Thesis Project Portfolio

Tongue-Driven Wheelchair for Quadriplegics: Exploring Assistive Technology’s Impact on Those with Disabilities

(Technical Report)

Movement Impairments From A Social Perspective: How Assistive Movement Devices Impact Those With Motor Disability

(STS Research Paper)

An Undergraduate Thesis

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Nicholas Talton

Spring, 2024

Department of Electrical and Computer Engineering

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Sociotechnical Synthesis

Spinal cord injuries (SCI) present significant challenges to individuals' mobility and independence, with global estimates indicating a substantial impact on quality of life. This paper works with the multifaceted assistive technology landscape for individuals with SCI, examining the societal, technological, and intersectional dynamics at play. Using empirical data and theoretical frameworks, including the Social Construction of Technology (SCOT) model and Hughes' concept of technological momentum, the paper looks into how assistive mobility devices evolve through innovation and competition, shaping societal perceptions and experiences of disability. The paper investigates the development and implications of alternative mobility solutions, such as tongue-driven systems and brainwave-controlled interfaces. These emerging technologies offer promise in enhancing independence and inclusion for individuals with SCI, yet they also pose usability, affordability, and social acceptance challenges.

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Nicholas Talton

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1 Abstract

The tongue drive system is a wearable assistive device that will help individuals with spinal cord injuries or any neuromuscular diseases, also known as quadriplegics, better navigate the world by allowing them to use their tongue to control an electric wheelchair. This head-worn device is equipped with magnetic field sensors to track the fluctuation of the magnetic field due to a magnet attached to the user's tongue. Using the data from the sensors, an MSP432 microcontroller performs some data processing to determine the tongue's position and transform that into control data that can be outputted to a wheelchair. Due to limited time and resources, this project does not use a physical electric wheelchair; instead, it sends the control data to a virtual wheelchair through a computer simulation. This device is designed to be easy and intuitive to operate with as little outside assistance as necessary.

2 Background

Spinal injuries affect more than 17,800 Americans each year - with the current amount living in the United States estimated to be approximately 294,000 [1]. Of these, 60 percent suffer from Quadriplegia, paralysis below the neck [2]. Quadriplegics are unable to use traditional motorized wheelchair controls such as joysticks and, as such, require assistive devices. The most popular method is called "Sip and Puff" and is a system where a user can inhale/exhale into a tube. The strength of the sip/puff, along with the direction of airflow, determines whether a user goes left, right, forward, or backward in their wheelchair. This system has limited control precision since one sip/puff is mapped to one corresponding movement. Additionally, this system can be tiring, lead to health concerns if the tube isn't regularly kept sanitary, and be non-intuitive [3]. Thus, we have decided to explore control methods based on tongue utilization. Using tongues to control wheelchairs for quadriplegics has been explored by various researchers, but there are no current devices for commercial use. The range and ease of motion for a tongue can be compared to a finger, so it is easy to see how these devices can be groundbreaking with regard to the new level of independence they have the potential to bring to quadriplegics.

2.0.1 Prior Research

One such group of researchers from Aalborg University developed a system that requires a ferromagnetic tongue piercing, which is localized using inductive sensor coils embedded in a PCB. This PCB is then installed in the oral cavity of a patient's mouth. This device aims to simulate an analog joystick or trackpad by having a user interact with the roof of their mouth using the tip of their tongue. [4] [5]. Another by Galgotias College of Engineering & Technology uses a series of hall effect sensors embedded in a mouth guard to localize a permanent magnet attached to the tongue [6]. What differentiates these devices from ours is they are installed internally. While utilizing tongue movement may be more intuitive and achieve finer control for users, these approaches still require considerable amounts of maintenance as they must be sanitized regularly and removed while eating. The project closest to production is the Tongue Drive System (TDS) developed by Georgia Tech, a system that uses sensors embedded in two casings that protrude on either side of the face like a microphone boom on a headset to interact with fields generated by a magnet on the tongue [7]. This design allows for greater control provided by utilizing tongue control while being easy to maintain since the electronics are all external. The TDS is the most similar device to the one proposed in this paper. What differentiates the proposed work is that all the processing is done on an MSP432 Microcontroller instead of a larger computer. This results in increased accessibility, ease of use, and significantly reduced cost. However, while the TDS only uses 4 equally spaced sensors to do localization, we use more sensors. This allows for higher resolution in terms of where exactly the tongue is. It also allows for dynamic calibration of different regions to different controls based on a user's comfortable tongue range of motion.

2.0.2 Required Background for Project Execution

To complete this project, we apply material across multiple courses. We use circuit/PCB design skills and a background in electronics from the ECE Fundamentals I, II, and III (ECE 2630, 2660, 3750) to design the sensor and power distribution circuits. Introduction to Embedded Computer Systems (ECE3430), Embedded Computing and Robotics I and II (ECE 3501, 3502), and Advanced Embedded Computing Systems (ECE 4501) are employed to program the microcontroller, process the sensor data into commands, and interface with a computer to relay those commands. Software Development Methods (CS 2110), Program and Data Representation (CS 2150), and Advanced Software Development Techniques (CS 3240) are used across all collaborative software engineering in this project, from firmware tasks for the microcontroller to programming a simulation to demonstrate the commands generated by the device. Electromagnetic Fields (ECE3209) provides foundational knowledge of fields required to complete this project.

3 Project Description

3.1 System Overview

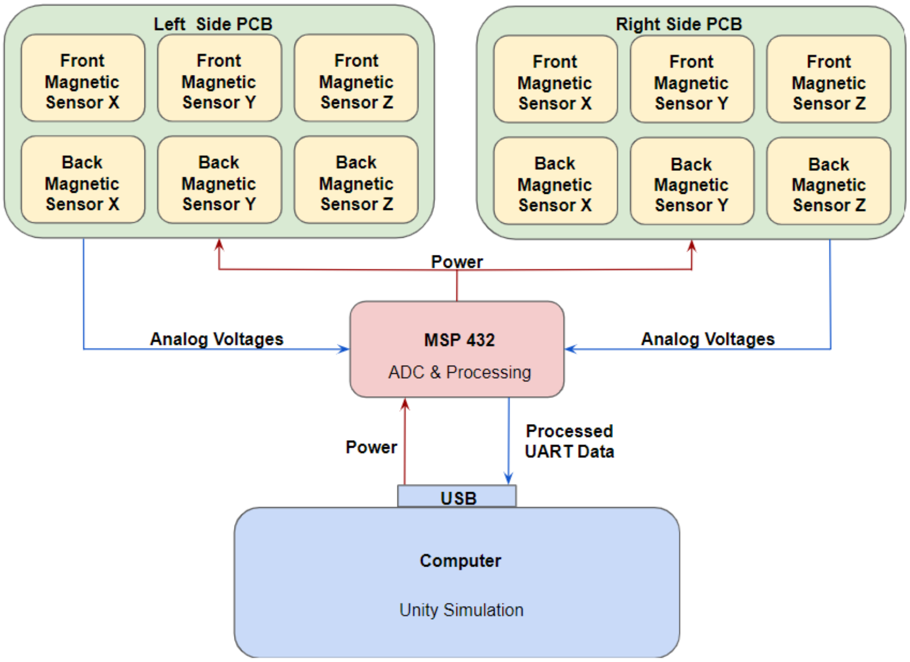

Figure 1: High-Level System Overview

The project comprises three key components: the magnetic sensor drive system, a headset designed to secure the sensor PCBs close to the user's mouth, and 3D simulation software to model wheelchair movement. For the magnetic sensor drive system, a custom PCB is strategically positioned near the mouth area on both sides of the subject's face. These boards house magnetic sensors generating analog signals proportional to the detected magnetic field. The MSP432 microcontroller reads this analog signal, converts it into wheelchair commands using our classification algorithm, and transmits it to a computer. The computer then runs a simulator. The sensor PCBs are affixed to a user-friendly headset for convenient wearability.

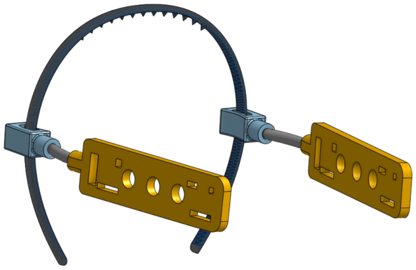

Figure 2: CAD of magnetic sensor system mount: Sensor Array PCB Mounting (Yellow), Flexible Material for Adjustment of Sensor Position (Grey), Headband for Mounting (Blue)

The 3D model to display wheelchair movement takes serial data from the MSP432 and translates that data into an interactive 3D rendering in a Unity Virtual environment, which simulates and shows the movement of the wheelchair in response to user action. The goal of the simulation is to serve as a stand-in for a motorized wheelchair. Since we are working with a reduced budget, the motorized wheelchair is substituted for the simulation. The goal of the project is to have a deliverable that can be plugged into a wheelchair and immediately serve as a source of movement for the user; thus, all processing with data and algorithms is conducted on the MSP432, and then the data is sent as serialized data for the laptop or computer to respond as if it were the motorized wheelchair.

3.2 The Role of Sensors in This Project

We employ linear analog hall effect and magnetoresistive sensors to gauge the magnetic field's strength, enabling us to discern tongue positioning and subsequently control wheelchair movement. The culmination of this project is presented through a 3D simulation depicting the functionality of the wheelchair.

3.2.1 Sensor Input

Hall effect sensors are a type of sensor that detects the presence and magnitude of a magnetic field using the Hall effect. The output voltage of a Hall sensor is directly proportional to the strength of the detected field [8]. Further, magnetoresistive sensors detect the presence and magnitude of an incident magnetic field and change the electrical resistance applied to the output signal proportional to the strength of the field. These changes in voltage or resistance can be sensed and characterized as a way to gain information from the user. [11]

3.2.2 Theoretical Framework

From our initial research, we found conflicting evidence about the rate of magnetic field decay with respect to the radius from the source in meters, where some sources claim that dipole magnets follow the inverse squared law, while others claim that the fields follow the inverse cube law in regards to field strength [10][9]. In order to solidify our theoretical framework, we acquired an axial Gaussmeter and determined that the magnets we are using obey the inverse square law. We also found that for our design to work practically, we would need a magnet with a strength of at least 12000 Gauss. Another consideration that had to be made was the geometry of the agent. The geometry of agents directly affects the concentration of the magnetic fields. We determined that we needed a magnet with high directionality for our applications. This high directionality is necessary for the classification stage of the KNN algorithm.

3.2.3 Sensor Selection

We chose to use an MSP432 Microcontroller for this project. Because of the nature of this board, we initially chose to use digital hall effect switch sensors, as we presumed that analog sensors were inconsistent, making magnet location initialization difficult in the software. However, to increase this device's robustness and implement the KNN algorithm, we decided to go with analog sensors. The sensors we used are the DRV5053VAQDBZR[17] and the RR112-1G42-531[16]. We chose the DRV5053VAQDBZR Hall Effect Sensor based on the specifications of the RR112-1G42-531 Hall Effect Sensor. This is because the RR112-1G42-531 are the only sensors on the market that are axially sensitive in the X and Y directions. These sensors have a sensing range of ±8 mT. We had to design around this constraint to maintain similar sensitivity scales for later characterization and minimize directional lopsidedness or error. Based on this constraint, we selected the DRV5053VAQDBZR, which is axially sensitive in the Z direction, because it has a similar sensing range at ±9 mT. This gave us 3-dimensional sensing capabilities with nearly congruent scales, making tongue localization feasible.

3.2.4 Addressing Field Disruption and Exterior Magnetic Noise

In this design, we considered the signal integrity of our I/O traveling down transmission lines, along with the integrity of the magnetic field source that is being used to interface with the sensors. The information that comes from the hall effect or magneto-resistive sensors will travel down a ribbon cable that then serves as an input for the MSP432 Microcontroller. There will be inherent transmission line coupling down the cable. We initially thought that we may have to do signal loss correction for the I/O from the sensors. However, this was found not to be necessary because we were using a classification algorithm to determine instruction based on I/O from the sensors, not hard-coded values.

3.2.5 PCB Design

For the final PCB design, we used Analog Hall effect sensors that would feed data into the ADC of the MSP. We used analog sensors oriented in the X, Y, and Z directions for full-dimensional characterization. This was needed to increase the robustness of the KNN classification that dictates user movement. We used DRV5053VAQDBZR Hall Sensors for the Z-axis sensing, then used RR112-1G42-531 Hall sensors, as the RR112-1G42-531 sensors gave X and Y dimension capabilities. The sensors are placed in 'clusters' that are used to collect data and send it to the MSP. These clusters are placed 4.5 cm apart. We came to this measurement after the first iteration of the boards was received. After testing, it was found to be more ergonomic and algorithm-friendly to reduce the space between sensor clusters from 6 cm to 4.5 cm. Each sensor has a very low current draw (3 mA for the DRV5053VAQDBZR Hall Sensors, 1.5 uA for the RR112-1G42-531 Hall sensors), so the MSP432 could supply enough current to these devices for them to operate. They also have a voltage range from 0 volts to about 2.5 Volts, which gives us enough resolution for the ADC to enumerate the values for classification. According to the datasheets, the sensors need a voltage supply minimum of 2.5 Volts. Because of this, the boards are powered from the MSP432, as the microcontroller meets the Current and Voltage requirements for the sensors to operate. When using the first iteration of the sensor boards, distortion and interference between wires were problems that did not arise, though they were anticipated. The final board size is 71.5 mm x 21 mm and features auxiliary testing points for troubleshooting purposes. A 3D render and the floorplan for the board are shown in Figures 3 and 2, respectively.

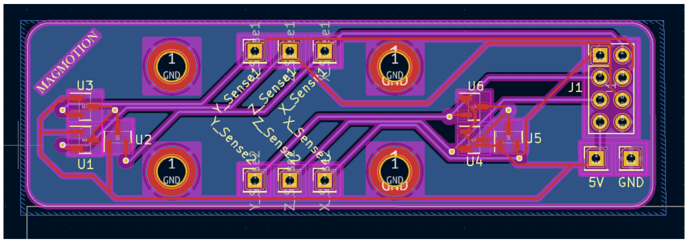

Figure 3: PCB FloorPlan

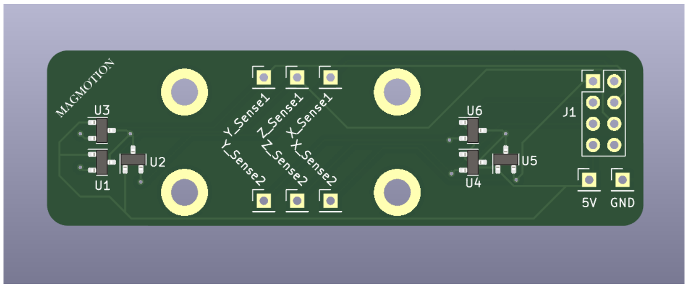

Figure 4: Hall Effect PCB 3D Render

3.2.6 Magnet Choice

We chose the Alliance ALC6416 cylindrical magnet for tongue direction detection. It is rated for 14800 Gauss. In order to increase its directivity, we change the total geometry of the magnet by stacking 3 of them on top of each other. The effect this made was a magnet with greater axial magnetic strength, improving the ability for field detection and, hence, classification ability. We experimented with rectangular magnets to produce the same effect. However, we found that the stacked cylindrical magnet geometry worked best for our applications.

3.2.7 Test Equipment and Validation

We used multiple pieces of equipment to test/observe the sensors' signal output and characterize the agents. We used the National Instruments (NI) Virtual Test Bench Software along with the NI Virtual Bench Oscilloscope and signal generator to observe the analog output of the hall effect sensors. To characterize the magnets, we used a PASCO 3-Axis Magnetic Field Sensor to measure the strength and field distribution of the magnets for testing. We used PASCO SparkVue software for data collection from the magnetic sensor. These instruments were provided to us for free by either the University of Virginia NI Lab or the ECE department faculty.

3.3 3D Modeling

3D modeling plays an important role in the development process for approaching a solution for our project. It serves as a bridge between the virtual and physical worlds, allowing us to visualize, design, and create a prototype of a helmet that allows for a fastened state of sensors to read input from the magnet on the individual's tongue.

3.3.1 Conceptual Design Requirements

The end goal is a device that can mount the PCBs along the user's jaw. This piece has to be durable and retain shape between uses, so calibration data remains true. It also has not to be bulky and should minimize the amount of space that is covered to better facilitate human connections. The design essentially fits someone's head and then has two whiskers sticking out as prongs with some mounting adapter to secure the PCB to hold all of the sensors for gathering and recording data from the user. Lastly, the general design of this headset is supposed to fit most head shapes.

The end result is shown in Figure 2. It is a flexible modified hairband that allows the headset to fit multiple shapes. Mounted on this hairband is an adapter to which a 20-gauge steel wire fits, and on the other side of that wire is a PCB adapter to which a PCB is screwed and attached. The steel wire's purpose is to adjust the PCB position on the face to accommodate multiple face shapes.

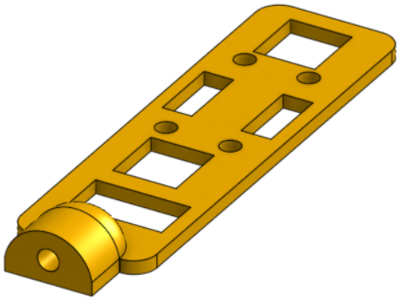

Figure 5: Final Design for Hairband to Wire Adapter

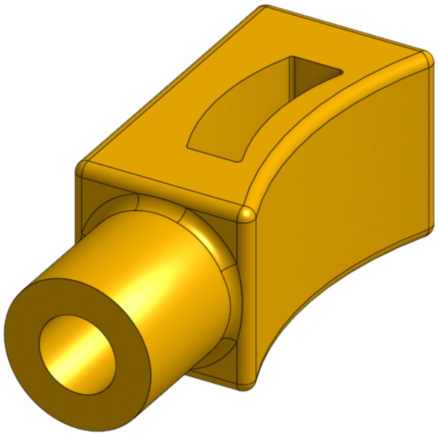

Figure 6: Final Design for Wire to PCB Holder Adapter

3.3.2 Software Tools

The software used on this prototype for the 3D model is a Computer-aided design service, Onshape. This service allows us to produce and refine our product for the headpiece. The parametric modeling, rendering, and simulation tools offered can conceptualize all our concerns before we proceed with building the headpiece via a 3D printer.

3.3.3 Prototyping and Iterative Design

Prototyping involves a series of discussions between group members, taking into consideration all aspects of development, such as how expensive it is, how large, how the customer feels about its design, and how the design makes the product better. Going through multiple variations of design, such as attaching a PCB board in front of a person's face for sensing, is considered, but it eventually is designed to maintain two identical but separate boards on either side of the face to maximize resolution within the mouth. After deciding on this approach, multiple iterations of design are made on the PCB adapter alone to maximize durability and aesthetics while minimizing size. Another important consideration is how the design fares in the manufacturing process. Since the PCB adapter is 3D-printed, designs that are flat on one side are able to be printed more cleanly and with higher quality.

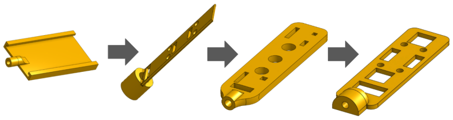

Figure 7: Iterations of PCB Mount designs

3.3.4 Material Selection

The type of material we pick for our helmet must have all of the following requirements: It must be durable, light, and cost-effective. It must be durable because it must be able to withstand impacts and provide long-lasting use for the user. The material should also be light because wearing headgear that may be heavy can be exhausting if you are wearing it all day. The goal of being lightweight is to counteract that issue by not straining patients with additional weight in the process. For the prototyping process, we choose PLA for accessibility purposes, but a more consumer-facing version of our product may use ABS, which better meets the above requirements. We chose 20 gauge steel wire for the adjustable material because of its malleability and ability to be easily manipulated yet retain shape.

3.3.5 Accessibility and Ergonomics

The accessibility and ergonomics of the headset were briefly addressed in previous sections, but the main purpose of the way it should be designed is to be able to fasten the sensors for reading input from the user, the comfort of the helmet so that it does not feel as if the user is constrained, and it should also avoid blocking as much of the user's face a possible so that others are still able to see the user and interact face to face without a metal sheet blocking that interaction [12].

3.4 Software and Firmware

The software and firmware of the project, in essence, is the component that is doing the sensor reading, processing, converting to meaningful movements, and simulation. Its purpose is to interpret sensor data and translate it into a sequence of meaningful commands that then move a simulated wheelchair.

3.4.1 Microcontroller State Overview and GUI

The firmware has nine states: Calibration Stand-by, a calibration state for each of the six commands(6 states total), a Reset state, and a Normal Operation state. This finite state machine described below works in tandem with a GUI used to calibrate the six different commands and to switch in and out of Calibration and Operation Mode. The GUI has a "Calibration Mode" switch, calibration buttons for each of the six commands, a command LED for each command, a command display, and a "Done" button. The calibration mode switch allows the user to enter calibration mode from operation mode. The calibration buttons allow the user to calibrate the corresponding command. The command LEDs indicate if the corresponding command is calibrated. The command display is used to display a command that corresponds to the current tongue position; this only occurs when the system is in calibration mode, and all the commands have been calibrated to help with recalibration. Finally, when the "Done" button is pressed, if all the commands have been calibrated, then the system changes from calibration to operation mode.

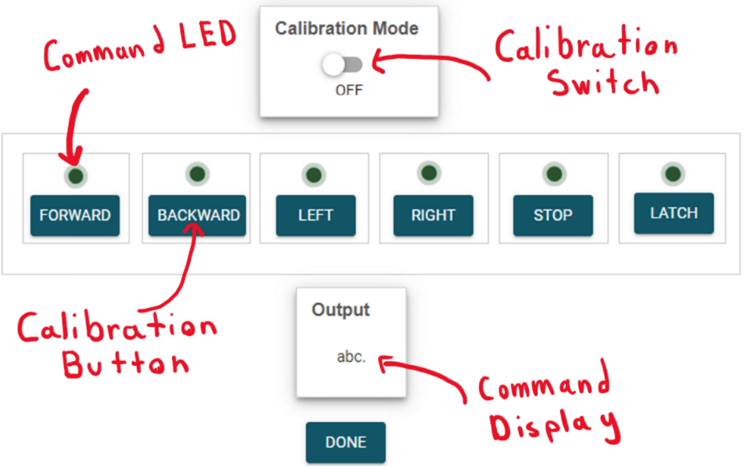

Figure 8: Calibration GUI

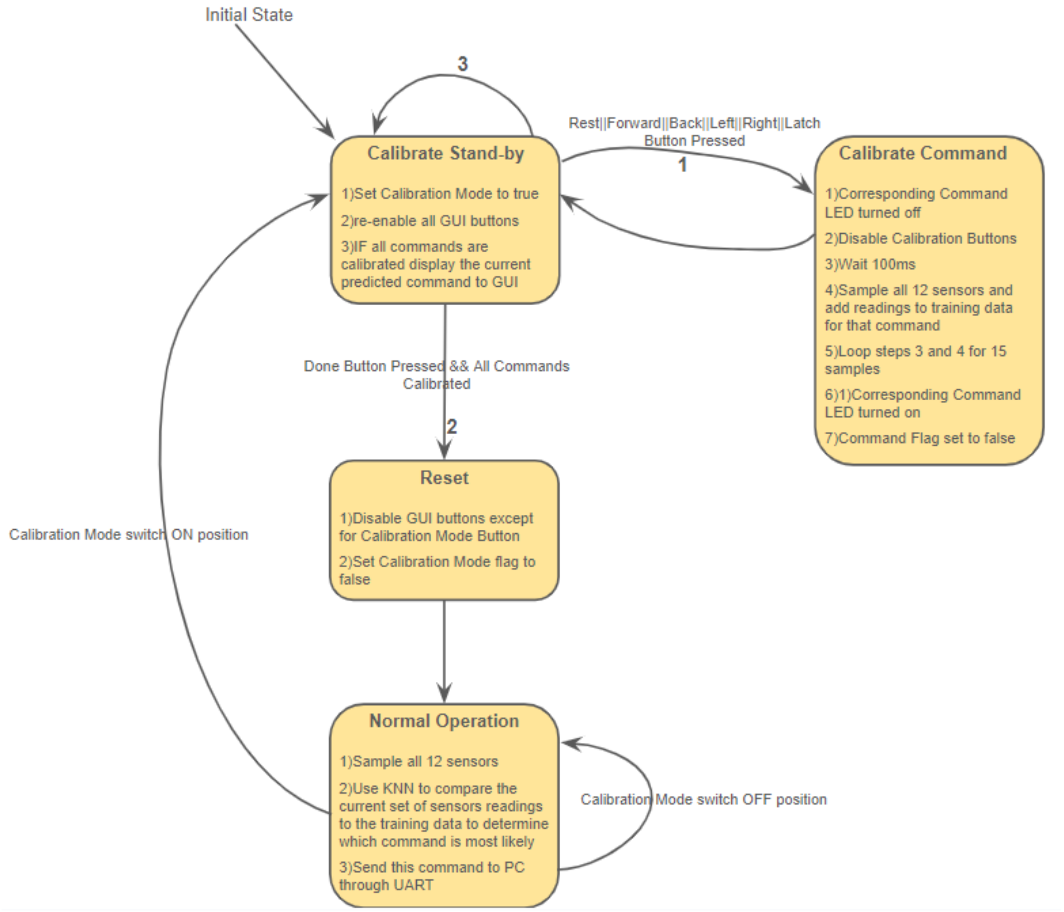

Figure 9: System FSM

Note: In the code, the Calibrate Command state is separated into six states, one for each command. The diagram differs for ease of understanding.

3.4.2 FSM States

The FSM starts in Calibration Stand-by Mode. In this state, the system sets the calibration switch to the ON position, enables all the calibration buttons to be pressable, and if all the commands are calibrated, indicated by the command LEDs, then it displays the current predicted command based on the current tongue position, in the command display. The system stays in this state until one of the calibration buttons is pressed or when all the commands are calibrated(indicated by all the command LEDs being on) and the done button is pressed.

When one of the calibration buttons is pressed, it switches to the Calibrate Command state. The first thing that happens in this state is to turn off the corresponding command's LED in case this command has already been calibrated. Next, the system disables all the buttons so that the user doesn't try to calibrate another command or leave the calibration state while a calibration going on. Afterward, the device enters a loop of waiting 100ms, then sampling all the sensors, doing this an overall of 15 times. All of these 15 samples(12 ADC readings each) are stored a specific part of training data list that corresponds to the command that's being calibrated. This training data list is used in our classification algorithm to map a set of sensor readings to a command during normal operation.

Once all the commands are calibrated and the "Done" button is pressed, the system moves to the reset state, which disables all the buttons except the calibration switch from being pressed and flips the flag that indicates calibration mode to false.

Finally, it reaches the Normal Operation state. During this state, the system samples all 12 sensors and sends unclassified points to the KNN classification algorithm. Using the training data list, the algorithm is able to determine what command the current reading corresponds best to and send this command to the computer simulation through the UART protocol. Once that processed data is sent, the system then samples all 12 sensors again and repeats the process. If the user wishes to get back to the calibration state, the calibration GUI switch can be flipped to on.

3.4.3 Sensor Sampling

The MSP432 is responsible for sampling analog readings from the sensors. This is done by setting up the Analog-to-digital(ADC) module for 12 pins one for each sensor.

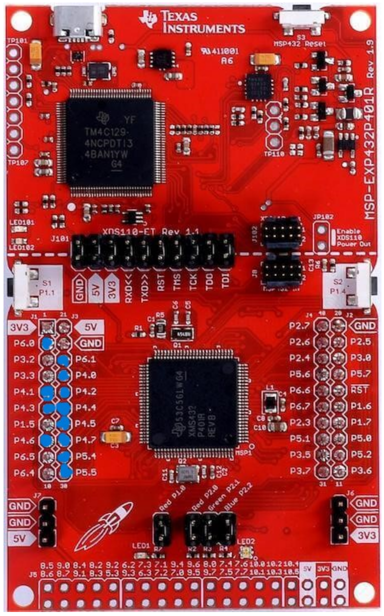

Figure 10: ADC Pins Used

The output from the sensors was not clean enough for our use, so after sampling, we had to do some signal filtering. We decided to perform digital filtering after sampling the sensors instead of using the ADC readings directly. An averaging filter was implemented to act as a low-pass filter and smooth out the sensor readings. The number of samples needed to make the sensor readings reliable enough was determined experimentally to be around 128 samples. This means each time the system asks for a sample of the current sensor readings, it uses the ADC to sample each of the 12 sensors 128 times and returns the average for each of the 12 sensors. We looked into using an analog low-pass filter instead of a digital one, but the digital filter worked well enough for our purpose and didn't require extra hardware components, so we committed to this method.

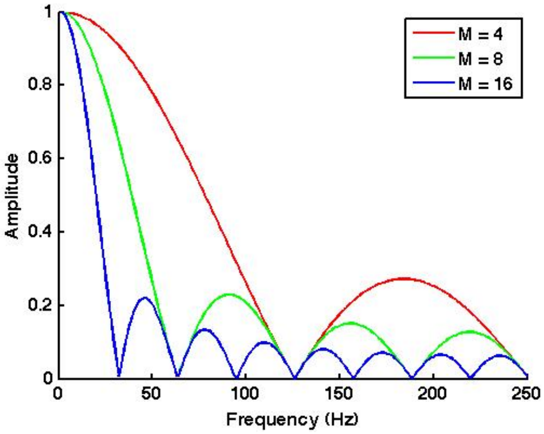

Figure 11: Frequency Response of Averaging Filter

3.4.4 Data processing and Algorithm Implementation

During the Normal Operation state, the microcontroller uses an algorithm that takes the current sensor reading and maps it to one of the commands by comparing to the training data. The algorithm that we used is the K-Nearest-Neighbors (KNN) algorithm.

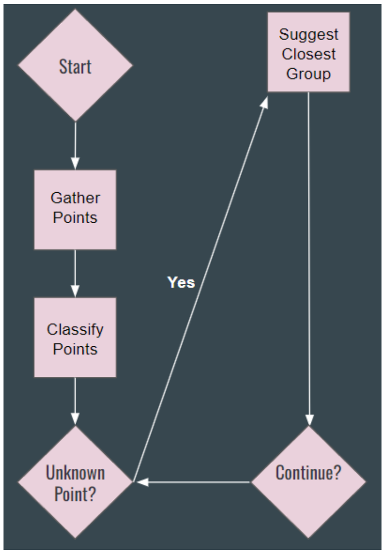

Figure 12: KNN Workflow

This algorithm is effective because it is a supervised learning algorithm that can allow the user to define where they wish to have particular commands mapped. This allows the user to customize their inputted data for comfort and command preferences. The KNN algorithm involves hyperparameters that can influence its performance so that it can make better, more concrete decisions. This parameter, known as k, allows users to balance between precision and robustness while determining the user's tongue position in a feature space, in this case, the mouth.

Every sensor sample comprises 12 ADC readings, one for each sensor, forming a vector with 12 elements. Each entry in the training set is likewise a 12-element vector, labeled with the corresponding command assigned during calibration. During the operational mode, when the system samples, it collects all the points from the training data and arranges them in ascending order based on their Euclidean distance from the currently sampled, unclassified sensor reading. Following this sorting process, the algorithm examines the first k samples from this ordered list of training data and identifies the command that occurs most frequently within these k samples. The unclassified sensor reading is then attributed to this most frequently occurring command.

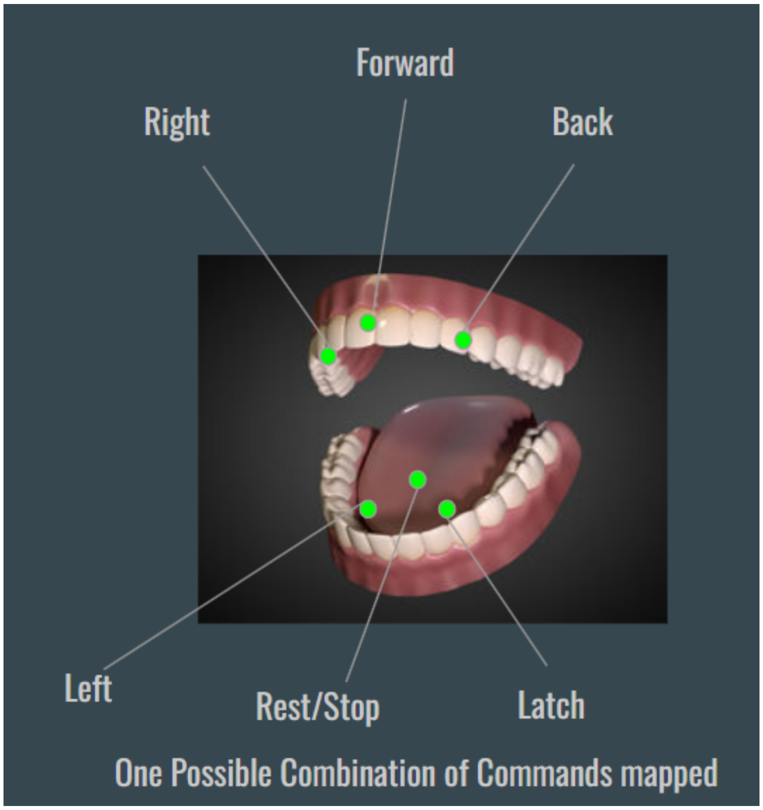

Figure 13: Command Centroids Mapped

Once the microcontroller decides which direction the user had requested using the KNN Algorithm, it sends a byte corresponding to the predicted command through the UART protocol, which a computer receives through the same protocol. UART is an asynchronous serial communication protocol. Asynchronous means there is no clock signal to synchronize the output bits from the transmitting device going to the receiving device[14]; this allowed devices running at different speeds to communicate. We used a serial communication port on the computer to set up UART communication by connecting the MSP432 and computer with a USB to Micro-USB cable.

3.4.5 Computer Simulation

Once the Computer receives the serial data from the microcontroller, it decodes it and processes it as a movement within a simulated environment. The simulation environment we elected to use is with Unity. Unity offers many benefits for simulation purposes, such as multiple free models for use as game objects as well as having a vast amount of documentation and video tutorials. In addition to this, it also has a built-in physics engine for any project using Unity, which makes integration and system testing easier for the final deliverable. In terms of the project, it allowed for the system to be tested by a simulated electric wheelchair that serves as a stand-in for the actual electric wheelchair. The final deliverable of the system can communicate with the simulation running on a computer via UART, where the computer can take data from the microcontroller and perform the specified operation on a virtual wheelchair in the simulated world as a substitute for a physical electric wheelchair. The resulting simulation is a track that is able to determine a series of defined inputs from the microcontroller where the simulation runs the simulated electric wheelchair through a track that tests the abilities to move forward, backward, and rotating clockwise and counterclockwise as well as a stop and latch command to be able to speak.

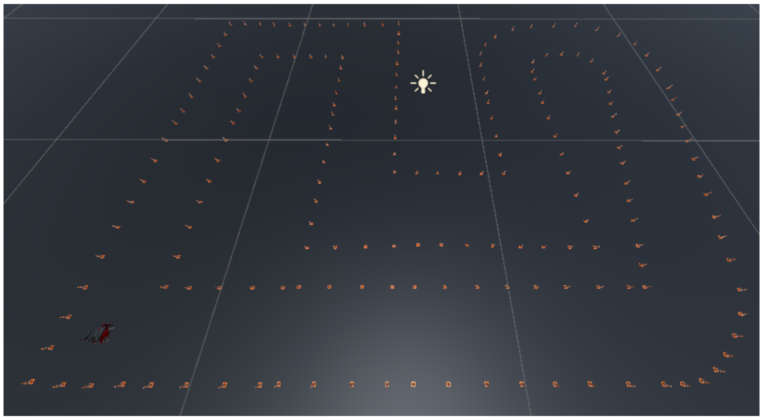

Figure 14: Track of the Simulation

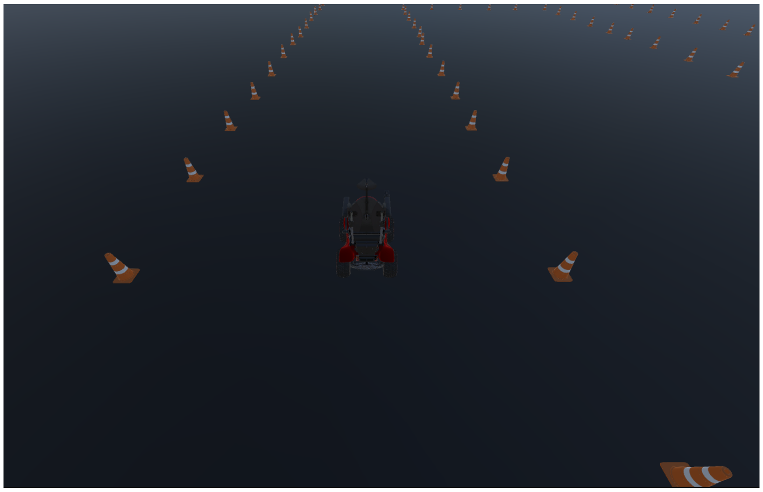

Figure 15: Point of View of Simulation Running

3.4.6 Error Handling and Testing

There are many errors and validations that we must consider handling to ensure that our microcontroller can work and maintain itself without the use of a computer monitoring its inputs and outputs. Items such as sensor data validity and error code logging are important for the development of the microcontroller, resulting in a more defined and robust intellectual motor for the project.

3.5 Project Testing

A significant part of the design for the project is testing, testing is a pivotal step in the project's lifetime to ensure that our subsystems are working as intended. Our primary subsystems will be the PCB and Sensor, Microcontroller, and Simulator.

3.5.1 PCB and Sensor Testing

The PCB and sensor testing were conducted to assess the functionality, reliability, and safety. In order to achieve this, a series of tests was carried out. The first test involved verifying whether the sensors were able to properly respond to changes in a magnetic field from a magnet. This was done by testing variable locations of the magnet and the Hall effect sensor in a manner that activated the Hall effect sensors in different patterns. Additionally, tests were performed to assess the reliability and longevity of the sensors in the presence of the magnet, with simple sustainable tests conducted to determine if the sensors remained active over an extended period. Finally, efforts were made to ensure that the sensors complied with safety standards for medical devices. Concerns such as heat generation, electromagnetic interference, and shock were investigated to ensure compliance.

3.5.2 Microcontroller Testing

The testing plan for the microcontroller was conducted as a series of four tests: Algorithm validation, communication testing, power testing, and error handling. Testing the algorithm for translating sensor data into control commands to send to the computer for emulation was crucial for communicating with the other subsystems. By implementing and adjusting the algorithm, it was verified that the microcontroller could properly differentiate against variable tongue locations. Calibration was also a part of the algorithm to generate tongue localization for algorithm testing. A microcontroller was used by itself with a hall effect sensor and a magnet to generate data to send to the microcontroller for processing. Communication testing was also a crucial part of the microcontroller, ensuring its ability to interact with the sensor and computer, which was important for communication between subsystems. Error handling was necessary testing to ensure that malformed data input or unexpected input data did not break the microcontroller and that it continued to work as intended afterward.

3.5.3 Simulator Testing

The simulation will serve as a stand-in for the actual wheelchair. As a result, it is important that the simulation is functional, compensates for edge cases, and integrates with the microcontroller. To test the simulation, we will use Unity software to generate a real-world scenario, such as grounds on UVA where a wheelchair can move based on the inputs from the microcontroller. Ensuring the simulation is able to read the serialized commands sent to the simulation is imperative for the project. Edge cases should also be tested such as rapid movements or tongue movements that are not as natural. Offering a tick rate would be able to account for the rapid movements and complex tongue instances. Finally, the simulator can integrate with the microcontroller to ensure that the inputs from the microcontroller can properly represent the user's movements with their tongue inside of the Unity simulation.

4 External Considerations

4.1 Navigating Challenges

4.1.1 Resource Constraints

Resource constraints were a tangible consideration in this project's research and development phase. This problem was encountered when trying to obtain certain components and agents for this project. Concerning magnet procurement, some constraints showed up when trying to buy magnets of varying strengths and geometries during the testing phase of this project. This is because trying to obtain a wide range of desired magnets to do ultra-rigorous testing is neither cost nor time-effective and was not even possible due to the limited selections of magnets that are available in the marketplace. To combat this, we had to set up experiments with the magnets we did have and then extrapolate expressions for a general case. This allowed us to figure out what minimum strength magnet we needed for this project. Further, finding sensors that could meet our 3-dimensional characterization requirements was difficult. The only sensor that had Hall effect sensitivity in the X/Y dimensions was the RR112-1G42-531 Hall Effect sensor. Due to this constraint, we had to build the rest of the system around the limitations of this device and the resource limitations of the online marketplace.

4.1.2 User Adaptability

User acceptability and adaptability were other restrictions that we had to be mindful of. A recent anecdote from a Georgia Tech report brought up the idea that quadriplegics still wanted the front of their faces shown to the world while operating their wheelchairs. We wanted to adhere to these considerations to make the product as user-friendly as possible. In accordance with that, our physical design went through multiple iterations.

4.1.3 Modeling Accuracy

Another limiting factor to consider was actually trying to model the interior of someone's mouth. It was impossible to account for all cases because everyone's skull is different. Because of this, we had to make approximations. We also had to account for the latent magnetic field that the earth creates. This was and could be a detectable field that might affect sensor performance.

4.2 Tailoring the Solution

4.2.1 User Variability

Everyone's face is different, so we must find ways to account for that in our software initialization and sensor placement. This is important because we need to ensure that the tongue drive system will work and be applicable to all face structures and variability. Exploring possible customization options can be used to be inclusive for all individuals using this system.

4.2.2 Structural Integrity

We need to make sure that our design has good structural integrity so users don't destroy it. It is possible that users may apply a variable amount of force to the device as a way to learn how the system works so it is important that the design is made to sustain general wear and tear and still be functionally complete.

4.2.3 Modularity and Ease of Replacement

If a user broke the item, we made it so pieces could be easily replaced or exchanged. By having a modular design process, we hoped to only need to replace certain parts that were approaching unacceptable levels of operation compared to replacing the whole system when a part became defective, thus making it more economically feasible for the user and product producer.

4.2.4 Prototyping in Real-Life Scenarios

We also had to find a way to prototype the magnet safely in a real person's mouth. Testing a prototype with real users was necessary to ensure that the magnet could be safely and comfortably placed in a user's mouth, be it from a piercing, wrapping around the tongue, or a medical adhesive on the tongue. Once figured out, we could simulate real-life scenarios and explore new factors such as comfort, ease of use, speaking while using, and a magnet's impact on maintaining oral hygiene.

4.3 Health, Safety, and Affordability

4.3.1 Health and Safety

We initially found magnets over 4000 G dangerous to the human body [15]. However, the magnet geometry is such that the magnetism seen by the human body is negligible, as the field drops to a harmless level about 1 cm from the magnet. Further, most of the materials that are in a human mouth are either slightly diamagnetic or paramagnetic. Materials that would fall under these categories are silver (such as fillings), iron in blood, water, etc. However, the effect is not enough to cause any interactions with these materials.

4.3.2 Material Toxicity

We also had to ensure that the materials the magnet was made out of were nontoxic. A nontoxic material for the magnet was necessary for the welfare of the user to ensure that the product they were using also did not inadvertently cause health risks to the user. Neodymium iron boron magnets in their solid form were found to possibly have low to moderate toxicity, though their long-term and short-term effects had yet to be fully researched [18]. The elements of this compound were not inherently toxic; however, corrosion, inhalation, and breakage were health hazards to be aware of when handling these magnets.

4.3.3 Affordability

Lastly, we wanted this to be affordable, so ensuring the price kept this option viable was important [11]. It was important that the system's design choices were consciously being considered for cost-effectiveness and optimal resource efficiency. These choices were intentional such that it was possible for any user who needed this system to afford one within an acceptable and viable price range.

4.4 Standards and Regulations

4.4.1 IPC Standards

We abided by IPC Standards for Board Fabrication. It was important to consider IPC standards to ensure the best quality board design and electronic components were used for the system. Compliance with this standard instilled a sense that the device would operate effectively and safely for users.

4.4.2 Medical Device Regulations

Depending on how we define the usage of the tongue-driven wheelchair mount, it is possible that we may run into a concern with medical device regulations. Even if this is just assistive technology, we may need to comply with regulations such as those from the Food and Drug Administration (FDA) or other proper authorities so that our device is able to be approved for safety and commercial use by any user who wishes to use it.

5 Expectations

The project aimed to emulate the tongue drive system to justify it as a viable solution for quadriplegics and those suffering from motor impairment. This project depended on four different divisions of components: Sensor Functionality, Microcontroller Programming, User Adaptability, Safety, and Health.

5.1 Sensor Functionality

The sensor functionality is expected to accurately respond to the magnetic fields created due to the user's tongue inputs. The sensors should then be able to send this data to the microcontroller.

5.2 3D Modeling/Mechanical functionality

This project's mechanical and modeling aspects had to be completed for the physical establishment and installation of the sensors to be placed and used for data input from the tongue's magnet. It was essential that the sensors be securely fastened to the user's head so the calibration data remains true even after multiple iterations of removing/putting the sensor mount from the user's head.

5.3 Microcontroller Programming

The microcontroller is imperative for success since it is the logic unit responsible for completing the data processing from the sensors and serializing this data after running it through an algorithm for the computer to produce a movement input instruction from the microcontroller.

5.4 User Adaptability

It was important that the implementation of the algorithm for the microcontroller and the design of the modeled headpiece to be held with consideration from all views and able to be intuitive and adjustable as needed for any users.

5.5 Safety and Health

It was crucial that the safety and health regulations be considered throughout the lifetime of the project. By meeting all the criteria of industry standards and regulations, we ensured that our product will be able to be used safely and without concern.

6 Final Results and Reflection

6.1 Results

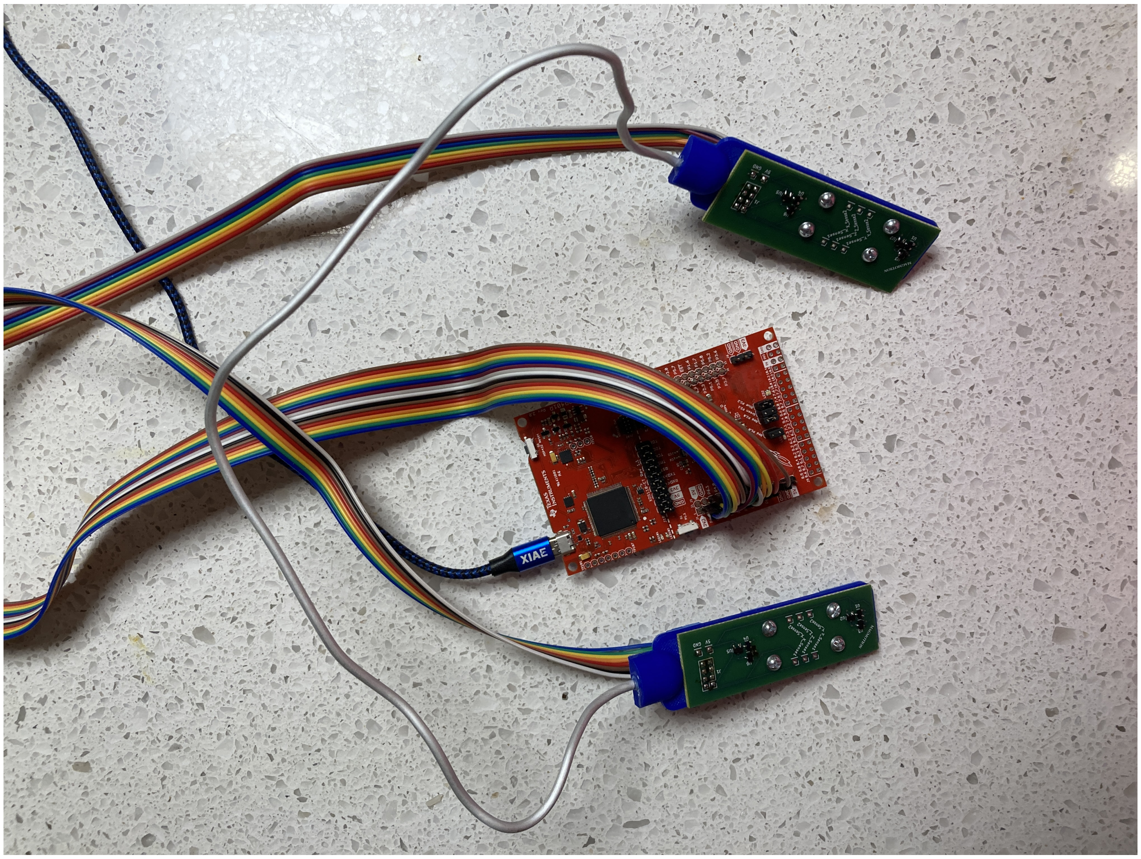

Figure 16: Full Picture of System

All components have been successfully interconnected, including Sensor design, 3D modeling, Software and firmware, and simulation. Following the integration of these elements, the system demonstrates its capability to accurately classify sensor data collected from tongue movement monitoring. The microcontroller, housing the KNN algorithm, processes this data to determine the most suitable command corresponding to the tongue's location. Subsequently, the information is transmitted via UART to the computer simulation, where the command manifests as a visual response within the simulation, showcasing effective and efficient operation.

6.2 Reflection

Overall, the system can work, but it has some limitations that we did not expect to happen until testing. One of the limitations that the system has right now is that it reads data too fast. Hence, when a user wishes to move forward and then rotate clockwise, the user may unexpectedly move backward for a brief moment because the movement the tongue used to reach the rotate clockwise (depending on the user's customized controls) passed through the backward command. Although brief, it is noticeable. We attempted multiple fixes, such as sampling slower, but sometimes the sample would catch the command that was not desired, which made the simulation fail to work as intended. Another approach was to have a list of commands over a span of time where the commands sent are the majority inside of the list. This approach did, in fact, work, but its caveat was that its computing power was demanding and failed to run at a competitive speed, which in turn served as an ineffective solution to the limitation.

While the limitation is minimal, it is still noticeable, and with consideration that this system is intended for real electric wheelchair integration, it serves as an important issue to address for a later iteration of the system.

7 Cost

The total cost to experiment, test, develop, integrate, and build the system came to approximately $428. The breakdown of this cost is shown below in Table 1.

Component	**Cost**
Magnets	$81.85
Sensors	$90.78
Other/Building Materials	$137.94
MSP432 Microcontroller	$17
PCBs	$100
Total Cost	**$427.57**

Table 1: Cost Breakdown of Components for the System

8 Timeline

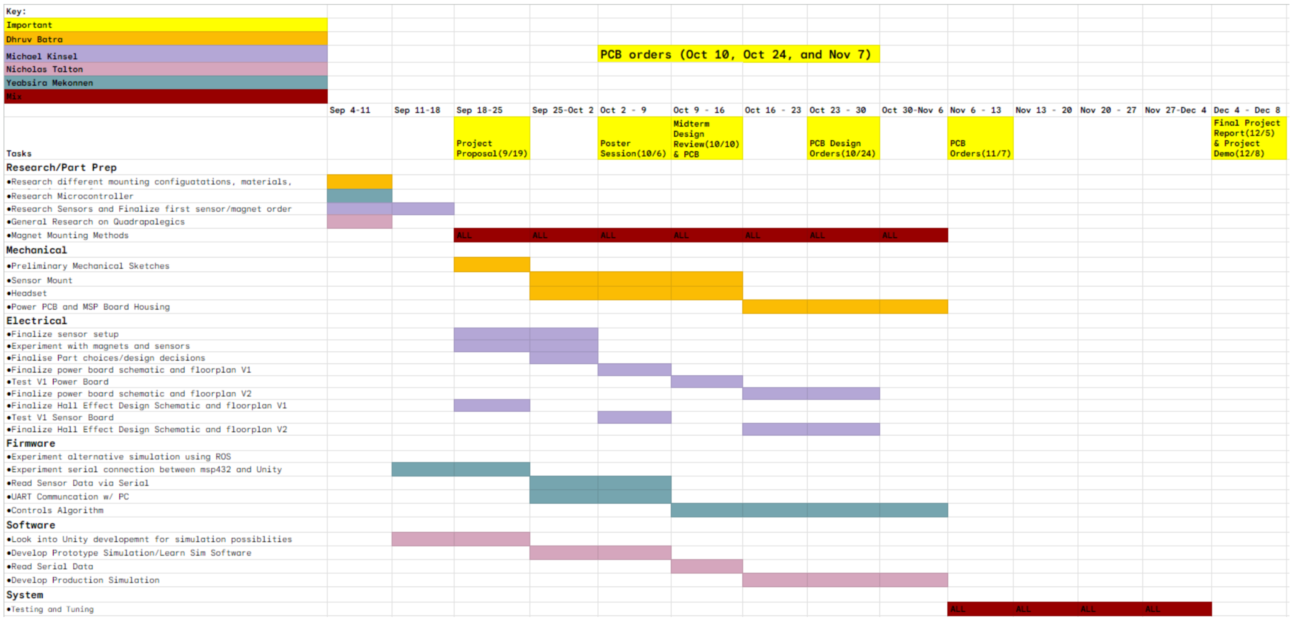

Figure 17: Gantt Chart

The above Gantt Chart shows the timeline for the project, including important deadlines. The Tasks are divided into six major sections: Research, Mechanical, Electrical, Firmware, Software, and System. Each individual in the group is assigned a color within the chart to make identifying priorities easy.

8.1 Division of Labor

Dhruv Batra was the primary lead responsible for the Mechanical tasks, with a secondary focus on the Firmware task. This took advantage of his background using CAD software from ENGR 1624 as well as embedded classes

ECE 4501 and ECE 3430. Yeabsira Mekonnen was primarily responsible for the firmware tasks with a secondary focus on the software tasks. He did this by applying embedded knowledge from ECE 4501 and ECE 3430 and previous uses of the Unity Engine. Nicholas Talton was primarily focused on the Software tasks but helped with Mechanical and Firmware tasks as needed. He completed these tasks by learning more about the Unity Engine and taking advantage of embedded knowledge from ECE 3430 and CAD experience from ENGR 1624. Finally, Michael Kinsel was primarily focused on the Electrical tasks, which were the PCB Design and the EMF knowledge needed to work with the magnetic field sensors. Michael pulled on his knowledge from ECE 3209 as well as the Fundamental course for his tasks.

8.2 Parallel Tasks and Serial Tasks

Up until the development of the controls algorithm, tasks in the separate sections were done mostly independently, with some connections between the Mechanical and Electrical sections as well as the Firmware and Software Sections. The exception to this was the system test and tuning, which was done after each section's tasks were completed. All the Research tasks were in parallel with all the other tasks within and outside of the Research section. For the mechanical section, the preliminary sketches for all the parts were done in parallel with all the other tasks. A set of serial tasks were the development of the sensor mounts and the design of the sensor PCB. The designing and production of the sensor mounts had to follow the design of the sensor PCBs because specific measurements of this board were needed to design the mounts. Once the sensor PCB design v1 was done, then the sensor mount and headset were developed independently of the other task. Lastly, the PCB and MSP432 Board Housing development had to follow after the power PCB design was finalized.

For the Electrical Section, the sensor PCB design had to precede the mounting of the sensor mounts. Also, the power PCB design had to be finalized before the housing for them was designed. Other than those two, the other tasks could proceed in parallel with each other. For the firmware section, once the development of the controls algorithm had started, it needed a usable prototype of the headset and sensor mount, prototype simulation code, and prototype PCBs as early in the development as possible. This was because it allowed for an easy way to test the classification algorithm if all the components for the final project were being used as the classification algorithm was being made. Before this point in the Firmware section, tasks were done in parallel with all other tasks.

For the Software section, the production of the final simulation software needed serial input from the MSP432 board to test, so this task needed to follow the achievement of Reading Sensor Data via Serial and UART Communication with the PC. Afterward, the final version of the simulation was worked on in parallel with all the other tasks being done. Finally, System testing needed to occur after all the tasks on the other established sections were done since it tested the whole system.

References

[1] J. E. Lasfargues, D. Custis, F. Morrone, J. Cars well, and T. Nguyen, "A model for estimating spinal cord injury prevalence in the United States," Spinal Cord, vol. 33, no. 2, pp. 62–68, 1995. doi:10.1038/sc.1995.16

[2] C. C. medical professional, "Quadriplegia (Tetraplegia): Definition, Causes & Types," Cleveland Clinic, https://my.clevelandclinic.org/health/symptoms/23974-quadriplegia-tetraplegia (accessed Sep. 20, 2023).

[3] S. Menon, A. Nambiar, A. Pariyarathu, and K. M, "Tongue Driven System," International Journal of Engineering and Technical Research, vol. 3, no. 4, Apr. 2015.

[4] M. E. Lund et al., "Inductive tongue control of powered wheelchairs," 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, 2010. doi:10.1109/iembs.2010.5627923

[5] E. R. Lontis, B. Bentsen, M. Gaihede, F. Biering-Sorensen, and L. N. Struijk, "Wheelchair Control With Inductive Intra-Oral Tongue Interface for Individuals With Tetraplegia," IEEE Sensors Journal, vol. 21, no. 20, pp. 22878–22890, 2021. doi:10.1109/jsen.2021.3111549

[6] M. Jain and H. Joshi, "Tongue Operated Wheelchair for Physically Disabled People," International Journal of Latest Trends in Engineering and Technology, vol. 4.

[7] J. Kim et al., "The Tongue Enables Computer and Wheelchair Control for People with Spinal Cord Injury," Science Translational Medicine, vol. 5, no. 213, 2013. doi:10.1126/scitranslmed.3006296

[8] "Hall Effect." http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/Hall.html (accessed Sep. 19, 2023).

[9] "How does distance affect magnetic force? — Socratic," Socratic.org. https://socratic.org/questions/how-does-distance-affect-magnetic-force (accessed Sep. 19, 2023).

[10] "Experiment of The Month — Millersville University." https://www.millersville.edu/physics/experiments/023/ (accessed Sep. 19, 2023).

[11] Magnetoresistance." Chhatrapati Shahu Ji Maharaj University. [Online]. Available: https://gyansanchay.csjmu.ac.in/wp-content/uploads/2021/11/303-L17.pdf

[12] J. Kim et al., "The Tongue Enables Computer and Wheelchair Control for People with Spinal Cord Injury," Sci. Transl. Med., vol. 5, no. 213, Nov. 2013, doi: 10.1126/scitranslmed.3006296.

[13] Texas Instruments, "MAGNETIC SWITCH UNIPOLAR TO92-3," DRV5023AJELPGMQ1 datasheet

[14] "UART: A Hardware Communication Protocol Understanding Universal Asynchronous Receiver/Transmitter — Analog Devices." https://www.analog.com/en/analog-dialogue/articles/uart-a-hardware-communication-protocol.html (accessed Sep. 19, 2023).

[15] "Electromagnetic Fields Factsheet." Iowa State University of Science and Technology, 2022. [Online]. Available: https://www.ehs.iastate.edu/sites/default/files/uploads/publications/manuals/emf.pdf

[16] "REDROCK® RR112-1G43-531/532 TMR ANALOG MAGNETIC SENSOR." [Online]. Available: https://cotorelay.com/wp-content/uploads/2020/10/RedRock-RR112-1G42-1G43-531-532-Datasheet.pdf

[17] "DRV5053 Analog-Bipolar Hall Effect Sensor." Texas Instruments. [Online]. Available:

[18] K. T. Rim, K. H. Koo, and J. S. Park, "Toxicological Evaluations of Rare Earths and Their Health Impacts to Workers: A Literature Review," Safety and Health at Work, vol. 4, no. 1, pp. 12–26, Mar. 2013, doi: 10.5491/SHAW.2013.4.1.12.

Movement Impairments From A Social Perspective: How Assistive Movement Devices Impact Those With Motor Disability

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
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In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Nicholas Talton
Spring 2024

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor
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I. INTRODUCTION

According to the National Library of Medicine the global impact of spinal cord injuries (SCI) with respect to the years lived with disability (YLD) and annual age-standardized years lived with disability (ASYR) was estimated to be about 6.2 million cases worldwide (Ding et al., 2022). In addition to this, about 76 in 100,000 people contribute to this statistic. SCI impacts more than 17,800 Americans each year, with an estimated 294,000 Americans concurrently experiencing such injuries (Lasfargues et al., 1995). According to the U.S. Department of Health and Human Services (2023), spinal injuries lead to a multitude of physical and neurological impairments such as paraplegia, quadriplegia, chronic pain, and respiration issues to name a few. Spinal cord injuries primarily hinder the motor functions of a person therefore minimizing or even removing the usage of their limbs to move and communicate with other people (Kuriakose, 2022).

Some spinal cord injuries have various impacts on a person depending on if the person is injured on a particular part of the spine. According to the National Institute of Health (2023), spinal injuries happening closer to the bottom of the spine closer to the T2 to S5 vertebrae result in paraplegia. Paraplegia as they define is considered the condition where people have lost feeling in or are not able to move the lower parts of their body where the most impacted regions of the body can be but are not limited to the chest, stomach, lips, legs, and feet. The Shepard Center (2024) also noted that the closer an SCI is to the skull or brain area the more “extensive is the curtailment of the body's ability to move and feel. If the lesion is low on the spine, say, in the sacral area, there will likely be a lack of feeling and movement in the thighs and lower parts of the legs, the feet, most of the external genital organs, and the anal area. But the person will be able to breathe freely and move his head, neck, arms, and hands. By contrast, someone with a broken neck may be almost completely incapacitated, even to the extent of requiring breathing assistance."

As a result of these injuries, there have been urgencies to regain and obtain ways of motor assistance for those suffering from any SCI that would benefit from an opportunity. Assistive technology is a field of engineering that aims to improve the quality of life of certain groups of people based on their needs by focusing on an aspect of their current life that needs more assistance than another part. One of the most important aspects of the impact of assistive technology is how society and politics perceive it. With this in mind, I ask the following question: How has assistive movement technology impacted those with physical limitations and how critical is the urgency for a new design research for individuals suffering from SCI? Understanding the urgent need for innovative design research, particularly for those with Spinal Cord Injuries (SCI), demands a comprehensive examination. By delving into a range of assistive technologies and examining case studies of existing systems within socio-technical frameworks, we can illuminate the multifaceted impact and nuanced challenges inherent in these technologies. From analysis of individual perceptions of self concerning an SCI, exploration of stigma surrounding people with SCI, and consideration of competency we can utilize the theories of the SCOT framework and Technological momentum to grasp a firmer idea of how to work with individuals suffering from SCI to better assist them in the future. Each system offers unique opportunities for enhancing user independence and societal integration, underscoring the critical importance of addressing control mechanisms and design considerations within specific contexts.

II. ANALYSIS WITH STS FRAMEWORKS

Francis provided a discussion on a previous study researching how able-bodied people perceive disabled people with and without bionic devices (Francis, 2022). She asserted bionic assistive devices can lead to more positive perceptions by able-bodied individuals and that perhaps in the future the competency gap will be bridged between people with and without disabilities.

With respect to the sociotechnical aspects of how assistive technology impacts those with disabilities, Bijker and Pinch's framework becomes relevant in this case because one of their most important points from the Social Construction of Technology framework was the multidirectional model which implies that different groups of people perceive some set of technology differently from another group (Bijker & Pinch, 1987). Considering the case of quadriplegics, multiple groups of people solve the same problem to assess a new solution that could provide a benefit to quadriplegics in a newly perceived way be it with brainwaves or with magnetic fields.

Hughes closely aligns with Bijker with assistive technology because Hughes' main points are that technology is influenced to improve upon itself such that it is always being influenced by factors such as innovation, reverse salient, and competition. Assistive technology is impacted by these factors such that a reverse salient provides the initial push for innovation which in turn inspires more groups of people to try and compete for a new assistive technology to be the traditional device in the future (Hughes, 1987). Bijker and Pinch's SCOT framework in combination with Hughes' aspects of technological momentum complement each other by challenging new growth for how newfound considerations with technological development begin. Development, where the phase in which the social construction of technology becomes clear. This involves the acquisition of social, political, and economic aspects necessary for the survival of a system beyond the technical artifact.

The SCOT framework builds upon Hughes' approach to Development by falling in line with the aspect of on how there can be multiple different perspectives on how a group values a particular technology and its function such that it can inspire another aspect of Hughes' which is innovation. Innovation can be defined as building and improving on past technological developments to establish a new technological system. Innovation in terms of assistive movement systems can benefit an individual who may need a more sophisticated movement system than there is currently, but with innovation, instills a sense of competitiveness. Competition is present with innovation since multiple groups of system builders are eager to become the new relevant common practice for a particular technological system. All of these factors can positively impact the technological momentum of wheelchair development but there is an issue that was underscored while discussing the benefits of Hughes' approach and SCOT which is if we are considering how the individuals are using the technological system.

One derivative of assistive movement devices is wheelchair mobility systems. There are multiple types of mobility devices for wheelchair users such as wheelchairs that can be moved manually, simply by rotating the wheels that move it by hand. Another way is for older people who are not as strong as they were previously to use a motorized wheelchair for assistance in moving around now. This allows the user to have freedom of movement at an older age while not forcing them to depend on society to help them but still have their freedom of movement. Now considering the case where a handicapped user has needs where they are not able to move anything below their neck, we call this tetraplegia or quadriplegia. This is an uncommon case where a spinal cord injury about the neck severs a connection of the body so that the brain cannot interact with the other appendages of the body such as the arms or legs. While this case is rare, it still impacts millions of people, thus the comfort and freedom of movement for people with this diagnosis depend on society and engineers to develop new technology where they too can experience the freedom of movement without the worry of needing society to burden them. The most common way a person with this injury moves is through a sip and puff system where the user sends a series of sips and puffs for the movement device to decipher as a command of movement whether it be forward, rotate, back, or stop. The current technology that is commonly accepted as the traditional way for quadriplegics to move is the sip-and-puff method where a series of sips and puffs serve as data for a particular command for the wheelchair (Jeff, 2023), but new solutions are being created to compete with the traditional method. There have been several studies for those with manual wheelchairs and those with motorized wheelchairs, but there are fewer case studies of those with tetraplegia even though this assistive device is equally if not more important than the previous assistive technology devices. Manual wheelchairs have autonomy and control, while motorized wheelchairs provide for enhanced mobility. In contrast, the forefront of assistive movement devices with tetraplegics is competitive in a sense because the current system of use has issues where the user feels exhausted after an extended period of use due to using cheek muscles that are not regularly used for a long time (Menon et al., 2015). The reason why there is competition for finding a better mobility device practice is because while using the sip and puff systems the problem arises that the idea of sending sips and puffs in a moment where time is of the essence can be stressful and tedious. For example, needing to stop or adjust the motorized sip and puff system before the user falls off the side of a sidewalk demands the user to remember the command within a time frame that if failed could eject the user from the wheelchair and they would not be able to move and would require help from another person. Therefore, the urgency for new design research for individuals suffering from

SCI is critical, and multiple developments are taking place for those in need with these aspects of STS in mind.

III. CASE STUDIES

The first sophisticated engineered device is from Izzuddin and his fellow researchers who used a system that uses an Electroencephalography (EEG) signal processing headset that reads electrical body signals and then classifies the signal into a movement command by using machine learning to objectively qualify the signal being sent to the system for the wheelchair (Izzuddin et al., 2015). A more recent application by research groups led by Lund and Lontis of providing a new solution to people suffering from tetraplegia is a tongue-driven system where the user takes advantage of the intricacies of how sophisticated the movement of the tongue is. Effectively, the tongue can be interpreted as a joystick where the user is able to use their tongue to send information to sensors to move a wheelchair in a direction they would like to move. This approach is more intuitive, which allows for the edge over inputting a series of sips and puffs to tell the wheelchair to move in a direction compared to simply moving the tongue forward to move forward. Researchers came up with using a magnet on the tongue to send data to a retainer in the mouth where the retainer would send information on how to move the wheelchair, essentially using the tongue as the joystick (Lund et al., 2010; Lontis et al., 2010). One of the benefits of this system is that a tongue-driven wheelchair has an easy learning curve and if very much more intuitive for those who have mobility impairments and those without, so both groups of people have the same learning rate. One of the difficulties with the system itself is that it is very user-centered, so it depends on the user to complete calibration protocols correctly for it to function as intended. In addition to calibration, processing speed is important, it needs to be fast enough where its not instantaneous but fast enough that it feels instantaneous, somewhere around 200 milliseconds at most which can be a difficult task to maintain for some wheelchair systems.

Similarly, Jain and Joshi wanted the system to focus on user comfort and be somewhat discreet to external observers, so they used an array of sensors that were external to the mouth that capture data which is processed by a microcontroller using a control algorithm that is then used to simulate a wheelchair in a program (Jain & Joshi, 2014). Wanting to focus on user feedback, technical, and social actors, Kim and Lu both focused on a voice-controlled assistive device project, which prioritized language inclusivity and explored facial movements for control (Lu & Chen, 2012; Kim et al., 2013). This research highlighted the significance of user feedback in designing assistive devices that improve mobility and minimize social challenges. Although both Hain, Joshi, and Izzuddin provided a system solution that is able to benefit individuals with SCI, perhaps the most revolutionary way to help assist users with SCI was recently developed through a company called Neuralink.

Neuralink announced in early 2024 that they had successfully implanted a brain-computer interface (BCI) into a human (Guarino, 2024). This success opens up a new window in assistive technology because it can find a perfect compromise between usability and user preferences in terms of facial visibility for a user. If the success at Neuralink is continued it is possible that the competency gap between able-bodied people and disabled people can be fully bridged, resulting in public perception of disabled people as being on the same level as able-bodied people. While Neuralink's breakthrough holds immense promise for advancing assistive technology and promoting inclusivity, it also prompts profound philosophical reflections on the nature of human identity and the intersection of biology and technology. In terms of the user's sense of self with Neuralink it is possible that the user could feel split between who they are as a person and who they are as a machine but, it is also possible that the user could consider the BCI an extension of their thought which would help the individual obtain and maintain their image and sense of self.

IV. FURTHER ANALYSIS

In terms of the social impacts of assistive mobility devices, especially those with tetraplegia, the impact is significant. These devices play a pivotal role in establishing a sense of independence freedom and inclusion within our society. Manual and motorized wheelchairs have served as major stepping stones to including the lives of individuals with motor impairments by allowing them the freedom to contribute to society individually. Having the means to be able to contribute individually to society more it allows for more interconnectedness between those who do not have motor impairments and those with motor impairments. Despite these advancements, however, challenges do persist as seen with individuals with tetraplegia. This motor inhibition is a new challenge that can pose an issue to individuals who are looking to have freedom of movement and independence. For example, as seen above with sip and puff systems it is crucial that we accommodate for fatigue and speed of movement processes since movement is a very quick and dynamic process. These two simple freedoms truly underscore the need for continued innovation in assistive technology.

Assistive movement has a promising future, with the development of multiple new systems to use this brings about competition, and competition brings about innovation. By furthering advancements in technologies such as sensors and signal processing we would be honing in more refined and intricate systems that are more responsive and positively impact a user. These innovations offer increased independence, mobility, and inclusion within society. While traditional methods like sip-and-puff systems have been the norm, newer solutions like tongue-driven systems provide a more intuitive and less physically demanding alternative. However, challenges such as fatigue, calibration requirements, and processing speed persist, underscoring the ongoing need for innovation and user-centered design in assistive technology. Collaborative efforts between engineers, stakeholders, and users are crucial in driving the future of these innovations and ensuring inclusivity and accessibility in society. I believe that one of the most important features comes from the actual user of products, so placing more emphasis on user-centered designs and customization in the development of assistive mobility devices will only help tailor a better solution for individual needs and preferences which in turn would maximize individual satisfaction and contribution to society. By simply working with multiple parties and individuals who will be using these devices we can contribute to the evolving needs of individuals with mobility impairments by bridging the gap between inclusivity and accessibility in today's society with people with and without mobility impairments.

V. CONCLUSION

As we have seen from Francis' study people have a particular social stigmatization and stereotyping for those with a disability. Although groups of engineers have been working to help bridge the competency gap created by those without disabilities and those with disabilities, there are still discriminatory practices in aspects of life, especially employment opportunities and access to public spaces (Barnes, 1992). Economic accessibility is also another prevalent issue for those suffering from SCI. This is because an SCI causes significant damage to important motor functions in the individual's body, as a result, to accommodate for the injury to adjust with new assistive movement devices it becomes costly to the extent that economic accessibility could be a driving force for what is withholding accessibility from individuals who need these devices to feel the same freedoms as an individual with no motor inhibitions (Barnes, 1992). Social isolation and loneliness also have impacts on individuals with SCI. Since individuals with SCI suffer from motor inhibition it is entirely possible that even though they may have an assistive movement device to bridge the competency gap, they could still struggle to fully participate in social activities and maintain meaningful relationships due to physical barriers and societal attitudes. Recognizing and addressing intersectionality is essential for promoting equity and inclusion within society and ensuring that individuals with SCI have equal opportunities to participate fully in all aspects of life. This requires adopting an intersectional approach to policy-making, advocacy, and service provision that considers the diverse identities and experiences of individuals with disabilities. Additionally, fostering collaboration between disability rights organizations, social justice advocates, and other marginalized communities is essential for advancing intersectional perspectives and dismantling intersecting forms of discrimination and oppression.

People with physical limitations, especially quadriplegics, need more user-friendly, discreet, and affordable assistive technology solutions. Traditional methods are often challenging and limit the independence of the impacted user. The impacts of the solution in mind from my capstone will hope to enhance the level of independence of a user as well as making it more inclusive and affordable by all people so that everyone is able to have their own mobile independence and freedom regardless of physical limitations. Being able to address the relevant assistive technology limitations can result in increased positive perceptions of society on those with disabilities. This paper aims to address or at least shed light on the relevant factors that shape the multifaceted relationship between assistive technology, the individual, and society with hopes that lead to a more inclusive and empowering future for those with disabilities.

References

Barnes, C. (1992), "Disability and Employment", Personnel Review, Vol. 21 No. 6, pp. 55-73. https://doi.org/10.1108/00483489210021080

Bijker, W. E., & Pinch, T. J. (1987). The social construction of fact and artifacts. *Philosophy of technology: the technological condition: an anthology, 107-139.*

Cleveland Clinic medical. (2022). *Quadriplegia (tetraplegia): Definition, causes & types*. Quadriplegia. https://my.clevelandclinic.org/health/symptoms/23974-quadriplegia-tetraplegia

Ding, W., Hu, S., Wang, P., Kang, H., Peng, R., Dong, Y., & Li, F. (2022). Spinal cord injury: The global incidence, prevalence, and disability from the global burden of disease study 2019. *Spine*, *47*(21), 1532.

Francis, N. (2022). *Novel EMG-IMU Sensor Array for a 5-DOF Wearable Robotic Upper-Limb Exoskeleton; Examining the Politics Surrounding Assistive Devices*. Charlottesville, VA: University of Virginia, School of Engineering and Applied Science, BS (Bachelor of Science). https://doi.org/10.18130/0fb2-bb76.

Guarino, B. (2024, February 20). Elon Musk's Neuralink has implanted its first chip in a human brain. what's next? Scientific American. https://www.scientificamerican.com/article/elon-musks-neuralink-has-implanted-its-first-chip-in-a-human-brain-whats-next/#:~:text=Elon%20Musk's%20brain%20science%20start,human%20for%20the%20first%20time.&text=Billionaire%20technologist%20Elon%20Musk%20announced,human%20for%20the%20first%20time.

Izzuddin, T. A., Ariffin, M. A., Bohari, Z. H., Ghazali, R., & Jali, M. H. (2015, November). Movement intention detection using neural network for quadriplegic assistive machine.

In *2015 IEEE International Conference on Control System, Computing and Engineering (ICCSCE)* (pp. 275-280). IEEE.

Jafar, M. R., & Nagesh, D. S. (2023). Literature review on assistive devices available for quadriplegic people: Indian context. *Disability and Rehabilitation: Assistive Technology*, *18*(6), 929-941.

Jain, M., & Joshi, H. (2014). Tongue Operated Wheelchair for Physically Disabled People. *International Journal of Latest Trends in Engineering and Technology (IJLTET)*, *4*.

Jeff. (2023, April 28). *Understanding assistive technologies: What are SIP-and-puff systems?*. WCAG Audits, ADA Accessibility Audits & Section 508 Audits. https://www.boia.org/blog/understanding-assistive-technologies-what-are-sip-and-puff-systems#:~:text=The%20system.

Hughes, T. P. (1987). The evolution of large technological systems. *The social construction of technological systems: New directions in the sociology and history of technology*, *82*, 51-82.

Kim, J., Park, H., Bruce, J., Sutton, E., Rowles, D., Pucci, D., ... & Ghovanloo, M. (2013). The tongue enables computer and wheelchair control for people with spinal cord injury. *Science translational medicine*, *5*(213).

Kuriakose, D. C. & SpinalCord.com Team, & (2022). *Quadriplegia & Tetraplegia: Definition, causes, symptoms, and treatment*. Quadriplegia & Tetraplegia: Definition, Causes, Symptoms, and Treatment. https://www.spinalcord.com/quadriplegia-tetraplegia.

Lasfargues, J. E., Custis, D., Morrone, F., & Nguyen, T. (1995). A model for estimating spinal cord injury prevalence in the United States. *Spinal Cord*, *33*(2), 62-68.

Latour, B. (1992). Where are the missing masses? The sociology of a few mundane artifacts. *Shaping technology/building society: Studies in sociotechnical change, 1, 225-258.*

Lontis, E. R., Bentsen, B., Gaihede, M., Biering-Sørensen, F., & Struijk, L. N. A. (2021). Wheelchair control with inductive intra-oral tongue interface for individuals with tetraplegia. *IEEE Sensors Journal*, *21*(20), 22878-22890.

Lu, Y., & Chen, Y. (2012). Prototyping potential control systems to assist complete quadriplegics. In *The 5th 2012 Biomedical Engineering International Conference* (pp. 1-5). IEEE.

Lund, M. E., Christiensen, H. V., Caltenco, H. A., Lontis, E. R., Bentsen, B., & Struijk, L. N. A. (2010). Inductive tongue control of powered wheelchairs. In *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology* (pp. 3361-3364). IEEE.

Menon, S., Nambiar, A., Pariyarathu, A., & Krishnamoorthy, M. (2015). Tongue Driven System. *International Journal of Engineering and Technical Research, 3(4). ISSN: 2321-0869.*

National Institute of Mental Health. (2022). *About Spinal Cord Injury*. U.S. Department of Health and Human Services, National Institutes of Health. https://www.nichd.nih.gov/health/topics/spinalinjury/conditioninfo#:~:text=The%20state%20of%20an%20individual,can%20usually%20be%20called%20paraplegic.

Newsome | Melton (2019). *Quadriplegia: Types of paralysis: Brain and Spinal Cord Injury Information*. Newsome | Melton. https://www.brainandspinalcord.org/quadriplegia/#:~:text=A%20patient%20with%20complete%20quadriplegia,control%20over%20their%20hand%20movements.

Shepherd Center, KPKinteractive, American Trauma Society, National Spinal Cord Injury Association, & Christopher & Dana Reeve Foundation. Levels of Injury. https://www.spinalinjury101.org/details/levels-of-injury.

Star, S. L. (1999). The ethnography of infrastructure. *American behavioral scientist, 43(3), 377-391.*

U.S. Department of Health and Human Services. (2023). *Spinal Cord Injury*. National Institute of Neurological Disorders and Stroke. https://www.ninds.nih.gov/health-information/disorders/spinal-cord-injury

Tongue Driven Wheelchair for Quadriplegics

Exploring Assistive Technology's Impact on Those with Disabilities

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Computer Engineering

By
Nicholas Talton

October 27, 2023

Technical Team Members:
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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Rider Foley, Department of Engineering and Society

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Introduction

According to the National Library of Medicine the global impact of spinal cord injuries (SCI) with respect to the years lived with disability (YLD) and annual age-standardized years lived with disability (ASYR) was estimated to be about 6.2 million cases worldwide (Ding et al., 2022). In addition to this, about 76 in 100,000 people contribute to this statistic. SCI impacts more than 17,800 Americans each year, with an estimated 294,000 Americans concurrently experiencing such injuries (Lasfargues et al., 1995). Accoridng to the U.S. Department of Health and Human Services (2023), Spinal injuries lead to a multitude of physical and neurological impairments such as Paraplegia, Quadriplegia, chronic pain, and respiration issues to name a few. Spinal cord injuries primarily hinder the motor functions of a person therefore minimizing or even removing the usage of their limbs to move and communicate with other people (Kuriakose, D. C. & SpinalCord.com Team, 2022).

Most traditional wheelchairs use a joystick for movement freedoms, but for those that are less fortunate to move their upper body, that becomes problematic for the user to try and move a joystick, thus the user is forced to use their mouth and head for movement, but from Newsome | Melton (2019) it was observed that not all individuals who suffer from quadriplegia are able to move their neck muscles. According to the Cleveland Clinic (2022) a quadriplegic can be defined as someone who suffered a SCI where the impacted vertebrae are between C1 and C8**,** indicating that a SCI pertaining to the neck region has a high chance of resulting in quadriplegia. The most traditional method that quadriplegics use to move around is a technological innovation that uses sipping and puffing characteristics. This device offers movement for an individual at a tradeoff of it being difficult to learn, and tiring from continuously using facial and throat muscles to perform movement (Menon et al., 2015).

The goal for this project is to provide a different perspective of movement for an individual by using a magnet fastened to the tongue to cooperate with a series of sensors external from the mouth that will send data to a microcontroller to process and send to a wheelchair for movement commands. This capstone project seeks to revolutionize the existing technology system employed by individuals with spinal cord injuries by offering a more intuitive, efficient, and less physically demanding method of mobility. The ultimate goal of this project is to empower users, providing them with enhanced independence and a greater sense of personal freedom.

Tongue Driven Wheelchair for Quadriplegics

The current technology that is commonly accepted as the traditional way for quadriplegics to move is the sip and puff method where a series of sips and puffs serve as data for a particular command for the wheelchair (Jeff, 2023), but new solutions are being created to compete with the traditional method. The first method is from Izzuddin and his fellow researchers where they used a system that uses a Electroencephalography (EEG) signal processing headset that reads electrical body signals and then classifies the signal into a movement command by using machine learning to objectively qualify the signal being sent to the system for the wheelchair (Izzuddin et al., 2015). In a different approach, researchers came up with using a magnet on the tongue to send data to a retainer in the mouth where the retainer would send information of how to move the wheelchair, essentially using the tongue as the joystick (Lund et al., 2010; Lontis et al., 2010). Similarly, Jain and Joshi wanted the system to focus user comfort and be somewhat discreet to external observers, so they used an array of sensors that were external of the mouth that captures data which is processed by a microcontroller using a control algorithm which is then used to simulate a wheelchair in a program (Jain & Joshi, 2014). Wanting to focus on user feedback, technical, and social actors, Kim and Lu both focused on a voice-controlled assistive device project, which prioritized language inclusivity and explored facial movements for control (Lu & Chen, 2012; Kim et al., 2013). This research highlighted the significance of user feedback in designing assistive devices that improve mobility and minimize social challenges. All of these ideas and solutions provide a benefit in some aspect to help assist an individual who may benefit from assistive technology, but my capstone project aims to make a solution that is both intuitive, discreet, and affordable.

The capstone system will be positioned externally outside the mouth, so it still uses a magnet to manipulate magnetic sensor fields for movement inputs. This cost-effective system comprises three subsystems and a testing phase: 3D modeling/electrical sensors, microcontroller programming, simulations, and testing. The workflow begins with a customizable headpiece equipped with prongs containing magnetic sensors along the inside, parallel with the user's cheekbones. This headpiece serves as the mounting point for sensors, which relay data to the microcontroller, defining objective movements for the wheelchair. The microcontroller handles system calibration and data processing. It processes serialized data from the sensors, calibrating cardinal directions and generating a continuous datastream for simulation. The simulation emulates wheelchair movement, receiving data from the microcontroller. This project separates itself from the rest of the projects made previously because it is attempting to provide an efficient product for quadriplegics while still maintaining affordability so that even those who are less economically inclined are still able to experience the same freedom as those who have a better system. The control algorithm is very bare bone and processing speed of the microcontroller is slow, but but still provides command data to the simulation within 100ms while still being under

$100 for the entire system, which is a fairly good tradeoff to allow for inclusion of a larger subset within those who suffer from quadriplegia. Although my capstone project hopes to create a better living situation for the people who may benefit from it, it may also impose newfound struggles that we did not think of initially such as relevant surgery, assistance with the headset, and calibration systems requiring constant checks to name a few.

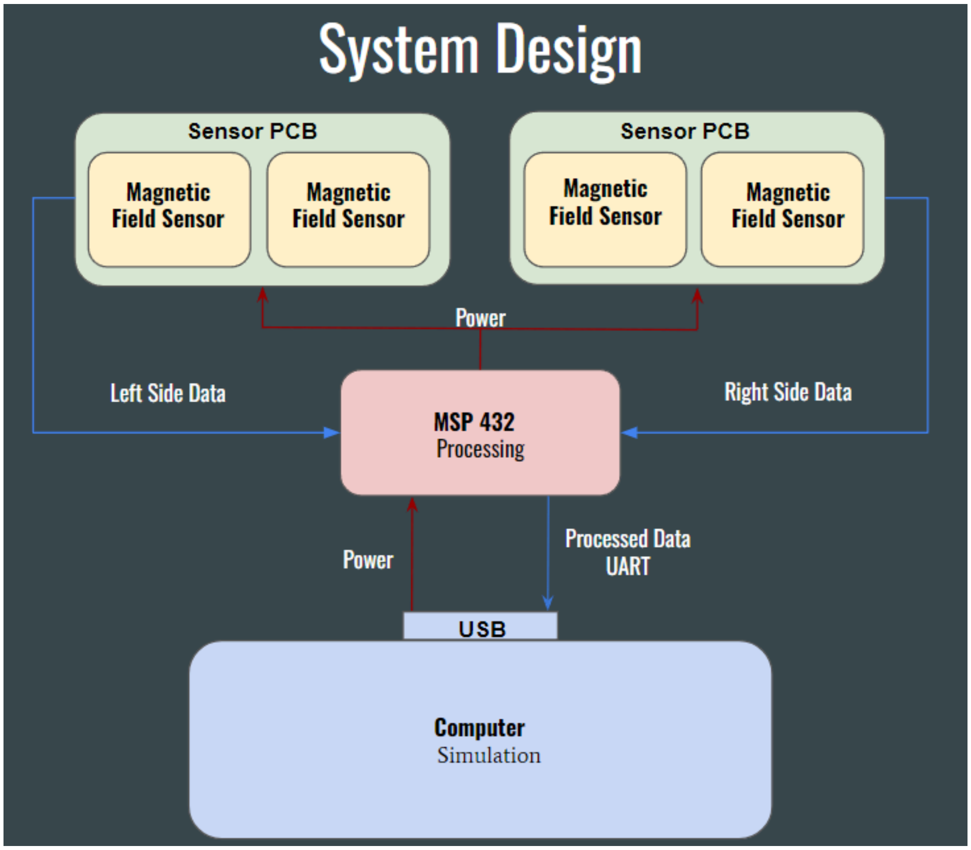

Figure 1. Image of the System design (Source: Talton, 2023)

Exploring Assistive Technology’s Impact on Those with Disabilities

Assitive technology is a field of engineering that aims to improve the quality of life of certain groups of people based on their needs by focusing on an aspect of their current life that needs more assistance than another part. One of the most important aspects of the impact of assistive technology is how society and politics perceive it. Francis provided a discussion upon a previous study researching how able-bodied people perceive disabled people with and without bionic devices (Francis, 2022). She asserted bionic assistive devices can lead to more positive perceptions by able-bodied individuals and that perhaps in the future the competency gap will be bridged between people with and without disabilities. Although assistive technology is meant to be a supporting device that is able to help people with everyday tasks, we know from Latour that when we choose to assign a non-human actor something of value, it is able to impose new values onto the human actors (Latour, 1992). Latour's concept of symmetry challenges the idea that assistive technology devices dont just assist but also exert its own influence on the human actor in a way such that the device could influence social perception resulting in the user's identity to be impacted. With respect to the sociotechnical aspects of how assistive technology impacts those with disabilities, Bijker and Pinch's framework becomes relevant in this case because one of their most important points from the Social Construction of Technology framework was the multidirectional model which implies that different groups of people perceive some set of technology differently from another group (Bijker & Pinch, 1987). Consider the case of quadriplegics, multiple groups of people solve the same problem to assess a new solution that could provide a benefit to quadriplegics in a newly perceived way be it with brainwaves or with magnetic fields. Hughes closely aligns with Bijker with assistive technology because Hughes' main points are that technology is influenced to improve upon itself such that it is always being influenced by factors such as innovation, reverse sailents, and competition. Assistive technology is impacted by these factors such that reverse salients provide the initial push for innovation which in turn inspires more groups of people to try and compete for a new assistive technology to be the traditional device in the future (Hughes, 1987). Hughes's assertions align closely with

Star's input on infrastructure. Star highlights that infrastructure is not easily defined as a single entity but rather a conglomerate of multiple aspects of infrastructure that generates an ethnography of some larger source of technology be it to be built on an installed base, where the fundamentals of some technology is intertwined with a previously established technology (Star, 1999). An additional aspect of infrastructure is learned by membership by a particular group of people, in this case assistive technology is a membership prioritized to those who would benefit from it but in some cases like in Francis' discussion with society perceiving assistive technology, this landscape has potential to encompass a larger group eventually. From all of the frameworks and cosndierations of relevant Science Technology and Society (STS) components, assistive technology and its impact on disabled people imposes a relevant, multifaceted, and evolving field of study. The influence of technology on user identity, societal perception, and the larger technological landscape highlights the need for ongoing research and dialogue within the field of assistive technology and beyond. With this in mind, I ask the following question: How has assisitive movement technology impacted those with physical limitations?

Research and Methodology

This question is important because it pertains to relevant aspects of STS where engineers may not perceive all valuable actors on a technological advancement, so this question opens a dailogue between the engineer and then individual. To begin exploring the aspects of this question we must decide on some type of data acquisition to gather data to analyse. One of the best ways to gather personal and relevant data for this research would be through interviews with people with physical limitations who use assistive technology and those who do not. Some of the questions I would ask them to gauge the data would be: How do you feel assistive movement technology has improved or hindered your independence and mobility? Is there any aspect of your life that has challenged you more now than it did before you acquired assistive technology? How has the introduction of assistive technology influenced your self-identity and the way you interact with others? Are there any particular aspects of assistive movement technology that you find most valuable or areas that you believe need improvement? Do you believe that there is a need for greater awareness and acceptance of assistive movement technology among society at large? If so, how do you think this can be achieved?

These questions provide relevant information for every aspect of importance from independence, newfound identity, assistive technology values, and how society perceives assistive technology from the user's perspective. In addition to this research, sending out surveys would be beneficial for a general consensus about their views on assistive technology. The questions on the survey would be more focused on a gauge of agree to disagree questions similar to the questions asked as if it were to be an interview.

Conclusion

People with physical limitations, especially quadriplegics, need more user-friendly, discreet, and affordable assistive technology solutions. Traditional methods are often challenging and limit independence of the impacted user. The impacts of the solution in mind from my capstone will hope to enhance the level of independence of a user as well as making it more inclusive and affordable by all people so that everyone is able to have their own mobile independence and freedom regardless of physical limitations. Being able to address the relevant assiitve technology limitations can result in increased positive perceptions of society on those with disabilities. This paper aims to address or at least shed light on the relevant factors that shape the multifaceted relationship between assistive technology, the individual, and society with hopes that lead to a more inclusive and empowering future for those with disabilities.

References

Bijker, W. E., & Pinch, T. J. (1987). The social construction of fact and artifacts. *Philosophy of technology: the technological condition: an anthology, 107-139.*

Cleveland Clinic medical. (2022). *Quadriplegia (tetraplegia): Definition, causes & types*. Quadriplegia. https://my.clevelandclinic.org/health/symptoms/23974-quadriplegia-tetraplegia

Ding, W., Hu, S., Wang, P., Kang, H., Peng, R., Dong, Y., & Li, F. (2022). Spinal cord injury: The global incidence, prevalence, and disability from the global burden of disease study 2019. *Spine*, *47*(21), 1532.

Francis, N. (2022). *Novel EMG-IMU Sensor Array for a 5-DOF Wearable Robotic Upper-Limb Exoskeleton; Examining the Politics Surrounding Assistive Devices*. Charlottesville, VA: University of Virginia, School of Engineering and Applied Science, BS (Bachelor of Science). https://doi.org/10.18130/0fb2-bb76.

Izzuddin, T. A., Ariffin, M. A., Bohari, Z. H., Ghazali, R., & Jali, M. H. (2015, November). Movement intention detection using neural network for quadriplegic assistive machine. In *2015 IEEE International Conference on Control System, Computing and Engineering (ICCSCE)* (pp. 275-280). IEEE.

Jafar, M. R., & Nagesh, D. S. (2023). Literature review on assistive devices available for quadriplegic people: Indian context. *Disability and Rehabilitation: Assistive Technology*, *18*(6), 929-941.

Jain, M., & Joshi, H. (2014). Tongue Operated Wheelchair for Physically Disabled People. *International Journal of Latest Trends in Engineering and Technology (IJLTET)*, *4*.

Jeff. (2023, April 28). *Understanding assistive technologies: What are SIP-and-puff systems?*. WCAG Audits, ADA Accessibility Audits & Section 508 Audits. https://www.boia.org/blog/understanding-assistive-technologies-what-are-sip-and-puff-systems#:~:text=The%20system.

Hughes, T. P. (1987). The evolution of large technological systems. *The social construction of technological systems: New directions in the sociology and history of technology*, *82*, 51-82.

Kim, J., Park, H., Bruce, J., Sutton, E., Rowles, D., Pucci, D., ... & Ghovanloo, M. (2013). The tongue enables computer and wheelchair control for people with spinal cord injury. *Science translational medicine*, *5*(213).

Kuriakose, D. C. & SpinalCord.com Team, & (2022). *Quadriplegia & Tetraplegia: Definition, causes, symptoms, and treatment*. Quadriplegia & Tetraplegia: Definition, Causes, Symptoms, and Treatment. https://www.spinalcord.com/quadriplegia-tetraplegia.

Lasfargues, J. E., Custis, D., Morrone, F., & Nguyen, T. (1995). A model for estimating spinal cord injury prevalence in the United States. *Spinal Cord*, *33*(2), 62-68.

Latour, B. (1992). Where are the missing masses? The sociology of a few mundane artifacts. *Shaping technology/building society: Studies in sociotechnical change, 1, 225-258.*

Lontis, E. R., Bentsen, B., Gaihede, M., Biering-Sørensen, F., & Struijk, L. N. A. (2021). Wheelchair control with inductive intra-oral tongue interface for individuals with tetraplegia. *IEEE Sensors Journal*, *21*(20), 22878-22890.

Lu, Y., & Chen, Y. (2012). Prototyping potential control systems to assist complete quadriplegics. In *The 5th 2012 Biomedical Engineering International Conference* (pp. 1-5). IEEE.

Lund, M. E., Christiensen, H. V., Caltenco, H. A., Lontis, E. R., Bentsen, B., & Struijk, L. N. A. (2010). Inductive tongue control of powered wheelchairs. In *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology* (pp. 3361-3364). IEEE.

Menon, S., Nambiar, A., Pariyarathu, A., & Krishnamoorthy, M. (2015). Tongue Driven System. *International Journal of Engineering and Technical Research, 3(4). ISSN: 2321-0869.*

Newsome | Melton (2019). *Quadriplegia: Types of paralysis: Brain and Spinal Cord Injury Information*. Newsome | Melton. https://www.brainandspinalcord.org/quadriplegia/#:~:text=A%20patient%20with%20complete%20quadriplegia,control%20over%20their%20hand%20movements.

Star, S. L. (1999). The ethnography of infrastructure. *American behavioral scientist, 43(3), 377-391.*

Talton, N.R. (2023) Midterm Design Review. Available at: https://docs.google.com/presentation/d/1kjzTwNK050S2tOjSgDINawHokvu5CVhypJNLhkQpeJs/edit#slide=id.g28ba5c15421_1_0.

U.S. Department of Health and Human Services. (2023). *Spinal Cord Injury*. National Institute of Neurological Disorders and Stroke. https://www.ninds.nih.gov/health-information/disorders/spinal-cord-injury