ELE 464 Final Report

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1 Abstract

The amount of information that humans seek to receive is constantly increasing. Humans already use senses such as hearing and vision to process most of their information, so these may not be the best mediums to receive additional information. Delivering information through tactile stimulation has shown great promise, especially for restoring vision in blind people. An electro-stimulation device used to convey a collection of words to a user is developed in this work. Words are mapped to stimulation patterns which have different frequencies at different points in time. An Arduino Uno controls the delivery of these stimulation patterns to the user. Test subjects successfully learned to associate words with stimulation patterns at a rate above chance. A method for generating stimulation patterns based on the meaning of the words is proposed.

2 Introduction

Haptic technology refers to a system of providing a user with information through tactile sensations [1]. In the age of computers, the term has come to refer to computer control over the tactile sensations associated with interactions with an interface [2]. Just as the touch screen allows for an infinite number of different interfaces tailored to different situations, haptic interfaces controlled through some form of a computer can adapt the form of the feedback to the relevant environment or situation [2].

2.1 Sensory Substitution Systems

Haptic technology can act as a form of sensory substitution. Research into sensory substitution has focused primarily on aiding people deprived of a fully functioning sensory organ [3]. Braille represents one of the most widely used sensory substitution systems, using the tactile sensation to acquire information normally received through sight [3]. Tactile-vision and auditory-vision are the two primary modes of sensory substitution.

In tactile-vision, electrical or mechanical actuators transmit visual information [4]. For electro-tactile systems, an array of electrodes is used in which the current through each electrode correlates to the intensity of the corresponding optical pixel [4]. Subjects do not use the natural sensory capabilities of the skin covered by the stimulation apparatus. The BrainPort device uses an array of electrodes on the tongue to convey visual information to blind individuals [3]. The benefit of BrainPort is correlated to an individual's training in how to use the device [5]. In audio-vision sensory substitution, a two dimensional image is converted into a one dimensional vector representing a sound [6]. The vOICe system, developed by Meijer, signified one of the first major efforts to use sound as a substitute for vision. In this apparatus, vertical position was encoded by frequency, horizontal position was encoded by timing, and intensity was encoding by amplitude [7]. The effectiveness of the vOICe system in different localisation tasks has been tested [8]. Blind subjects have been able to infer mental models of different scenes and objects based on different musical clips [9].

Although some systems have relied on a direct mapping from one sensory modality to another, this technique is difficult to scale for tactile-vision systems. Because of the limited spatial resolution of the skin, the resolutions of these systems cannot exceed about 1000 pixels [4][10]. Despite the skin's inferiority of parallel processing, its higher frequency response enables it to excel at serial processing [10]. Information is often unrefined during this mapping process from visual stimuli to auditory or tactile stimulation, due to concerns that removal of redundancies would complicate the training process [7].

Beyond developing a mapping between a stimulation in one sensory modality to a perception in another, sensory substitution systems often seeks to achieve a level of generality, allowing an individual to use acquired perceptual skills to understand a new stimulus. [11].

2.2 Novelty of Work

This project will build off of existing work using electro-stimulation. It will involve some novel components and components upon which there is currently limited literature:

- An electrical stimulator capable of delivering stimulation associated with different words is developed.
- A data structure to represent different stimulation patterns is presented.
- A method for generating unique stimulations to associate with different words is introduced.

2.3 Outline of Report

In Section 3 background information will be provided. In Section 4 the motivation for this project will be described. Section 5 will detail the approach taken to build the stimulation device. Experimental results will be presented in Section 6. Discussions and limitations of the work will be presented in Section 7 and Conclusions as well as Future Work will be discussed in Section 8.

3 Background

3.1 Stimulation Types

Mechanical/electro-mechanical, ultrasonic, and electric forms of haptic feedback can exploit the skin's sensitivity to various types of stimuli such as heat, pressure, vibration, voltage, and current to convey information to a person [12]. Mechanical and electro-mechanical stimulation can be achieved through vibration devices, an array of small pins, or fluids that change viscosity in response to different electrical impulses.

3.1.1 Electrical Stimulation

An electro-tactile display can directly stimulate nerve fibers using current provided by electrodes. Electro-stimulation has a number of uses in healthcare providing pain relief and assisting patients in regaining motor control [13] [14] [15]. The ability to pattern the electrodes onto flexible substrates makes electro-tactile stimulation especially conducive for portable use and provides an edge over many mechanical actuators with regard to size [16]. Electro-tactile interfaces offer a limited variety of sensations and require high voltages between 10 and 100 volts [16].

3.2 Graph Based Semantic Analysis

Graph theory represents complex situations as a set of vertices and weights connecting vertices to one another [17]. WordNet is a lexical reference system in which words are organized by concept [18]. Version 2.0 contains over 80,000 concepts [19]. There is a large amount of literature on semantic similarity with the Hirst-St-Onge and Leacock-Chodorow methods utilizing some variant of the path length between words as an indication of their similarity [20].

4 Motivation

4.1 Tactile Stimulation

Tactile response times often are much less than visual and auditory response times [21][22]. Moreover, tactile stimulation often proves valuable in conveying a message to a user already loaded with information, especially in the context of driving [12] [23]. Cross-modal information can yield greater benefits than simple increases in information from one sensory modality. Speed of response tends to increase when the stimuli in the different sensory modalities align (ex. right hand vibrates and an arrow on the screen points to the right) [24]. Despite covering the entire body, human skin is rarely used as a major sensory modality. For this reason it is available to process additional information

4.2 Electrical Stimulation

The under-utilization of the skin for information transfer motivates development of electro-tactile interfaces to communicate with a human [25]. While other forms of tactile stimulation provide greater diversity of sensations, electro-stimulation is unique in its portability as well as its capability to serve both as a platform for information transmission and a medical tool. In recent years, the distinction between devices focused on information exchange and those committed to health has blended. The rise of meditation apps, fitness trackers, and meal planners on smartphones epitomizes this trend. Electro-stimulation is uniquely suited for this fusion. Learning to map stimulation patterns to different concepts can be challenging for the user.

5 Description of Proposed Approach

One can divide this project into 3 primary tasks:

1. Hardware was developed to deliver the electrical stimulation.
2. Software was created to control the electrical stimulation.
3. A game or set of tasks was formulated to assess the value of the proposed system.

5.1 Hardware Apparatus

The system consists of an Arduino Uno micro-controller sending signals to a circuit that contains a boost converter (DFR0123 from DFRobot) to increase the voltage, an H-bridge to invert the voltage, and an NPN-PNP transistor pair to turn the voltage on and off.

5.1.1 Power Delivery

The system is powered by the USB-c port of a MacBook Pro. The Arduino can accept voltage supplies from roughly 6 V to 20 V. The 5V output pin of the Arduino is the input voltage to the boost converter. The output voltage of the boost converter is determined by a screw driver adjustable digital potentiometer.

5.1.2 H-Bridge

Biphasic waveforms are the preferred type of stimulation for longer use, since they will mitigate issues related to buildup of charge in the body [26]. The use of biphasic waveforms makes this device applicable to uses in athletic recovery and pain relief. To create these biphasic waveforms, an H-brdige is utilized to invert the current. An H-bridge provides a means of inverting the voltage and current through a portion of a circuit. The H-bridge is widely used in robotics to change the direction of motors [27][28]. The circuit generally uses two PNP transistors whose emitters are connected to the power supply and two NPN transistors whose emitters are connected to ground. Depending on which transistors are on, the voltage drop inverts across a resistive element connecting the PNP transistors to the NPN transistors. The design of the H-bridge must be modified when the control signals for the transistors have very different voltages than the power supply. Since this phenomena occurs in this apparatus, the bases of the PNP transistors are driven by two additional NPN transistors.

5.2 Software

5.2.1 Data Structure and Control Signals

The stimulation patterns associated with different words are created in Python. A stimulation pattern lasts for at most 10 seconds. There are blocks of time all less than 10 seconds. A block is randomly chosen. A frequency is randomly selected to be provided during the duration of this block. The frequency is randomly selected amongst a set of choices such that there is not an abundance of frequencies whose associated periods exceed the length of the block. This process is repeated as long as the sum of the block lengths is less than 10 seconds. The data pertaining to a specific pattern is stored in a data structure referred to as a Pattern in this paper. Creating a special structure for this data makes it much easier to debug the software and stay organized. This abstract data type supports the appendage of new blocks and frequencies as well as the reading of different blocks and frequencies.

For each block, the control signals to the H-bridge change at a rate determined by the frequency assigned to the block. The time at which the Arduino first began to access this block is recorded. Once the difference between the current time and the start time of the block exceeds the block length, the Arduino repeats the process using the next block or disconnects the power supply from the H-bridge if there are no more blocks present in the pattern. The range of possible frequencies was varied in different settings to ensure that the test subjects were comfortable yet able to perceive the presence of the stimulation.

5.2.2 Metric of Distance Between Stimulation Patterns

The objective is to maximize the perceived difference between the stimulation patterns, making it easier for the subjects to learn to identify the word associated with each pattern. A pattern is specified by an array of frequencies and an array of durations referring to how long each frequency is applied. Directly comparing the frequencies is not appropriate because one frequency may only be associated with a 1 second block, while another might be associated with a 7 second block. Different patterns will have different numbers of blocks. To try to standardize the patterns, each pattern is mapped to an array containing the frequencies, which is denoted as the expanded array. The number of consecutive times that each block frequency occurs is proportional to the duration of the block. The duration of each block is multiplied by a constant of proportionality, 100, to remove the decimal from the time and increase the number of times that the given value appears. Since the sum of all of the blocks describing a pattern will differ for different patterns, the lengths of these expanded arrays will differ. All expanded arrays that have fewer entries than the longest array are padded with zeros.

One can directly compare the expanded arrays. The naive approach of using the mean square error can be problematic because it views neighboring entries as being just as distinct as far away entries. Neighboring entries in this expanded array represent the frequencies roughly 10 milliseconds apart. Using this naive method, a pattern that only pulses for 1Hz during the first second would be equally distant from a pattern that only pulses for 1Hz during the next second and a pattern that only pulses for 1Hz during the tenth second. These three stimulation patterns may be orthogonal to one another in a vector space, but this does not guarantee that they will be perceived as equally distinct from one another. Intuitively there is a greater chance that the user will confuse patterns whose pulses occur near one another in time than patterns whose pulses do not occur near one another.

An algorithm is proposed to incorporate both the temporal and frequency differences of signals into a measure of the dissimilarity between patterns. In the pseudo-code below, X and Y are the expanded arrays of two different patterns.

for x_i in X:
for y_j in Y:

$$d+=\frac{1}{(1+(\alpha*abs(i-j)}\cdot(x_i-y_j)^2$$

end inner loop
end outer loop

$$d=\frac{d}{abs(X\bullet Y)+0.1}$$

In the above expression, d is the distance between the stimulation patterns and α is the constant of proportionality that controls the rate at which the difference between two frequencies is discounted based on the temporal difference between them. The algorithm relies on the assumption that the greatest emphasis in the distance calculation should be placed on the distance between corresponding entries of the two expanded arrays, with less emphasis on entries whose indices are further away from one another. The number 0.1 in the denominator ensures that a division by zero error will not occur.

5.2.3 Generating Patterns Using the Distance Metric

The following steps were taken in an effort to maximize the distance between patterns as defined above. A pattern was randomly generated and mapped to each word. The collection of patterns mapped to the words is referred to as a pattern set. The patterns were expanded using the previously mentioned technique. The distances between each pair of patterns were computed and summed together. This process was repeated a given number of times and the pattern set associated with the largest total distance was saved.

The stimulation pattern generation techniques presented so far have not accounted for the relationship between the words in the English language. A method to consider the semantic relationship between words is proposed. A set of N words are represented as an undirected graph in which the weights represent the semantic dissimilarity of the words. The Natural Language Toolkit and the WordNet database are used to compute the semantic distance between each pair of words and populate a weight matrix, W, with these distances. The following method is used to create a pattern set intended to reflect the semantic relationship among the words.

Randomly generate a pattern to map to the zeroth word.

for i in range[1,N):
generate a pattern such that:
$distance_{i,k} > B\cdot W_{i,k}, \quad k\ \epsilon$[0,i-1]

A pattern is randomly generated and mapped to a word. This word is then considered mapped. An un-mapped word is selected. A pattern is generated such that its distance to the first word is at least B times the distance between the current word and the original word. This process is repeated for all words in the set of words. For the ith word, a pattern is generated such that the distance, $distance_{i,k}$, between the pattern and the pattern for mapped word k is greater than B times the semantic distance between the ith word and the kth word for all values of k between 0 and $i-1$.

5.2.4 Transmission

The pattern is transmitted to the Arduino by sending the block lengths and corresponding frequencies over serial. The baud rate was set to 9600. The frequencies and block lengths often have decimal values. It is difficult to directly transfer decimal values over serial. To resolve this issue an array containing every possible block length and an array containing every possible frequency is constructed. Rather than directly sending the block lengths and frequencies, the Python script sends the indexes of the block lengths and frequencies from this master array.

The software used to control the Arduino is written in C programming language. The Arduino stores the data sent from the Python script in a buffer. Using the same reference arrays used to index the block lengths and frequencies, the Arduino decodes the received data.

5.3 Testing

A simple task involving word identification is used to assess the effectiveness of the device in conveying information to the user. Due to the circumstances surrounding the COVID-19 pandemic, the experiment used only two subjects and it was not possible to conduct a full set of trials.

The possible frequencies and the gain of the boost converter were varied in different trials to ensure that the test subjects were not in pain. The voltage across the electrodes was at most 13V and the frequency took on values between 10Hz and 0HZ. Although this introduced an additional variable in terms of the parameters used to control the circuit, this process maintained a relatively constant level of comfort and perceptibility of the patterns.

5.3.1 Training

Three stimulation patterns are randomly generated by the computer and mapped to the words ”sugar”, ”car”, and ”ham”. A word is randomly chosen and the user receives the corresponding stimulation pattern. This process occurs 15 times with 5 second breaks between words to allow the user to develop a mental mapping between the words and the stimulation patterns.

5.3.2 Assessment

A word is randomly selected. The user receives the associated stimulation pattern, but is not told with which word the pattern is associated. The user verbally expresses his or her guess regarding the identity of the associated word. This process is repeated 15 times with 5 second breaks between stimulation patterns to test the ability of the user to remember these mappings. If the electro-stimulation provided no information to the subjects and the subjects randomly guessed one of the three words, then one would expect them to correctly answer 5 out of 15 words on average.

6 Experimental Results

6.1 Randomly Generated Mappings

A random stimulation pattern was mapped to each of the three words.

The frequency and duration of these stimulation patterns were free to vary. Subject 1 provided the correct word for 14 out of the 15 stimulation rounds, while Subject 2 provided the correct answer for 10 out of the 15 stimulation rounds.

6.2 Frequency Encoded Mappings

The frequencies varied among stimulation patterns, while the duration of all of the stimulation patterns was 9.5 seconds. Subject 1 provided the correct response for 10 out of the 15 rounds, while Subject 2 provided the correct response for 8 out of the 15 rounds.

6.3 Temporally Encoded Mappings

The duration of the stimulation patterns was varied while all of the stimulation patterns had the same frequency. Only Subject 2 participated in this experiment, providing the correct response in 9 out of the 15 rounds.

6.4 Enhanced Pattern Distance Mappings

Only Subject 2 participated in this experiment. The program attempted to maximize the distance between the stimulation patterns mapped to each word using the protocol described in Section 5.2.3. Subject 2 provided the correct response in all 15 of the rounds when 10 different pattern sets were generated and the pattern set with the greatest distance among its constituent patterns was selected. Subject 2 provided the correct response in 12 out of the 15 rounds when 3 different pattern sets were generated and the pattern set with the greatest distance among its constituent patterns was selected. Subject 2 correctly identified 14 out of the 15 words when 3 different pattern sets were generated and the pattern set with the least distance among its constituent patterns was selected.

6.5 Semantic Aware Mappings

A Python program implemented the semantic mapping approach introduced in Section 5.2.3. The actual run time of the algorithm has not been sufficiently analyzed. The number of distance measurements that must be computed is at least quadratic with respect to the size of the word set. While generating the pattern for the first word only requires satisfying a constraint from the zeroth word, generating the pattern for the kth word requires satisfying constrains for all $k - 1$ patterns. The pattern set for the word set "Sugar", "Sweet", "Dog", "Cat" was created. The generated patterns are in the proper format to deliver stimulation to the user; however tests on the efficacy of this method were not assessed due to time constraints.

7 Discussion and Limitations

Due to the unforeseen circumstances during which this project developed, the sample size was limited to two individuals. The available frequencies varied in different experiments because maintaining the same frequencies caused stimulation patterns to be either imperceptible or painful. This introduced another variable into the experiment, making it difficult to directly compare between trials. Since the computer randomly selected a word during each round of the training phase, the participants sometimes had more exposure to certain words. While it is not ideal for the familiarity with words to vary, the alternative of iterating through the words in a set order introduced the possibility of participants remembering the order of the words rather than the stimulation patterns. Randomizing the order, but ensuring that each word is featured the same number of times may be a valuable compromise, although the user will be able to deduce a word by process of elimination as the training phase nears its end.

Participants were not informed as to how stimulation patterns differed among the words. They commented that the lack of a conceptual basis for how the stimulation patterns differ (frequency, amplitude, time) made it difficult to comprehend which aspects of the pattern they should focus on. Participants were not informed as to how the information was encoded in order to assess which mapping strategy was most intuitive and reduce the chance of the participants developing a very formulaic conception of the differences. In addition, by verbally conveying the mapping strategy to the participants, one could argue that an auditory component to this task would have been introduced.

It was expected that using a pattern set in which the patterns differed greatly from one another would yield the best results. While this was the case, it was surprising that choosing the pattern set with the most similar patterns among three different pattern sets yielded 14 out of 15 correct responses. This result occurred when choosing among only 3 different pattern sets, so it is possible that the patterns within the chosen set were not very similar at all in this trial.

8 Conclusions and Future Work

An electro-stimulation device was successfully constructed. A data structure was developed to represent different stimulation patterns. Different mapping schemes between words and stimulation patterns were tested. Subjects performed above chance in all of the trials. The accuracy achieved using distance maximized mapping was the greatest out of all of the trials. The sample size was not large enough to draw any conclusions on the comparisons of the efficacy of the different methods. Software was introduced to consider the semantic relationship among words in mapping these words to stimulation patterns. The effectiveness of this method was not tested.

To truly assess the merits or lack thereof of this system, a larger sample size is needed. A greater selection of words should be used. It is worth exploring the extent to which an apparatus similar to to the one presented in this work could convey information from multiple sensory modalities in addition to information not usually conveyed through any one sensory modality such as compass direction.

This work focused on modifying the

frequency of the stimulation at different points in time. It would be interesting to see how varying the amplitude and using multiple electrode pairs would impact performance on similar tasks to those explored in these experiments.

Accuracy was the only metric used to quantify the test subjects' performance. Since conveying information through tactile stimulation is especially pertinent for high stress situations in which latency must be minimized, further research should assess the response times of the methods introduced. More attention should be devoted to determining how the relationship between words should be encoded into the patterns associated with the words. The method introduced in this paper is not computationally efficient and its effectiveness needs to be tested. To improve its efficiency, the graph of the word set could be pruned.

While it is important to test the accuracy of the semantic-aware method in the manner used to test the other techniques, there may be other useful metrics. It would be valuable to know the shortest path from the user's guess to the actual word. This would provide some insight into how much the semantic-aware technique conveys the underlying concept associated with a word to the user.

Exploring tractable or heuristic optimization strategies to generate a dissimilar set of patterns warrants further research. Genetic algorithms may be especially conducive to this type of problem.

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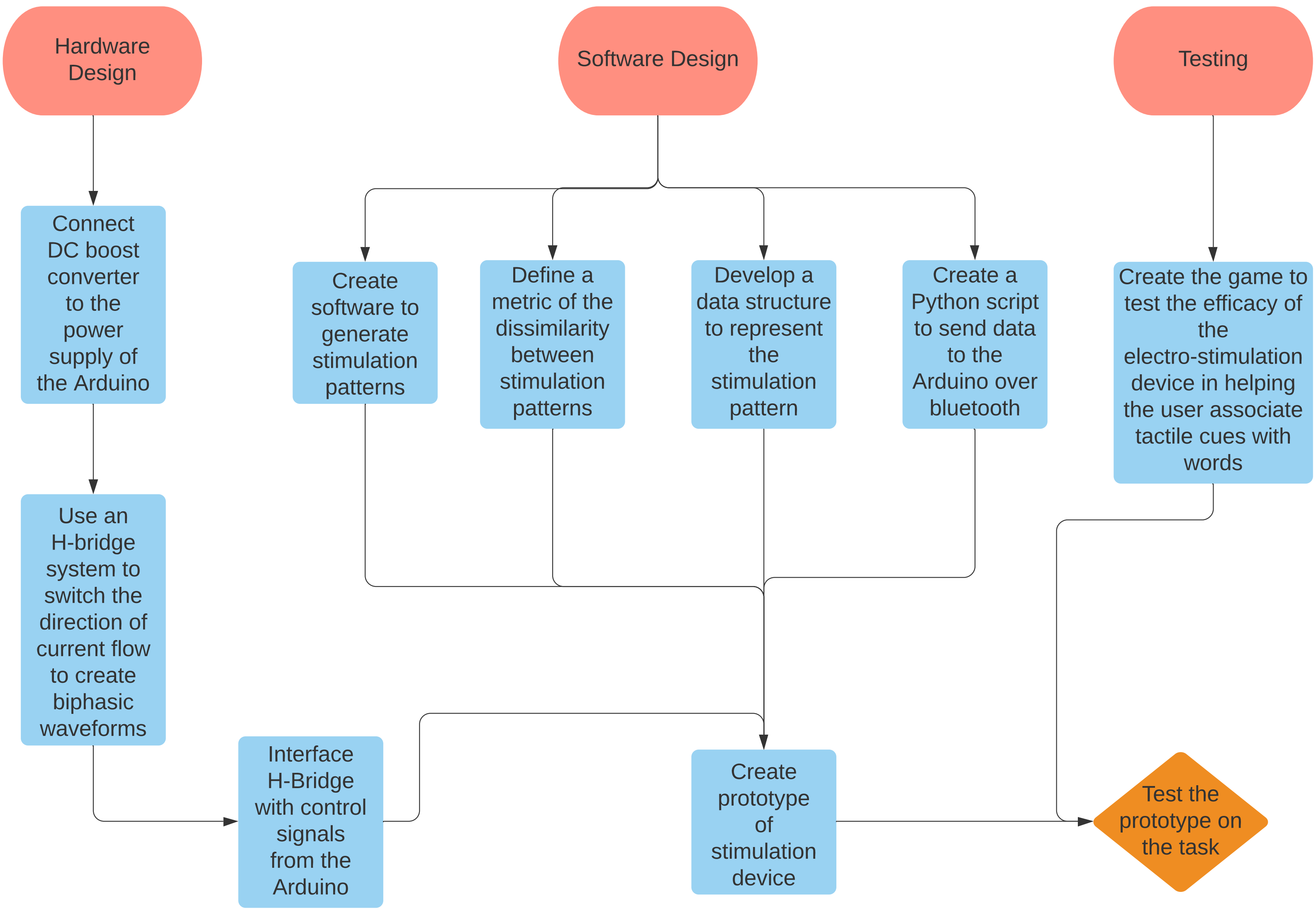
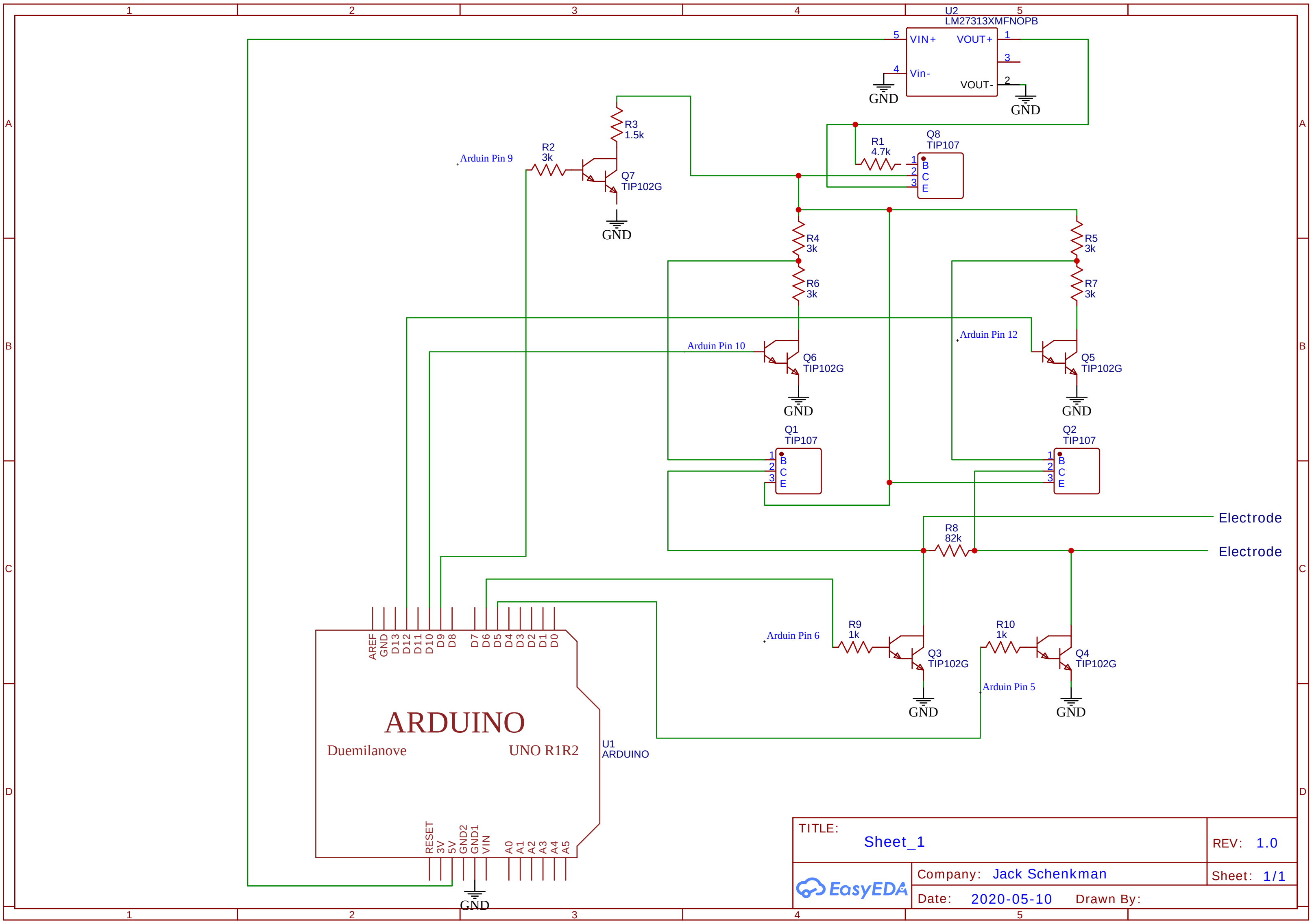
Project Overview





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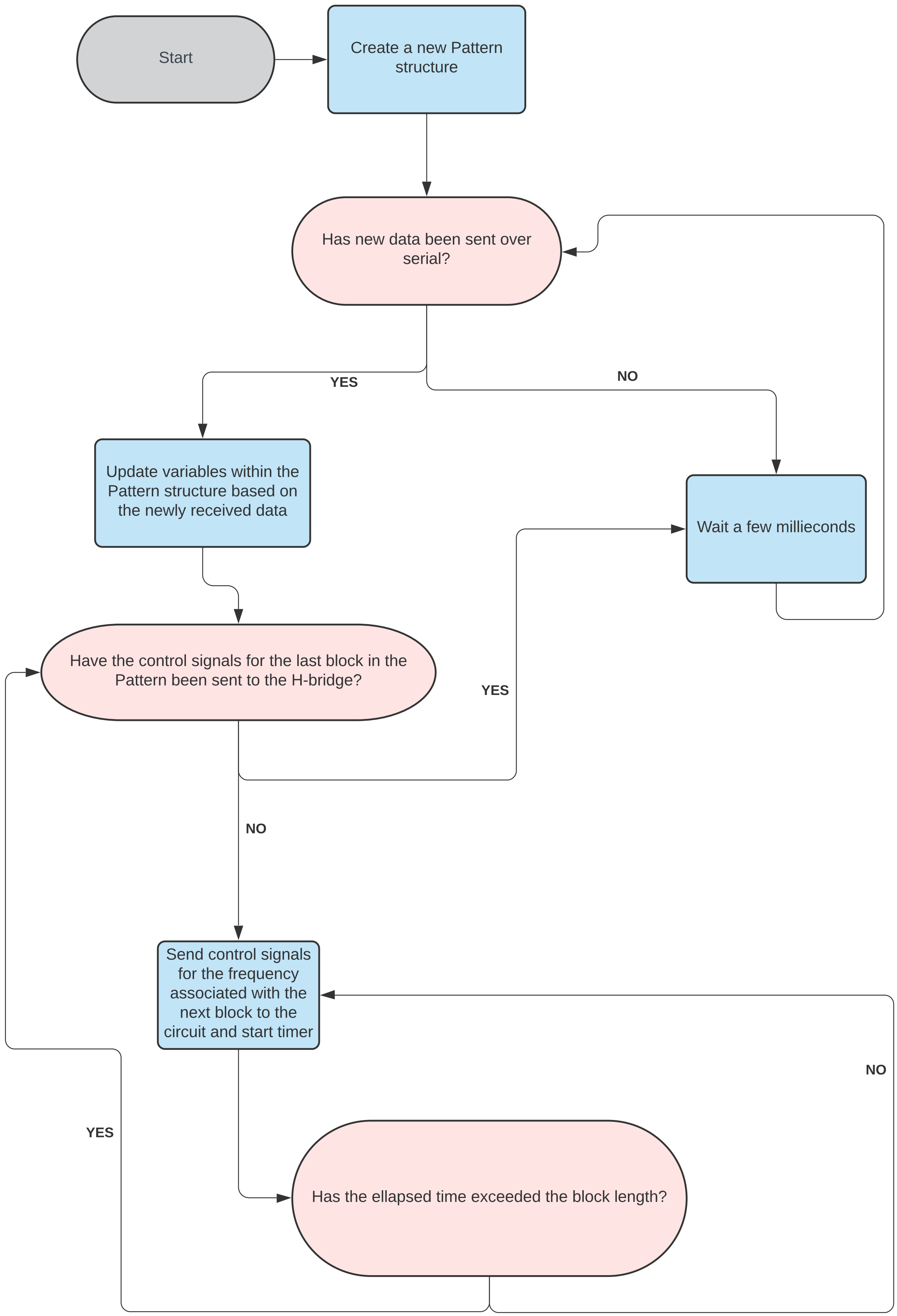
Software Flowchart



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