cognition (serious difficulty concentrating, remembering, or making decisions)

(3) Hearing (serious difficulty hearing)

(4) Vision (serious difficulty seeing)

(5) Independent living (difficulty doing errands alone)

(6) Self-care (difficulty dressing or bathing)

Also, disability data comes from the American Community Survey (ACS), the Survey of Income and Program Participation (SIPP), and the Current Population Survey (CPS) were used [2].

- Disabilities defined by ACS [2]: The Census Bureau fielded a Content Test to assess new and modified content for the ACS questionnaire. The new disability questions were tested against the existing set of questions. The ACS currently covers six disability types: hearing, vision, cognitive, ambulatory, self-care, and independent living which can be used together to create an overall disability measure, or independently to identify populations with specific disability types. Having difficulty bathing or dressing are included in the self-care difficulty section.
- Disability in the 2014 SIPP [1], [2], [7]: Disability is collected using the six disability questions from the ACS as well as three additional question related to child disability, and three additional questions related to work disability. Disabilities, or commonly known as physical challenges, such as difficulty with putting on clothing or bathing, which are activities of daily life, for persons 5 or older.
- ADL (Activities of Daily Living) and IADL (Instrumental of Activities of Daily Living) [7], [12]: consistent with other national surveys like the Medicare Current Beneficiary Survey and the National Health Interview Survey. Having difficulty with one or more activities of daily living (ADLs) is motivating around the home, performing everyday life tasks, without the need of assistance from another person or persons, to execute ADL's. This includes common living tasks such as going to the bathroom, getting in and out of bed, dressing oneself, eating and getting into and out of furniture, such as a chair.

1.5.2 Zipper Mechanisms

A zipper is a device to bind two edges into one seam of an opening of fabric or other materials. It is normally divided into three different categories [22]: (1) Coil zipper, (2) Metallic zipper, and (3) Plastic molded zipper as shown in Figure 1.

Figure 1. Coil zipper, Metallic zipper, and Plastic molded zipper

On the leftmost, coil zippers, also known as nylon zippers, have several parts which work together. The slider connected to both right and left coils (teeth). Zippers, made from metal, act in the same way was coil zippers. All zipper types commonly use a tape support membrane to hold together both individual sides. Plastic molded zippers are similar to metallic zippers, except the teeth are molded plastic, and the plastic teeth can be dyed to the color of the garment.

The components of a zipper and standard terminology of the subassemblies of the zipper are shown and labeled in Figure 2, based on the American Society for Testing and Materials (ASTM) standard description [11].

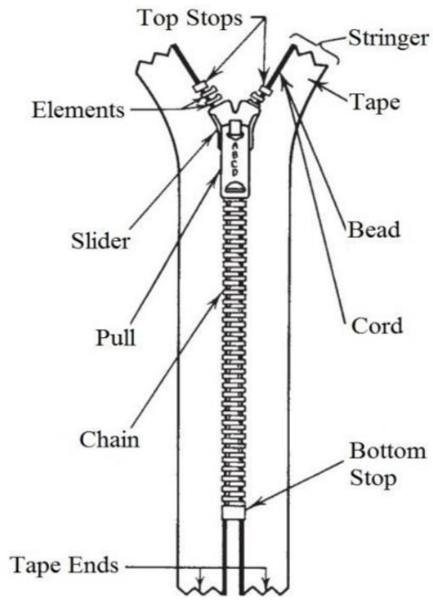

Figure 2. Components of a zipper [11]

1.5.3 Wearable Devices and Intelligent Systems

- A wearable device: It is a completely different product category than conventional mobile devices – is a smart electronic device that can be worn on the body can be a form factor. It can be any form and design. Wearable devices represent a number of different applications beyond just smart clothing. There are military, commercial and recreational uses for wearables, such as navigation and cover.
- An intelligent system: An actor with and ability to communicate with other actors, in a general sense, and the capoability to sense its environment for the goal to gather information. As stated by Russell and Norvig [30] the intelligent agent has the ability to interact with its environment in a number of different levels of perception, memory, application of logic, rationality and collection of a percept history.
- An intelligent agent: intelligent agent (IA) refers to, "an autonomous entity which acts, directing its activity towards achieving goals, upon an environment using observation through sensors and consequent actuators" [10].
- A multi-agent system: It is computerized, non-human system composed of multiple interacting agents, interacting with their environment, or environments. Typically they exhibit qualities of autonomy, goal orientaion and communicative capabilities.

1.6 Assumptions

The assumptions for this study include:

- The intelligent wearable technology is significant development in IT fashion.
- All evaluations data will come from real experimentation of the zipper robot and the system.

1.7 Delimitations

The delimitions for this study are:

- The research conducted will only be concerned with clothing such as dresses or shirts only.
- The focus is on populations with the physical disability defined from the CDC, or elderly (65-79 age).
- Only the coil zipper design is used, not metallic zippers or plastic molded zippers.

1.8 Limitations

The limitations of this study are the follows:

- Given the current situation with pandemic COVID-19, the testing will occur with local personnel due to the limitations for accessing of disabled populations. Potentially, it might be normal population for the first step if the disabled population cannot be accessed due to health precautions.

1.9 Summary

In summary, the intelligent system to control the zipper robot is made as the assistive device for people with physical disabilities or elderly so that they can perform their activities of daily living by themselves. The rest of this thesis outlines the experiment design and implementation to answer the above questions.

Chapter 2 of this thesis addresses a review of the literature, highlighting a background on the evolution of zippers based on the patent, and covering the physical characteristics of zipper robot in current situations, CRS to evaluate the user experience and intelligent agents as a tool to control the system. The novelty of this work is established by comparison to other recent works in the area.

Chapter 3 explains the methodology design, the experiment setup and execution to validate the previously mentioned research questions, as well as the physical, mechanical and electronic design choices for the intelligent zipper robot.

Chapter 4 presents the results for the experimental executions for the intelligent zipper robot and an interpretation of the results. The results were achieved through a progression of improved designs to arrive at the best prototype.

Chapter 5 discusses the outcomes, limitations, discoveries and potential future works.

CHAPTER 2. REVIEW OF LITERATURE

This chapter exhibits a review of relevant literature for the background and evolution of the zipper, from the basic functionality, through the augmentation with technologies, including the development and patents of automatized zippers. The chapter initiates with an overview of the intelligent system to control the zipper robot. Concepts used for a review of the literature will relate to quality assurance in the wearable technology and the technology responsibility.

2.1. Automated Zipper Technology

According to Baharom *et al.*, who created Cliff, an automatized zipper [4], [5], [21], the research involves the zip and unzip processes for those with special needs who have physical problems, or difficulties or ladies with the concern of zipping their dress to complete the task. The author mentions that it is necessary to recognize the evolution of the zipper's slider, which shows how it is developed with people's needs, as time goes by.

Firstly, Eddie Howe invented the first zipper about 167 years ago [13]. Since then, there has been continuously further development of the slider, however, the slider of a zipper is regarded as the central machine element of the zipper's performance. For the past 167 years, the design of the zipper's slider has developed from a basic structure to the removable, rollable, adjustable and currently, the inventors are moving towards enhancing an automatized robotic zipper with advances in the technology industry. Figure 3 shows the design evolution of the zipper's slider based on the patent application.

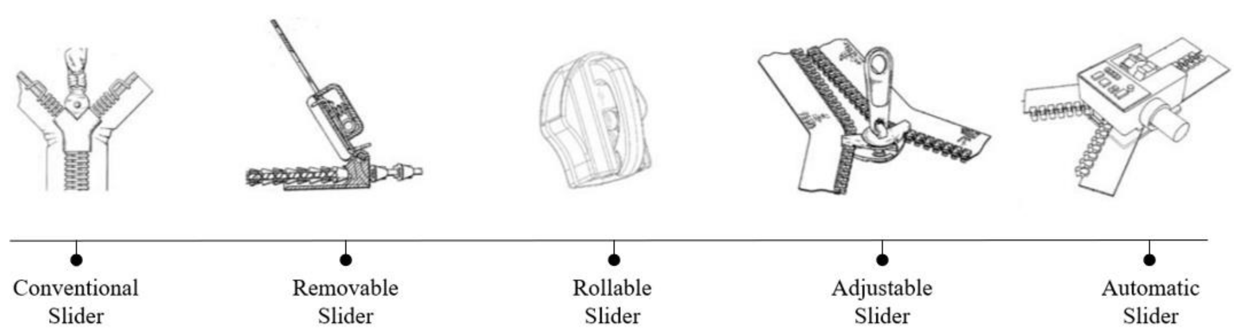

Figure 3. Zipper's slider development [15], [16], [18], [20], [3]

Gideon Sundback [15], an early developer of the modern zipper, obtained a U.S. patent built upon the previous work of other engineers such as Elias Howe, and Whitcomb L. Judson [14]. What is the perceived as the modern zipper, which is similar to the current design, was born. Sundback's invention, "had two facing rows of teeth that pulled into a single piece by the slider and increased the opening for the teeth guided by the slider" [15]. Initially, the zipper achieved pervasive adoption on pants and for various military garments during the period surrounding World War II, due to the ease of use, durability and strength. Several decades later, zippers became popularized in the fashion industry in the design of wearable garments, and many additional textile items.

A removable slider, who's function is to allow removal at any point along the axis of the zipper without requiring further movement along the axis. The limits the any negative actions for the performance of the removable slider, which was invented by Mucci in 1938 [16], and then Nissen patented a reversible slider, where the main goal is to allow a better reversible slider with the addition of slide fasteners [17]. Both inventions resulted in the beginning of building a flexible or practical slider. In 2013, Wang patented the roller-loaded zipper slide which has a top slide body block consisting of a vertical slot bisecting the top and bottom sides connecting both side of the coupling [18]. A rolling contact method was employed to replace the more tradition design that relied on surface tension and friction [18]. A wheeled slider model, consisting of two wheels sliding under the side of each element, was patented by the Under Armour company, in the same year [28]. One year later, the Genmore Zipper Corporation patented a different roller-loaded slider design [19], comprised of at least one roller bracket, where each of the roller brackets carry a front roller.

An adjustable slider was invented by Alberto, from Argentina [20]. The advantage and innovation were a slider fitting into a slide fastener which allows for an easily adjustable variation for a variety of sizes and types of slide fasteners. This design can be opened and closed horizontally. It can also be locked at an appropriate size, relative to the size of the slide fastener.

In 2017, recently, a robotic zipper system patented by Adam Whiton [3] is for joining and separating zipper halves of a zipper tape, shown in Figure 4. The left side shows a perspective view of the robotic zipper system by Whiton, whereas the right side shows an exploded design view providing a complete view of the system components that cannot be seen from the perspective view.

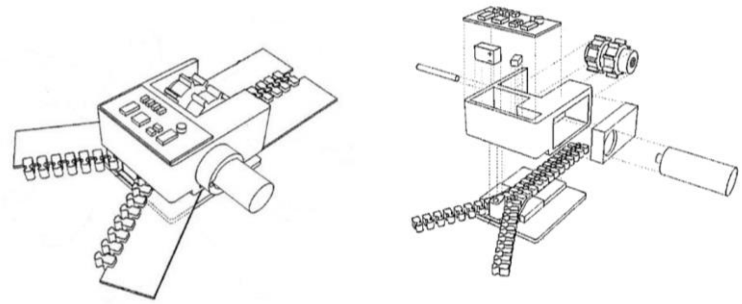

Figure 4. The robotic zipper design by Whiton [3]

Whiton’s design begins with a chassis which holds an actuator motor which drives a zipper slide along the axis of the zipper tape to join the two sides of the zipper or split them depending if the zipper is opening or closing. A sensor is built in to determine the zipper slide position along the long axis of the zipper. The controller provides the positive electrical signal to initiate the actuator motor to move the robot along the zipper either with forward or reverse motion. The actuator partners an electric motor with a gear reduction drive system that provides stepped up torque and engages the zipper teeth. The zipper slide is integral in the chassis, residing in a channel, with a central post. The design of the zipper’s slider and the desire for vertical climbing robot developments initiates efforts for a novel zipper robot instance which could be potentially wearable and would exist and traverse on an actively worn garment. However, Whiton’s robotic zipper did not utilize the slider of the zipper to zip or unzip. This factor makes it a non-generic system where all garments would need a specialized and custom built instance of a zipper robot. The limitation of a specialized instance creates issues for the functionality of Whiton’s invention.

Thus, Cliff [4], [5], [21] enhances the original zipper’s structure and offers a more general purpose and universal type of robotic zipper apparatus as shown in Figure 5.

Figure 5. A model wearing Cliff on her jacket and 3D view of Cliff prototype [21]

The prototype of Cliff consists of a top chassis, a bottom chassis and two rotating wheels, combined two different materials on the rotating wheels which were created through 3D printing. A 6V DC motor with a gearbox producing a speed of 145 rpm and 68mNm torque was used to drive Cliff. The prototype is powered by the two LiPo batteries, which are 3.7V, 180mAh. Two permanent magnets with a pull strength of 1.7 kg are used to provide sufficient force to hold the top and bottom chassis elements together. Figure 6 visualizes the traction mechanism of Cliff which has two gears on opposite sides of the zipper tape (F_N = *normal force*, F_f = *friction force*, *V* = *velocity*). The gears on each side allow for the distribution of force and good motion for the actuator to move across the zipper tape.

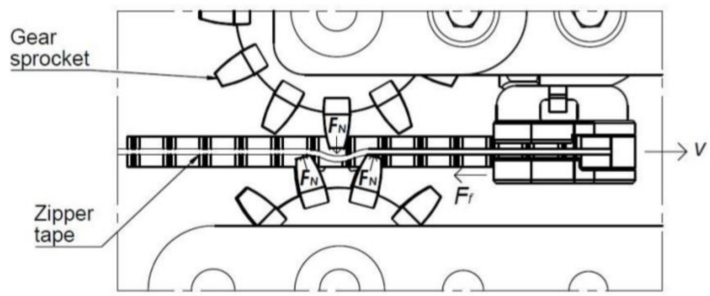

Figure 6. Cliff traction mechanism [21]

The investigators used Cliff in a real experiment with a population of older people with physical challenges, brought on by advanced age. The main issue of the feedback received was that the further improvement of design of the meticulous interaction between the zipper and the robot. Therefore, good communication through the product is essential to ensure that the user and the society can accept the kind of assistive product like Cliff. Another way to reduce the stigma is through the personalization of a wearable device. Just as choice in personalization of a person's garments reflect their personality and style, the choice of a wearable robot is like that of any accessory. Personalization will enable the user to make their choice in a product which can match and fit with their identity, style and personality.

2.2. Bluetooth Remote Controller Using Zipper Interface

Nehls and Allen invented a wireless remote control device for transmitting control commands to a Bluetooth™ enabled an electronic device, such as cellular telephone to manipulate a garment oriented zipper in 2007 [22]. The electronic device contains the controller and will transmit control signals for positioning of the motion of the zipper's slider to a utilization device, based on sensor input. Figure 7 and Figure 8 exhibit how the remote controller works.

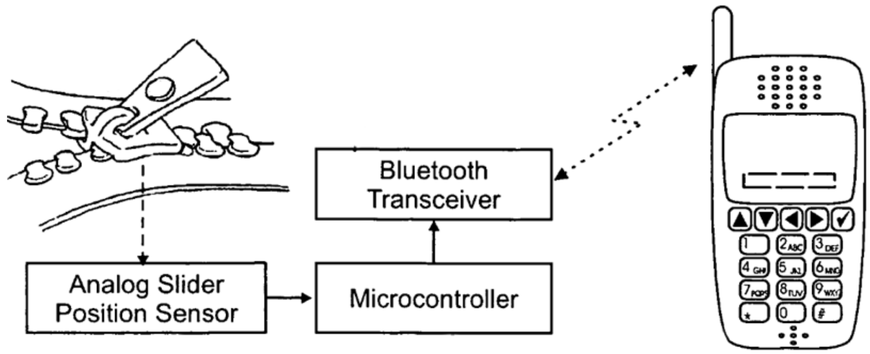

Figure 7. The operation of the Bluetooth enable control [22]

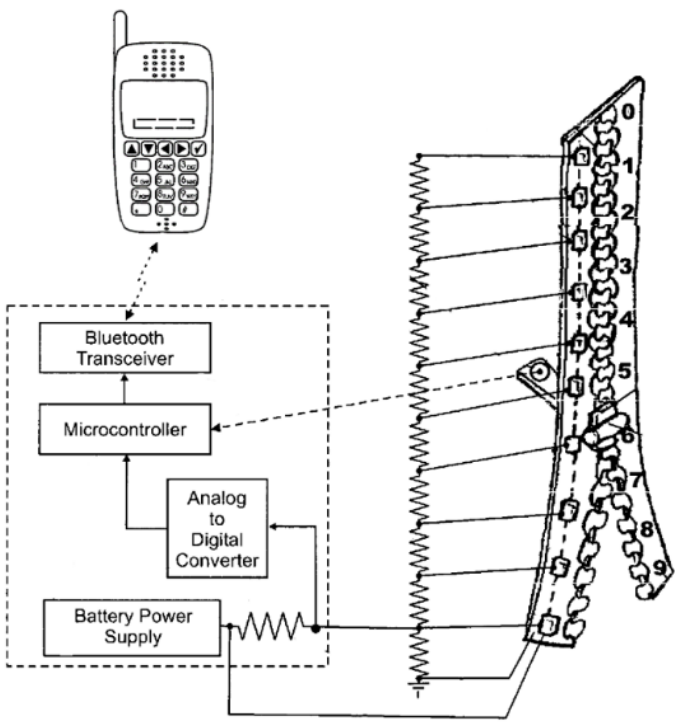

Figure 8. Schematic diagram illustrating the structure and function of an embodiment of the invention used with a zipper [22]

The zipper fastener is similar to previously designed zippers which have includes opposite tapes with teeth attached to flexible supports and a traversable slider which travels along the axis to lock or unlock the teeth. The system can generate a position signal indicative of the slider’s current position within the two tape supports. A Bluetooth™ transmitter coupled to the sensor sends control commands relative to the current slider position, along the zipper axis, and the push button status, which is attached to the slider.

The zipper parameters are the percentage to which the zipper is opened or closed, as well as the velocity and acceleration during the actuation of the zipper's slider activity as it moved in either direction. The button switch augments the functionality to provide a setting for the zipper to arrive in a certain position along the axis by setting the sensor output value to initiate or stop at a desired position along the axis. The zipper controller may perform functions often utilized for other devices, for example the scroll wheel on a mouse, when the condition exists that there is basic interaction between the button and the actuation and movement of the zipper.

2.3. The Comfort Assessment of Wearable Computers

Knight *et al.*, completed a study compiling a method to measure the comfort of wearable computers for humans [23]. The Comfort Rating Scales, also known as CRS, measure wearable comfort across 6 dimensions: (1) Emotion, (2) Attachment, (3) Harm, (4) Perceived change, (5) Movement and (6) Anxiety.

Initially, in order to establish the different comfort dimensions, the authors first created a list of 92 terms that explored what effects that wearing a device has the human that wears the device. The dimensions for the wearer are measured on how the human feels physically and mentally about the wearable device. These terms were categorized into affinity groups, finally resulting in the set of groups shown in the term-by-term association matrix Figure 9. It was developed by counting the number of instances each term was placed in the same group as another was scored. The matrix was then subjected to Multi-Dimensional Scaling (MDS) statistical analysis. This is accomplished by assigning observations to specific locations in a conceptual space such that the distances between points in the space match given similarities. The closer each element appears to others in 3 dimensional spaces, the more similar those two terms are related. By using MDS on the comfort term matrix, a spatial representation of how the synonyms related to each other was enhanced.

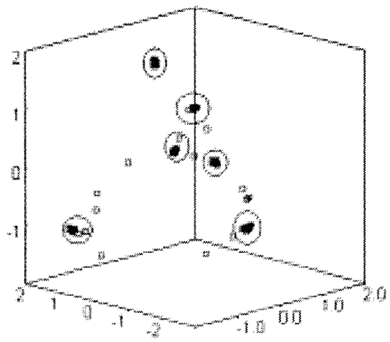

Figure 9. Six clusters representing each comfort term location in respect to each other [23]

From this analysis, terms were gathered into six definable cluster sets. Each cluster was inspected to establish what aspect of comfort the terms generally described that disassociated them from the other clusters shown in table 1.

Table 1: Comfort descriptors [23]

Cluster	Description
1	Emotions, concerns about appearance and relaxation
2	Physical feel of the device on the body, attachment
3	Physical effect, damage to the body
4	Feeling physically different, upset
5	The device physically affects movement
6	Worry about the device, safety, and reliability

Cluster 1 is associated with emotional concerns. It concludes such as a concern as how appearance or the wearer looks wearing the device and feelings of relaxation.

Cluster 2 relates to the non-harmful sensations of the device on the body, for example, the feel the device either directly as pressing on the body or indirectly as it pulls on clothing or moves in relation to the body.

Cluster 3 relates directly to harm brought about by the device conveyed through sensations of pain. The context is the same in that both are related in that they are both concerned with direct physical feelings of the device on the body.

Cluster 4 also relates to non-harmful physical affects of the device of the body, however, cluster 4 mostly suggests that wearing the device leads the wearer to feel different themselves with perceptions of being awkward and uncoordinated forcing the wearer to make conscious compensations or modifications to movements or actions.

Cluster 5 differs though in that the descriptors suggest that the device itself gets directly in the way of carrying out normal movement patterns, rather than just making the wearer feel that they are moving differently.

Cluster 6, lastly, is similar to cluster 1 in that it is concerned with a cognitive dimension of comfort. These 6 clusters of CRS design are based on many fields for testing of the NASA-TLX. The NASA-TLX is a proven tool which measures the subject's mental workload capacity, at a given time, as shown in Table 2 [23].

Table 2: General description of each general comfort dimension [23]

Dimension	Endpoint	Description
Emotion	Low	I am not worried about how I look when I wear this device.
	High	I feel tense or on edge because I am wearing the device.
Attachment	Low	I cannot feel the device on my body. I cannot feel the device moving.
	High	I can feel the device on my body. I can feel the device moving.
Harm	Low	The device is not causing me some harm. The device is not painful to wear.
	High	The device is causing me some harm. The device is painful to wear.
Perceived Change	Low	Wearing the device did not makes me feel physically different. I do not feel strange wearing the device.
	High	Wearing the device makes me feel physically different. I feel strange wearing the device.
Movement	Low	The device did not affects the way I move. The device is not inhibits or restricts my movement.
	High	The device affects the way I move. The device inhibits or restricts my movement.
Anxiety	Low	I do feel secure wearing the device.
	High	I do not feel secure wearing the device.

2.4. Methodology to Evaluate and Validate Wearable Devices

A user study must be defined with specific criteria in which to evaluate input and validate success or failure. The study measures the wearability assessment (WA) [24]-[26] on general comfort towards the wearable devices, perceived usefulness and perceived ease of use (PEOU) [27], and the credibility and expectancy (CE) [29]. The following methods are employed to study the comfort, biomechanical and physiological effects of the system:

- *Wearability Assessment (WA)*
- *Perceived Usefulness (PU) and Perceived Ease of Use (PEOU)*
- *Credibility and Expectancy (CE)*

Wearability assessment (WA) is defined when wearing something, the level of comfort can be affected by some factors, such as the item's weight, how it affects movement, and direct or indirect pain physically [24]-[26]. In general, developing a method to validate a wearable garment's functional and quality requires input data of the physiological, biomechanical and comfort effects, when a person wears the garment [24]. A taxonomy of wearable assessment is shown in Figure 10, developed for this research, but based upon the previous work [24].

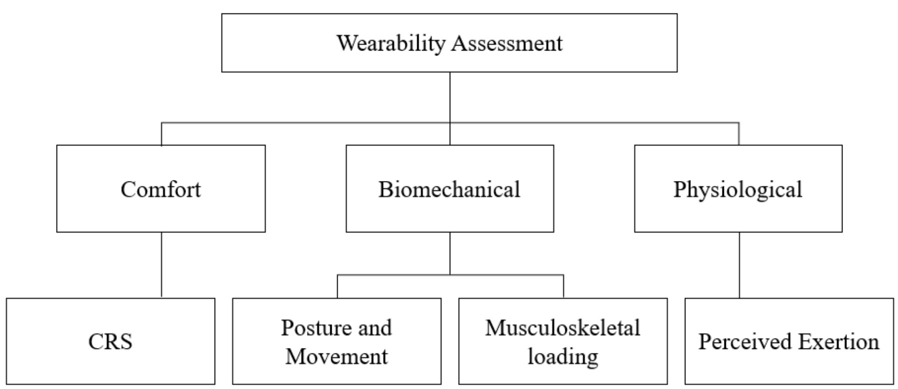

Figure 10. Wearability assessment scheme

Perceived usefulness (PU) refers to the degree where a person believes that using a specific system would affect his or her job performance [27]. It relates to useful which means as capable of being used advantageously. [27]. Also, *Perceived Ease of Use (PEOU)* is the level to which a person thinks that using a particular system would be free of effort [27]. It means freedom from difficulty or great effort. Even if the users feel the wearable device is useful for their daily lives, if they think that the automatized zipper is too hard to be used at the same time, it would get lower grades. The performance benefits of usage are outweighed by the effort to use the device itself.

Lastly, *Credibility and expectancy (CE)* is defined as how believable, convincing, and logical the system is. It contains both cognitive and affective components [29].

2.5. Intelligent Agents

According to Russell and Norvig, [30], an agent is a key development in artificial intelligence has been the autonomous agent, defined as an actor which perceives its environment via sensors and acts rationally upon that environment with its effectors. Figure 11 visualizes diagram of agent.

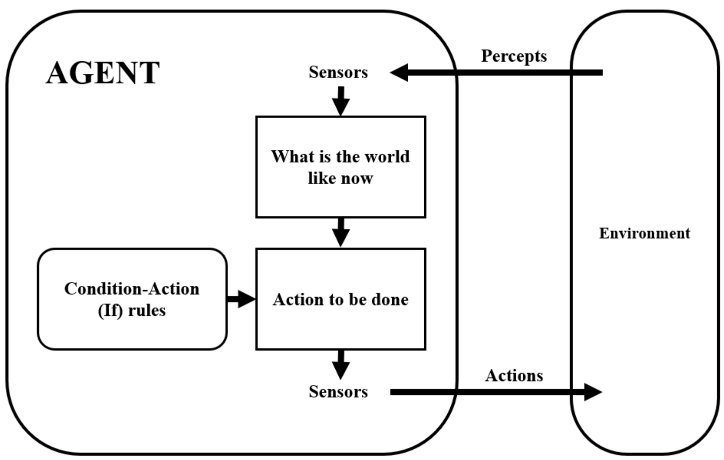

Figure 11. Diagram of agent [30]

The key properties of Intelligent Agent Autonomy are following [30]:

- Responsibility: Agent accepts requests from other agents or the environment but decides individually about its actions. That is, agent is fully accountable for its given state.
- Reactivity: Agent is capable of near-real-time decision with respect to changes in the environment or events in its social neighborhood
- Intentionality: Agent maintain long term intention. the agent meets the designer's objectives. It knows its purpose and executes even if not requested.

- Rationality: Agent is capable of intelligent rational decision making. Agent can analyze future course of actions and choose an action which maximizes his utility. The basic notion that an agent can choose a course of action that is consistent with doing what is in its own best interest.
- Social capability: An agent has the innate ability to communicated and collaborate with other agents and also to navigate with its environment.

2.6. Multi Agents

A multi agent system is regarded, "as a collection of multiple autonomous agents, each acting towards its objectives while all interacting in a shared environment, being able to communicate and possibly coordinate their actions. A multi-agent system is a decentralized multi-actor software system, often geographically distributed whose behavior is defined and implemented by means of complex, peer-to-peer interaction among autonomous, rational and deliberative entities. autonomous agent is a special kind of a intelligent software program that is capable of highly autonomous rational action, aimed at achieving the private objective of the agent – can exists on its own but often is a component of a multi-agent system – agent is autonomous, reactive, proactive and social agent technology is software technology supporting the development of the autonomous agents and multi-agent systems agent-based computing is a special research domain, sub-field of computer science and artificial intelligence that studies the concepts of autonomous agents" [30].

2.7. Multi Agents System and Robots

The field of autonomous agents has grown fast over the last two decades to expand into other areas. Agents are used in many ways to emulate human type behavior or act as a non-human actor. One area which has been a common integration point is the connection between agents and robotics, especially in the areas of control, team and organization. Integrating human and non-human actors is an area where agents have been actively employed [37]. The integration of humans, robots and sensors, utilizing multi agent systems has become an effective tool for complex systems integrations, as with UAV detection [36], [38]. Further defining the capabilities of sensors and robots using agent teams has also been accomplished [39]. In this work, a multi agent system will be used as a composite framework to bind together a team for managing the various sensors, compute points and a robot, all integrated to fit on the body of a human, using a similar control methodology.

2.8. MQTT Protocol

People sometimes are required to have a conversation using the same language for development of systems use standards which enables proceeding with a common process in all parts of the world; With desire for M2M level communication, it is not only humans but also computers, machines, sensors, robots and intelligent agents. A protocol is a communication or commitment that helps transmit information via any kind of variation of physical quantity under a common and well publicized system of rules and conventions. A standard is used to exchange a various type of data through various devices such as laptops, mobile phones, and IoT.

As the development of IoT technology accelerates, the fielding and usage of IoT platforms has also diversified, enabling the amount of data exchanged through global networks to significantly increase every year. Naturally, new requirements have arisen in each field, and as a result, the environment in which IoT needs to adapt has diversified. In order to simplify and communicate faster, IoT uses protocols like CoAP (Constrained Application Protocol), XMPP (Extensible Messaging and Presence Protocol), AMQP (Advanced Message Queuing Protocol), MQTT (Message queuing telemetry transport), and so on [40]. Among them, MQTT has been proven to be efficient in terms of battery consumption as a lightweight message protocol. It is featherweight, created for networks which are restricted especially for low bandwidth and IoT devices where there are environments that exhibit high latency. MQTT is a lightweight solution, a data-agnostic protocol which has the capability to transmit binary, text, XML and several other data forms utilizing a publish and subscribe technique, rather than pure client and server model for the system between a controller and a robot [42]. Another important aspect of the protocol is that MQTT is rather easy and flexible to develop clients to access the broker. The ease of use factors is a key component for MQTT development and enables it to be a good match for constrained devices that have minimal or limited resources.

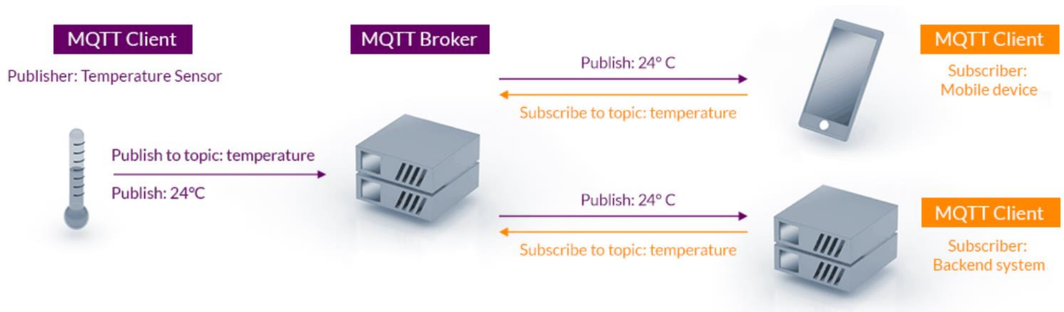

Figure 12. An example of the publish and subscribe IoT system model with MQTT [41]

"The MQTT protocol is based on the principle of publishing messages and subscribing to topics" [43]. In the publish-subscribe pattern, each client does not engage in the existence of the other clients. A client can subscribe to a specific topic, on the broker, which they are interested in, such as the temperature or environmental sensor reading. The publish and subscribe method has a broker, which is the server that takes in all requests and publishes responses. A client simply just establishes a connection with a broker and specifies its requested topics. The broker takes the incoming messages and manages the correct distribution of messages back to the clients to provide the type of received messages, content and data. Hence, both publishers and subscribers establish a connection with the broker, not a specific server. The broker is an abstraction of the server model that takes the user away from specific implementation details. Use of the MQTT protocol and the Mosquitto software enables a persistent session from a number of clients to a broker, with each single connection between a client and broker, being a single persistent connection, allowing sessions to persist during a network outage. For example, if a sensor and a robot are both in a task environment, then can continue to work, independent of specific networks. When the network connection if recreated the MQTT link is reactivated and connection is reestablished between client and broker. "This is one of the key features that makes the MQTT protocol more efficient than HTTP for use over unreliable networks" [44].

Eclipse Mosquitto is an open source (EPL/EDL licensed) message broker that implements the MQTT protocol versions 5.0, 3.1.1 and 3.1. A Mosquitto broker is lightweight and is suitable for use on all hardware devices from low power single board computers to full servers [45].

MQTT is a standardized protocol which needs software-based client implementations. The Eclipse Paho project is part of the Eclipse Foundation's M2M mission to provide high quality implementations of M2M libraries and tools. Open-source client libraries for MQTT have been developed and maintained; there are numerous languages support for MQTT with the Paho client software such as C, C++, Python, Java and JavaScript, at various stages of development [46].

MQTT has software support for common platforms, such as Raspberry PI and Arduino. With MQTT standard libraries, Arduino interacts with MQTT servers to publish and subscribe data [47]. For example, the PubSubClient for the Arduino platform was released in the year 2009 [48]. The Arduino is a constrained environment and it is important to minimize the software footprint. The Arduino platform contains an Application Programming Interface (API) for network client libraries to implement. Between the Arduino API and the MQTT libraries the integration is rather direct.

CHAPTER 3. THE PROPOSED METHODOLOGY

This chapter is broken into three sections, each with several sub-sections. The first section outlines the physical characteristics of the zipper robot realization, including the placement of zipper's mechanism, design choices within the possibilities. The second section describes the design methodology of the software to control the device. Lastly, the third section merges all phases to maximize achievement to develop the intelligent control algorithms and functionality, to extend previously developed zipper robots, where this research employs a multi agent system approach to increase user convenience and usability. In summary, after the description of the experiments are discussed in section 3.1, which provides a general overview, the phenomena tested and observed at each stage are described. Then the complete system results in a prototype, through a phased approach shown in Figure 13, which shows all the steps for this research effort.

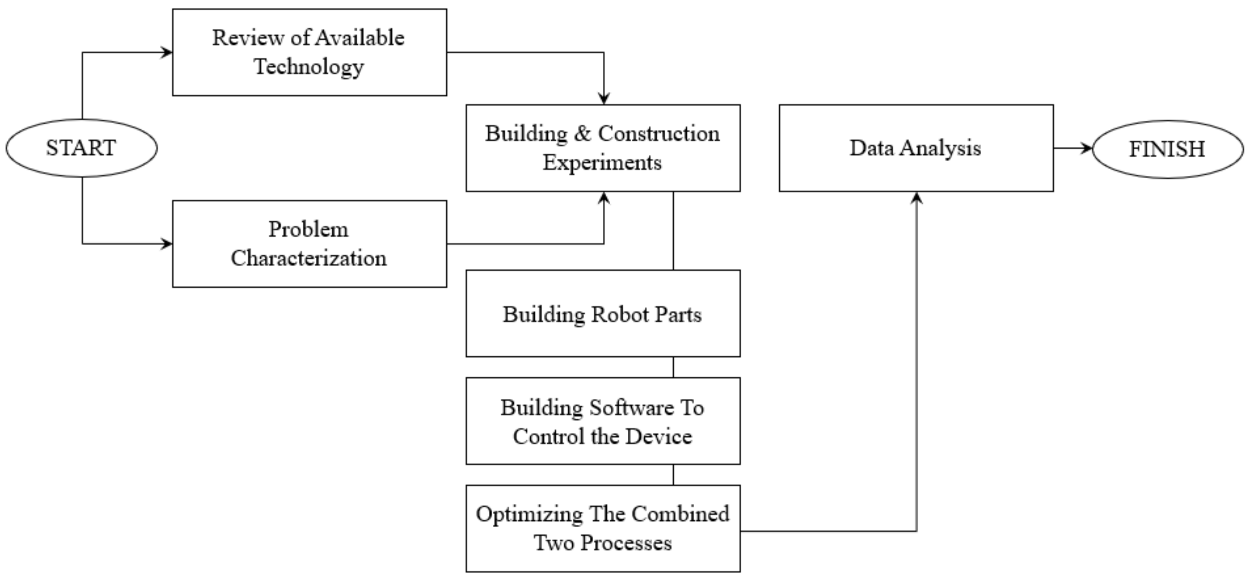

Figure 13. Flow chart of the proposed methodology

The steps will be to:

(1) Build the autonomous zipper robot physical elements

(2) Creating a system application to control the device

(3) Optimizing the cyber-physical processes

3.1. Experimental Setup

This research is a multi-step study combining hardware and software development. The equipment shown to introduce the specific utilized hardware elements. Mainly, the Raspberry Pi, wireless router, Arduino with Arduino ethernet shield, ESP8266 Wi-fi MCU, motor relays, DHT-22 temperature/humidity sensor, DC motors with gearbox assemblies, and different versions of altered types of zippers are used for this work.

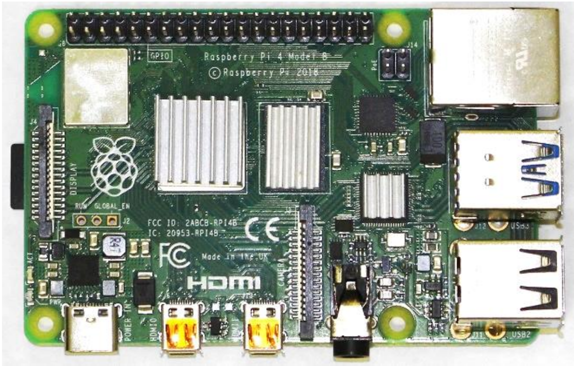

Figure 14. Top view of a Raspberry Pi 4 Model B

The Raspberry Pi 4 Model B, shown in Figure 14, uses a 32 Gigabyte SD card installed with the Raspbian Stretch as the operating system. This experiment seeks to validate the Raspberry Pi as a platform for the MQTT Broker with which the intelligent agents interact with to publish and subscribe messages in service of the zipper robot. Due to the Arduino limited compute power as a micro-controller, the Raspberry Pi provides several key functions to the project. Firstly, the Raspberry Pi is a main control hub of running on ESP8266 Wi-Fi MCU module. Secondly, the Raspberry Pi serves as a broker to connect to other networks through Wi-fi microchip and user's device. Lastly, the Raspberry Pi acts as a local storage for the data packages sent and received between sockets.

To provide stable network connections, the Netgear Nighthawk to LTE mobile router [33] is used. The Arduino with Arduino ethernet shield or ESP8266 with a motor relay is attached to the zipper robot to control the motor control and enable the zipping and unzipping processes. Since the Arduino does not automatically contain libraries required to this research, the DNSServer, WiFiManager, PubSubClient, ESP8266Wifi, ESP8266Webserver, and DHT libraries are installed on the Raspberry Pi to provide the correct software platform. The temperature sensor uses the DHT library and connects directly to the Arduino or ESP8266 module, attached to the human armpit or side, and tested ambient values outside of the garment for visibility.

Meanwhile, the study begins with the control of the zipper, so the design of the zipper is artificially manipulated before using the zipper which is a common sold zipper pervasive throughout the market. The results of the detailed experiment are analyzed with Chapter 4 experiments.

3.1.1 Robot Mechanical Parts

The first experimental stage was designed to gather baseline measurements, as well as raw data on the basic performance of the zipper robot initial prototype and how it interacts with the physical design of the mechanical zipper.

Figure 15. View of different types of zipper sliders

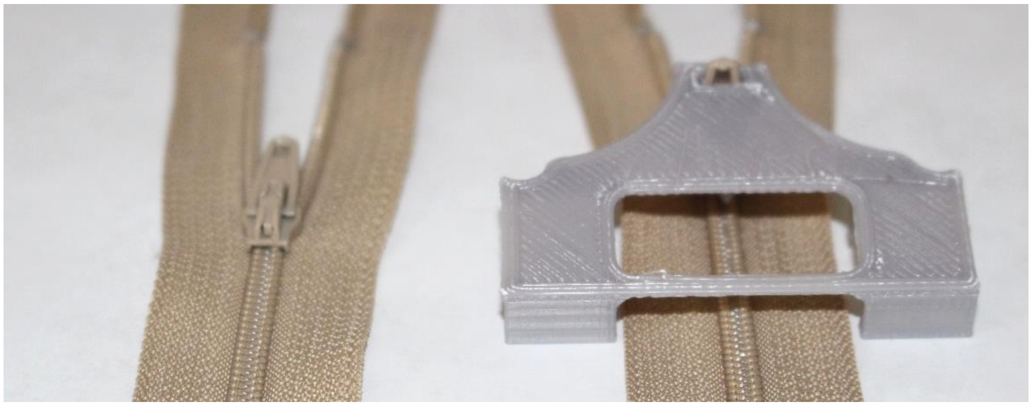

Figure 16. Prototype robot body

The slider of a zipper is the main part of the zipper to zip and unzip in zipper movement. The slide is the main spindle that controls the pieces of metal that engage when applying force. In other words, being able to move a slide is like being easy to zip and unzip. In this study, experiments were conducted that modified slides to allow the robot to open and close the zipper itself. Due the fact that the results such as design, power size of current supply, and wheel size can vary depending on the force of pushing the slide, the slide was set as a central variable and the experiment was conducted. Figure 15 visualizes different types of zippers; a zipper without a slider, a zipper with pin instead of a slider, and a zipper with slider and puller as a normal design. The slider-free zipper is the easiest design to control, and it can be used with the least amount of force to control the teeth, such as the function of a regular zipper. Even if it has the advantage of being the easiest to control, there is no way to control it without puller. The second zipper with pin instead of a slider is simple, and easy to be controlled. A small pin was attached to the center where the slider was removed. Yet it is same issue as the slider-free zipper, there is an inconvenience of removing the slider to use the zipper robot, which causes negative stigma of using wearable devices. Thus, it proceeded in the direction of designing the handle differently, while maintaining the shape of the slider. Figure 16 shows the first prototype for the zipper robot body.

Next, the first design is used to conduct a baseline experiment 3 voltages, (3 volts, 6 volts and 12 volts) to determine the correct level of power required to motivate the zipper, shown in Figure 17.

Figure 17. Motor size for 3v and 12v

There will also be a test of the best revolutions per minute (RPM) gear ratios to determine the best velocity and power mix for actuating the robot across the long axis of the zipper. The basic proposed motor assembly design is shown in Figure 18, where there are two motors and a 3D printed axle between them. The motors are mounted in a 3D printed frame. The motors are affixed opposite from each other, but form a single axle with equal power from each side.

Figure 18. Motor cradle placement

In Figure 19, the motor axle assembly is shown on a zipper. The two wheels of the axle will contact the zipper tape on either side of the zipper teeth. This will be the contact point of the robot to move the zipper through the process of zipping or unzipping.

Figure 19. Top view of zipper robot front and back side

The wheel diameter as part of the 3D printed axle, which fits between the motors in the motor cradle, is critical to making good contact with the zipper tape. Achieving solid contact which creates enough friction or surface tension is paramount for success of the robot. Figure 20 shows prototypes for wheels. Different wheel size and types are designed to fit the zipper robot’s movement.

Figure 20. Different wheel size and types

To increase the coefficient of friction on the wheels, several potential contact materials is utilized, such as rubber bands, as shown in Figure 21. These will be bonded to the circumference surfaces of the contact wheels. The goal is to increase the contact for stable propagation across the zipper tape.

Figure 21. Materials for wheel contact

To provide rigidity and structure for the motor cradle, a top will be designed for the zipper robot. This will be a 3D printed part, similar to the items shown in Figure 22. The top will also secure the slide to the zipper robot, which is critical to proper function. All 3D printed models will be created on the Lulzbot TAZ 63D [32] printer shown in Figure 22 and Figure 23.

Figure 22. Top assemblies for zipper robot

Figure 23. LulzBot TAZ 63D printing machine

The automated, intelligent zipper robot is fabricated by using 3D printed parts and common robot elements and electronics. Some of the same functions, as zipper robots developed by previous studies are in this system, but there are a number of novel elements also. The system must be modified so that agents can control the perception and actions as zippers, given that they do not have zipper feedback control loops, which is their biggest limitation. Therefore, in the research, the products that will be made as a zipper-shaped designs with the same functions as a normal mechanical zipper, but with the novel contribution of the intelligent control and several mechanical novelties. There are design choices of whether to create a two part or single part body, as shown in Figure 24, and motor cradle. Each has advantages and disadvantages. It seems a simple task, but the design is actually quite complex, for a successful robot.

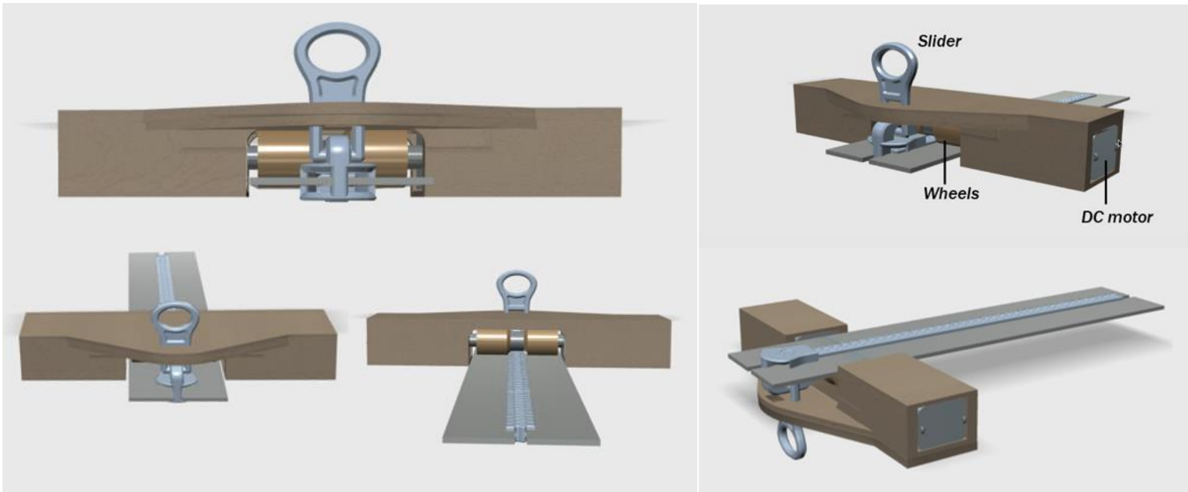

Figure 24. 3D view zipper robot simulation

Scale is also important. In this prototype, the scale will be larger than future designs. For example, Figure 25 shows a direct comparison of common products, coins, to the scale of the motors. Since the size of wearable device is crucial, as much as small the size motors will be used. For prototypes, 3V 50R/min High Torque Speed Geared Gear Box motors will be used. While this is not the complete end result, the scale of the device built in this study will be functional for a human. Future designs will be reduced in size.

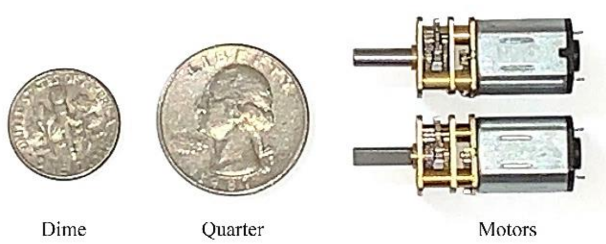

Figure 25. The size of motors (3v and 6v) compared to coins

3.1.2 Control Algorithm and Client

As mentioned, this paper will focus on an implementation where the zipper robot is integrated using the MQTT protocol with the 'Paho-mqtt' library, using the Mosquitto broker for the system where the broker runs on a Raspberry Pi board and has several possible. The proof-of-concept clients will be deployed in several platforms just to test initial prototypes and to select the best options. Also, this will allow a reference platform for the zipper robot.

The front-end application to control the robot will be built in Java, where the intelligent controller system will reside as a cooperative multi-agent system, taking into account user input and the user profile. The interface is then made in Java GUI, and undergoes a verification process to reduce errors. The test process will only be applied to Java GUI running on a laptop. A new platform, in the future, will be built for iPhones OS.

The basic process of the system: Once the Raspberry Pi and Zipper Robot boot up, the Raspberry Pi will attempt to connect, through the broker, to the Zipper Robot with IP address and port number already embedded inside the Raspberry Pi. Once the connection set up, they both are expected to run and stay active continuously. Then the user needs to manually input the IP address and port number of Raspberry Pi on the client and interact with the controls for activity. Assumed that the process is properly followed, the client will start to connect to Raspberry Pi. Once the connection is established, the user could communicate from the clients to the broker on the Raspberry Pi and to the robot, which will pass commands to the robot.

3.2. Sensor Specification

The DHT sensors consist of two main elements, a capacitive humidity sensor and a thermistor. Internally there is a basic chip inside which converts analog to digital and publishes digital temperature and humidity value. Table 3 shows the difference and similarity of DHT-11 and DHT-22, as shown in Figure 26, compared to both specs [49] [52].

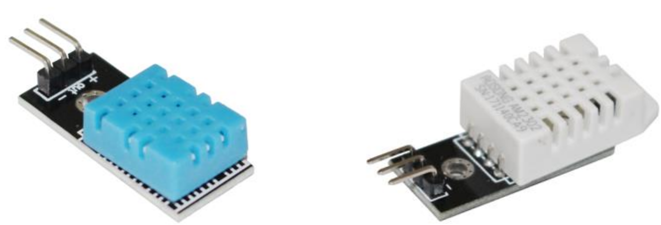

Figure 26. DHT-11 and DHT-22 Temperature/Humidity Sensors, respectively

Table 3: DHT-11 and DHT-22

	DHT-11	**DHT-22**
Voltage	3-5 V power and I/O	
Max Current	2.5 mA max current use during conversion	
Temperature Range	-20 to 60℃	-40 to 80℃
Temperature Accuracy	±2%	±0.5%
Humidity Range	5 to 95% RH	0 to 100% RH
Humidity Accuracy	±5%	±2%
Body size (mm)	15.5 * 12.0 * 5.5	15.1 * 25.0 * 7.7

DHT-11, and DHT-22 both use a capacitive humidity sensor and thermistor for environmental readings of ambient air, and simply outputs a digital signal through the digital data pin. Its small size allows for the attachment to the robot and to a human comfortably [49]. Since DHT-22 outshines DHT-11 in every aspect from temperature/humidity range, and a precise degree, DHT-22 is used in this research.

Comfort is based on heat index, which is a combination of both ambient temperature and humidity, as shown in Figure 27 and Table 4. In this project, the DHT-22 sensor will be used as the main comfort sensor to detect the surface temperature of the object or person and direct the zipper robot to either open or close the zipper for reaching the proper comfort level.

Temperature / Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Key to colors: Caution Extreme caution Danger Extreme danger

Figure 27. Heat Index of temperature and humidity [51]

Table 4: Effects of the heat index (shade values) [50]

Celsius	**Notes**
26~32 °C	Caution: fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
32~41 °C	Extreme caution: heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
41–54 °C	Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
over 54 °C	Extreme danger: heat stroke is imminent.

Table 4 shows the effects of heat index on people. This table is an indicator of the DHT-22, the code that will be used later in Arduino. This is a reference for why the venting using the zipper robot, with commands from the DHT-22 is reasonable and needed.

3.3. Research Approach and Scope

The type of research conducted in this project is a developmental research. This is a system which manages the zipper robot's status, reports its direction of arrival relative to the goal, and alerts in real time about this information. The scope of this project included the development and configuration of all the previously defined cyber-physical elements.

3.4. Reliability and Validity

The main instrument for reliability of the measures is a Test-Retest Method. From the experiment base to the final experiment, data collection was executed repeatedly under same conditions. Content validity is constructed by using the same measuring and statistical methods that are the state of the art.

3.5. Variables

In the methodology, the important variables include the following:

- zipper slider
- zipper size
- length of zipper
- pull angle
- number of teeth per inch
- zipper top force
- zipper pull force
- speed of robot motor
- robot size
- wheels size
- granularity of robot sensor radian articulation

3.6. Experimentation

This is the proposed experimentation section to validate the design of the zipper robot system. For each one of these experiments, it is planned to conduct 50 runs of each test.

0) Test of initial prototype for functionality

1) Baseline experiment: Zipper on a board

(a) controlled strictly by the application

- Binary zipping; 0 or 100%
- Percentage or zip distance

(b) Controlled by temperature sensors

2) Dress experiment

(a) garment with zipper robot

- Test control using the application of zipper robot for binary (0 or 100% zipped)
- Percentage or zip distance

3) Body temperature control experiment: For each

(a) Create garment with robots, such as shirts or dresses.

(b) User will wear a garment in ranging ambient temperatures.

(c) Temperatures that go outside of the user comfort level profile, will cause a zip event, based on their profile.

3.7. Summary

This chapter described experimental setup, defining a scope for the project, which is the development and configuration of three main components: building the zipper robot physical elements, creating a system application to control the device, and optimizing the cyber-physical processes. The design for each of these components, and the development methodology for the whole project was explained as well. The criterion for the procedures of the project was settled to be connection between zipper robot and the clients using MQTT protocol while keeping an acceptable performance.

CHAPTER 4. RESULTS: EXPERIMENTS AND DATA ANALYSIS

The purpose of this research is to build an intelligent system to control zipper robot towards the augmentation of service and aid of the population with physical disabilities, as a main group, to enhance their daily life experience. In this chapter, the progression of designs is shown through the results cultivated from these designs. Each design was evaluated with experiments and data analysis. The progression from the initial designed, not only of the robot and intelligent agents, but also the redesign of the physical zipper systems is described to arrive at a final prototype design. The chapter is laid out in chronological order given the methodology from chapter 3. The logical design progression includes the failures and successes of the each of the zipper robot research experiments.

The experiments explained, in this chapter, are decomposed into multiple stages due to the number of various variables that occur in the zip and unzipping process. Each experiment is based on the explanation of the prototype and the results of the experiment with figures, descriptions, and problems are observed and analyzed through the dataset of the experiment.

4.1. Physical Device and Variables Explanation

Based on the literature reviewed on the chapter 2 and a zipper robot made during previous work made by Karnan [35], it is possible to assume the feasibility to build a robot to control the zipper's movement. To set up experiment 0-A, for the first approach to build a zipper robot, which was successfully executed using a zipper, a preliminary test is required to ensure that a correctly sized wheel is capable to roll over the zipper to provide solid contact and torque sufficient to control zip/unzip process as shown in Figure 28.

Figure 28. Wheels size comparison connected to DC 3V 50RPM

Experiment 0, which is a test with 50 experimental executions was conducted with 3 volts motor each for forwards and backwards as shown as Table 5. The key, in this phase is the size and friction of the wheel. Firstly, for the forward and backward motion, the wheel is designed with a 1 centimeter diameter and a wrapping of Velcro around the circumference of the wheel. If the size of wheel is smaller compared to the zipper robot's body size, as the wheels do not provide contact or friction with the ground sufficient to motivate the robot, in either direction, Then, the motor simply rotates in the same place and without any physical movement or the zipper robot body along the axis of the zipper.

Again, when it comes to the size of wheels, if the wheel is slightly larger than the body can accommodate in the design of the zipper robot's frame, the issue is a slowing phenomenon, due to excess friction, especially when used with lower voltage power systems such as 3 volts. The operation of the robot requires high power in proportion to the friction force. At the same time, an issue occurs when the size of robot's wheels is not correctly fitted with the main body. This was a key element in the initial design of the zipper robot and took a number of different 3D printed designs to arrive at the correct size, friction and tolerance. The 3D models were correct in design but the lack of precision by the printer, often caused issues with fit, friction and tolerances.

Another problem was the usage of Velcro. Commonly, foreign substances attach to the Velcro surface, the zipper would stick in the main body. The hook-and-loop fastener, hook-and-pile fastener, touch fasteners commonly known as Velcro, where the coefficient of friction is different for when an object is at rest and when it is moving. Figure 29 shows how Velcro works.

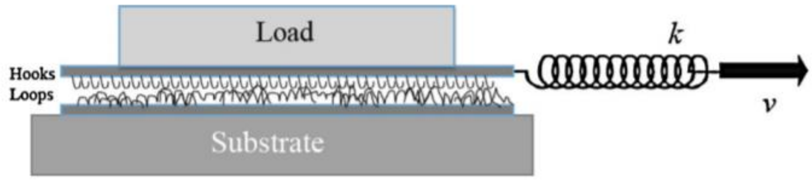

Figure 29. Observations of Stick-Slip Friction in Velcro (R) [34]

There were many problems in using Velcro which were identified that, however, the adhesion of Velcro is significantly lost in situations where foreign substances penetrated either hook or loop surface. Due to the issues with Velcro, a simpler solution of using a rubberized surface was tried. A thick, standard rubber band was glued to the circumference of the wheels due to the problems with Velcro. The rubber bands provided good flexibility but do not attract foreign materials to gather and cause problems with the fit, contact or friction. The flexibility and pliability of the rubber bands actually provided much better surface contact between the actuation wheels and the surface to push. The change from Velcro to rubber made a tremendous improvement in the operation of the zipper robot as it moved along the long axis of the zipper. There were still issues with alignment which frequently was adjusted to prevent entrapment of the zipper, but moving to rubber was a valuable transition.

In the next section, the first set of preliminary experiments to test the initial prototype was executed. Each successive experiment leads to the improvement and progression of the zipper robot design, function intelligent action and eventually success.

4.1.1 Experiment 0-A: Movement along the top of the long zipper axis

When beginning the development of the zipper robot, the kinematics of moving the zipper was uncertain, as this is a relatively new field and the lack of data in the literature for this application. The initial design consisted of two 3 volts, 50 RPM motors on each side of the robots main drive axle, with the rubber coating around the wheels. The intent was to test whether the robot could successfully move along the long axis of the zipper, from one end to the other end. A power supply was used to supply current at 3 volts to power the twin motors with a constant and stable current flow. A picture of this initial setup is shown in Figure 30. The test was done for both forward and backward control of the actuating unit of the zipper robot.

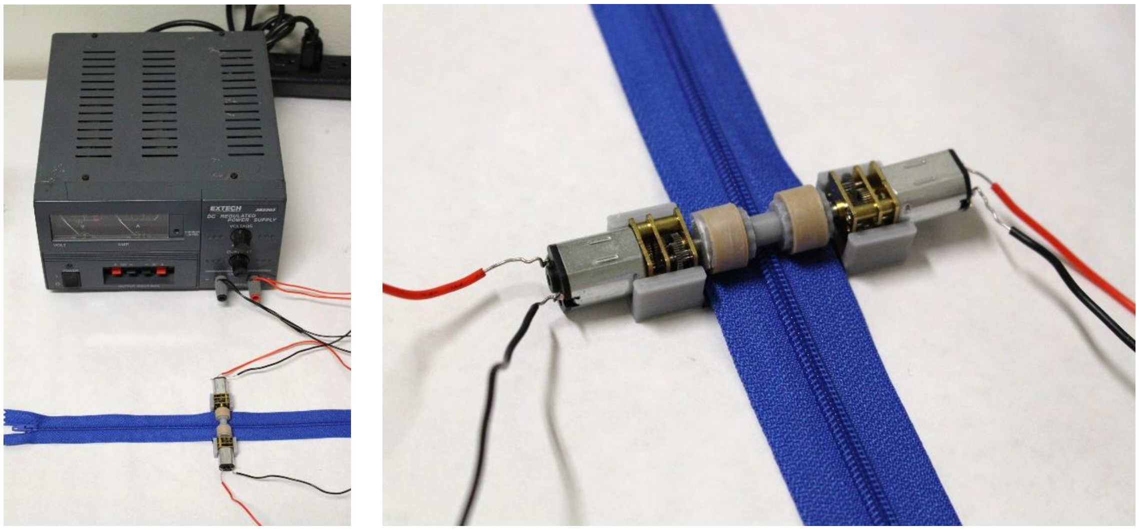

Figure 30. Preliminary test 0-A with power supply

Table 5: Results for experiment of robot on the top axis of the zipper with 3V 50RPM both test forwards and backwards

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Forwards (zip)	50	20	14.88	5.13	3.31

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Backwards (unzip)	50	20	18.61	10.8	4.12

Table 5 contains:

- Direction – oriented direction of the robot, zipping or unzipping
- Sample size – number of executions of this data
- Length – length of the zipper test from full open to full close
- Time – amount of time taken to zip or unzip from start to finish (on average)

- Stops – number of times the robot stopped in the middle of operation, normally due to a lack of frication and proper contact with the surface
- Delay – when there was a delay, but not a full stop, in movement

Based on a raw dataset, Table 5 reflects the data analysis of this first experiment. When the zipper was closed, which is moving forwards, the average performance time of the zipper was determined to be 14.88 seconds. It was a stable result compared to the result of zipper stops or delay-performance during operation, but it was found that the process of stopping in the backward motion, the uncollected process of the zipper, was twice as high as the previous forward movement experiment. The cause of the problem is assumed to be too low power to properly operate the zipper robot across the long axis of the zipper. To move the research forward, moving to a more powerful motor is proposed to work. The next experiment will be used with a more powerful motor and the same gearbox to see if it yields a better result. The experiment will use the same environment, the motor has the same size and function and gearing, but is 6 volts instead of 3 volts.

4.1.2 Experiment 0-B: Movement on the top of zipper with 6V 50RPM

Based on the experiment 0-A, both motors, have the same form and size and gear ratio for RPM. The only difference is the voltage. The two motors with the 3V 50RPM and 6V 50RPM are shown in Figure 31. The 6 volts motor is significantly more powerful can be checked using an electrical supply to identify the motor's motion, which is 1.4 times stronger on average.

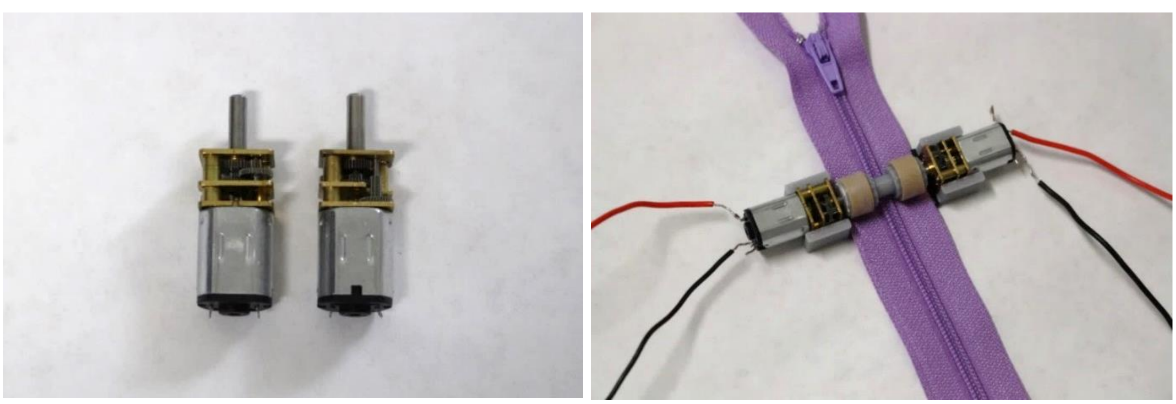

Figure 31. the 3V 50RPM and the 6V 50R. 6 volts version of original robot cradle

Table 6: Results for experiment of robot on the top of the zipper with 6V 50RPM testing both forwards and backwards

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Forwards (zip)	50	20	12.73	3.96	3.1

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Backwards (unzip)	50	20	17.07	7.11	5.3

The updated, 6 volts zipper robot version of the experiment, is shown in Figure 31. All experimental variables are the same for 0-B as they were in 0-A. The sample size and the length of the zipper were tested in the same environment as in the previous experiment, and both forward and backward movements were faster. The increase in power significantly reduces the number of times the zipper stops or slows down during execution. However, as before, when the zipper is in the unzip direction, backwards, noticeable pauses and consequent slowdowns occur. This is mostly due to issues with design and the orientation of the zipper robot. The design issues are the next focus of the progression in development of the final prototype.

4.1.3 Experiment 0-C: Control the zipper with pin replacement in slider

As first shown in Figure 2, a zipper is comprised of several elements. Each element plays an important role in zipper movement and function, but the slider is the core integral element for control of the zipper since a slider joins or separates the elements when the zipper is opened or closed. This version used the same 6 volts 50 RPM gearbox motors as the previous experiment version.

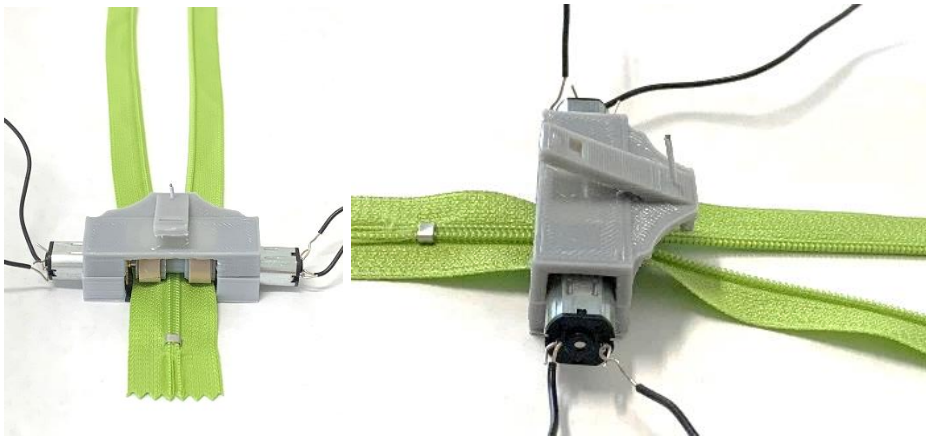

Figure 32. Initial zipper robot prototype with complete body

The slider also causes friction inside the zipper so the zipper does not freely fall on a garment. This inside friction or tension makes the zipper more difficult, from a force perspective, to pull across the long axis of the zipper, joining the two sides. To reduce the force required, the slides handle and pin were removed from the zipper assembly and a simple wire pin was affixed in the slider using glue. The pin was bent 90 degrees so that the vertical part of the pin could slide through the body of the zipper robot. This is shown in Figure 32. The intent was two folds:

1. *Reduce the amount of force needed to pull the zipper through the zipper robot assembly*
2. *Create a better interface from the zipper to the zipper robot with easy attachment.*

This experiment is the first full and complete zipper robot prototype which performs all of the functions, at least physically, of the proposal.

Table 7: Initial zipper robot with 6 volts motors

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Forwards (zip)	50	20	23.93	11.67	0.73

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Backwards (unzip)	50	20	24.77	13.2	2.34

Compared to the previous experiment, this experiment and the data is much more meaningful as it is the first fully functioning zipper robot. This experiment is significant since the zipper robot functioned completely in the planned manner by traversing across the zipper while pulling the slider. The zipper robot body connected to the slider and opened and closed zipper teeth. This slider variable has shown significant progress in advance and significantly stable results in reverse. However, the model had a fatal disadvantage because it required the removal of the zipper's sliders. While it was functional and worked, it changed the core functionality of a common zipper and made a specialty solution. With the focus on using off the shelf zippers, this could be better. On key result of this phase was the discovery that the attachment to the zipper slider was crucial to the stable zipping and unzipping process.

4.1.4 Experiment 0-D: Zipper Control with sensor with slider

To build a universial design, where the fully intact zipper was used without modification, a new 3D design was modeled with an port for the slide to connect through to affix the zipper robot to the slider . The length of the cover, around each end of both motor was elongated and changed to maximize the stability, rigid frame and secure the motor during movement. This is not only to provide a functional advantage but also to provide a stable feeling by covering the motor when it comes to the design as well as shown in Figure 33. The top and bottom parts of the body were adhered together.

Figure 33. Experiment 0-D prototype

Table 8: Final prototype with slider

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Forwards (zip)	50	20	21.7	2.7	0.44

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Backwards (unzip)	50	20	25.36	5.22	2.6

A key problem in earlier versions was the unstable nature of the zipper robot, especially when unzipping. This was mainly due to the movement of the slide pin connection to the zipper robot body. The slide would move vertically creating tension by pulling the zipper vertically or pushing it down. This created additional tension, and an unstable movement across the zipper. In this version the original pull was used. The use of the wider slide stabilized the movement and alleviated the vertical tension on the slider. This was a huge improvement.

One major shortcoming is the robot body is a bit light and has issues creating sufficient friction with the zipper tape to traverse the full length in a steady, straight manner.

4.2. Zipper Robot with Arduino Nano and Sensor

The control module was completely redeveloped in this version of the prototype. While there are advanced goals for this research, we have discovered some limitations based on available equipment. Sensors that are cost effective and safe to be connected to a human body also have some issues with error. In this case, there were some issues with accuracy and reliability of the temperature/humidity sensor, for example. The sensor only gets new data from it once every 2 seconds, sensor readings can be up to 2 seconds old with an error range as shown in Table 9. Also, once the humidity level went up, the sensor took over 30 seconds, on average, for the sensor to receive new data again unless the humidity and moisture were physically removed. This results in users may feel that data is not being accepted in real-time.

Figure 34 shows the zipper robot control circuits and temperature sensor. Figure 35 shows the controller mounted on top of the zipper robot and shown on top of the zipper it is to traverse.

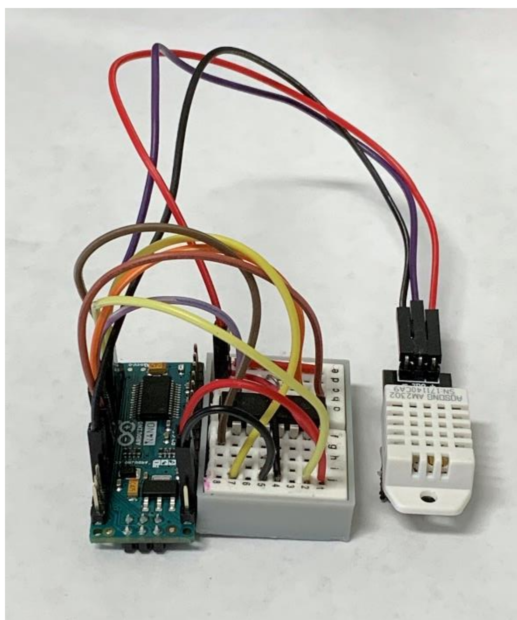

Figure 34. Arduino Nano circuit with DHT-22

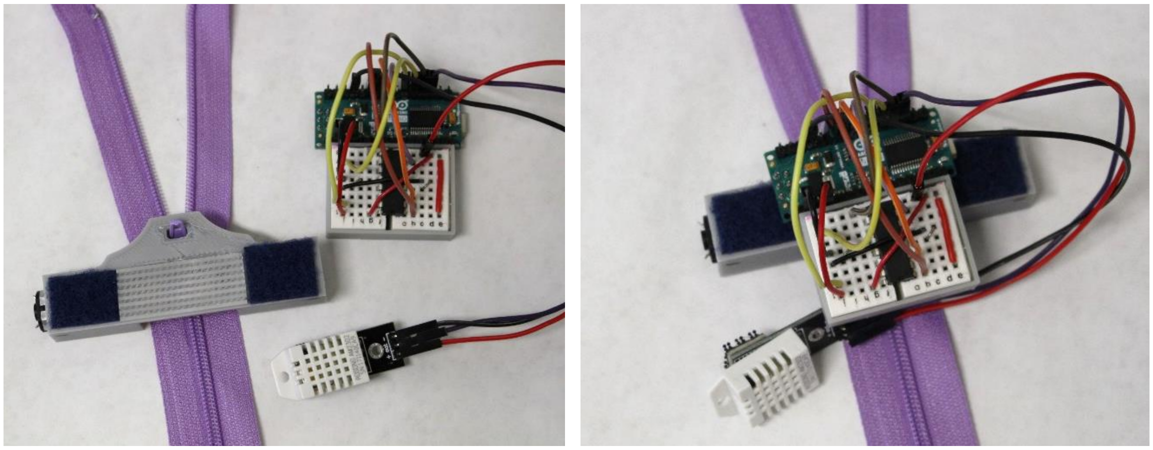

Figure 35. Zipper robot with the Arduino circuit

Table 9 consists of Real Time, Humidity, Temperature, the Heat Index range, and Movement, and shows the data coming from the Arduino indicating the index and movement of the zipper robot. The standard humidity level is set equal to 32.00%, and if it is more than 32 on humidity level, it moved to backwards. If not, forwards.

Given a steady temperature, of the humidity goes below 32% you see a change in direction to close the zipper. The colors in green show when the robot will change direction due to the comfort index level. This shows that the complete control is working to allow the robot to change direction based upon the index value set for a particular person or object. It also shows some error data such as shown in red.

Table 9: Raw data set of humidity temperature sensor to define movement

Real Time	Humidity	Temperature	Heat Index range	Movement
10:25:00.625	35.40%	25.40°C 77.72°F	24.92°C 76.86°F	backward
10:25:02.795	37.30%	25.40°C 77.72°F	24.97°C 76.95°F	backward
10:25:04.914	36.30%	25.40°C 77.72°F	24.94°C 76.90°F	backward
10:25:07.082	35.00%	25.40°C 77.72°F	24.91°C 76.84°F	backward
10:25:09.202	34.20%	25.40°C 77.72°F	24.89°C 76.80°F	backward
10:25:11.363	33.60%	25.50°C 77.90°F	24.98°C 76.97°F	backward
10:25:13.529	33.20%	25.50°C 77.90°F	24.97°C 76.95°F	backward
10:25:15.642	32.90%	25.50°C 77.90°F	24.96°C 76.94°F	backward
10:25:17.814	32.60%	25.50°C 77.90°F	24.96°C 76.92°F	backward
10:25:19.974	32.40%	25.50°C 77.90°F	24.95°C 76.91°F	backward
10:25:22.095	32.20%	25.50°C 77.90°F	24.95°C 76.90°F	backward
10:25:24.263	32.10%	25.50°C 77.90°F	24.94°C 76.90°F	backward
10:25:26.428	32.00%	25.50°C 77.90°F	24.94°C 76.89°F	forward
10:25:28.553	31.80%	25.50°C 77.90°F	24.94°C 76.88°F	forward
10:25:30.718	31.80%	25.50°C 77.90°F	24.94°C 76.88°F	forward
10:25:32.832	31.70%	25.50°C 77.90°F	24.93°C 76.88°F	forward
10:25:34.998	31.60%	25.50°C 77.90°F	24.93°C 76.88°F	forward
10:25:37.122	31.60%	25.50°C 77.90°F	24.93°C 76.88°F	forward
10:25:39.296	81.90%	25.70°C 78.26°F	27.14°C 80.85°F	backward
10:25:41.416	97.00%	26.00°C 78.80°F	28.30°C 82.94°F	backward
10:25:43.583	99.90%	26.10°C 78.98°F	28.74°C 83.73°F	backward
10:25:45.731	99.90%	26.10°C 78.98°F	28.74°C 83.73°F	backward
10:25:47.859	99.90%	26.00°C 78.80°F	28.41°C 83.14°F	backward
10:25:50.028	99.90%	25.80°C 78.44°F	27.77°C 81.98°F	backward
10:25:52.192	95.40%	25.60°C 78.08°F	27.10°C 80.79°F	backward
10:25:54.312	82.30%	25.60°C 78.08°F	26.95°C 80.51°F	backward
10:25:56.479	70.00%	25.60°C 78.08°F	26.04°C 78.88°F	backward
10:25:58.642	60.40%	25.60°C 78.08°F	25.79°C 78.43°F	backward
10:26:00.764	53.70%	25.60°C 78.08°F	25.62°C 78.11°F	backward
10:26:02.926	48.30%	25.60°C 78.08°F	25.48°C 77.86°F	backward
10:26:05.048	44.50%	25.60°C 78.08°F	25.38°C 77.68°F	backward
10:26:07.214	41.90%	25.60°C 78.08°F	25.31°C 77.56°F	backward
10:26:09.385	Failed to read from DHT sensor			
10:26:09.437	Failed to read from DHT sensor			
10:26:09.497	Failed to read from DHT sensor			
10:26:09.560	Failed to read from DHT sensor			
10:26:09.618	Failed to read from DHT sensor			
10:26:09.677	Failed to read from DHT sensor			
10:26:09.736	Failed to read from DHT sensor			
10:26:09.800	Failed to read from DHT sensor			
10:26:09.928	Failed to read from DHT sensor			

4.3. Zipper Robot on the Garment

In this experiment the fully functioning zipper robot is attached to the back of standard dress with a zipper mounted in the top back of the dress. This is a common example of a garment that presents difficulties for a person with challenges, and even some people without physical challenges encounter difficult, zipping a garment like this up or down. In this experiment, the robot will be tested in a flat state where the garment is on a table and also with a human wearing the garment.

The sample garment is shown, at a complete level, in Figure 36. The DHT-22 sensor is attached near armpit, on the outside of the garment. The zipper robot is located at the top of the zipper in fully zipped position. In Figure 37, there is a close up view of the zipper robot with the wireless control unit fixed to the top.

Figure 36. Large view of zipper robot on a garment with a top back zipper

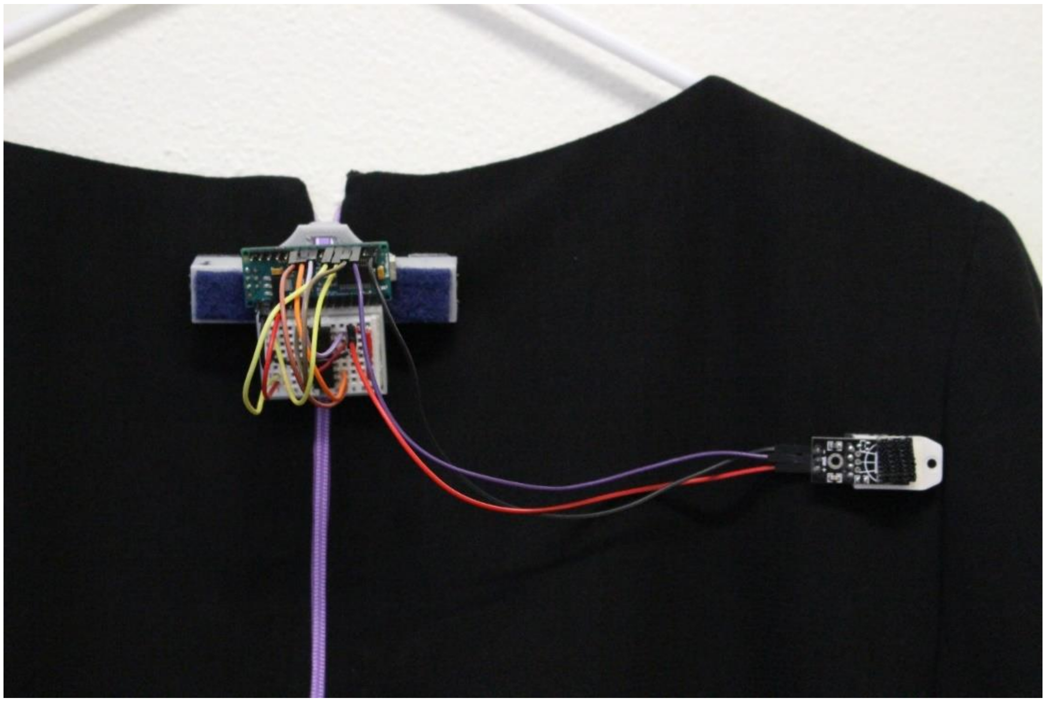

Figure 37. Close up view of zipper robot on garment

The data for the experiments are run with twin 6 volts motors and the standard prototype robot cradle and frame. The experiment consisted of zipping from one end to the other along the long axis of the zipper, with the same result set as in previous sets. The dress was placed in a flat position, on a table to do the initial test.

The results are in Table 10. The sample size was 50 and length of the standard zipper remained at 20 cm. For the forward motion the average time to traverse the zipper was 24.11 seconds with some stops and several delays. The backward zip showed a shorter time with 22.24 and a large reduction in stops and delays. This is an issue with the design in that pushing or pulling a zipper is of differing difficult, physically. It also seems directly related to a slight under powering of the zipper robot for the heavier cloth of a real garment.

Table 10: Final Prototype with 6 volts motors

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Forwards (zip)	50	20	24.11	4.2	5.91

Direction	Sample Size	Length of the zipper (cm)	Amount of times for one way trip (sec)	Number of stops	Number of delays
Backwards (zip)	50	20	22.24	1.9	1.12

The experiment was setup again but with an increase in power. The controller was also changed to better support the weight of running on the garment.

4.4. Zipper Robot with ESP8266 and Motor Relay

In this version of the controller, the larger Arduino with the Wi-fi Shield has been replaced with a similar board, which is much smaller. The new board is shown in Figure 38 and is a ESP8266 NodeMCU CP2102 ESP-12E development board.

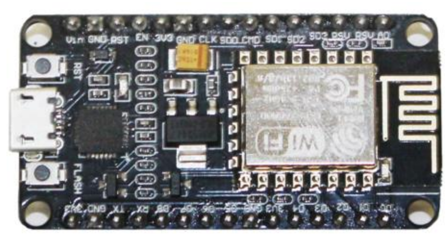

Figure 38. Replacement ESP8266 wireless controller for Arduino

An issue with the change in controller is the limitation that it cannot power motors greater than 3.3 volts but the switch was made to a 12 volt motor to increase power. To solve this problem, the controller was rewired with relays with the higher voltage coming from an external source as shown in Figure 39.

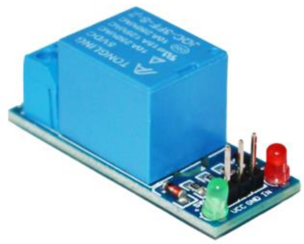

Figure 39. Arduino single channel relay to support 12 volts power input

The resulting new control system is shown in Figure 40. It was mounted on a board and tethered to the robot in this case.

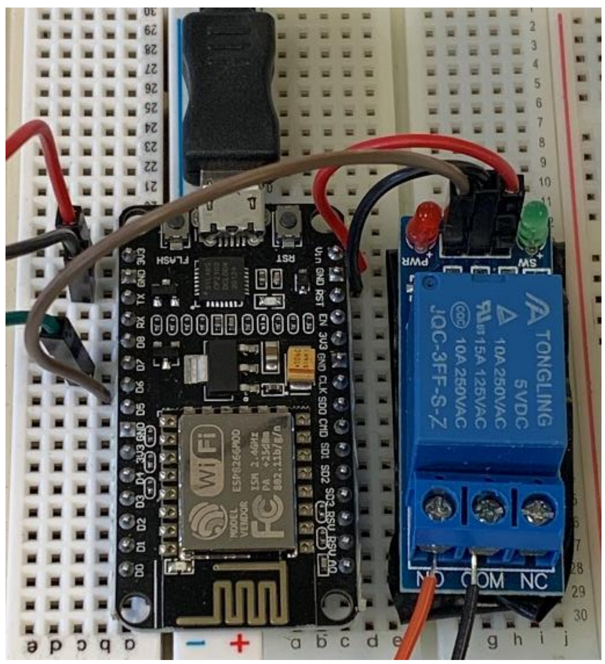

Figure 40. Control for 12v system with relay

A larger view of this system is shown in Figure 41, with the DHT-22 temperature and humidity sensor.

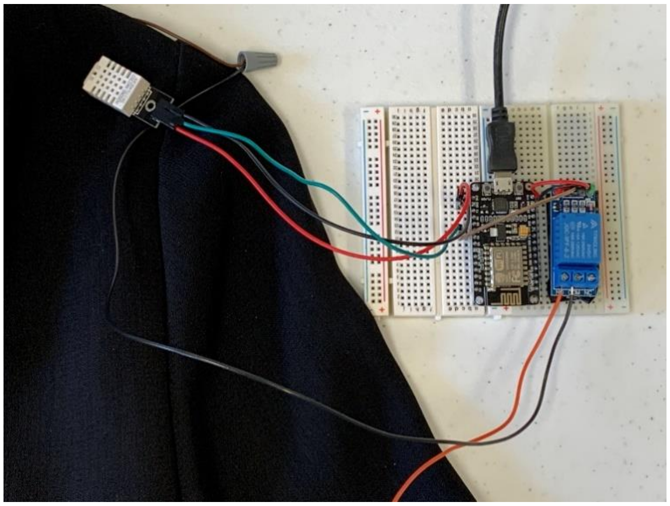

Figure 41. Control system with DHT-22 sensor

The complete system for the new experiment, with 12 volts input to solve the power problem is shown in Figure 42. The garment is laying in a flat position and the controller is tethered by a wire. This changes the weight of the controller which creates some issues of being to light and not creating enough pressure on the axle wheels but the extra power is meant to compensate for that. A small weight was also added to the top of the zipper robot.

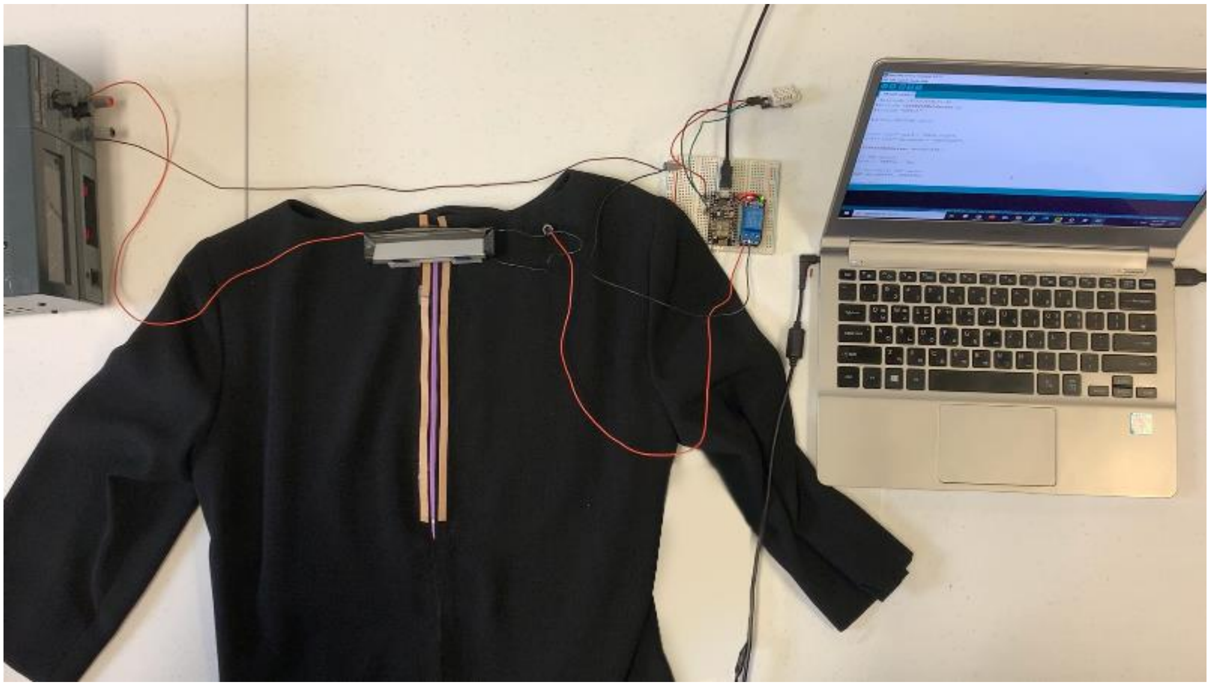

Figure 42. Complete system with external 12v power supply and added relay circuits

The resulting data for 50 executions of this experiment are shown in Table 11. In this experiment, the added power resulted in the elimination of delays and stops, so they were eliminated from the table. The time to traverse the long axis of the zipper also was reduced significantly. For forward runs the shortest time is 13.7 seconds and the longest time is 17.67 seconds with the average time being 15.74 seconds. For the backwards movement, the shortest time is 13.68 seconds and the longest is 19.66 seconds with the average being 15.82. The elimination of the delays and stops is the overall best results. From the previous experiment, adding the higher power reduced the traverse times significantly.

Table 11: Final prototype raw dataset

	Forward time in seconds	**Backward time in seconds**
1	13.70	16.90
2	15.20	17.21
3	16.52	15.96
4	15.05	15.33
5	16.01	16.02
6	15.08	16.66
7	15.02	15.92
8	14.98	15.21
9	13.94	13.98
10	14.66	17.16
11	15.90	15.95
12	14.43	19.66
13	15.58	15.90
14	16.61	16.77
15	16.02	15.56
16	15.82	16.01
17	15.84	15.92
18	16.01	14.32
19	16.15	13.98
20	15.87	13.68
21	14.59	16.14
22	15.10	17.29
23	15.88	17.01
24	14.80	16.17
25	15.48	16.22
26	16.38	17.06
27	16.00	16.90
28	17.03	16.60

Table 11 continued

29	15.92	15.98
30	16.88	14.46
31	17.67	15.98
32	15.91	14.44
33	16.87	15.33
34	16.33	15.07
35	16.55	15.88
36	17.11	15.02
37	15.97	15.05
38	15.36	14.78
39	15.87	15.33
40	15.88	15.65
41	17.00	15.90
42	16.09	15.64
43	15.44	14.87
44	14.98	16.32
45	16.11	16.10
46	15.90	16.08
47	15.65	15.48
48	16.01	16.09
49	15.09	15.31
50	14.66	14.98
AVG	15.74	15.82
MAX	17.67	19.66
MIN	13.7	13.68

The final experiment is to test the robot with a person wearing the garment as shown in Figure 43. This is a more complex test as the surfaces a not as uniform and standard and there is more undulation to navigate along the contour of the human form than a flat surface. The addition of the extra power was in preparation of this experiment. Table 12 describes the simulation data at different, variable angles while zipping and unzipping.

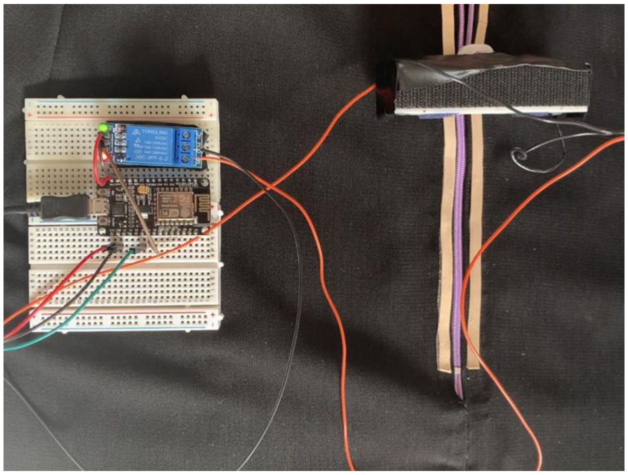

Figure 43. Final experiment with a person wearing the garment

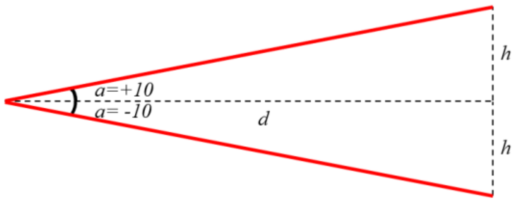

Figure 44. Set slope to 10 degrees

Table 12: Final data for human simulation experiment

Status	**Sample Size**	**Angle Side**	**Length of the zipper (cm)**	**Amount of times (avg)**	**Number of stops (avg)**	**Number of delays (avg)**
unzip	15	-10°	16	13.75	0.6	0.2
	15	+10°	16	35.20	5.8	3.3
zip	15	+10°	16	30.10	4.76	2.2
	15	-10°	16	14.95	1.1	0.86

A limitation of this study was the causes from the gravity of force to the zipper robot. When the robot was tested in a horizontal and vertical state, the force of gravity and its own weight reduced the magnitude of the forward force. On the other hand, when the zipper robot operates to act backwards, which is the unzip process, it significantly reduces the accumulated error. In whether zipping or unzipping, going down the 10 degrees slope was much faster and easier than going up the 10 degrees slope.

It was difficult to diagnose the exact accuracy of the zipper robot, as each person will have a different pose, gait, angles and movements, but overall the robot will function as planned.

The last issue of this research relevant to the second limitation is the zipper's robot's weight. The equipment should be as light and small as possible, but a certain amount of weight is needed because it requires pressure to fix the slider and press the torso itself. Therefore, it is required to check the degree to which users do not feel uncomfortable, through the CRS table, and receive design prototype feedback from the wearer in the real world.

4.5. Complete System Architecture

As proposed, the complete system architecture consists of numerous interactive elements, shown in Figure 45. The systems integrate from a Java interface to the Zipper robot.

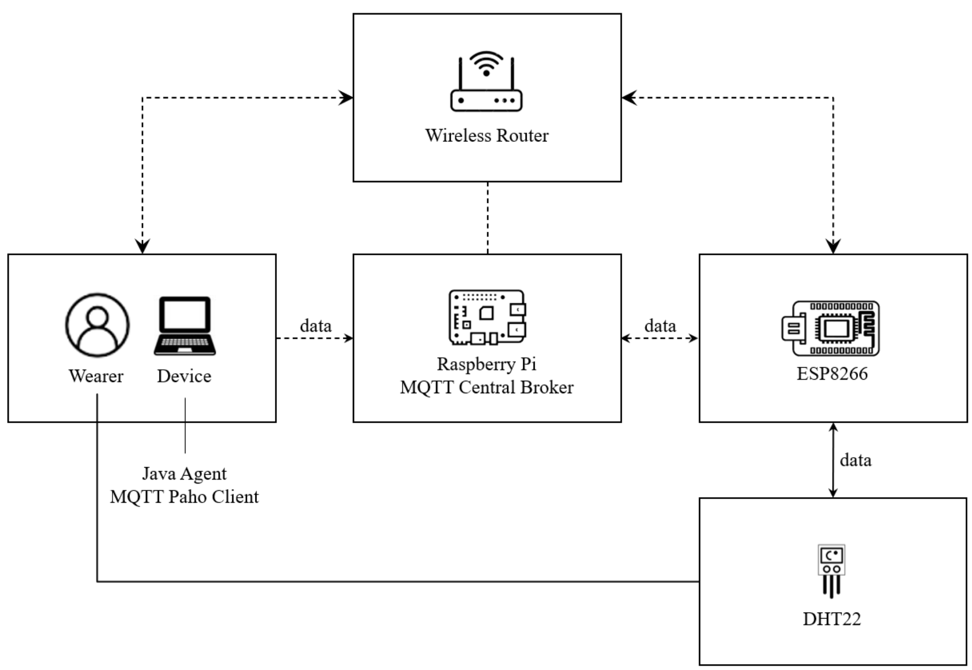

Figure 45. Complete intelligent zipper robot architecture

The elements of the system are described in this section starting with the Java interface, PAHO client, Intelligent agent, MQTT broker, Raspberry Pi, MQTT client, Arduino controller, a temperature humidity sensor and the zipper robot. All elements are wireless and work together using a Netgear Nighthawk M1100 Wi-fi router [33].

There are several solutions to subscribe to the topic from the broker on Raspberry Pi. In this research, three solutions are implemented: (1) Local on the Raspberry Pi, (2) Java Paho Client and (3) MQTT dash. Finally, the last complete architecture shows real time data on web server on the Raspberry Pi.

4.5.1 Local Communication using Mosquitto

To test local MQTT/Mosquitto messaging in a terminal, subscribe to the test/message topic:

mosquitto_sub -h localhost -t "test/message"

This will send a message to subscribe to a particular topic with the MQTT broker. So long as the broker is instantiated and executed, it should be listening for topic subscribe requests from any MQTT client.

On another terminal session, a publish message to the test/message topic like this:

mosquitto_pub -h localhost -t "test/message" -m "Hello, world"

After this initial test, a more salient message can be used, for temperature. In this case, when the goes to broker to publish the message, which is “100”, then zipper robot starts working.

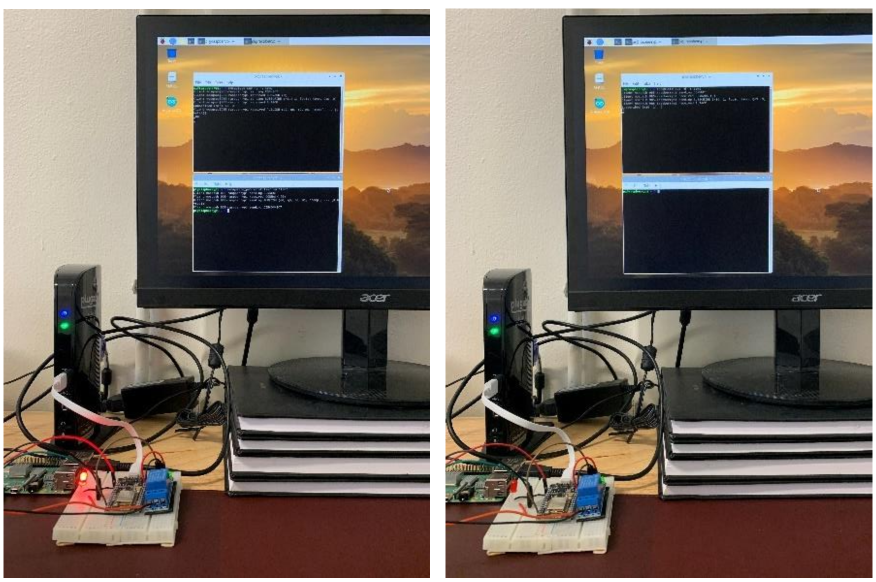

Figure 46. Pi local Mosquitto test with LED

To subscribe to the broker, to get messages, for example, where the topic is “temp”:

mosquitto_sub -d -t temp

Another example is that to the broker publishing the message, which is “100” or “0”, then the zipper robot will get the message and begin working:

mosquitto_pub -d -t temp -m “100” or mosquitto_pub -d -t temp -m “0”

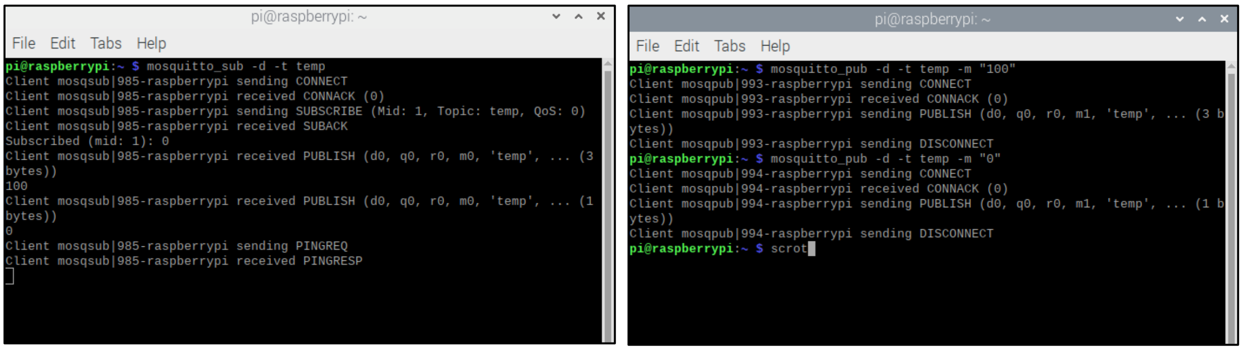

Figure 47. Raspberry Pi local test

4.5.2 Java with Agent and PAHO client

In the complete system, the initial application interface is a simple Java graphical user interface (GUI). The Java GUI allows the user to enter basic information and also provide high level control for the robot. The Java GUI is shown in Figure 48. This is not an extensive interface but was created to test the system from human user to robot operation.

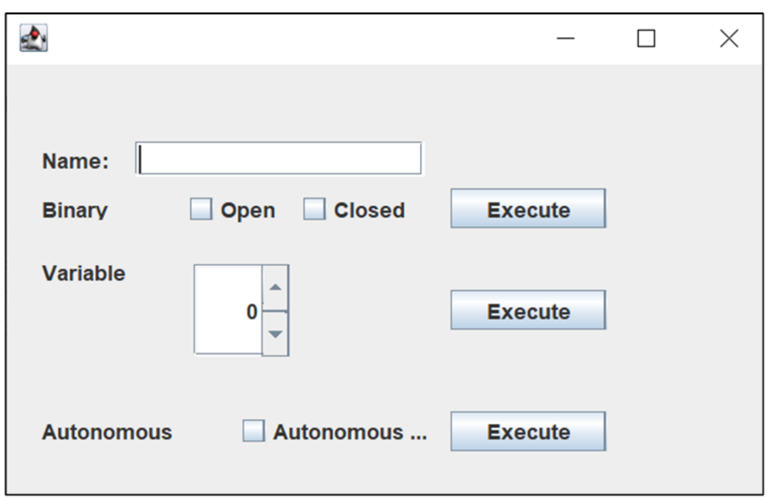

Figure 48. Zipper robot Java GUI

The interface has 4 essential elements:

1) Name entry to match with a user profile
2) Selection of binary operation where the robot will simply either completely zip or unzip
3) Selection of variable operation, where the user enters or scrolls to a given number between 0 and the robot will slide to that position along the long axis of the zipper.
4) Autonomous mode where the robot will take the profile name and comfort setting, primarily, temperature and humidity, and intelligently open and close the zipper, to allow venting of the clothing to cool down or warm up the user.

The Java GUI is developed using the Eclipse Integrated Development Environment (IDE) version 4.18.0 (2020) [45]. Eclipse was used due to the integration of the PAHO Java client for MQTT [46]. The PAHO client allows direct connection to a MQTT broker to publish and subscribe messages. PAHO clients are developed for a number of different program languages with library support to allow MQTT clients to directly access a MQTT Broker.

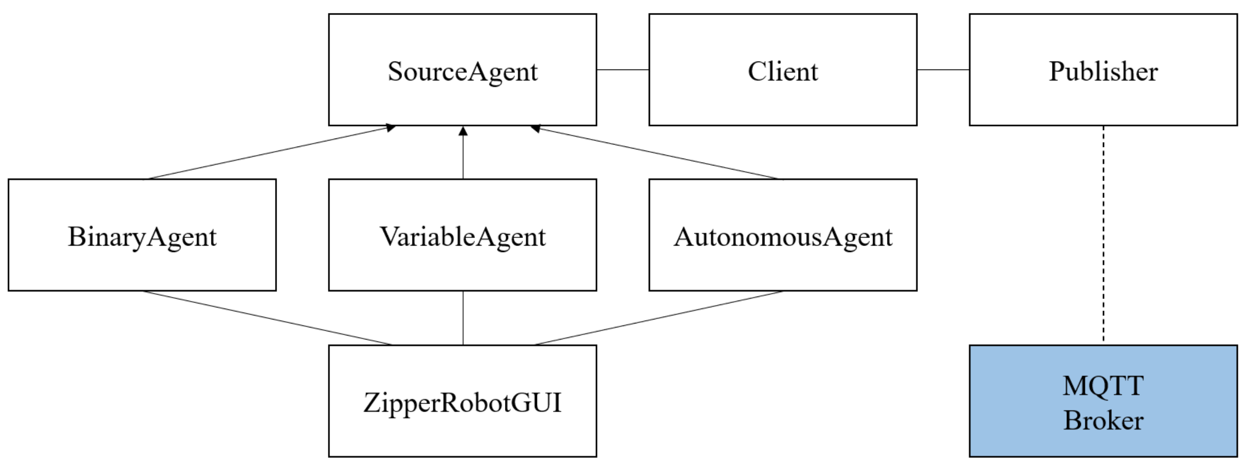

Figure 49. Class diagram of Java GUI, Agents and Client/Publisher

In this case, the Java GUI, Agents, Client/Publisher are shown in Figure 49. There are 7 new Java classes create for the front end of this project. The *ZipperRobotGUI* is the front end user interface. The *SourceAgent* is a basic agent with the ability to retain static knowledge and is the base, parent agent for *BinaryAgent*, *VariableAgent* and *AutonomousAgent*, which are all inherited child classes of *SourceAgent*. *SourceAgent* contains the basic static memory of the person, or user, and each child agent controls the ZipperBot in a unique way. *BinaryAgent* takes a simple command to either completely zip or unzip the ZipperBot to the end of the long axis of the zipper. *VariableAgent* takes a user input number from 1 to 100, interprets the raw number as a percentage to zip, or unzip, and moves the zipper to that location along the long axis of the zipper. AutonomousAgent gives the control to the ZipperBot agent, which is not part of the Java base of this project. When *AutonomousAgent* transfers control, the ZipperBot will zip or unzip based on the temperature and humidity of the object or person wearing the clothes. If the person, the user, is too hot, the zipper will unzip to vent the body and cool it off. If the person is too cold, the ZipperBot will zip up and reduce or close the venting so the object or person can warm up.

Each of the three child agents are individually called using one of the execute buttons from the Java GUI that corresponds to their specific command type. When each is pressed, the event will instantiate the specific agent type. Each of the agent types will then, in turn, instantiate the *Client* class with the specific call type to make. The Client object will then instantiate and invoke the Publisher class/object. The Publisher object is the MQTT PAHO client connection to the MQTT broker that runs resident on the Raspberry Pi. The MQTT software installed in this instance in Misquitto [41], an implementation of the MQTT protocol. That then transitions the command as a publish to the MQTT Misquitto Broker executing on the Raspberry Pi and a specific message type request.

4.5.3 MQTT Dash in Android Device

The MQTT Dash [31] application enables IoT devices, such as a smart home application. It is simple and easy to use user interface and has basic scripting support using JavaScript and supports almost any basic devices such as smart phone, tablet or computers, based on Android. This application uses the standard MQTT protocol making is rather easy to connect all devices. MQTT dash supports for ESP8266, M2M, Arduino, Raspberry Pi, Microcontrollers (MCU), sensors, computers, and wireless devices which are used in this work.

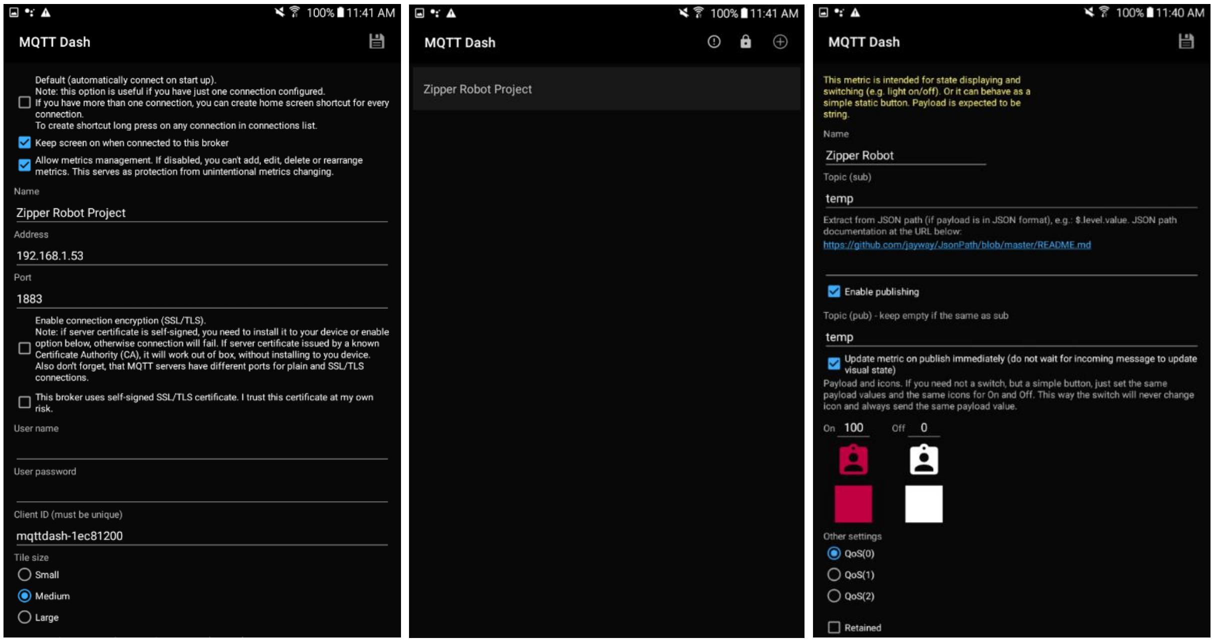

Figure 50. MQTT Dash setup

Topic can be hierarchically constructed using a slash, which is intuitive and can use many sensors. Many sensors usually use a slash(/), but again, this application has been tested using only a topic called "temp" without a slash because it is a simple structure. A total of two types were created and the same topic was set up to be subscribed and published. The first one is in switch/button format and the other is in text format as shown in Figure 51 and Figure 52. Once the value is setup, these values will remain in this state for an hour, a day, and two consecutive days unless reset.

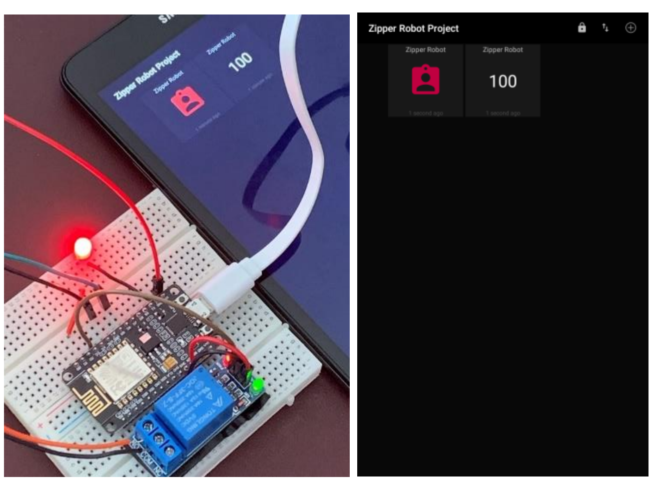

Figure 51. Manual mode zipper robot ON

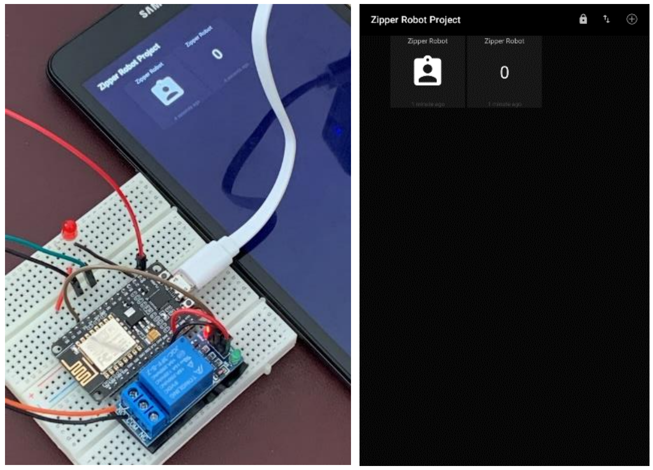

Figure 52. Manual mode zipper robot Off

If the user wants to use more than one zipper robot, it can be created with new categories, added topics and IP addresses. Once the topic and the IP address are clear, it can also be used with other IoT edge devices than zipper robots.

4.5.4 Complete Zipper Robot System

The final experiment was performed with an enhanced prototype made in consideration of the realistic scenario. It was conducted using the Raspberry Pi environment as the broker, and Arduino serial monitor was provided to check the environment of that Wi-fi connection, get IP address, connection to MQTT, and publishing and subscribing the data in real time as shown in Figure 53.

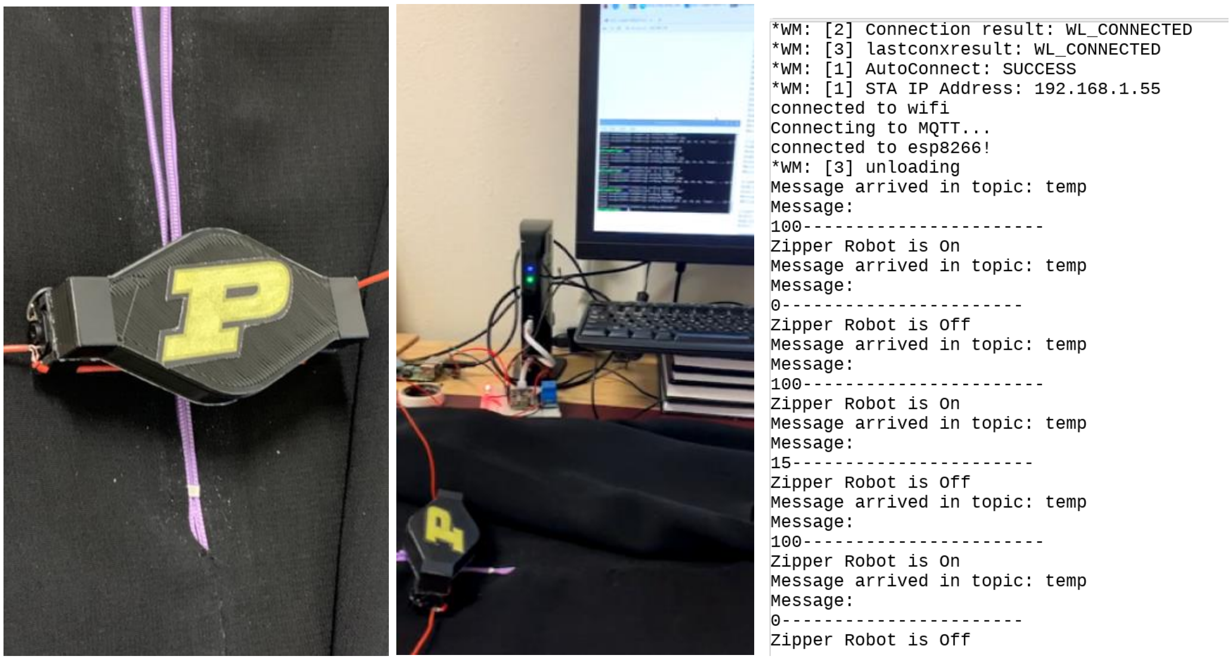

Figure 53. Final testing environments

Due to the hardware limitations, the experiments were conducted in a single direction of either zipping or unzipping. As shown in Figure 53, the final prototype on the left, the whole system in the middle, and screen print out of the output on the right. The input to the robot could be sent to the broker by any of the clients but the data in Figure 53 was experiments using MQTT Dash application.

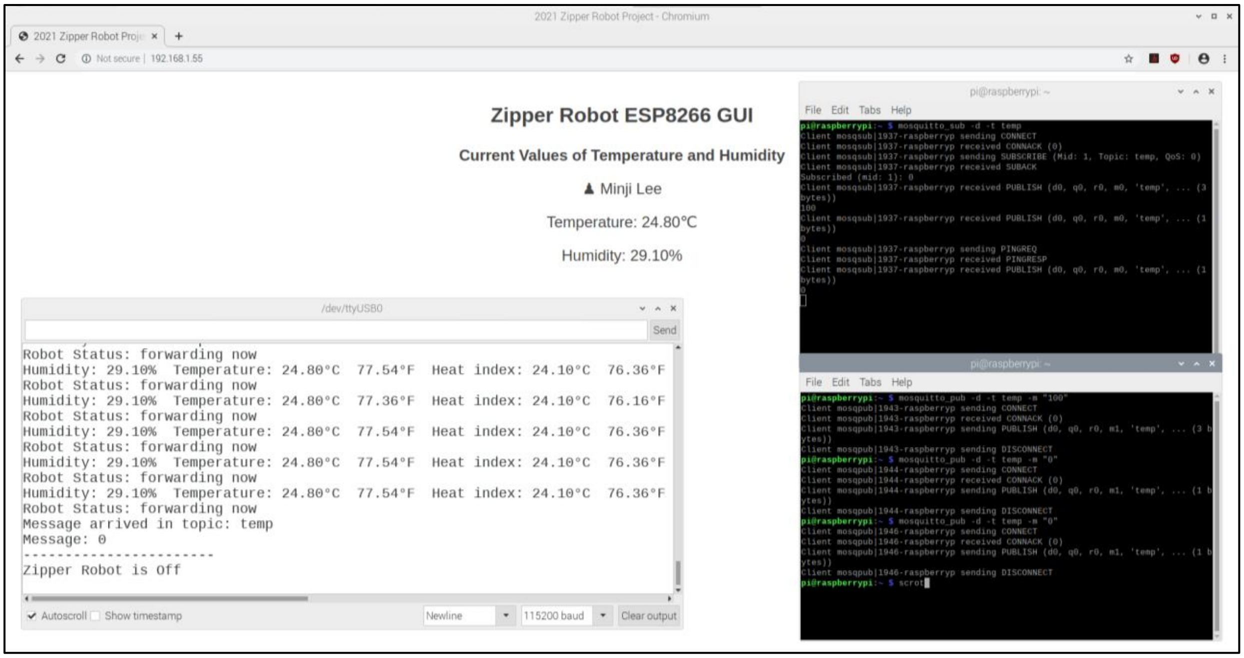

Figure 54. Real time data on web server

Finally, the last complete architecture shows real time data on web server on the Raspberry Pi.

4.6 Summary

In this chapter, the whole experimental process that resulted in the model proposed by this project was explained. This explanation included details about the equipment used, the initial approaches of the project performed. These results are satisfactory to consider that the proposal meets the expectations for a system which can control the zipper robot in a realistic scenario.

CHAPTER 5. CONCLUSION AND FUTURE WORK

In this chapter, a summary and interpretation of the results is given based on materials presented in Chapter 4. The research questions asked in section 1.4 are answered; limitations of the research are explained; and finally, ideas for future works are discussed with reasons why these works are relevant and should be pursued.

5.1 Research Questions and Answers

There were 4 research questions were investigated in this study. The results and analysis of each of this will be discuss in this section as the interpretations of:

Is the prospect of WT (Wearable Technology) research area future-oriented and valuable for business innovation? This study shows that the technology is not only possible, but also viable. There were no expensive elements to this study that would exclude anyone from accessing this technology, as all was made or cheaply bought and many parts can be source off the shelf. The economics of this technology show to be viable for a venture to further enhance this technology. As sensors and computing become smaller and cheaper, as well as, battery technology becoming more powerful, compact and safer for humans, the possibilities to improve this technology will only increase. The ability for an average person to self manufacture many elements also reduce or completely remove barriers to access.

How can the WT systems benefit a general population of humans with physical challenges? Although in this study, due to temporary complications for accessing physically challenged populations, due to the COVID-19 pandemic, the technology developed, the results of the experiments and the ease and use of this technology, used with common zippers found in all clothing, show that this can help many challenged populations. Given the access and low economic burden of this technology, it can also be used in almost all circumstances, as the technological barriers to sustain and operate are common and pervasive in all parts of the world.

Is an intelligently controlled zipper robot viable for automation of apparel for humans? All humans wear clothing and due to the human form being very common, all people around the world wear clothing that can be considered similar. The zipper, while not the only apparatus to secure clothing on a human, is very common in all parts of the world. Given this fact, an automated, common zipper apparatus that is easy to access, easy to maintain and easy to use, but solves a common need shows promising viability. Eventually, this technology will contain all of the intelligent platforms as am app for an Android or Apple phone. Given that a majority of the world has a smart phone and that penetration increases each year, an intelligent application is very viable.

How will the development and implementation of an intelligent zipper control system improve comfort, usability and autonomous function for people with physical disabilities? With full disclosure, the current world pandemic situation interrupted the capability to test and integrate this technology with challenged populations, but given the data, functional prototypes and improvement in operation, the technology can work for people with various challenges. In the future, the availability to work with, listen to and fulfill requirements for challenged people will arise and will be used for the next phase of this project.

5.2 Interpretation of Results

The progressive results from the very first prototype to the final fully functional prototype are very encouraging and exceed the expectations of the primary investigators. While there are many complex challenges in this project and still many problems to be solved, the results gained were not only encouraging to continue this work, but show, and to some extent, validate that wearable zipper robots are a technology that can come to complete fruition. The data leads to the conclusions that the final results can be improved on a great deal, but that the improvement from the first prototype to the final prototype shows that a small, accessible, maker type zipper robot can serve as a full functional aid to those who require physical assistance, or even those that do not require assistance, but just prefer to have it.

5.3 Limitations of Results

Due to COVID-19 pandemic issues, which have been ongoing the entire duration of this project, we did not have the chance to work with physically challenged populations at any time during this study. While it did not limit the creativity or prototype development, working with the target audience, for this technology, we admit that having that additional insight would have produced a sharpened result.

5.4 Future Works

Based upon the results of this study, there are several additional studies which can be performed, with additional data to be collected. Due to the relationship between temperature and humidity, further experimentation needs to be done to isolate each from the other. A future study should look at several ranges of temperatures, including non-spring or warm temperatures.

A novel idea that came up was the use of metal based wheels on the zipper robot axle and magnetic tape on a garment, or vice versa. This would prevent having the issue of something on each side of the garment to provide rigidity of the zipper. While we technically solved that problem with this work, it has a lot of room for improvement, especially with applications that are vertical or irregular.

Developing a smaller functional prototype with more power is a definite future plan for this research. The current prototype is not large, but decreasing the size while increasing the power and balance is a definite plan.

The third step will be the evaluation and testing phase to verify and validate the initial effectiveness of the developed zipper robot and control system elements of the system. In this process, collected data from the sample will be stored in the system. This will help determine how to build the novel system model to best satisfy the users and maximize the benefit to their needs. Figure 55 shows aspirational interface concepts for the user with physical challenges. Figure 55 shows a brief concept for the final prototype result. The user is able to control the movement of the zipper robot on the application.

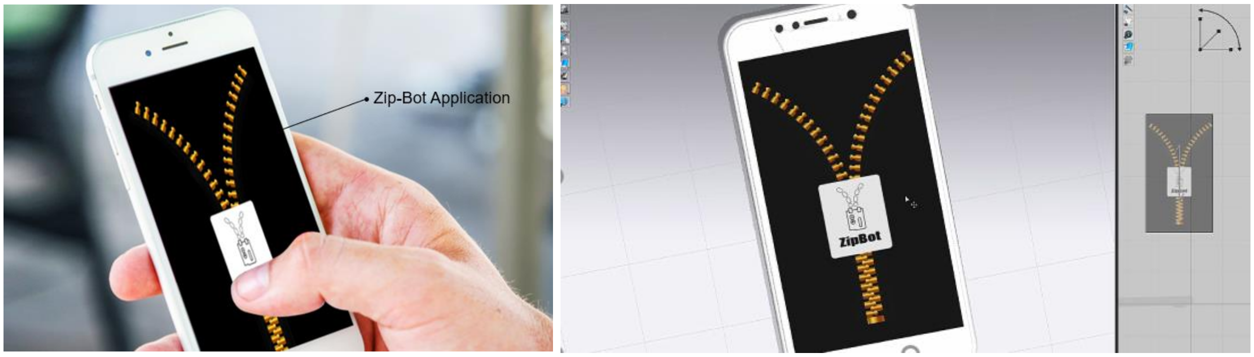

Figure 55. Future application concept for the final prototype result

After the pandemic subsides, engage populations of people with physical challenges to get their input, requirements, participation, feedback and usability data. This will be invaluable to building better technology that will continually best serve those populations.

5.5 Summary

In conclusion, the results indicate that this project, while very complex and challenging, did produce a functional prototype, though ta number of improved increments. The results gathered results support that this technology is possible, viable and can potentially be very important for people with physical challenges but many other populations and constituencies also.

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