TECHNISCHE UNIVERSITÄT BERLIN

BACHELOR THESIS

Electrotactile Sensory Feedback for a Myoelectric Hand Prosthesis

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A thesis submitted in fulfillment of the requirements
for the degree of Bachelor of Science

in the

Technische Universität Berlin
Fachgebiet Regelungssystemte

October 24, 2018

Declaration of Authorship

I, Ongun TÜRKCÜOGLU (371690), declare that this thesis titled, "Electrotactile Sensory Feedback for a Myoelectric Hand Prosthesis" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

TECHNISCHE UNIVERSITÄT BERLIN

Abstract

Fakultät Elektrotechnik und Informatik
Fachgebiet Regelungssystemte

Bachelor of Science

Electrotactile Sensory Feedback for a Myoelectric Hand Prosthesis

by Ongun TÜRKCÜOGLU (371690)

Eine Amputation ist die Entfernung einer Extremität, deren Implikation für den Patient drastisch ist und die Häufigkeit solcher Operationen scheint zu erhöhen. Eine spezielle Klasse der Amputation ist die Amputation oberer Extremitäten und sie beeinträchtigt die Lebensqualität. Patienten können sich für Handprothesen entscheiden, deren Steuerung mittels EMG-Signalen erfolgt. Jedoch müssen Patienten sich für die Steuerung auf visuelles Feedback verlassen und die Implementierung des sensorischen Feedbacks ist gewünscht. Elektrotaktiles sensorisches Feedback ist als Ansatz vorgeschlagen und unterschiedliche Ansätze mit diskreten und kontuniuerlichen Stimulationen werden verglichen. Aussagen über die Fähigkeit des Systems für Mustererkennung und Steuerung der Stimulation werden geprüft und die Ergebnisse werden diskutiert. Am Ende wurde festgestellt, dass diskrete Feedbackstimulationen das Potential haben, ein ausreichendes sensorisches Feedback zu liefern.

An amputation, removal of a limb, has drastic implications on the patient and the prevalence of amputations is expected to rise. An upper-limb amputation is the removal of upper-limb extremities and is associated with loss of quality of life. Patients, who undergo the procedure, can opt for a myoelectric hand prosthesis, which is controlled by the user's muscular electrical activity. Users of aforementioned prosthesis have to rely on visual feedback to determine the orientation of the hand and sensory feedback is among the requested features. Electrotactile sensory feedback is proposed and approaches using continuous and discrete stimulations have been compared. Ability to recognize stimulation patterns and feasibility of control using EMG signals (implementing an abstracted hand prosthesis) have also been researched and results have been discussed. As conclusion, discrete feedback stimulations have been determined to have the potential to provide adequate sensory feedback.

Acknowledgements

- Many thanks to my advisors Dr. Thomas Schauer and Dariusz Swieczkowski-Feiz for helping me throughout this thesis.
- Special thanks to Alkım Cebeci, for suddenly coming up with the idea of the stimulation pattern, that eventually made its way into implementation and testing.
- Special thanks to Serdar Gareayaghi, for testing the system with me, which allowed me to find mistakes I might not have find otherwise.
- Special thanks to Alkım Cebeci, Göksu Işık, Doruk Süzer and Onur Akdemir for participating in the testing phase, which allowed me to quantify the quality of the method.
- Thanks to Ana Carolina C. de Sousa, Markus Valtin, Antonio P. L. Bo and Thomas Schauer for authoring the paper "Automatic Detection of Stimulation Artifacts to Isolate Volitional from Evoked EMG Activity" and implementing the method using MATLAB function blocks, which I could use.
- Thanks to the TU Berlin Control Group, for helping me with every question I had, from programming tips to hardware-related problems.

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Dedicated to my Mother

Chapter 1

Foreword

Firstly, I, the author of this bachelor's thesis, Ongun Türkcüoglu, would like to thank you for taking the time to read my project, which took me about four months to complete. This thesis serves as a proof-of-concept for a novel electrotactile sensory feedback method, which is targeted for upper-limb extremities amputees.

The Introduction chapter will take you through the history of amputation, with a small instruction into the human hand. As it was thought with end-user in mind, the project also explains, rather simply, the prosthetic devices currently in the market. Since the electrotactile method is far from the only implementation currently being researched, other systems have also been investigated.

Since we are using the electrotactile method, it was fair to focus on it. Fairly simple concepts have been explained and their connection to the human physiology have been mentioned.

Actually, this thesis is not my first time implementing a similar method. During the Winter Term of 2017/2018 at the Technical University of Berlin, another electrotactile feedback system was implemented using a different stimulator and a different approach, and the results we gathered from that project was not satisfactory, to say the least. The concept was promising, however the way it was implemented left something to be desired. However, what we realized from that project laid the idea and the foundation of what this thesis implements. More in detail have been discussed in the Introduction section.

The Methodology section goes into detail which hardware is used, how the system is implemented and how tests are conducted. However, explaining every line of code is counter-productive and therefore I opted for a detailed explanation of how every component is linked to one another and to the bigger picture. Still, the source code (the Simulink model) is uploaded into a Github repository, along with the aforementioned preliminary research and the bachelor's thesis. The link to the Github repository can be found at the end of this chapter.

Finally, the results are presented and a conclusion have been written. The outlook also presents a couple of points, where more research and experimentation is required.

Thanks again for spending the time and hopefully you'll find it as interesting as I thought it was.

Ongun TÜRKCÜOGLU

Github repository: `https://github.com/onguntoglu/etsfm_bachelor`

Chapter 2

Introduction

2.1 Amputations in General - Definitions

Amputation, from the Latin word *amputare*, is defined by the Oxford dictionary as the action of surgically cutting off a limb. It is usually performed as a preventative or an emergency surgery, where the removal of a limb could potentially save the life of a patient or halt the progress of a certain disease. A study of data from Chiang Mai University Hospital in Thailand, consisting of 216 surgical specimens, found that, "Dysvascular (46%), tumor-related (36%), and infection-related (10%) amputations were the three most common scenarios" (Settakorn et al., 2005, see Abstract). Furthermore, the amputation can occur in different sections of the aforementioned limbs. For example, the nomenclature of upper-limb removals are shown in Figure 2.1.

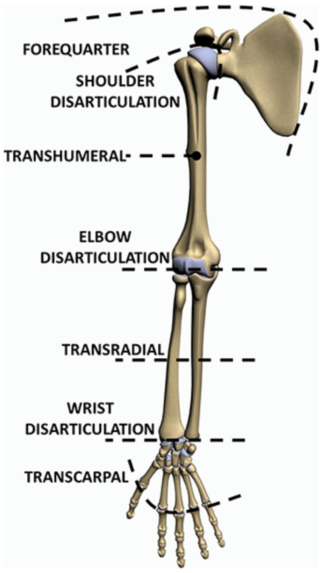

FIGURE 2.1: Nomenclature of upper-limb removals, taken from Cordella et al., 2016

A patient, who undergoes the surgery of amputation, is referred to as an amputee. The study indicates (Ziegler-Graham et al., 2008), in the year 2005, 1.6 million were living as amputees and this population is projected to rise to 3.6 million in year 2050 (Ziegler-Graham et al., 2008). A similar research conducted in Norway, estimated the prevalence of upper-limb amputation to be 11.6 per 100.000 adults (Østlie et al., 2010).

An amputation has drastic implications on the patient, their families and the society as a whole (Sahu, 2016). According to a review of studies on the subject

(Sahu, 2016), loss of a limb can be possibly seen as "loss of spouse, loss of one's perception of wholeness, symbolic castration and even death". As significant as these surgeries are, amputees can opt for a prosthetic limb, which can help the patient get through their everyday life.

2.2 The human hand

The human hand is an integral part of every living person, and it fulfills a spectrum of activities, from driving a car, to writing and playing sports. It consists of five digits, four of which are opposable to the thumb. It is primarily involved in gripping and grasping actions and the musculature and the tendons responsible for said actions are located in the forearm. Figures 2.2 and 2.3 illustrate the hand and the forearm of a human.

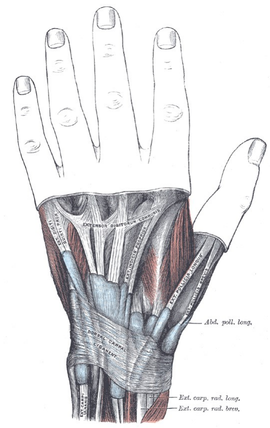

FIGURE 2.2: The mucous sheaths of the tendons on the back of the wrist - taken from *Illustrations. Fig. 1234. Gray, Henry. 1918. Anatomy of the Human Body.*

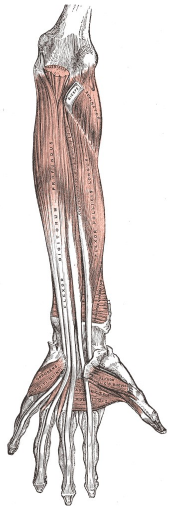

FIGURE 2.3: Front of the left forearm. Deep muscles - taken from *Illustrations. Fig. 415. Gray, Henry. 1918. Anatomy of the Human Body.*

Aside from gripping and grasping, the hand can also rotate, which is called, depending on the direction of the rotation, the supination and/or the pronation of the hand. The rotation, however, is not a function of the hand itself, but the function of the elbow. It is also worth noting, that the wrist is not capable of rotation itself, which is a major difference between an actual human hand and some prosthetic hands, which is discussed in Section 2.3.1.

Lastly, the hand can be lifted upwards and pressed downwards, which is called an extension and a flexion, respectively. These actions are also performed by the musculature in the forearm.

2.3 Prosthetic Devices - Definitions, Advantages, Drawbacks and Rejection Rates

A prosthetic device, also known as a prosthesis, is an artificial tool, which is designed to replace a missing body part, as opposed to an orthesis, which is only designed as a support for existing parts. In medicine, a prosthesis can take a number of different forms, however, one of the most common forms are prosthesis of extremities. The Figure 2.4 shows a commercially available hand prosthesis by Ottobock, designed for patients with upper-limb removals.

FIGURE 2.4: *Michelangelo by Ottobock*

As mentioned before, prostheses can take many forms and they can fulfill different requirements. However, for this research, it is important to focus on one type, which is the prosthesis of the upper-limb. A study on the history of upper-limb prosthetics (Zuo and Olson, 2014) details the different technologies used to realize the practical application and classifies prosthetics into different groups.

The most primitive prosthesis is a passive one, which is not capable of movement and actions characteristic of an actual hand. On the other side, an active hand prosthesis can implement the aforementioned movements, although each class achieves this using different approaches:

- A **body-powered prosthesis**, as the name suggests, is controlled using the patients own body-power. The transmission of power is usually conducted using cables. Zuo and Olson, 2014, page 46 details the Bowden cable body-powered, introduced in 1948. The paper also mentions that, " Furthermore, by sensing cable tension, the amputee is able to predict and adjust the position of the prosthesis **without visual feedback**. Although prolonged wearing can be uncomfortable, complicated motor tasks are limited and appearance is not human-like, body-powered prostheses are widely used."

- A **myoelectric prosthesis** is controlled using the EMG (electromyography) signals originating from the remaining limb, captured using surface electrodes. Compared to body-powered prosthesis, they must be recharged externally. Also, the control of the prosthesis is not intuitive, is accompanied by a steep learning curve and the signal processing can be unreliable due to natural bodily function. Additionally, due to a lack of **sensory feedback**, the user must depend on visual feedback, which may not always be available (i.e. insufficient light) or, it can feel unnatural and tiring (Zuo and Olson, 2014, page 47). The Figure 2.4 is an myoelectric prosthesis.

- **Targeted motor reinnervation** (TMR) and **target sensory reinnervation** (TSR) is a surgery which involves the redirection of the stump limb's nerves to another denervated area (target muscle). The patient can then contract the target muscle, resulting in intuitive control of the prosthesis and sensory feedback. Results indicate "discriminative pressure sensation, ability to grip and release objects, and the ability to discriminate between size and density without visual or auditory stimuli" (Zuo and Olson, 2014, page 48-49). However, high financial costs related to the procedure have been reported.

Although technological advances have made it easier for an amputee to integrate a prosthetic device into their life, rejection has always been associated with upper-limb prosthetics. The study Biddiss and Chau, 2007 provides an outlook regarding rejection rates and possible reason, compiled using a 25 year survey span.

A closer look at Biddiss and Chau, 2007, Table IV: Documented rejection rates of myoelectric prostheses indicates that, among 22 studies (from 1980 to 2005) rejection rates spanning from 0% to 75% have been reported. These numbers are of particular interest, because myoelectric prosthetics are, compared to other types, more costly and the financial burden needed to be justified. Although it is premature to try to pinpoint an exact reason for these numbers, the data does not point to a decrease in rejection, even though it was hypothesized to happen (Biddiss and Chau, 2007, page 243). Furthermore, the same study provides a table (see page 246, Table V) detailing the ongoing research and development of myoelectric prosthetics. It is clearly stated, that sensory feedback is regarded as one of the active research areas. Lastly, an Internet study (Pylatiuk, Schulz, and Döderlein, 2007, pages 366-367) found that force and temperature feedback are desirable additional functions to a prosthetic.

2.3.1 Movement Patterns and Capabilities of a Myoelectric Hand Prosthesis

CHAPTER NEEDS WORK
Each commercially available hand prosthesis offers different configurations and movement capabilities. The table 2.1 comprised from Cordella et al., 2016 illustrates three different hand prosthetics from three different companies with various capabilities.

TABLE 2.1: Characteristics of poliarticulated commercially available prosthetic hands - taken from Cordella et al., 2016

Hand and company name	i-Limb by touch bionics	Bebionic by RSL steeper
Weight	443–515 g	550–598 g
No of actuators	6 DC motors	5 DC motors
No of DoFs	6	6
Active DoFs	F/E of MCP joint of each finger and thumb opposition	F/E of MCP joint of each finger
Passive DoFs	–	Thumb opposition (i.e., it is changed by the user)
Joint coupling mechanism	Tendon linking MCP to PIP	Linkage spanning MCP to PIP
Grasping configuration	Power, precision, lateral, hook, finger-point	Power, precision, lateral, hook, finger-point
Maximum applied force	100–136 N	140 N

Hand and company name	Michelangelo by ottobock
Weight	420 g
No of actuators	2 DC motors
No of DoFs	2
Active DoFs	F/E of all the fingers contemporarily and thumb opposition
Passive DoFs	–
Joint coupling mechanism	Cam design with links to all fingers
Grasping configuration	Opposition, lateral, neutral mode
Maximum applied force	70 N

Various active and passive degrees of freedom (DoF) allow the user to adapt to different situations, from holding credit cards to pinching an object and pointing a finger. To simplify, we are going to focus on basic movement patterns that are easy to distinguish and mimic the function of an actual hand:

- Neutral mode - when the prosthetic is passive and not being used
- Finger flexion/extension
- Wrist flexion/extension
- Rotation of the wrist - Supination and Pronation

2.4 Feedback - Principles of Sensory Feedback, Feedback Methods and Existing Research

The human body is capable of perception of itself and of the environment, in which it finds itself, which is called the sensing ability. The organ responsible for sense is, among others, the brain, or more generally the central nervous system. A network of efferent and afferent nerves connects the brain and the body, which allows the information to be gathered and processed.

Traditionally speaking, there are five senses; sight, touch, hearing, taste and smell. Additional to these five elements, the human can sense pain, temperature, movement, relative positioning of the body to itself (which is called proprioception) and more.

Since the amputation involves the removal of the limb, it naturally involves the removal of the nerves that are connected to that limb, which means the removal of afferent nerve pathways, which lead from the limb to the brain. A severed connection therefore results in the loss of perception of movement, touch, proprioception and more. Even if a prosthesis can restore the ability to grasp and hold on to objects, the relative positioning of the hand itself might not be readily perceivable.

Sensory feedback, in this context, aims to provide perceivable functional feedback that is ideally intuitive, comfortable and allows the user to integrate the feedback into their usage of the prosthetic limb. Currently, hand prosthetics provide a rudimentary feedback, that is either auditory (resulting from the actuators during execution of an action) and/or visual (direct observation of the device by the user). However, as mentioned in the previous sections (refer to 2.3) they are insufficient and unreliable, with functional sensory feedback being "desirable".

The idea of sensory feedback is not new and some of the existing research papers provide outlooks into different technologies which achieve sensation. Svensson et al., 2017 is an extensive review paper, which summarizes sensory feedback methods in two different classes, the noninvasive sensory feedback and the invasive sensory feedback:

2.4.1 Noninvasive Sensory Feedback

Mechanotactile feedback

Mechanotactile feedback is a class of methods, in which sensation is achieved using pressure normal to the skin. The review paper points out that mechanotactile sensation provides a stronger body-ownership, reason being that the artificial sensation is modality-matched with the actual feedback of the limb (i.e. pressure on the prosthetic finger is mapped as pressure on the skin). Therefore, it is thought to be cognitively less intensive. Furthermore, somatotopically matched sensation could also be provided, which is the sensation evoked in the same region as the healthy limb, which can lessen the cognitive burden. However, mechanotactile feedback systems have been described as big and bulky, and high in power consumption (Svensson et al., 2017, page 441)

Vibrotactile Feedback

In contrast to mechanotactile feedback, vibrotactile sensation is usually defined as modality-mismatched feedback (i.e. pressure on the prosthetic finger is mapped as vibration on the skin). The research paper indicates that this class is mostly used to communicate grasping force, however it can also be used to define proprioceptive feedback (i.e. position and velocity).

Even though the method still utilizes visual feedback and an improvement in performance was not shown, it is the only commercially available system today and it boasts advantages such as ease of use, low power consumption and small size. However, the continuous vibration has been described as "annoying". (Svensson et al., 2017, page 6)

Electrotactile Feedback

Electrotactile feedback involves the usage of on-the-skin electrodes to implement the delivery of small currents to invoke sensations on the skin, which could be used to map feedback.

One major downside of the method is the interference of the electrical stimulation with the EMG signals used to control the prosthetic device itself. However, certain methods (time-division multiplexing (stimulation and recording of signals take place in individual time intervals) and/or blanking (removal of artifacts)) have been shown to lessen the interference. Furthermore, the sensation has been described as unpleasant".

Since this thesis implements the electrotactile feedback method, in-depth explanations of the advantages and disadvantages of the method and the review of existing research have been provided in later sections (refer to 2.5).

Auditory Feedback

As mentioned in the previous sections (refer to 2.4), most prosthetic devices provide a rudimentary form of auditory feedback, in form of sound originating from the actuators responsible for the movement. However, this section refers to the amplification of sounds emanating from surfaces. The review paper refers to a study, in which researchers amplified the sound resulting from friction using a microphone built into a glove. The amplified sound could be identified by subjects.

Another study found that a combination of visual and auditory feedback resulted in lower cognitive burden (refer to Svensson et al., 2017, Section 3.5 Auditory stimulation)

Hybrid Feedback

Hybrid feedback refers to the usage of multi-modality systems (i.e. a combination of both vibrotactile and mechanotactile feedback). Even though certain combinations of tactile stimulations are of particular interest (i.e. vibrotactile and electrotactile systems, due to lower power consumption and small size), multi-systems are not always equivalent to lesser cognitive loads. However, one study "showed that vibrotactile and electrotactile could be distinguished when stimulated simultaneously in a multi-modal haptic device (Svensson et al., 2017, page 442)"

2.4.2 Invasive Sensory Feedback

Invasive sensory feedback methods are usually characterized by irreversible procedures and surgical implementations of electrodes, which stimulate the afferent nerves directly. However, certain methods like **Targeted Sensory Reinnervation (TSR)**, introduce nerves to a target muscle, which provides sensation without electrical implementation. As a general rule of thumb, the freedom of stimulation is proportional to the invasiveness of the procedure. The review paper Svensson et al., 2017 classifies three different methods of invasive feedback:

Targeted Sensory Reinnervation (TSR)

Targeted sensory reinnvervation method implements the nerves affected from the amputation to areas not influenced by the amputation, which results in ease of control, but also in cutaneous sensations. It has been shown that the resulting feeling is more natural, but it is not somatotopically matched.

Peripheral Nervous System Feedback

Peripheral nervous system (PNS) stimulation involves the implementation of electrodes in or around the afferent nerve of the amputated limb, which can be stimulated to provide tactile feedback. *Extraneural* electrodes, such as cuff electrodes, are implemented around the nerve which can cause nerve damage, but the risk is offset due to close proximity of the electrode and the nerve, resulting in smaller currents. *Intraneural* electrodes are implemented directly in the nerve which allow for different choices in nerve selection, but at the risk of increased nerve damage. Lastly, *regenerative* electrodes are the most invasive PNS implementation of an electrode, in which the nerve regenerates around the implemented electrode. On one hand, the method allows for even more freedom (selectivity) in stimulation selection, one the other hand it is associated with a healing time and possible nerve damage.

Central Nervous System Feedback

Central nervous system feedback method extracts commands from the motor units in the brain and delivers the stimulation to somatosensory areas as feedback. The non-human primates (monkeys) were able to control a virtual arm with the "brain-machine-brain-interface". The tactile feedback was also deemed to increase the body-ownership.

Another study, conducted on a person with a spinal cord injury, showed that the tactile sensations were perceived on the fingertips (distal part) as a pushing sensation without the feeling of touch, and have been reported to be "almost natural" Svensson et al., 2017.

2.5 In-depth Analysis of Electrotactile Feedback

As mentioned before, this thesis implements the electrotactile sensory feedback method, and therefore it is important to examine the existing research and textbooks throughly. The following section has been summarized from the book Johnson, 2014, Transcutaneous Electrical Nerve Stimulation (TENS): Research to Support Clinical Practice, Chapter 3 and aims to provide the basics, the characteristics and the physiology of electrotactile stimulation.

A standard transcutaneous electrical nerve stimulation (TENS) setup includes a stimulator, electrodes and connecting lead wires. An example stimulator can be seen in Figure 2.5 and further explanation regarding each part has been provided in individual sections.

FIGURE 2.5: Stimulator RehaMove3

2.5.1 Characteristics and Parameters of a TENS device

Principles of electricity

The flow of electric charge is defined as the **electrical current (I)** and is measured in amperes(A). The force that drives the current from one place to another is called the **voltage (V)** (measured in volts(V)) and the resistance of the medium (can be solid or liquid conductors, i.e copper and water), in which the currents flows is called the **resistance (R)** (measured in ohms (Ω)). The relationship between these parameters are described by the *Ohms law*: $V = I \cdot R$.

Furthermore, direct current (DC) describes current flowing in one direction whereas alternating current (AC) is used for current that changes direction periodically, which is particularly interesting for TENS.

Impedance is the opposition to the flow of AC, and has two components, the magnitude and the phase of the current. Since TENS regularly employs pulses that have magnitudes and phases (which is to say, it uses AC), the impedance becomes an important parameter that plays a role in the stimulation.

Although human skin itself has impedance, the impedance between the electrode and the contact skin is of great importance, since the resistance to the flow will be greatest at that point. Generally, lesser impedance (equivalent to better flow) is desired.

Waveform

Waveform is the shape of the current and is acquired by plotting the amplitude against time. The Figure 2.6 shows a symmetrical biphasic pulsed square-wave with corresponding parameters, which affect the overall shape. Frequency, which is another important parameter, is defined as the number of periods in 1 second.

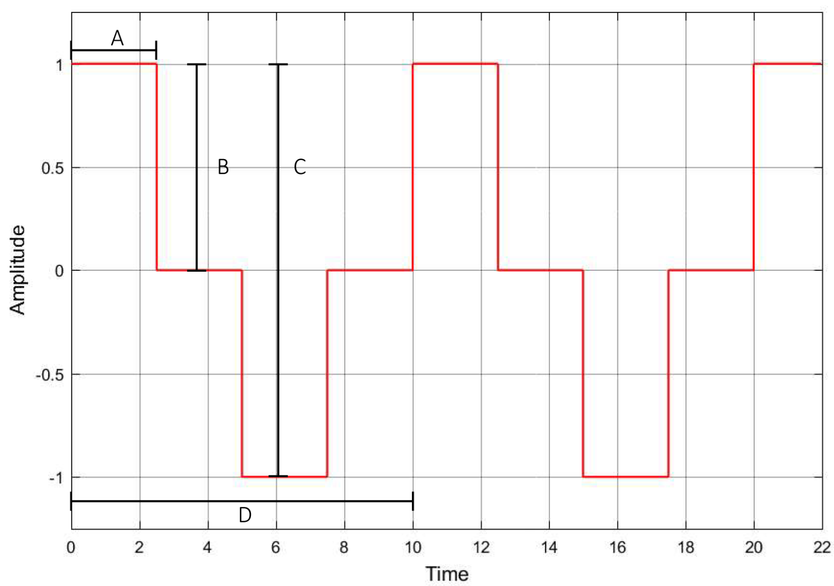

FIGURE 2.6: Symmetrical biphasic pulsed square-wave - A: Pulse width | B: Pulse amplitude | C: Peak-to-peak amplitude | D: Pulse period

The selected waveform has several implications on the stimulation. A major difference between monophasic (direct current) and biphasic waveform is the possible accumulation of ions, which can cause issues in the skin (i.e. electrolysis). Furthermore, the usage of symmetrical biphasic pulses result in zero net current flow and therefore cannot result in accumulation of ions. If asymmetrical biphasic pulses are used, it is possible that the current flow is not zero and other configurations (i.e. placement of electrodes) must be considered. Finally, the relationship between the human skin and the waveform is not linear, meaning the waveform will change once exposed to the skin.

Pulse amplitude

Pulse amplitude is defined as the magnitude of current flowing. As the Figure 2.6 indicates, there are two different, but related parameters regarding the amplitude: pulse amplitude and peak-to-peak amplitude. In a symmetrical biphasic waveform the pulse amplitude is the half of the peak-to-peak amplitude, whereas the peak of the pulse is defined as the maximum current flowing in a given waveform.

Increasing only the pulse amplitude corresponds directly to increased sensation. However, it has been shown that the sensation fades gradually, resulting in adaptation (a decrease in evoked action potentials) and habituation (a decrease in response to the stimulation). Therefore it is important to adjust the intensity accordingly to provide sufficient stimulation (Pantaleão et al., 2011).

Pulse width (duration)

Pulse width is defined as the time interval between the beginning and the end of an individual pulse (refer to 2.6). Increasing pulse width results in an increase in intensity of the stimulation due to high impedance, which relates to lesser penetration of the tissue. Y. J. Szeto, 1985 found that, under constant pulse amplitude, the pulse width must be decreased as the pulse frequency is increased, if the same stimulation intensity is desired.

Pulse frequency

Pulse frequency is defined as the number of cycles (periods) in one second. Increasing pulse frequency results in sensations being more rapidly felt at low frequencies (<10 pps (pulses per second)), rapid pulsation at intermediate frequencies (10 to 60 pps) and electrical paresthesia (tingling like feeling) at higher frequencies.

It has also been shown that an increase in pulse frequency results in an increase in the perceived magnitude of sensation (Jelinek and McIntyre, 2010).

2.5.2 Lead connectors and Electrodes

Lead connectors

Lead connectors are the medium in which the current travels from the stimulator to the electrode. Just like any other connector used for similar purposes, they need to be encapsulated using an insulating material. Furthermore they need to be flexible to fit under clothing and durable enough to be portable.

Electrodes

Electrodes provide the interface which allows the current to enter the skin, deliver the stimulation and evoke sensations. Electrodes need to establish good contact with the skin to ensure sufficient current density. Furthermore, electrodes that are not in good condition, dry or otherwise damaged may cause pockets of high current densities, which can cause from irritation to mild skin burns.

The perceived stimulation is also a function of the electrodes being used, which means two identical stimulations may elicit different sensations, if the electrodes are varied. Electrodes with smaller contact surfaces are usually associated with higher current densities in comparison to their counterparts with larger contact surfaces, which results in lower sensation thresholds (refer to Section 2.5.4 for further discussion). Likewise, electrodes with larger contact surfaces require higher intensities to evoke sensations.

Modern electrodes employed for TENS are usually self-adhesive and reusable, however contact electrodes with adhesive tape for stability and wet-gel for conductivity are also commercially available.

2.5.3 Physiology at the Interface

The contact area where the electrodes deliver current to the skin is called the interface and electrically, it can be modeled as a resistance and a capacitance connected in parallel. As mentioned in the previous sections, the impedance is an important parameter and it is inversely proportional to the frequency of the current, which means higher frequencies are correlated with lower impedances. Therefore, higher frequencies equate to better penetration of the current.

Properties of the skin

Although the properties of the skin is largely out of scope for this research, it is important to know that it is comprised of three layers, the epidermis, the dermis and the hypodermis. The outermost layer of the epidermis is called the stratum corneum and it is largely made out of corneocytes (dead cells), which increases impedance.

Furthermore, as mentioned in Section 2.5.2, electrodes work with the skin to create the interface, and dryness and cleanliness of the skin will either increase or decrease impedance (i.e. dry skin will result in higher impedances). Skin irritation due to adhesive material and exposure to higher-than-normal (refer to 2.5.4) currents also need to be taken into account.

Neural innervation

The integument (natural confinement) contains nerves that regulate the physiological responses provided by the skin. The sensations depend on the stimulation itself and the corresponding sensory receptor. Broadly speaking, there are three main branches of receptors: Nociceptors (sensors related to damaging and painful stimuli), thermoreceptors (related to temperature changes) and mechanoreceptors (related to physical distortion, i.e. bending, stretching, pressure). More importantly, these receptors are subject to certain phenomenon:

- **Peripheral adaptation:** reduction in response to constant stimulation, which may be rapid or slow. Similarly, **peripheral habituation** describes a decline in response to constant stimuli by the central nervous system.
- Above mentioned phenomenons are contrasted by **peripheral sensitization**, which describes an increase in sensitivity to tissue damage and **wind-up**, which is defined as gain in activity to repetitive damaging stimuli.

Furthermore, the distance of the nerve fiber to the electrode is also an important parameter. As the distance increases, the effect of the current will diminish.

The aforementioned properties provide the basis in selection of threshold values, which are discussed further in Section 2.5.4.

Nerve fiber activation

The electrical current flowing results in excitation of the nerve fibers, and the reaction depends on the dimensions of the nerve fiber itself. Large-diameter myelinated axons have lower thresholds and faster conduction rates in comparison to smaller diameters and unmyelinated axons. An overview on the types of nerve fibers has been provided in Table 2.2.

As the pulse amplitude is increased, the electrical stimulation will excite nerve fibers with larger diameters. The excitation of the nerve fibers A-β to A-γ (ordered proportionally to pulse amplitude) will evoke non-painful electrical paresthesia (tingling, prickling sensations) without any muscle twitching. Higher amplitudes will stimulate nerve axons with smaller diameters, which will be interpreted by the nociceptors as painful tingling under the electrodes. As the intensity gets higher, relatively powerful muscle contractions will occur as the nerve fiber A-α is stimulated. The contradictory hierarchy of excitation of the axons is the result of the relatively longer distance between the surface electrode and the A-α nerve fiber.

Furthermore, shape of the waveform also affects how the nerve fibers are going to be activated. Generally, the rise time of the leading edge (i.e. if the pulse amplitude

Name	Structure	Conduction velocity	Afferent role	Efferent role
A-α	Myelinated, large diameter, 22-13μm	120-70 ms^{-1}	Muscle spindle, Golgi tendon organs Mechanoreceptors	Contraction of slow and fast skeletal muscle fibres
A-β	Myelinated, large diameter, 8-13μm	40-70 ms^{-1}	Mechanoreceptors, Proprioceptors Muscle spindles	Contraction of muscle spindle fibers
A-γ	Myelinated, medium diameter, 4-8μm	15-40 ms^{-1}	Mechanoreceptors	Contraction of muscle spindle fibers
A - δ	Myelinated, small diameter, 1-4μm	5-15 ms^{-1}	Nociceptors, Mechanoreceptors Cold-sensitive temperature	
B	Myelinated, small diameter, 1-3μm	3-14 ms^{-1}		Pre-ganglionic autonomic
C	Unmyelinated, small diameter, 0.1-1μm	0.2-2 ms^{-1}	Nociceptors, Mechanoreceptors Cold-sensitive and heat-sensitive thermoreceptors	Post-ganglionic autonomic

TABLE 2.2: Erlanger-Gasser nerve fiber classification, simplified, taken from Johnson, 2014

is being titrated, a rise from 0 to 20 mA) is configured to be as short as possible, with the ideal situation being the instant change, which is equivalent to a vertical edge. This minimizes adaptation of the nerve fiber and results in overall increase in perceived stimulation. Lastly, the pulse amplitude and the pulse width are **inversely proportional** for constant stimulation intensity. As the pulse width decreases, the pulse amplitude must be increased in order to achieve the same stimulation. Figures and further discussion have been provided in 2.5.4

2.5.4 Threshold Values and Placement of Electrodes

Hughes, Bennett, and Johnson, 2013 conducted a study in order to determine the relationship between transcutaneous electrical nerve stimulation sensation and placement of the electrodes on various body parts, in three different frequencies(2pps, 30pps and 80pps). The variable being titrated is the pulse amplitude and five body parts were investigated in total: Tibia (bone), knee joint (connective), lower back (skeletal muscle), forearm (nerve) and lastly waist (fat), depicted in Figure 2.7. Table 1 of the study shows the mean intensities for different frequencies for different placements of the electrodes, in which the sensation was classified into three subclasses: Sensory Detection Threshold, Strong Non-painful Sensation, and Absolute Pain Threshold.

Overall, it was concluded that the stimulation sensation was most comfortable when applied over areas with muscle and soft tissue. Furthermore, stimulation over bone and forearm was the least comfortable. Additionally, it was shown that a strong, non-painful sensation was reached, when the intensities corresponded to approximately %80 of the absolute pain threshold.

2.6 Preliminary Research

A preliminary research conducted during Winter Term 2017/2018 (by Christopher Jendretschak, Ongun Türkcüoglu, Onat Tanriöver and Jennifer Netes), dated 09.03.2018 , has implemented the idea of electrotactile feedback method using an 8-channel stimulator with a common electrode. Eight electrodes have been placed on the back using groups, which means certain electrodes have been assigned to certain feedback modus.

The implemented method used a linear interpolation between electrodes, which means there were no discrete levels. The idea was that the stimulation could be

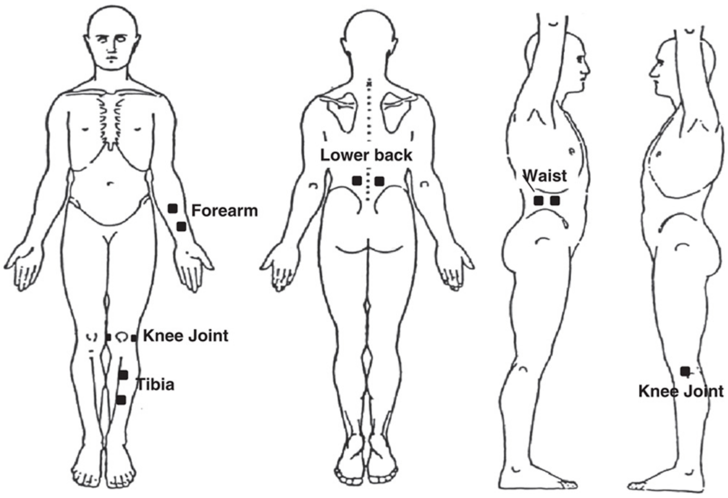

FIGURE 2.7: Placement of the electrodes (taken from Hughes, Bennett, and Johnson, 2013, Figure 1)

located between the electrodes (i.e. if the hand position was 22.5° -between 45° and 0°-, the feeling was expected to be right in the middle, refer to Figure 2.8). However this was not the case. The stimulation was strongest as the command signal matched with that certain electrode and intermediate stages were not as intensely perceived, and for some cases the feeling was completely gone. The habituation effect was proposed for this phenomenon.

The project report can be seen in the Github repository.

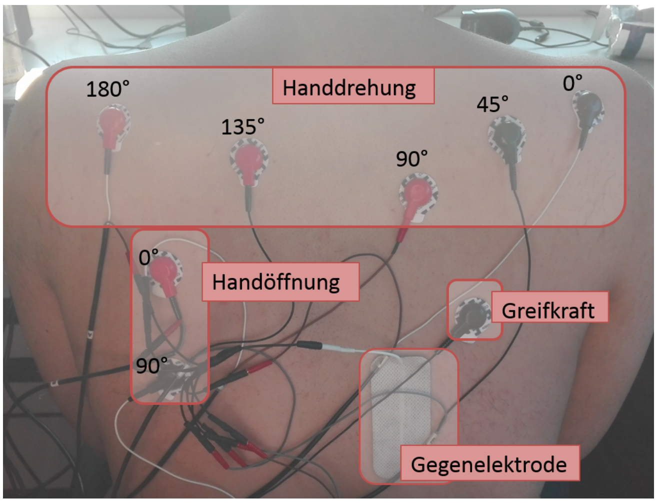

FIGURE 2.8: The experimentation setup for the preliminary research

2.7 Scope of the Research and Objectives

In this Introduction section, we examined the definitions, statistics and possible outcomes of amputations. Furthermore, the human hand has been (very briefly) introduced and available prosthetic devices for upper-limb removals have been investigated. A clear shortcoming of aforementioned devices has been identified as sensory feedback and further discussion and methods for feedback have been provided. Lastly, an in-depth analysis of electrotactile feedback has been written.

This study focuses on sensory feedback reconstruction for upper-limb prosthetic devices using the electrotactile feedback method. It aims to provide an intuitive system that is reproducible and scalable, while being comfortable to use. Further sections will provide design methods, justifications around these methods and will also include detailed documentation of the programming which implements the methods. Preliminary results and extensive experimentation in respective sections will also be provided. Lastly, the conclusion provides shortcomings and possible problems regarding the implementation, including prospective improvements.

Chapter 3

Methodology

In contrast to the Introduction section 2, the Methodology section provides information related directly to this study. This part, therefore, includes an overview of the system, hardware description, design decisions (and justifications) and iterations on the design, which leads to the final system, which is being tested on a number of subjects. Related advantages and disadvantages are also being discussed at every step of the turn to provide insight regarding aforementioned decisions.

3.1 Overview of the System

This thesis, as indicated in Section 2, uses the electrotactile feedback method to develop sensory feedback in order to provide better control of a myoelectric hand prosthesis. Therefore, the central hardware is the electrical stimulator RehaMove3 by HASOMED. Myoelectric hand prosthetic devices require the use of an electromyography recording device to capture user intentions to control the hand. Therefore, to mimic this connection, the system also includes such a device to capture electrical activity from surface electrodes on the skeletal muscle. The electromyography (EMG) capturing device is in our case the StiMyo II, developed by TU Berlin.

Another central hardware is a personal computer (PC) running Linux and is equipped with MATLAB R2016b. This computer communicates with the hardware (the stimulator and the EMG recording device) to provide the test subjects and the experimenter an interface, which can be manipulated in real time.

Other hardware includes a controller (Powermate), lead connectors for both the stimulator and the EMG device and various skin interfaces to conduct the electricity provided by the stimulator and to receive muscular electrical activity with the EMG device.

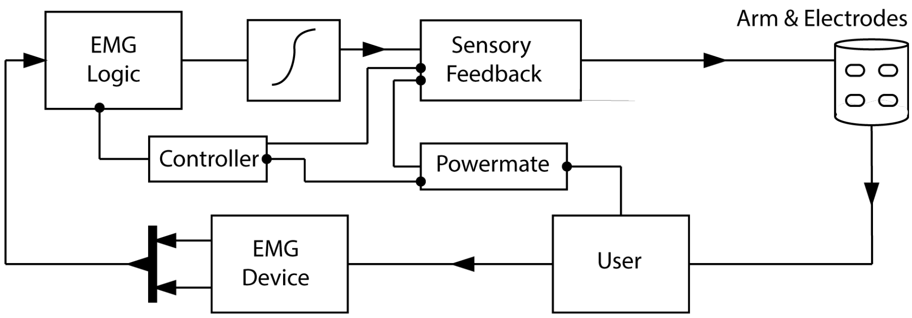

FIGURE 3.1: Overview of the system - arrows: information flow, from-block-to-dot: control flow

3.1.1 Electrodes and their Placement

The electrotactile feedback method introduces tingling-like sensations (refer to Section 2 for the detailed explanation) on the skin to provide information regarding the hand prosthesis. The interface to the human skin is provided by electrodes and how useful this interface ultimately depends on the placement of said electrodes. This thesis implements several different types to meet certain goals. The Figures 3.2 and 3.3 display the implemented electrodes and the associated adapters.

FIGURE 3.2: Upper-right: Common electrode, left: EMG electrodes, lower-right: Stimulation electrodes.

FIGURE 3.3: Adapters for stimulation electrodes (4 pieces), an analog multiplexer.

Electrodes being used can be split into three different categories: The common electrode, the EMG electrodes and the stimulation electrodes. The **common electrode** is a relatively large interface (ValuTrode™Model CF4090, Size 4x9cm, Axelgaard™) that is placed on the shoulder. It will provide a node for the current to flow from the stimulation electrodes. The large dimensions are inversely correlated with current density, which means that the same current flowing through will have a much smaller density on the common electrode in comparison to the stimulation electrodes. This will in turn help eliminate sensations that can be mistaken for actual feedback.

The **EMG electrodes** (Ambu®Neuroline 720, Ambu A/S, Denmark) are placed on the dorsal and the palmer side of the forearm (two pieces for each side, four in total), near the elbow. One electrode, labeled as the **reference EMG electrode** is placed somewhere in the vicinity of the elbow and preferably on the bone, where no muscular electrical activity is expected. These electrodes have built-in conductive gel, which helps reduce skin impedance and helps deliver an unadulterated EMG signal.

The **stimulation electrodes** (Kendall™ECG Electrodes H124SG, Covidien™, 30mm x 24 mm, 4 pieces) are placed around the biceps/triceps area, just below the shoulder, in a ring-like structure. As such, each of these electrodes represent a direction. For our purpose, one electrode is placed directly on the biceps and another on the

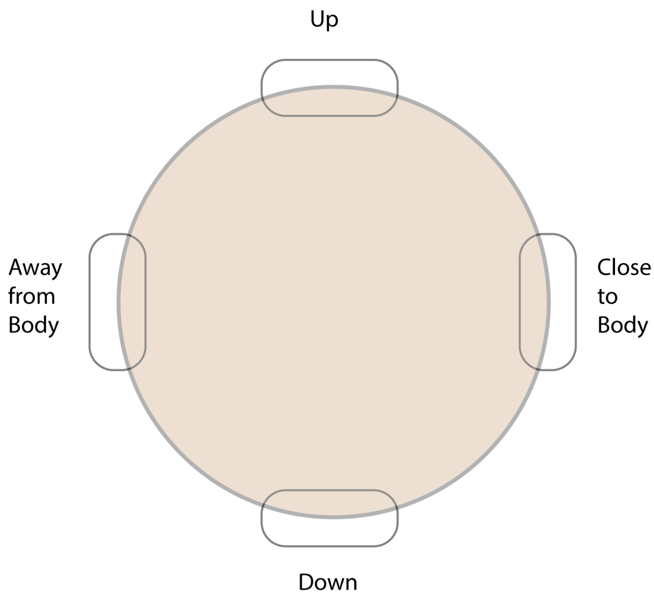

FIGURE 3.4: Cross-section of the left upper-arm - electrodes as rectangles.

triceps. The third electrode is placed in between the first two, as the dormer side of the hand is looking upwards and last electrode is placed directly under the third one. The Figures 3.5 and 3.6 illustrate the explained placement. The illustration of the cross-section of the left upper-arm is also shown in Figure 3.4. The positioning of the arm relative to the body is not uniquely defined, however, the standard anatomical position can be referenced, in which case the up-electrode would be located on the biceps and the down-electrode on the triceps.

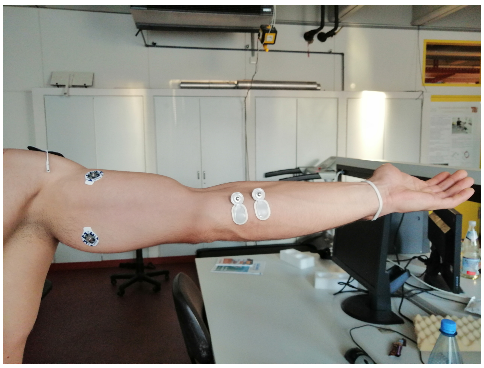

FIGURE 3.5: Placement of the electrodes - side 1

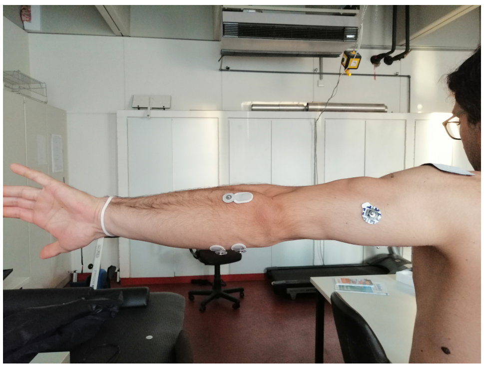

FIGURE 3.6: Placement of the electrodes - side 2

The Figure 3.3 shows **adapters** for the stimulation electrodes and an **analog multiplexer**. A two-piece adapter is introduced, as the stimulation electrodes aren't directly compatible with the lead connectors of the stimulator. The adapters themselves do not possess any functionality regarding the electrotactile feedback, and only act as an intermediate medium.

The analog multiplexer has eight inputs and one output and it allows the usage of one unique common electrode, providing a node for all four stimulation electrodes. It also saves a considerable amount of space, since instead of having an anode for every stimulation electrode, we can use only one, larger interface, guaranteeing smaller current densities.

3.1.2 Stimulator - RehaMove3

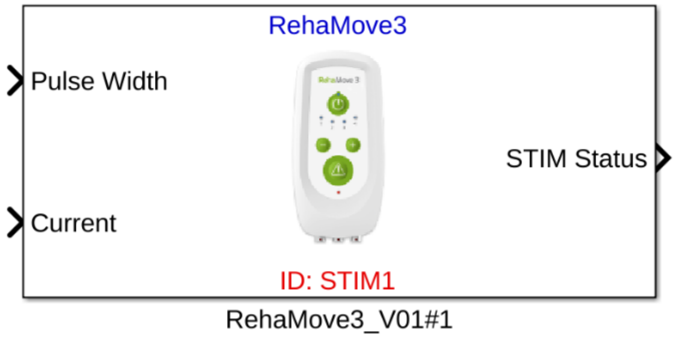

FIGURE 3.7: RehaMove3 MATLAB Block

The stimulator RehaMove3 (see 2.5) by HASOMED is a 4 channel stimulator which accepts user-defined pulse-forms. The MATLAB Block (see 3.7) (provided by the TU Berlin Control Group) provides 2 input ports (one for the current vector and one for the pulsewidth vector) and a mask to set hard-coded parameters, like sampling frequency, waveform points and maximum current amplitude and pulsewidth. The input ports receive (respectively) one matrix with dimensions m x n (m = waveform points + 1, n = number of channels being used). As the input ports (current and pulsewidth) are related to each other, the dimensions of both inputs must be identical. The following example aims to illustrate the relation of these two input ports and shows the resulting waveform.

$$\text{current} = \begin{bmatrix} 1 \\ 5 \\ 10 \\ -3 \\ -8 \end{bmatrix} \qquad \text{pulsewidth} = \begin{bmatrix} 1 \\ 30 \\ 50 \\ 100 \\ 20 \end{bmatrix} \tag{3.1}$$

Suppose that the vectors displayed in Eq.(3.1) are the input vectors to the respective input ports on the RehaMove3 MATLAB Block. The first element of each vector represents the channel, in this case channel 1 is being used. Every other element is a point in the waveform, such as: the first point has the current amplitude 5 mA and the pulsewidth 30 μs, and so forth. The resulting waveform is a combination of the four waveform points, as shown in Figure 3.8.

$$\text{current} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 10 & 5 & 12 & 15 \\ 1 & 0 & -3 & 4 \\ -2 & 5 & -10 & -3 \\ 2 & 1 & 3 & 0 \end{bmatrix} \qquad \text{pulsewidth} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 10 & 20 & 30 & 40 \\ 47 & 5 & 11 & 23 \\ 10 & 17 & 28 & 31 \\ 10 & 15 & 19 & 41 \end{bmatrix} \tag{3.2}$$

Suppose that the matrices in Eq.(3.2) are input matrices to the respective input ports. Similarly, each individual column represents the current and/or the pulsewidth

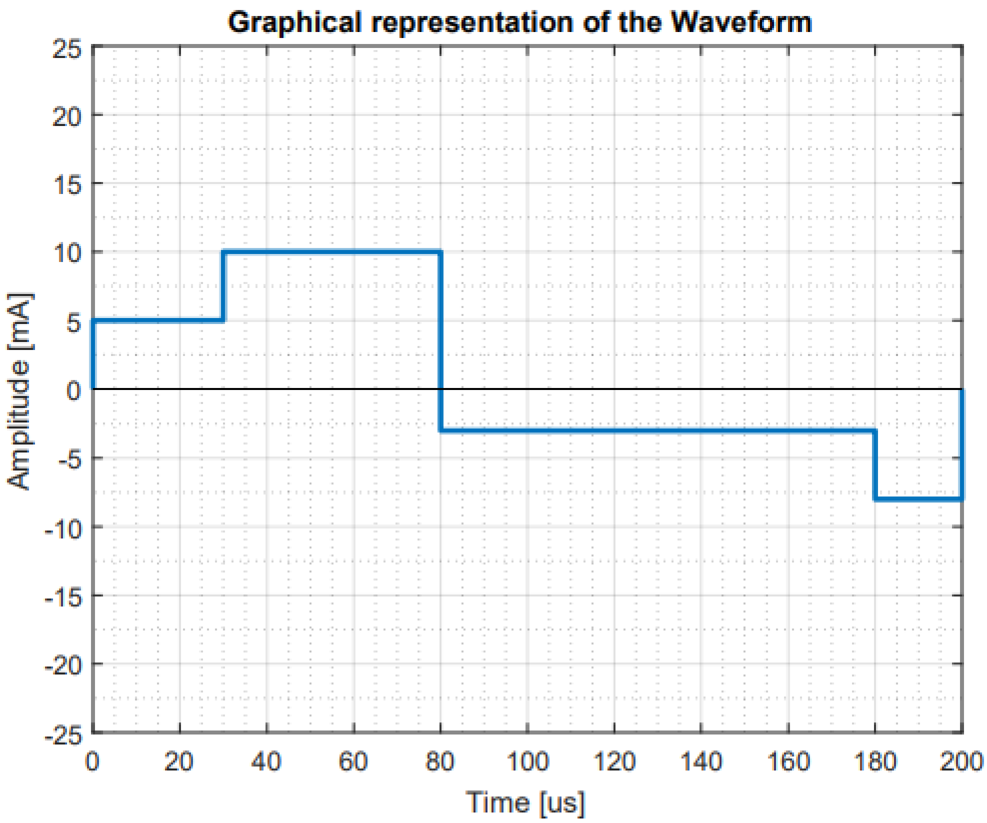

FIGURE 3.8: The resulting waveform from the input vectors 3.1

vector of the respective channel and each element in this vector represents a waveform point. Let it be noted that the dimensions of both matrices are identical. The resulting waveform of this 4-channel stimulation is shown in Figure 3.9.

Both waveforms are periodically repeated with the sampling frequency specified in the MATLAB Block. The most important hardware limitations are the maximum pulsewidth (4000 μs), the maximum current amplitude (130 mA) and the maximum waveform points (16 points). However, these limitations are mostly irrelevant for an electrotactile sensory feedback stimulation, as the threshold levels are much lower than the maximum limit for both pulsewidth and current. The limit regarding the maximum waveform points can be problematic, if exotic waveforms are being used (i.e. other than the commonly used symmetrical and/or asymmetrical biphasic charge balanced waveforms).

A property worth mentioning is the null pulsewidth vector (apart from the channel identicator element). If the MATLAB Block receives a null pulsewidth vector, it will not provide current to the channel. Similarly, any element following the zero element in a pulsewidth vector will be disregarded. The inverse is, however, not true. If there exists a null current vector (or a null current element) with a corresponding, non-zero pulsewidth vector, the current provided will be 0 mA and the duration of the corresponding pulsewidth element will be regarded as a pause in stimulation.

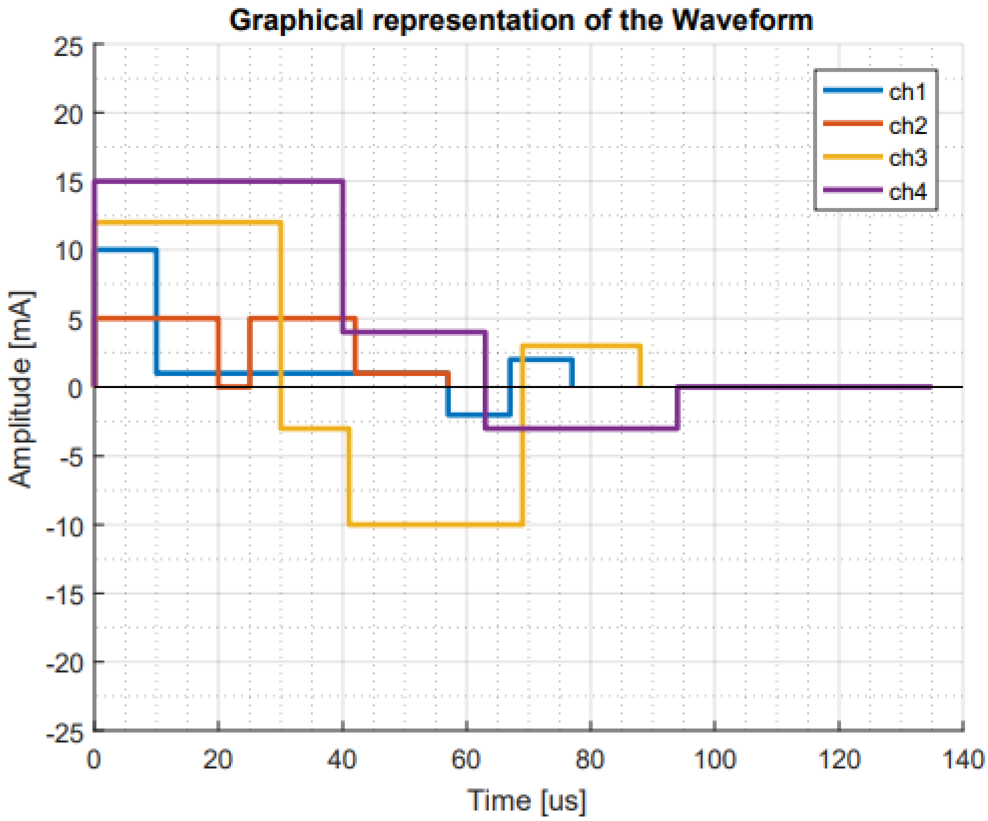

FIGURE 3.9: The resulting waveform from the input matrices in Eq.(3.2)

$$\text{current} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 10 & 5 & 12 & 15 \\ 1 & 0 & -3 & 4 \\ -2 & 5 & -10 & -3 \\ 2 & 1 & 3 & 0 \end{bmatrix} \qquad \text{pulsewidth} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 10 & 20 & 30 & 40 \\ 0 & 5 & 0 & 23 \\ 0 & 17 & 28 & 0 \\ 0 & 15 & 19 & 41 \end{bmatrix} \tag{3.3}$$

is equivalent to

$$\text{current} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 10 & 5 & 12 & 15 \\ 0 & 0 & 0 & 4 \\ 0 & 5 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \qquad \text{pulsewidth} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 10 & 20 & 30 & 40 \\ 0 & 5 & 0 & 23 \\ 0 & 17 & 0 & 0 \\ 0 & 15 & 0 & 0 \end{bmatrix} \tag{3.4}$$

Let it be noted that the input matrices still have the same dimensions. The only difference is how the stimulator interprets the individual waveforms for the channels: The channel 1 has one waveform point, the channel 2 has four waveform points, the channel 3 has one waveform point and the channel 4 has 2 waveform points. The resulting waveform is shown in Figure 3.10.

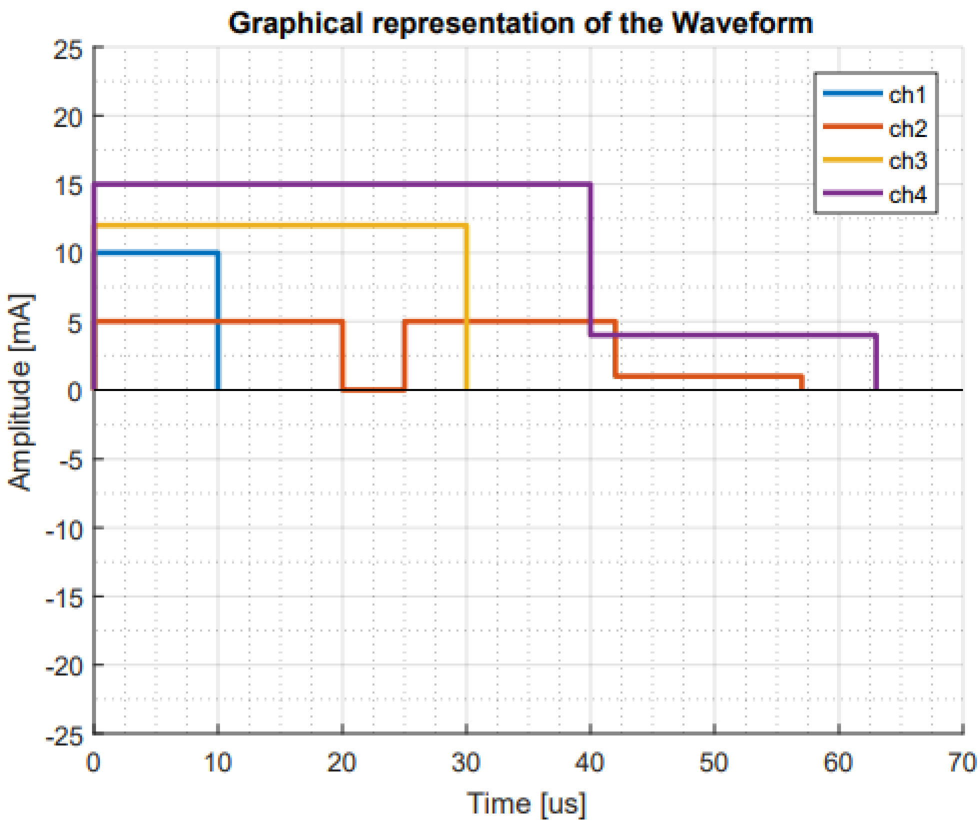

FIGURE 3.10: The resulting waveform from the input matrices in Eq(3.3)

It is important to note, that the illustrations in Figures 3.9 and 3.10 are simplifications and do not reflect the actual flow of current over time. The stimulator is equipped with only one current source and a demultiplexer (DEMUX), which means the waveforms are not parallel, but sequential.

On the hardware side (apart from the stimulator itself, which can be seen on Figure 2.5), the lead connectors play a major part in delivering the current to the skin interfaces. The Figures 3.11 and 3.12 illustrate the lead connectors that are compatible with the stimulator.

Each individual lead connector comes with its own color coding, and the respective input port on the stimulator also has identical color coding, making incorrect connections difficult. The closeup (3.12) of the lead connector shows one input port (colored red with silver jack) and three output ports. As the waveforms are programmable, there are no clear definitions which output is the anode and which is the cathode. Therefore, for consistency purposes, it is advisable to mark one output depending on the definition the programmer established. The off-color output (in this case, green) is largely irrelevant for feedback purposes.

This thesis uses a biphasic, unsymmetrical, charged balanced waveform consisting of 2 waveform points. The functions provided in Section 3.3.3 implements the waveform using three parameters: current amplitudes for the positive and the negative (balancing) waveform points, and the time duration of the positive charge. Using the relationship between the current amplitudes, a duration for the negative charge is calculated, ensuring a charge balanced stimulation. The following is the

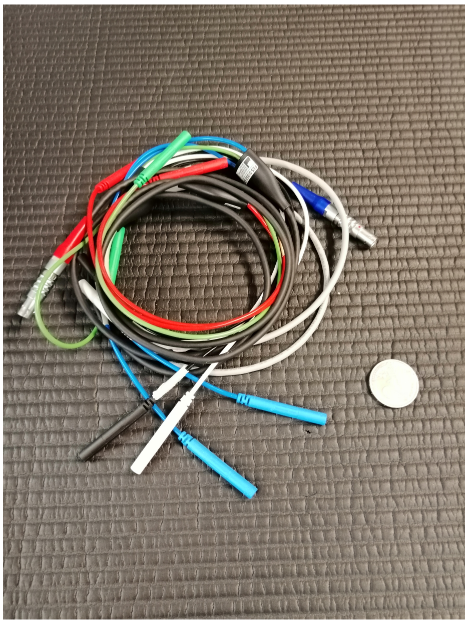

FIGURE 3.11: Lead connectors for RehaMove3

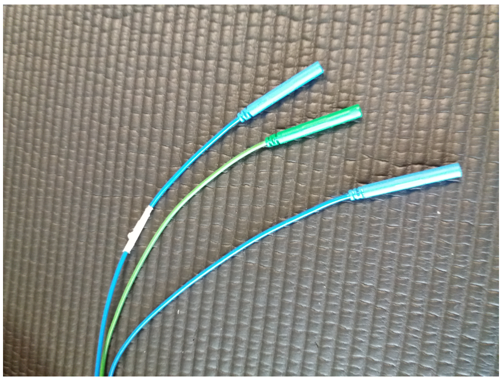

FIGURE 3.12: Lead connector - closeup with marked cable

mathematical model of the described schema.

$$
\begin{aligned}
\text{Let } p_1, p_2 \in \mathbb{N} \quad c_1, c_2 \in \mathbb{Z} \\
p_i \rightarrow \text{Pulsewidth for point i} \\
c_i \rightarrow \text{Current amplitude for point i} \\
|p_1 \cdot c_1| \stackrel{!}{=} |p_2 \cdot c_2| \\
sgn(c_1) \neq sgn(c_2) \implies \text{Biphasic charge balanced waveform}
\end{aligned}
$$

As long as the current amplitudes do not have the same sign, it is possible to achieve a charge balanced waveform. Given that

$$|c_1| \neq |c_2|$$

the waveform will still be charge balanced, however not symmetrical. Figure 3.13 illustrates the mathematical model with parameters

$$
\begin{aligned}
p_1 = 30\mu s \quad p_2 = 120\mu s \\
c_1 = 12\text{mA} \quad c_2 = -3\text{mA}
\end{aligned}
$$

3.1.3 EMG recording device - StimYoII

StimYoII is a two-channel EMG-recording device, which captures muscular electrical activity. The MATLAB block (provided by TU Berlin Control Group) has no inputs, and three output ports. The outputs "ch1" and "ch2" refer to the output of the unfiltered and unprocessed EMG signals, which are, in this form, unusable. The

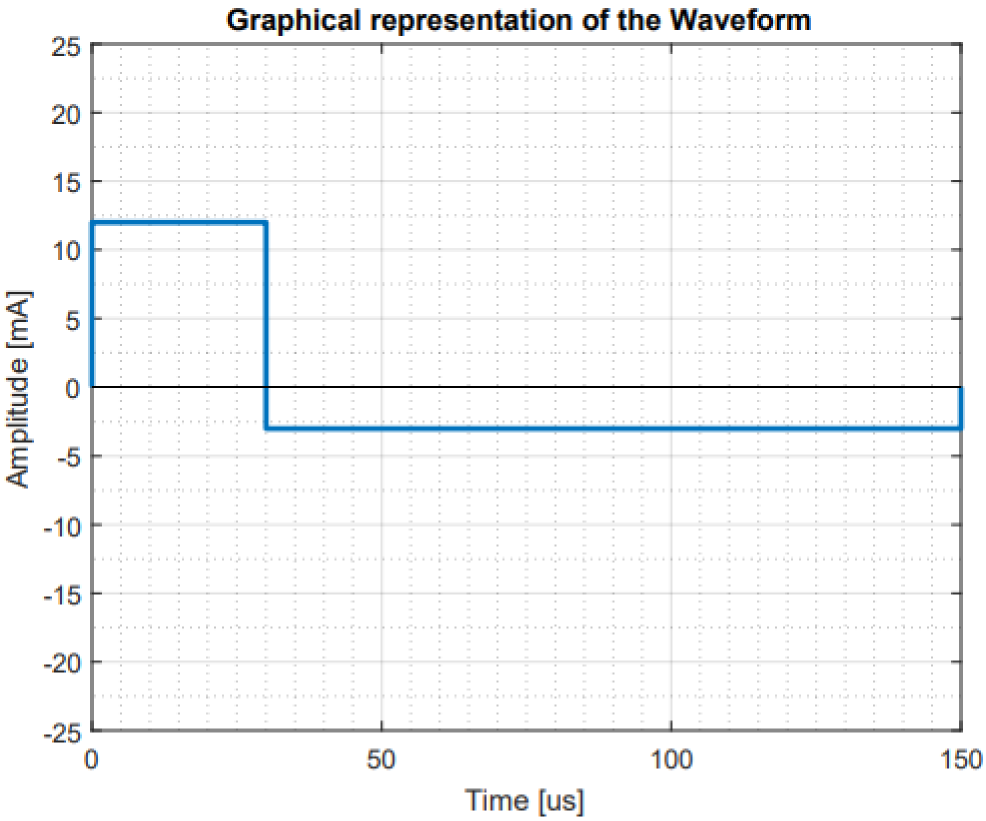

FIGURE 3.13: Illustration of the biphasic unsymmetrical charge balanced waveform

"status" port contains information about the aforementioned outputs, and marks the valid elements of each row. With this knowledge, an unfiltered EMG signal can be created. However, since this form of the EMG signal is still contaminated and therefore cannot be used in this form to capture volitional EMG.

The Figure 3.15 shows the EMG recording device. On top of the device, there are three groups of electrodes: EMG electrodes for channel 1 (top pair) and 2 (middle pair), and the reference electrode (marked with yellow tape). The connection to the computer is establish with a standard Mini-USB-Connector.

The scope of this research does not include the implementation of the artifact detection and the filtering, which returns the volitional EMG signal from the raw EMG signal input. Special thanks goes to Ana Carolina C. de Sousa, Markus Valtin, Antonio P. L. Bo and Thomas Schauer for authoring the paper "Automatic Detection of Stimulation Artifacts to Isolate Volitional from Evoked EMG Activity" (in proceedings of) and implementing the method using MATLAB function blocks.

3.1.4 USB-Controller - Powermate™

The USB-Controller Powermate™(by Griffin Technology™, Figure 3.17) is a control knob that is completely programmable to accommodate different needs. Together with the MATLAB block provided by the TU Berlin Control Group, it provides basic IO-functionality. For this thesis, two basic functionalities have been implemented. First, setting the threshold values for the stimulation electrodes and a trigger-like behavior. Upon clicking on Powermate once, the MATLAB block (Figure 3.16) sends the preset value as output. The event-driven programming method chosen for this

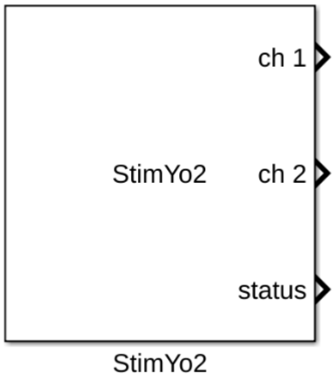

FIGURE 3.14: StimYoII MATLAB Block

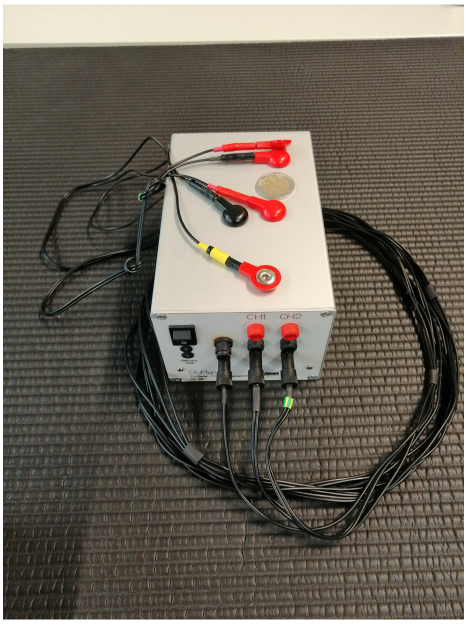

FIGURE 3.15: StimYoII

system depends on the synchronization of different finite state-machines, which is mostly centrally controlled by the Single-Click functionality of Powermate.

3.1.5 Linux Computer

A Linux computer with the operating system Ubuntu 14 LTS (Long Term Support) has been used to control the stimulation and to generate the code. Finite-state machines have been implemented using the Stateflow toolbox of SIMULINK and the real-time code generation is performed using the Linux Target for SIMULINK Embedded Coder.

3.2 Setting Up the Sensory Feedback

The way the sensory information is delivered plays a central role in electrotactile sensory feedback method. Preliminary research (refer to 2.6) has shown that, the habituation effect can indeed be problematic. Also, the tingling-like sensation associated with electrotactile feedback is indeed strongest near the vicinity of an electrode,

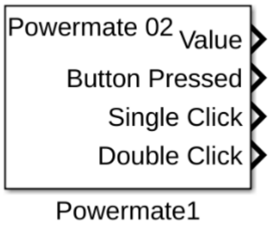

FIGURE 3.16: Powermate

FIGURE 3.17: Powermate

whereas it becomes less discernible as the current flowing to the electrode becomes smaller. This effect is compounded by the habituation effect, because after an electrode is stimulated at the maximum threshold level, smaller amplitudes (or shorter pulsewidth) might not be easily perceivable. Therefore, the method that is being presented in this thesis aims to overcome this effect by switching from a continuous linear feedback system to a discrete one.

Each electrode has a minimum and a maximum threshold level. The minimum threshold level is defined as the stimulation intensity, where sensation is evoked, and the maximum level is associated with a strong but non-painful sensation. In further sections (i.e. Section 3.3) these parameters are labeled TH_MIN,TH_MAX or THRESHOLD_MIN,THRESHOLD_MAX, respectively.

With the hypothesis, that every stimulation under the maximum threshold level risks being not identifiable, the solution is to always stimulate at the maximum threshold. As it was explained in Section 3.1.1, the ringlike structure around the upper-arm area contains four stimulation electrodes. A naive approach is to use only one electrode at any given time with a continuous stimulation, however the disadvantage to this approach becomes clear, as only four points of reference will not provide enough information for a closed-loop control system. Therefore, a combination of different stimulations and patterns can be used to convey information that is uncomplicated and easily distinguishable.

Experimentation has shown that an oscillating stimulation between adjacent electrodes has the potential to overcome the habituation effect, and provide intuitive information. Combinatorially, two electrodes can have the following configurations:

- Both electrodes off
- One electrode continuously on, the other continuously off
- Electrodes turn on and off at the same time (simultaneously on/off)
- Electrodes turn on and off after one another (alternating on/off)
- Both electrodes on

In order to keep the information clean and simple, following decisions have been made:

- At any given time, no more than two electrodes will convey information.
- At any given time, only one electrode can be turned on continuously.
- Only two adjacent electrodes can simultaneously be turned on and off.
- All stimulations will be conducted at the maximal threshold values.

These restrictions aim to satisfy the KISS (keep it simple, stupid) principle in order to avoid complexity. Naturally, a larger subset of combinations would theoretically provide more information, but the added complexity could result in loss of intuition, which could in turn compromise the information channel. Exceptions to these restrictions have been made to improve robustness of perceived feedback (refer to Sections *Stimulation Pattern for Hand Opening - Closing* under 3.2.3 and *Indication Stimulation* under 3.2.1).

3.2.1 Indication Stimulation

The implementation of four different feedback modi requires an indication stimulation in order to signify a change in feedback. The indication also has to be unique, both the combination of the electrodes being used for this purpose and the pattern of the stimulation.

One possible solution is to use a combination that is restricted, so that it is not associated with sensory feedback information. A simultaneous on/off pattern of the electrodes close and away from the body fulfills the requirements. For each feedback modus the indicator electrodes would blink (turn on/off) once, twice, thrice or four times, depending on the feedback mode currently selected.

3.2.2 Stimulation Pattern for Hand Positioning

Unlike a human hand, a myoelectric hand prosthesis can rotate along the axis of the wrist without assistance from the elbow or the shoulder. Therefore, the sensory feedback pattern should ideally be able to map a complete circle as electrotactile sensations. However, within a discrete stimulation schema, this is not feasible. Considering the aforementioned restrictions, the 360 degrees of the circle can be mapped to an eight-point reference structure. The electrodes corresponding to the main directions (up, down, close, away) are continuously turned on, and the derivative

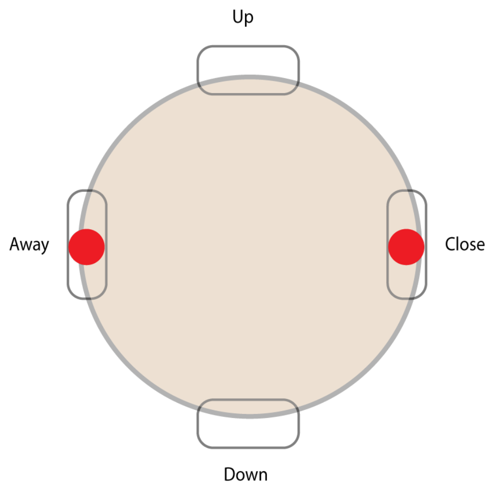

FIGURE 3.18: Indicator Electrodes Illustrated

directions (i.e. up-close) are mapped to simultaneous on/off. Therefore, each reference point would map exactly 45 degrees. Within this context, **the stimulation follows the dorsal side of the hand and the indicator electrodes blink once!**. The Figures A.1 and A.2 summarize the stimulation pattern for hand positioning.

3.2.3 Stimulation Pattern for Hand Opening - Closing

A myoelectric hand prosthesis also has the ability to open and close the hand. Similar to the indication stimulation, exceptions for this stimulation pattern have also been made in order to distinguish this one from the rest. The sensory feedback should be able to provide information whether the hand is opened (neutral) or closed. Furthermore, two levels of stimulations with unique oscillation frequencies have been implemented to realize intermediate steps between closed and opened. The electrodes corresponding to up and down are allocated for this pattern and there are four distinct levels:

Level 1: The hand is open (in the neutral position), no stimulation is provided.

Level 2: The hand is partially closed, the corresponding electrodes simultaneously turn on and off with a frequency of 2 Hz

Level 3: The hand is mostly closed, the corresponding electrodes simultaneously turn on and off with a frequency of 4 Hz.

Level 4: The hand is closed, the corresponding electrodes are continuously on.

The indicator electrodes blink twice! The Figure A.3 summarizes the stimulation pattern for hand opening-closing.

3.2.4 Stimulation Pattern for Force Feedback

One of the major functions of a hand prosthesis is its ability to grasp objects. However, grasping an object requires the user to understand exactly how much pressure he is applying to prevent slippage and breakage of the object. Therefore, the sensory feedback should be able to provide high resolution for ideal control of the applied force.

The proposed method implements nine different levels for a normalized applied force ranging from 0 to 1. The pattern of the electrodes are as follows:

Level 1: Away-down electrodes simultaneously turn on/off. Normalized force of 0.

Level 2: Away electrode turns on/off.

Level 3: Away electrode is continuously on. Normalized force of 0.25.

Level 4: Up-away electrodes simultaneously turn on/off.

Level 5: Up electrode is continuously on. Normalized force of 0.5.

Level 6: Up-close electrodes simultaneously turn on/off.

Level 7: Close electrode is continuously on. Normalized force of 0.75.

Level 8: Close electrode turns on/off.

Level 9: Close-down electrodes simultaneously turn on/off. Normalized force of 1.

The indicator electrodes blink three times! The Figure A.4 summarizes the stimulation pattern for force feedback.

3.2.5 Stimulation Pattern for Continuous Interpolated Hand Positioning

As previously mentioned before, this thesis implements a discrete system to provide feedback. The contrast, continuous interpolated hand positioning, is also implemented to compare both types. Depending on the orientation of the hand (position), the stimulation corresponding to those electrodes are adjusted based on distance from the pair.

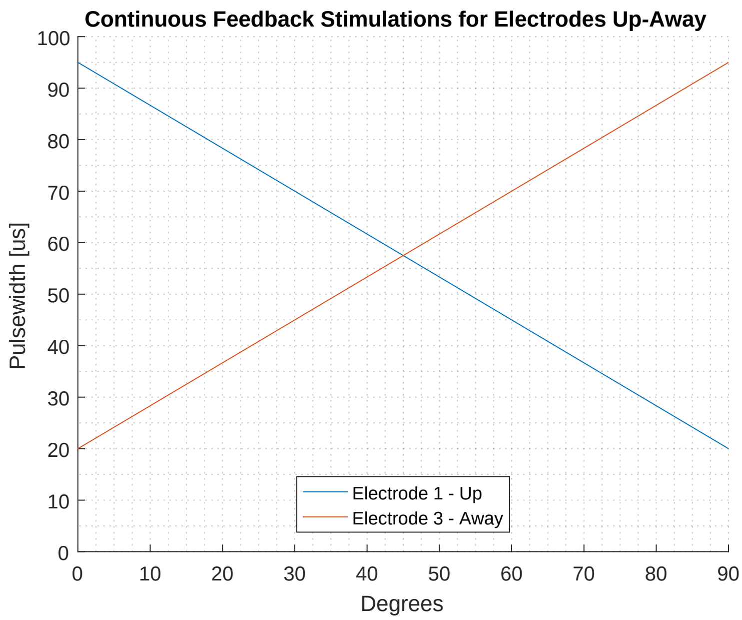

FIGURE 3.19: Continuous interpolated hand positioning between degrees 0 and 90

Figure 3.19 illustrates the evolution of pulsewidth (at constant current amplitude) over degrees between 0° and 90°. 0° corresponds to maximal and minimal threshold levels of electrodes up and away, respectively. The opposite is true for 90°. Every intermediate step between two end points is linearly interpolated. For example, at the intersection (45°), both electrodes are stimulated using the same intensity.

3.2.6 How patterns are formed?

At the first look, the discrete stimulations appear to be arbitrary, however, each category (hand position, hand opening-closing and force) of discrete stimulations has distinctive characteristics. These characteristics are outliers from the restriction we have previously discussed and they have been implemented in order to investigate different sensations and how well they could convey information.

The indicator electrodes are unique in the way they communicate information: These pair of electrodes (away and close to the body) are used only for this purpose and they are not identified across all stimulations. Therefore, when the indicator electrodes come online, a direct association will be made, which makes it easier to understand which modus is currently activated.

The stimulation patterns for the hand position represent a complete circle, and every individual pattern is a successor or a predecessor of another pattern. Therefore, a circular motion, like the hand prosthesis is capable of, is successfully implemented.

In contrast to the hand position patterns, the patterns for hand opening-closing are similar to one another and apart from the neutral position (Status 1, see Figure A.3), all stimulations make use of the same two electrodes, up and down. The main difference between the stimulations is the frequency. This implementation allows the experimenter to investigate the ability to successfully distinguish the instantaneous frequency, which implies a change in status. This characteristic is unique to this pattern.

The last stimulation pattern, force feedback, is the implementation of axial symmetry of a linear map. Normalized force is mapped to 9 different points and every status, apart from the status corresponding to the axis (Status 5, A.4), has a symmetrical correspondent. Therefore, a faster localization depending on the stimulation side (close or away from the body) is achieved.

3.3 Programming the System

THE SOURCE FILES FOR THE SYSTEM ARE PROVIDED IN THE FOLLOWING GITHUB REPOSITORY: `https://github.com/onguntoglu/etsfm_bachelor`

As it was previously mentioned, a programming environment consisting of MATLAB and Simulink has been used to realize the concept of sensory feedback. Picking this route made it significantly easier to program, test and gather data, since most of the peripheral devices have already been implemented in MATLAB/Simulink.

As discussed in the Introduction section (refer to 2), the stimulation provided to the skin needs to be strong, but also non-painful to avoid uncomfortable outcomes. However, these threshold levels are not predictable. Even for one subject, the threshold levels might differ day-to-day. Therefore it is important to be able to set individual threshold levels, before actual tests can be conducted.

Similarly, the power of the EMG signals vary from person to person, making it hard to select a predetermined threshold level, after which the EMG signal can be taken into account.

Only after setting the threshold levels can we expect to provide sensory feedback in way that is easily discernible, and also robust against noise.

The Section 3.4 explains in detail how a subject test is to be conducted. After the threshold levels are set, a preview of discrete sensory stimulations is presented. The test subject is encouraged to repeat the preview until he feels comfortable with the system. Consecutively, the pattern recognition and the task completion tests are conducted. Therefore the system in question needs to be manipulatable.

MATLAB/Simulink programming environment also includes a toolbox capable of creating a finite-state machine, called Stateflow. The programming paradigm is event-driven programming and mainly consists of four parts: The controller, which controls the entire system with the functionality provided by Powermate, the EMG-logic, which processes the EMG signal, the stimulation-chart, where the vectors responsible for electrical stimulations are generated and the testbench, which controls the pattern recognitions tests.

3.3.1 Programming the Controller

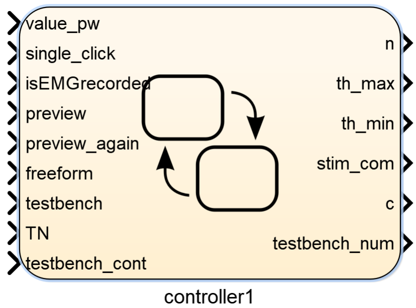

FIGURE 3.20: Controller

The central piece of the finite state-machine is the controller, shown in Figure 3.20. Together with the functionality of the Powermate, the controller chart synchronizes the entire model using command signals as outputs.

When the program runs, the controller sets the value of the output N to 1 upon receiving the command SINGLE_CLICK == 1 from Powermate, which in turn sets the same variable in the stimulation-chart, signaling the start of threshold value selection. The outputs TH_MAX and TH_MIN are the result of the process and is linked with the identical input of the stimulation-chart.

After the threshold values are set, the EMG threshold values (refer to Section 3.3.2 for a detailed explanation) set with the synchronization of charts EMG-Logic, Controller and Stimulation-Chart, with the variables N as output and ISEMGRECORDED as input from EMG-Logic chart.

The inputs PREVIEW, PREVIEW_AGAIN, FREEFORM and TESTBENCH are Boolean variables, set by using a manual switch on the control panel (refer to 3.3.5). These inputs allow the experimenter to select different settings without any restriction, whereas the inputs PREVIEW and PREVIEW_AGAIN selects the preview of discrete stimulations and the output C controls the preview. The input TESTBENCH activates the pattern recognition test and lastly FREEFORM allows for full control over the stimulation with the EMG signals as closed-loop controller and is used for the task completion objective from Section 3.4.

The command signals STIM_COM, TESTBENCH_NUM are the control integer for the stimulation-chart and the control integer from the internally generated random sequencer for the testbench, respectively. The Figure 3.21 exemplifies the generator of the command signal STIM_COM.

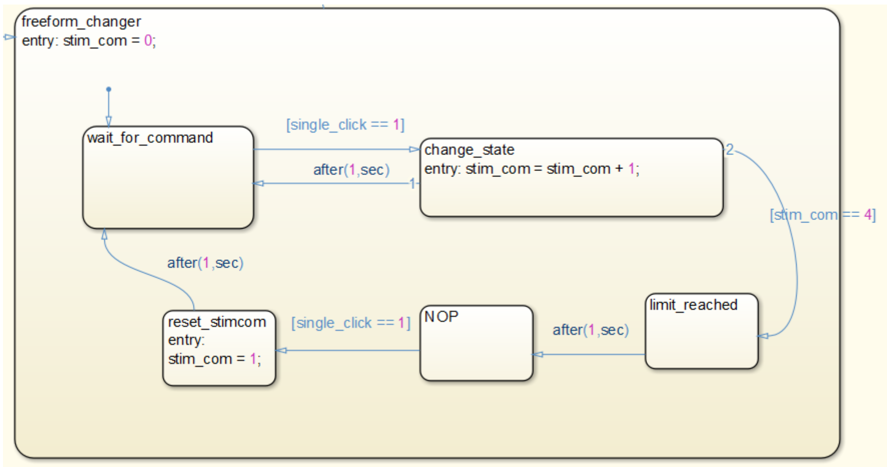

FIGURE 3.21: Sequence Generator for Freeform - Controller

The state initializes the variable STIM_COM to 0. The initial state is called WAIT_FOR_COMMAND. As soon as the condition SINGLE_CLICK == 1 is fulfilled, the current state changes to the next state. Upon entry in state FREEFORM_CHANGER, the variable STIM_COM is incremented by one. After the temporal condition of one second is fulfilled (since the second condition STIM_COM == 4 is not fulfilled), the state returns to the initial state. As soon as condition STIM_COM == 4 is true, the finite state-machine sets the variable to 1 and returns it to the initial state. Therefore, the variable STIM_COM controlling the feedback modus during freeform control of the system, is never out-of-bounds and always selects one of the four feedback modi.

3.3.2 Programming the EMG-Logic

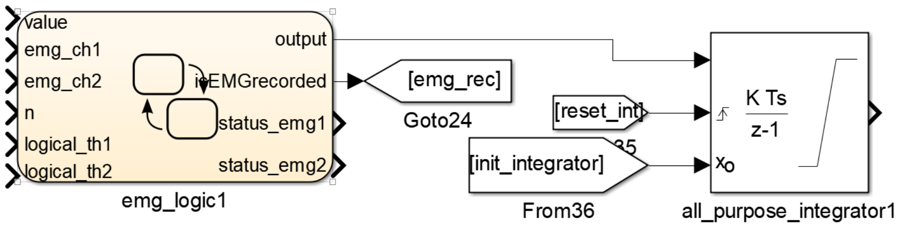

FIGURE 3.22: EMG Logic

The EMG signals captured by the EMG device and processed by the artifact detection and the filter blocks are still subject to white-noise. Therefore, a change in EMG signal does not necessarily imply a command (i.e. flexing or extending the hand), which means the processed EMG signals have to be classified.

Similar to a myoelectric hand prosthesis, our EMG electrodes are also placed on the palmer and the dorsal side of the forearm, which correspond to two opposing actions, flexion and extension. Therefore, it is logical to define the channels as opposites. By our definition, the first channel (dorsal side of the forearm) will indicate "+1", and the second channel (palmer side of the forearm) will indicate "-1".

The idea of a comparator is also suitable for our needs. A comparator is a kind of switch, which will output a preset value after a certain predetermined threshold is exceeded. As previously mentioned, the power of the EMG signals varies from person to person, and for a robust control, personal threshold levels are desirable. This marks the first feature of the EMG-logic group: Setting the threshold values.

A conditional chart checks the volitional EMG signal, so that the signals resulting from an actual intend of flexion or extension can be recorded. The user has to pass several checks, which are both signal and time-dependent. If at any time during setup should both of these condition not be met, so will the state revert back to the initial state. The condition of recording is only met, if the EMG-signal is above a certain threshold for a certain period of time, which is selectable. During recording, all four stimulation electrodes are stimulated using the minimum threshold level. It has been seen, that electrical activity over skin worsens signal-to-noise ratio and tends to drive the amplitude of the EMG signal upwards. As the EMG signals are meant to be used at the same time during stimulation, including the electrical noise into the recording will possibly prevent false positives of overcoming the threshold. After recording 32 values, the mean of this vector is calculated and set as the EMG threshold value.

The second feature is the classification of the received EMG signals. The classifier needs to be able to decide between the following outcomes:

- **EMG signal from channel 1 fulfills the difficulty condition:** The user is extending his hand. The output for the integrator is 1.
- **EMG signal from channel 2 fulfills the difficulty condition:** The user is flexing the forearm. The output for the integrator is -1.
- **EMG signals are not significant:** The hand is in a neutral position. The output is 0.
- **If both signals fulfill the difficulty condition:** The OR-Composition (explained below) does not allow this status. One of two outputs will be selected depending on which condition was fulfilled first (i.e. if EMG signal from channel 1 fulfills it earlier than the other, the output for that condition will be the result.)

To realize this classifier, two types of comparators are implemented for both channel. If the current EMG signal is above the threshold value, the first comparator writes 1 into a buffer and 0 otherwise. This buffer is constantly refreshed in a cyclical manner, which means it will be filled with zeros, unless the comparator writes a 1. The sum of the elements of the buffer give exactly how many successful threshold checks have been attempted (in a 32-element buffer, with a sample time of 0.02 seconds, it amounts to a time window of 0.64 seconds). Each EMG channel has a corresponding comparator, which records the successful attempts.

The second comparator compares the sum of the elements of both EMG buffers to difficulty conditions. If the sum of elements of the EMG buffer is larger than the difficulty condition, than the output corresponding to that channel is activated.

To achieve this in Stateflow -after both EMG threshold levels are set- the EMG-logic chart goes to the last state, which is a nested AND-Composition holding 3 sub-states. Due to the composition, every sub-state is executed at the same time (parallel). The first two types of comparators are implemented for both channels. In parallel, a third comparator checks which difficulty condition has been fulfilled. With this, a robust system of classification is implemented, and the difficulty levels can be set at any time during stimulation. The outputs and the inputs of the EMG-Logic are as follows:

- VALUE: The value of the output, normally set to 1.
- EMG_CH1 and EMG_CH2: The processes EMG signals from the artifact detection and the filter blocks.
- N for synchronization with the controller and stimulation chart.
- LOGICAL_TH1 and LOGICAL_TH2 are the difficulty levels for respective channels
- OUTPUT is the input to the integrator.
- ISEMGRECORDED is a control variable for synchronization with the controller-chart.
- STATUS_EMG1 and STATUS_EMG2 are for debug purposes. They show whether the current EMG signal has overcome the threshold value.

The Figures A.7 A.6 illustrate the charts for the setup of threshold values and the classifier.

The integrator is saturated over 0 to 12, with a gain value of 1.

- RESET_INT is a trigger, that sets the integrator to a preset initial condition.
- INIT_INTEGRATOR is the initial condition for the integrator.

The importance of the initial condition and the triggering-event has been discussed in the following Section 3.3.3.

3.3.3 Programming the Stimulation-Chart

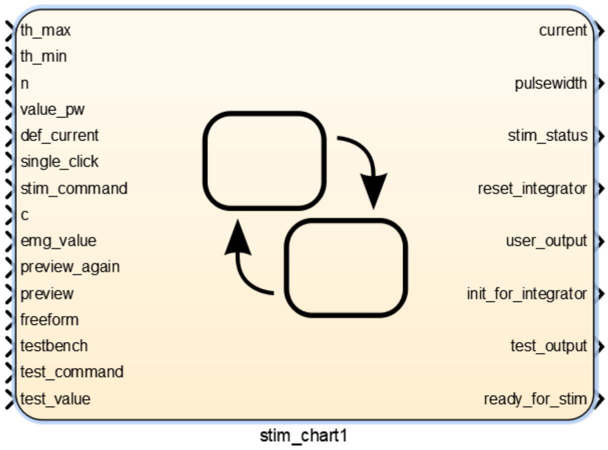

FIGURE 3.23: Stimulation-Chart

The stimulation chart is responsible for the generation of the vectors which are the inputs to the RehaMove3 MATLAB block. The information being conveyed by the vectors have been discussed in detail in Section 3.1.2. Like with any other chart, the stimulation-chart is controlled by the Controller-Chart, but the stimulations themselves use other signals as command signal, i.e. the output from Powermate, the output from the Testbench or the output of the integrator from the EMG-logic (explained in the respective sections). The major outputs have the following function:

- RESET_INTEGRATOR: Resets the integrator to the initial value set by the output INIT_FOR_INTEGRATOR
- USER_OUTPUT and TEST_OUTPUT are for experimentation purposes. They allow the experimenter to observe the state of the stimulation.
- READY_FOR_STIM signals the testbench, when the chart is ready to output stimulations.

This chart can be summarized into two main building blocks: The threshold value stimulations, the discrete and the continuous feedback stimulations:

Programming the Threshold Value Stimulations

LISTING 3.1: Function: commonElectrode_4ch_threshold

```
commonElectrode_4ch_threshold
(stimpw,stimcr,balancecr,pausepw,select_channel,
   select_output)
```

Setting up the threshold values is the first step for sensory feedback. The function (listing 3.1) implemented provides an easier way to select the electrodes to be stimulation (using the variable SELECT_CHANNEL), select the output (using the input variable SELECT_OUTPUT).

- STIMPW refers to the current pulsewidth selected using Powermate
- STIMCR refers to the current amplitude hard-coded in the model
- BALANCECR refers to the balancing current amplitude (this variable needs to be negative for positive STIMCR, and vice versa.)
- PAUSEPW refers to the length of the pulsewidth after the balancing charge.By using this variable one can implement a pause in stimulation between two wavelets.
- CURRENT is the matrix that entails the current amplitudes for each point of the waveform, which is the input to the RehaMove3 MATLAB Block.
- PULSEWIDTH is the matrix that encodes the current pulsewidths of the waveform.
- STIM_STATUS is a Boolean variable and is equal to 1, if the stimulator is active, and 0 otherwise. It feeds into the artifact detection block.

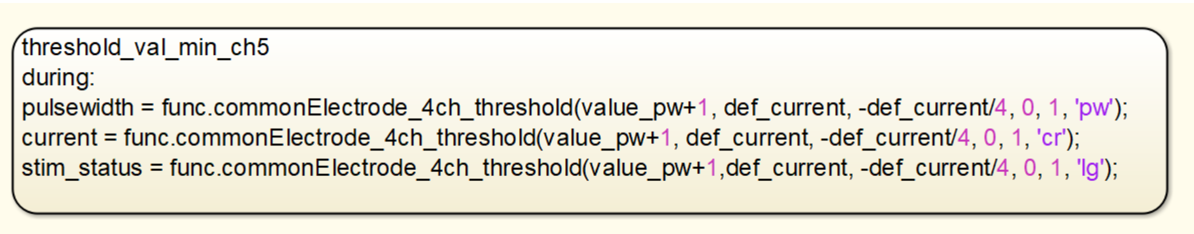

FIGURE 3.24: State - Threshold Value Stimulations

The function calculates the current pulsewidth of the balancing charge based on the parameters. Therefore, a balanced stimulation is ensured. The Figure 3.24

illustrates the usage of the function is a state. The three different settings for SELECT_OUTPUT (PW: pulsewidth, CR: current, LG: logical) are responsible for the creation of the required matrix. The output STIM_STATUS returns a logical 1, when the charge is non-zero.

Programming the Discrete and Continuous Feedback Stimulations

After the threshold values are set, the discrete stimulations for feedback purposes can begin. The function (listing 3.2) implements the creation of the matrices for the stimulator

LISTING 3.2: Function: commonElectrode_4ch_stim

```
commonElectrode_4ch_stim
(threshold_max,threshold_min,stimcr,balancecr,pausepw,
   select_direction,select_output)
```

- THRESHOLD_MAX and THRESHOLD_MIN refer to the maximum and minimum threshold values, respectively.
- STIMCR refers to the current amplitude hard-coded in the model
- BALANCECR refers to the balancing current amplitude (this variable needs to be negative for positive STIMCR, and vice versa.)
- PAUSEPW refers to the length of the pulsewidth after the balancing charge.By using this variable one can implement a pause in stimulation between two wavelets.

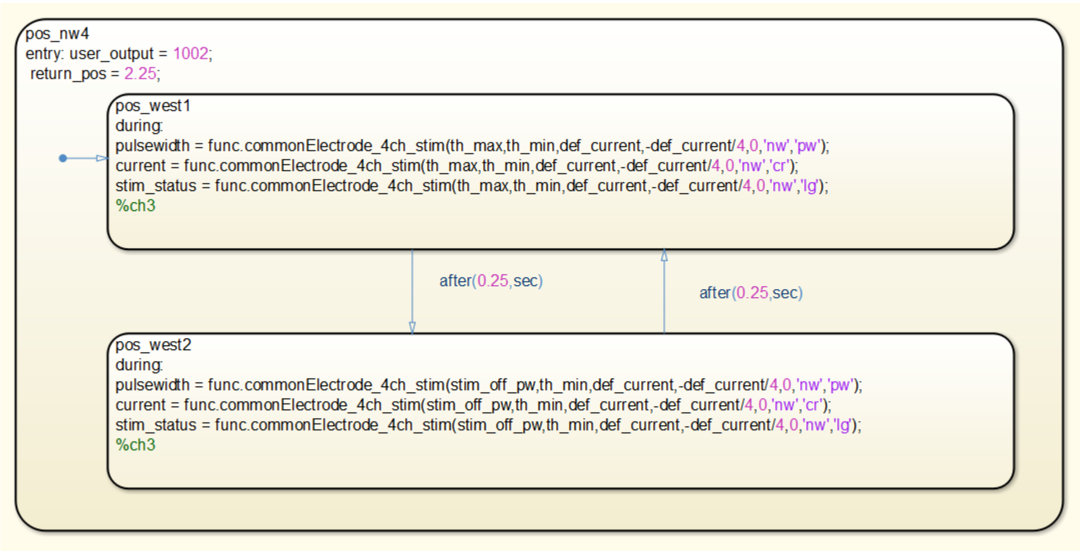

FIGURE 3.25: State - Discrete Feedback Stimulations

The state shown in Figure 3.25 has implemented a discrete sensory stimulation for feedback modus "Hand Position, Setting 2 (45°)". The variable SELECT_DIRECTION has been set to NW, which means northwest. Referring back to the illustration 3.4, this direction corresponds to the electrodes UP and AWAY FROM BODY.

The next important feature of the state is an oscillation between states NO STIMULATION and STIMULATION NW with a time constant of 0.25 seconds. This creates the simultaneous on/off behavior linked with "Hand Position, Setting 2 (45°)".

The last important feature of the state is seen in the entry condition of the superstate. The variable RETURN_POS = 2.25 sets the initial value for the integrator and takes on the function of a nonvolatile storage. During freeform control, the user has the ability to change the feedback modus at will. However, doing so does not necessarily imply the reset of the previous condition. Say the hand is looking 45 degrees upwards. Upon changing the feedback modus to "hand opening-closing", the hand would still be looking upwards at 45 degrees. When the user changes back to feedback modus "hand position", the integrator would be initialized at the value set by the variable RETURN_POS.

The stimulations for the preview, the testbench, the indicator and the freeform are all based on the same principal.

The continuous sensory feedback has only been implemented for hand positioning. The basic principle of discrete stimulations also applies here. The only major difference is that, the adjacent electrodes are continuously interpolated. Example: As the hand turns left (from 0° to 90°), the stimulation shifts linearly to the third channel while the current flowing to the first channel becomes smaller and smaller until it is zero. To achieve this, an If-Else structure has been implemented, which checks where the hand is currently positioned, and selects the stimulation intensity accordingly. Therefore the discrete variable SELECT_DIRECTION has been replaced with the continuous variable DEGREE.

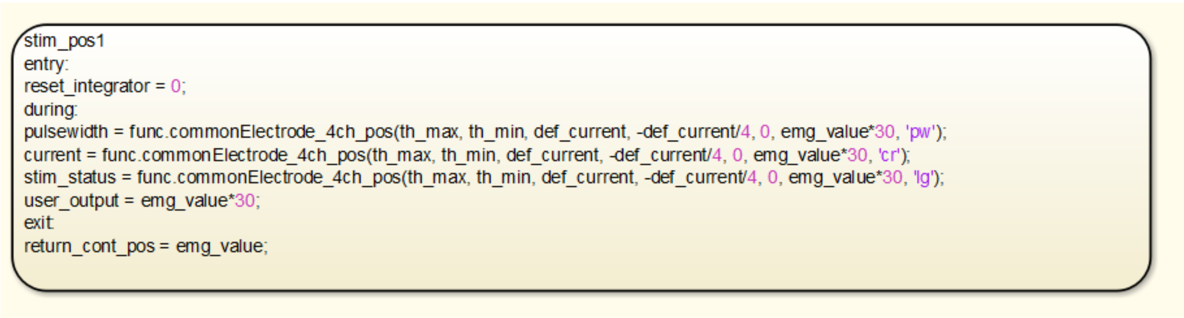

FIGURE 3.26: Continuous Feedback Stimulation

3.3.4 Programming the Testbench

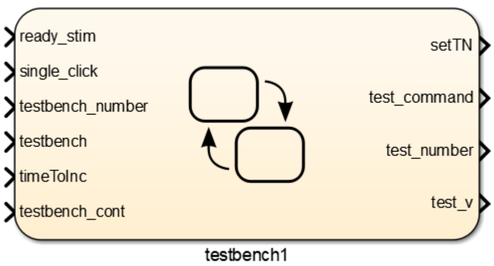

FIGURE 3.27: Testbench

Part of a subject test is determining the ability to correctly assess what kind of sensory information is being delivered, without being in control of the stimulation (or the idea of the abstracted hand prosthesis). The existing system for the stimulation of the selection FREEFORM has been adapted by replacing the control variables with variables of identical function. Therefore, the testbench chart effectively replaces the integrator from the EMG-logic chart. The input and the outputs is explained in the following list:

- READY_STIM is an output from the stimulation chart, an is a command signal to convey that indicator stimulations have been completed.
- SINGLE_CLICK is the single-click functionality of Powermate.
- TESTBENCH_NUMBER is the random number from the generator in the controller chart.
- TESTBENCH and TESTBENCH_CONT are the Boolean values for turning on/off the testbench for discrete and continuous stimulation, respectively.
- TIMETOINC is the time constant, which determines how fast the integrator will change its value (Dimension: seconds).
- SETTN and TEST_COMMAND are control variables for the controller and the stimulation chart respectively. The first output restricts the single-click functionality to certain substates within the controller and the second one signals the stimulation chart which feedback modus should be used.
- TEST_NUMBER allows the experimenter to see which test is being currently conducted. Meant for both debug and data analysis purposes.
- TEST_V is the output of the integrator.

A sample test has been showcased in Figure 3.28:

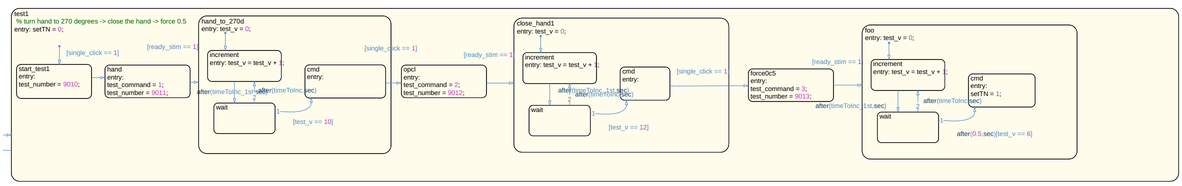

FIGURE 3.28: Sample Test from the Testbench

Upon entering the test, the state will output the test number, which the experimenter can note down. The state is comprised of two basic building blocks. The first one (on the Figure 3.28 the second one on the left) will output the test number for that pattern and the selection of the feedback modus. Upon receiving the command READY_STIM == 1 the state changes to the next building block: This state (the third one on the left) implements the integer, which changes the orientation of the stimulation (i.e. hand turned from 90° to 0°). After last position has been reached, the process is repeated until the last state has been arrived. The only difference of this state is, is that it sets the variable SETTN to 1. This setting lifts the restriction on the controller chart and allows it to send another test by clicking on the Powermate button. Upon entering a new test, the variable is set to 0 to place the restriction once again. The restriction allows the usage of the Powermate button for two tasks at the same time, without falling out of sync (output of new patterns and output of new tests).

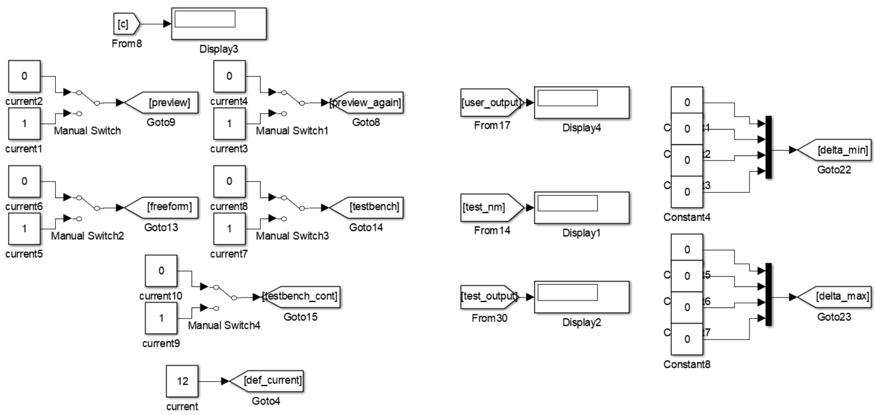

FIGURE 3.29: Control Panel

3.3.5 Control Panel

The control panel is the interface, using which the experimenter communicates with the Simulink model. The corresponding Goto blocks have been explained in the respective sections. At the bottom, the current amplitude can also be selected. The outputs from the stimulation and the testbench are displayed to the right.

One major function of the control panel is the ability to manipulate threshold levels. Every time a subject test is taken on, the first thing to be done is the selection of the threshold values of the stimulation electrodes. However, first threshold levels are not always ideal and the subject may become habituated or they might have been too strong. If there is no way to change the threshold values online, then the only other way would be to stop the test and start again, which still might not result in the ideal setting.

The multiplexed variables change the minimum or the maximum threshold value, depending on the group. The constants may be of positive (increasing the threshold) or negative (decreasing the threshold) value.

3.4 Approach to Subject Test

The subject being tested is seated in front of the computer and is asked to rest his left hand flat on the table. The electrodes corresponding to the first channel of the EMG device are placed on the dorsal side to the forearm, near the elbow. Similarly, the electrodes for the second channel of the EMG device are placed on the palmer side of the forearm, near the elbow. The fifth electrode (the reference electrode) is placed near the vicinity of the first two pairs, ideally on the ulna.

The stimulation electrodes are then placed in a ring-like structure around the biceps and triceps area. It is important, that the first electrode is looking upwards, the second one is looking downwards (directly under the first channel), the third one is looking outside and the last electrode is looking inside at the body, directly opposite of the third electrode. When placing the first electrode, it is advised to consult the subject, which direction he would consider to be up. After placing that electrode, the rest are done in the described fashion.

The common electrode is placed on the shoulder head, just above the stimulation electrodes.

The output of the analog multiplexer is connected with the common electrode, and the marked cables of the lead connectors are connected as inputs to the analog multiplexer. Since this analog multiplexer has 8 inputs, only 4 of them remain unconnected. At this point, the test can be started.

The first task for the test is to set the threshold levels for each stimulation electrode, and furthermore set the EMG threshold levels for a robust control system. Setting the levels for the stimulation electrodes follows a pairwise pattern: For each electrode (each channel) exists two distinct threshold points. The minimum stimulation, where sensation on the skin has been evoked, and the maximum stimulation where the sensation becomes strong, but non-painful. After the last threshold level is set, (corresponding to the maximal threshold level for the fourth channel) every stimulation electrode turns on with the minimum threshold level. The test subject is to extend this hand (upwards) until the sensation disappears. This action sets the EMG threshold level for the first EMG channel. Likewise, when the sensation returns, the test subject will flex the forearm (downwards motion with the hand) until the sensation subsides, which will similarly set the threshold level for the second EMG channel.

The amount of information being delivered to the test subjects can, at times, be overwhelming, especially considering that the test subject hasn't done a similar experiment before. Therefore it is ideal to keep the feedback information summary (which electrodes are turned on, what do different indicator patterns mean, etc.) in sight in an easily understandable format. These pages are already created and can be seen in Section A.

Even with the feedback information summary, the actual stimulation can be distracting enough, so that the subject cannot concentrate on the tasks given. To offset this effect, a preview of all individual discrete stimulations has been implemented as the first objective and the experimenter is advised to repeat the preview until the test subject feels comfortable. Ideally, each discrete stimulation would be matched with the graphical representation of the stimulation on the feedback information summary, ensuring a robust learning mechanism.

The second objective is a pattern recognition exercise. Out of five different groups, each consisting up to four different patterns are presented to the test subject randomly across three tests. The randomization is done on the group-level, and the pattern sequence in individual groups are kept orderly. At the beginning of each group, the test subject is informed that a new group has begun. At the end of each pattern, the test subject is asked to match the pattern to a feedback category (hand position, hand opening-closing and force) and match the stimulation to an action (i.e. *"hand turning from 0 degrees to 235 degrees"* or *"feedback modus 1, changed from 1 to 6*). At the end of each group, the subject is informed that the group has been completed. A test is regarded as completed, when all five groups have been presented.

The pattern recognition exercise is performed to a total of three times for discrete stimulations. In the first test, the test subject tries to recognize the pattern without any feedback from the experimenter. In the second test, the test subject is told, whether the pattern he just guessed is correct or false. If it was incorrect, the experimenter explains the actual pattern (i.e. shows the pattern on the feedback information summary). In the last test, the test subject does not have any feedback, and has to rely on the stimulation. The same exercise is done also for the continuous stimulations, albeit only two times. At all times during the exercise the feedback information summary is within eye-sight of the test subject.

The third and the last objective is task completion. Out of six predefined, but randomly selected tasks, the test subject will control the stimulation with the help of Powermate and the EMG electrodes connected to his forearm. The experimenter explains the task to the subject: *"Turn your hand to 135 degrees"* or *"Feedback modus 1, setting 4"*. The exemplified task requires two separate actions: First, selecting the correct feedback modus using the Powermate and relying on the indicator stimulation, and second, using the EMG to get to the correct setting (stimulation). The tasks are not time-trials, however, the subject is expected to inform the experimenter, when he gets to the correct modus/stimulation. The task completion objective will be completed two times. During the first test, if the test subject fails to arrive at the correct solution, the experimenter will not correct him. During the second test, the test subject is informed, whether what he has perceived to be the correct solution, is indeed the correct solution or not. At all times during the exercise the feedback information summary is within eye-sight of the test subject.

At the end, the subject is asked, what he/she liked/dislike about the system amd what he/she would improve on.

3.4.1 Pattern Recognition and Task Completion Tests

Pattern Recognition

Every sensory feedback stimulation has a corresponding physical and system description. The physical description is the relates the stimulation with the myoelectric hand prosthesis, i.e. *Hand opens fully*. The system description provides the relationship between the stimulation and the model, i.e. *Feedback modus 1 - Status 1 to 9*.

For the discrete feedback stimulations:

Group 1:

P1: Hand position from 0° to 270° - System description: Feedback Modus (FM): M1, Status 1 to 7.

P2: Hand from neutral to fully closed - System description: FM2, Status 1 to 4.

P3: Normalized force from 0 to 0.5 - System description: FM3, Status 1 to 5.

Group 2:

P1: Hand from neutral to fully closed - System description: FM2, Status 1 to 4.

P2: Normalized force from 0 to 1 to 0.25 - System description: FM3, Status 1 to 9 to 3.

P3: Hand from fully closed to neutral - System description: FM2, Status 4 to 1.

Group 3:

P1: Hand position from 315° to 90° - System description: FM1, Status 8 to 3.

P2: Hand from neutral to mostly closed - System description: FM2, Status 1 to 3

P3: Normalized force from 0 to 1 - System description: FM3, Status 1 to 9.

P4: Hand from mostly closed to fully opened - System description: FM2, Status 3 to 1.

Group 4:

P1: Hand from neutral to partially closed - System description: FM2, Status 1 to 2.

P2: Hand position from 0° to 135° - System description: FM1, Status 1 to 4.

P3: Normalized force from 0 to 0.75 - System description: FM3, Status 1 to 7.

P4: Hand position from 135° to 225° - System description: FM1, Status 4 to 6.

Group 5:

P1: Normalized force from 1 to 0.5 - System description: FM3, Status 9 to 5.

P2: Hand position from 225° to 45° - System description: FM1, Status 6 to 2.

P3: Hand from fully closed to neutral - System description: FM2, Status 4 to 1.

P4: Hand position from 45° to 135° - System description: FM1, Status 2 to 4.

There are no system descriptions for the continuous feedback stimulations and the test subject is expected to call out degrees, as best as he can:

Group 1:

P1: Hand position from 0° to 90°

P2: Hand position from 90° to 135°

P3: Hand position from 135° to 0°

Group 2:

P1: Hand position from 315° to 90°

P2: Hand position from 90° to 270°

P3: Hand position from 270° to 0°

Group 3:

P1: Hand position from 120° to 30°

P2: Hand position from 30° to 225°

P3: Hand position from 225° to 0°

Task Completion

For this objective, six random tasks are proposed. However, after these tasks are completed, other inofficial tasks may be conducted or the test subject might be encouraged to play with the system by himself. During this time, questions (both technical and design related) about the system might also be answered. As in the discrete feedback stimulations, there is a physical and also a system description associated with every task.

T1: Hand position from 0° to 35° - System description: FM1, Status 1 to 4.

T2: Normalized force from 0.75 to 0.25 - System description FM3, Status 7 to 3.

T3: Hand position from 315° to 45° to 225° - System description: FM1, Status 8 to 2 to 6.

- T4: Hand from fully closed to neutral to partially closed - System description: FM2, Status 4 to 1 to 2.
- T5: Normalized force from 0.125 to 0.875 to 0.375 - System description: FM3, Status 2 to 8 to 4.
- T6: Hand from mostly closed to neutral to partially closed - System description: FM2, Status 3 to 1 to 2.

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Chapter 4

Results

The proposed system has been tested on four healthy subjects, aged 21 $\pm$ 1 (2 female and 2 male subjects).The quantifiable results have been derived from pattern recognition tests and categorized into two parts: Accuracy of indicator electrodes and discrete feedback stimulations.

Accuracy of continuous feedback stimulation and the control of the stimulation using EMG signals have been investigated in regards of both quality and quantity and have been corroborated with observation and verbal feedback from the test subjects.

Due to extreme situations (i.e. cognition load too much, painful sensations) certain tests had to be omitted for one subject.

4.1 Accuracy of indicator electrodes

The bar plot in Figure 4.1 illustrates the number of successful recognition of correct indicator stimulation patterns across tests and for each subject. An indicator pattern is considered successful, if the test subject can correctly assess the indicator pattern, which is a Boolean output of true or false. The related Figure 4.2 maps the results as percentiles.

4.2 Accuracy of discrete feedback stimulations

The accuracy of discrete feedback stimulations has been investigated using the absolute deviation from the desired condition. The start of a stimulation pattern is considered as the first information after the indicator stimulation and the end is considered as the last stimulation pattern. A case differentiation between start and end of stimulation has been considered across individual test patterns (3.4.1) for every subject. If an indicator stimulation has been incorrectly assessed, the deviation of that pattern is considered to be -1.

Another important data structure is the deviation from the desired condition in individual feedback modus (hand position(FM1), hand opening-closing(FM2) and force(FM3). The absolute derivation of feedback modi were filtered from each group and placed into a vector. Therefore, each vector described the absolute derivation of a unique feedback modus across three tests and every element corresponds with a pattern of a group. Let this vector be $x[n]$.

$$\text{Relative Derivation}_{\text{FM}_i} = \frac{\sum_1^n x[n]}{n \cdot \max(D_i)} \qquad D_i \rightarrow \text{absolute derivation of feedback modus i}$$

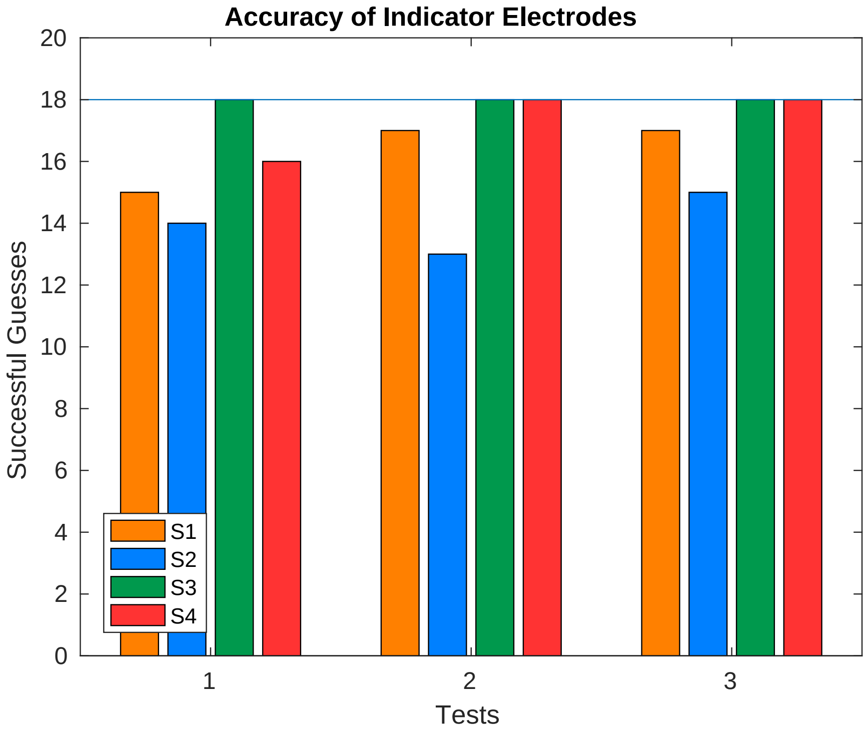


FIGURE 4.1: Accuracy of indicator electrodes - for a total of 18 per test per subject (line at the top)

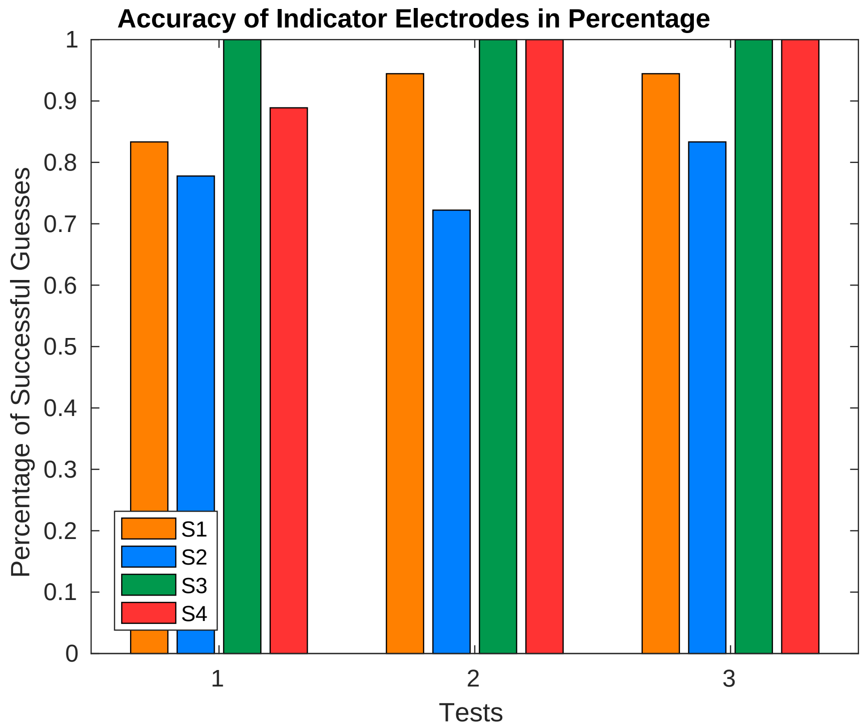
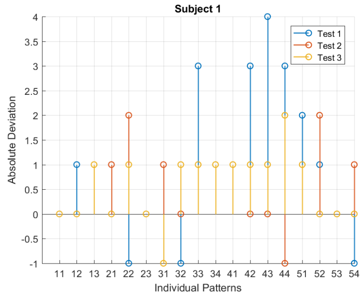
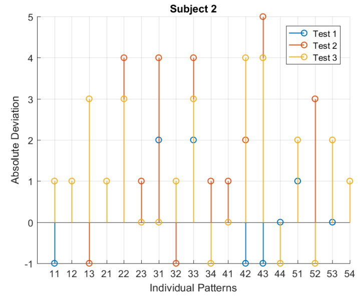


FIGURE 4.2: Accuracy of indicator electrodes in percentage

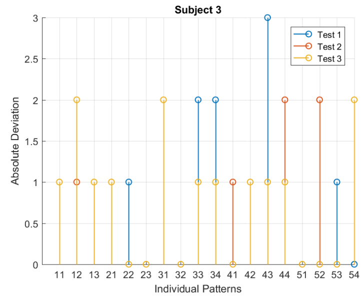
The data is analyzed at the start and the end of stimulation patterns. Figures 4.5 and 4.6 illustrate the relative derivation from desired condition at the start and end of stimulation pattern, respectively.



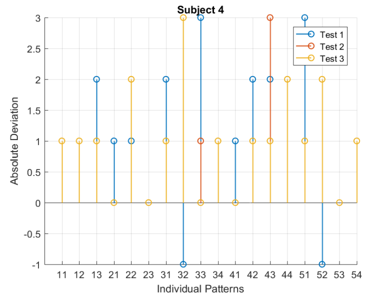
(A) Subject 1



(B) Subject 2



(C) Subject 3



(D) Subject 4

FIGURE 4.3: Absolute deviation from desired condition at the start of discrete stimulation - on the X-axis -> XY: Group X, Pattern Y

4.3 Accuracy of continuous feedback stimulations

The accuracy of continuous feedback stimulations has been, like in the previous accuracy analysis, derived using the absolute deviation from start and end points. As this class of stimulation has been implemented for one activity (hand position), whether the stimulation was correctly identified or not is not part of this analysis. A case differentiation between start and end points has been made.

4.4 Accuracy of task completion tests

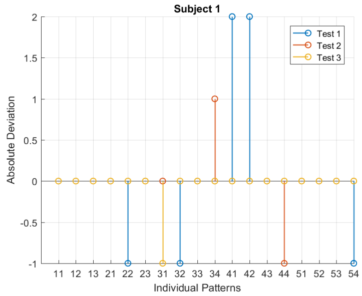
Out of four different subjects, across two tests, every subject (except subject 2) could complete the tasks in a reasonable amount of time. Given that, across 2 tests, each consisting of 6 tasks and a total of 4 subjects, there are 48 tasks in total. One subject could not complete any taks whatsoever (due to not being able to participate), which means 36 successful attempts. This amounts to an accuracy rate of %75.

4.5 Qualitative Results

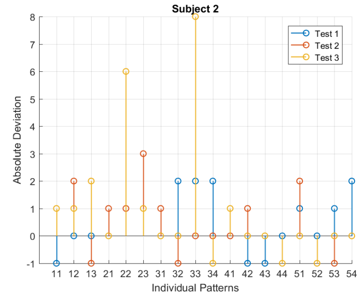
This section is reserved for the results of other, not-easily-quantifiable information.

4.5.1 Continuous Feedback Stimulation

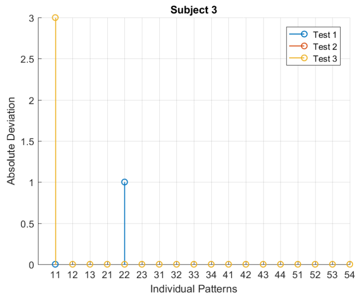
As previously mentioned in Section 3.4.1, there are no system descriptions for this class of feedback. Additionally, the interpolated nature of this feedback and the loss



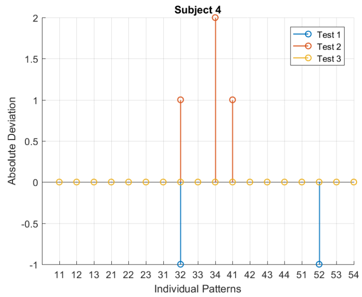
(A) Subject 1



(B) Subject 2



(C) Subject 3



(D) Subject 4

FIGURE 4.4: Absolute deviation from desired condition at the end of discrete stimulation - on the X-axis -> XY: Group X, Pattern Y

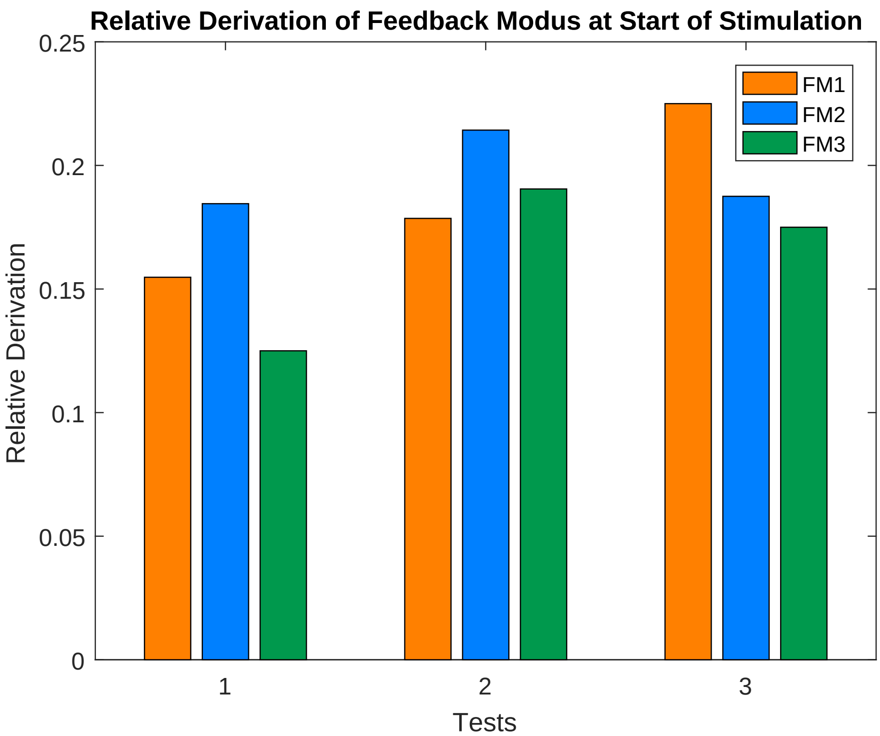


FIGURE 4.5: Relative Derivation of FM at the start of stimulation pattern across tests

of sensation due to habituation effect (refer to 2.6) make it even harder to objectively quantify this class.

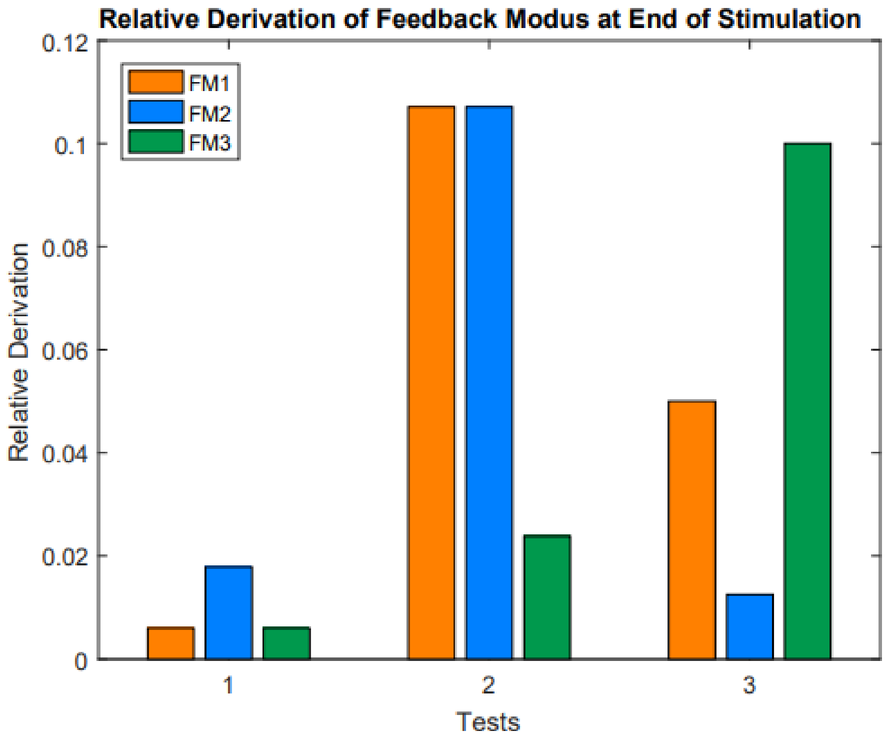


FIGURE 4.6: Relative derivation of FM at the end of stimulation pattern across tests

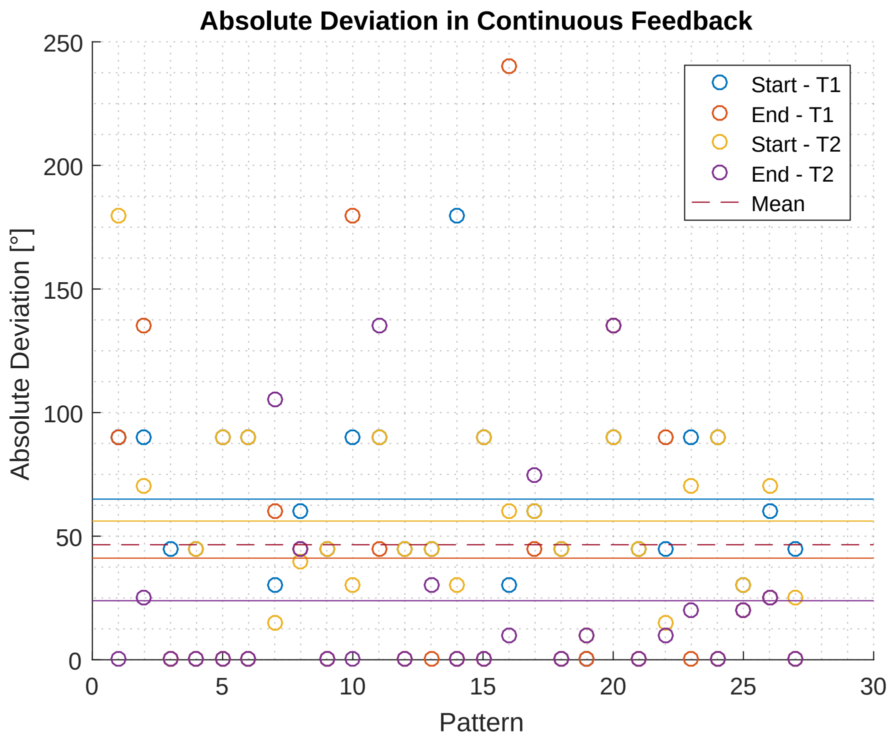


FIGURE 4.7: Absolute derivation of degrees, case differentiation - Dashed line marks the mean of all points

However, it was observed that subjects have picked the first electrode that was stimulated at the maximum threshold level as the start point. Subjects could also distinguish direction as the abstracted hand turned (either clockwise or counter-clockwise), but in majority of the cases, the selection of the final degree was the last electrode which was stimulated at the maximum power.

Even with the explicit knowledge, that every degree is a possible outcome, most subjects could not pinpoint a location, apart from specifying an interval between two electrodes.

4.5.2 Control of the Stimulation using EMG Signals

At the end of testing, the subjects are given the control of the stimulation, which they can manipulate using EMG signals. After a brief amount of learning period, virtually every subject could fulfill any task given using Powermate to change the feedback modus, and EMG signals to change the stimulation status.

Furthermore, the reaction time to overreaching (more flexion/extension than required to reach desired state) seemed to be rapid. The subjects could easily tell when they overreached (i.e. verbally express where they are, even if they couldn't precisely reach the state) and could correct themselves without external feedback.

4.5.3 Further Observations

As the threshold values are set in the beginning, the first couple values tend to be smaller than the others. This was mostly realized by the subjects themselves during the preview phase and threshold values were adjusted dynamically until a comfortable solution was found. The loss of feeling (habituation) tended to show itself in about 20 minutes into the experimentation. It was observed that a brief break brings the sensation back and tests could be completed.

Out of four different subjects, only one subject (subject 2) could not complete the entire test. At some point during the pattern recognition test, it was observed that the subject had lost feeling on one or possibly more electrodes. Attempts have been made to dynamically adjust threshold values, so that the feeling could return. However, this approach was not successful, which prompted a break. After 5 minutes had passed, it was noted that the loss of sensation did not reverse itself, and further attempts to adjust threshold values (i.e. setting longer pulsewidth) also failed. The subject could either feel nothing, or a strong painful sensation was evoked. Therefore the test was stopped to alleviate the situation.

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Chapter 5

Discussion,Outlook and Conclusion

Up until this point, the thesis presented an introduction to the subject, and the methods used to implement the idea of electrotactile sensory feedback. The previous section also described the results in detail and objectively. The following section provides a discussion regarding those results.

In the Introduction section, the preliminary research (refer to 2.6) predating this thesis has been summarized. A similar technique also found its way into this implementation, mainly to compare it with the discrete stimulation.

The continuous stimulation provides an interface that is intuitively easy and allows for really precise control of the stimulation. Theoretically, every degree could be sensed and the user could adjust accordingly. However, in practice it was shown not to be the case. The electrotactile sensation behaves non-linearly, which is to say that the feeling evoked is not a linear map of electric charge. Both the preliminary research and this thesis indicates, that a sensation evoked using one threshold level is subject to time-related changes. When a longer time is spent under stimulation, less feeling is evoked, which was labeled as the "habituation effect". Furthermore, the usage of non-maximal threshold values (shown by continuous feedback stimulations) after stimulation at maximum threshold levels is uncharted waters and the feeling evoked is significantly less than expected.

The discrete stimulation patterns have the advantage, that every state is unique, which helps train the subject. The separation of indicator stimulations and feedback stimulations has resulted in a success rate over 70% and for subsequent tests it was, for some cases, 100%.

The pattern recognition tests have shown generally favorable outcomes. Excluding the extreme event for subject 2, the recognition of the start of the stimulation has partly improved with each test. Additionally, the smaller deviation from desired outcome at the end of stimulation could be seen as a improvement over subsequent tests. The relative derivation of feedback modi was also calculated and a maximal relative derivation of %22.5 was established.

Given that discrete hand position stimulations and continuous stimulation patterns implement the idea of hand position using different approaches, a comparison of resolution between them was also of interest. As previously discussed, the discrete hand position stimulations have 8 different statutes, which amount to a resolution of 45° per status. In the previous section, the mean of the absolute deviation of desired condition at the start and the end of stimulation has been calculated and is equal to around 48°. On a full circle, this amount to a relative deviation of %13.3. Compared to Figures 4.5 and 4.6, the resolutions do not seem to have a significant difference at the first look, however, as Figure 4.7 shows, the deviation at the start of the stimulation is the highest, while extreme cases show deviations up to 240°. Individual assessment of quality by the test subjects illustrate the almost comparable resolution even further: Most subjects felt like they could feel the electrode at its maximum and as the electrical charge decreased, the localization of the positioning (therefore the degree of the hand) was harder compared to discrete feedback stimulations.

The discrete stimulation patterns have also shown promising results during task completion tests. The inability of one subject to participate in the test has taken the accuracy down from the perfect score to %75. However, it was seen that if a subject could participate in the test, the results were successful. The subjects were able to control the stimulation without any help and could easily manipulate the system to reach a certain state. Even if there was overreach on the subject's end, the mistake was rapidly realized and the subject could adapt to the stimulation.

5.1 Outlook

Even though this thesis reached the final destination of its scope, more research opportunities exist on this subject. In no particular order, following areas need implementation and/or improvements:

- In this thesis a biphasic unsymmetrical charge balance waveform is implemented. Further waveforms can be investigated for effects that cancel the habituation effect or delay its onset.
- The proposed method is implemented using a 4-channel stimulator. Using more channels, coupled with discrete stimulation patterns may open the way for quasi-continuous feedback systems, resulting in a better, more precise control system, without an increase in complexity.
- It was shown that one subject found the proposed system to be cognitively overloading. Approaches which could eliminate this effect should be investigated.
- Further patterns may be researched, which might make it possible to distinguish further levels, all the while still using a 4-channel stimulator.

5.2 Conclusion

The system proposed in this thesis implements the elecrotactile sensory feedback system using discrete stimulations over three different feedback categories (hand position, hand opening-closing and force feedback). The system is generally well-tolerated. Only one subject reported discomfort and was not able to complete the entire experiment.

Tests have shown that the pattern recognition has a maximum relative deviation from desired condition of %20. However, when the subjects were in control of the stimulation, virtually every subject could successfully complete the task and they were able to correct overreaching by themselves without external feedback. Therefore, this thesis indicates a favorable outcome regarding electrotactile sensory feedback using discrete stimulation patterns.

Appendix A

Appendix

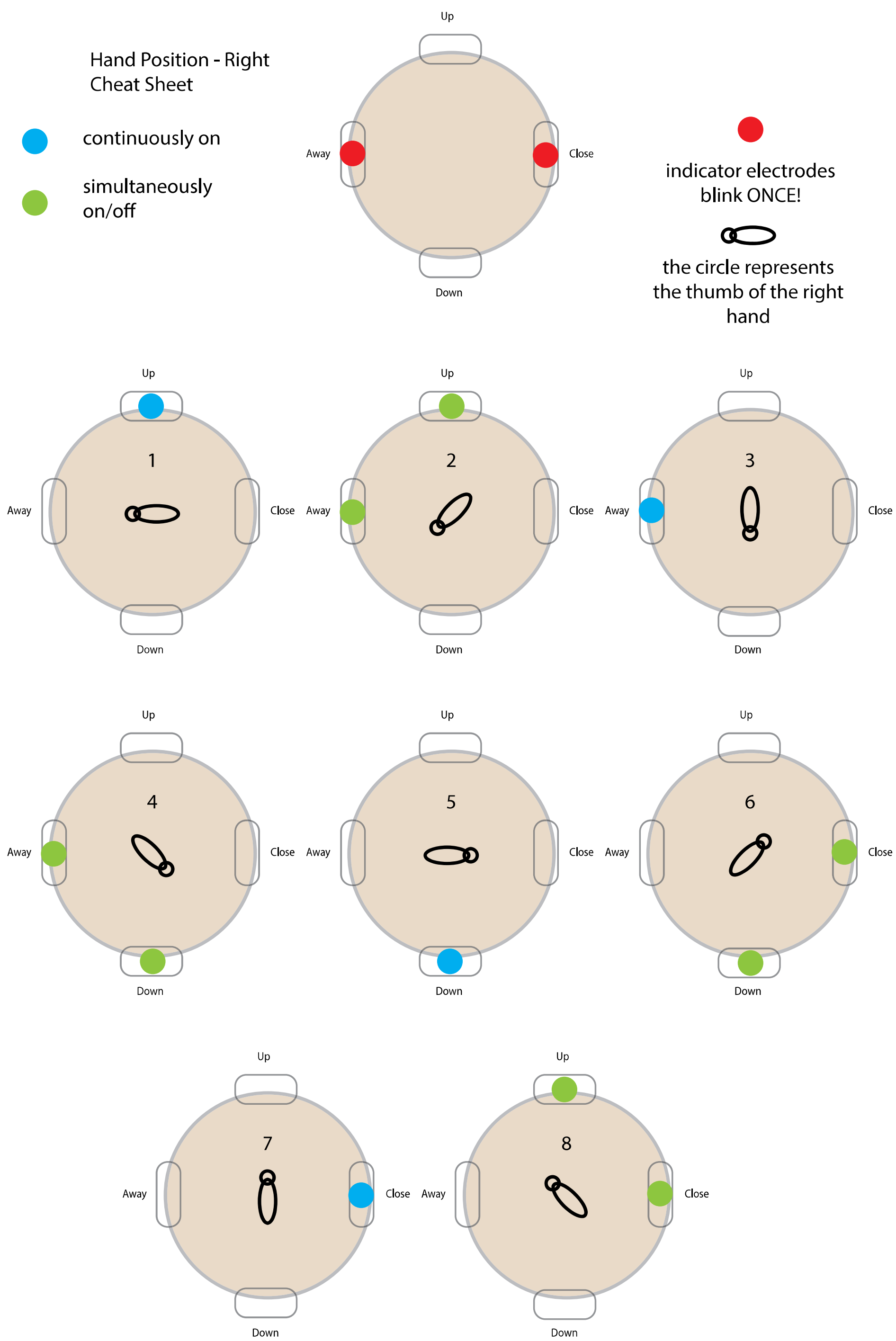

FIGURE A.1: Hand Position Cheat Sheet - Right Hand

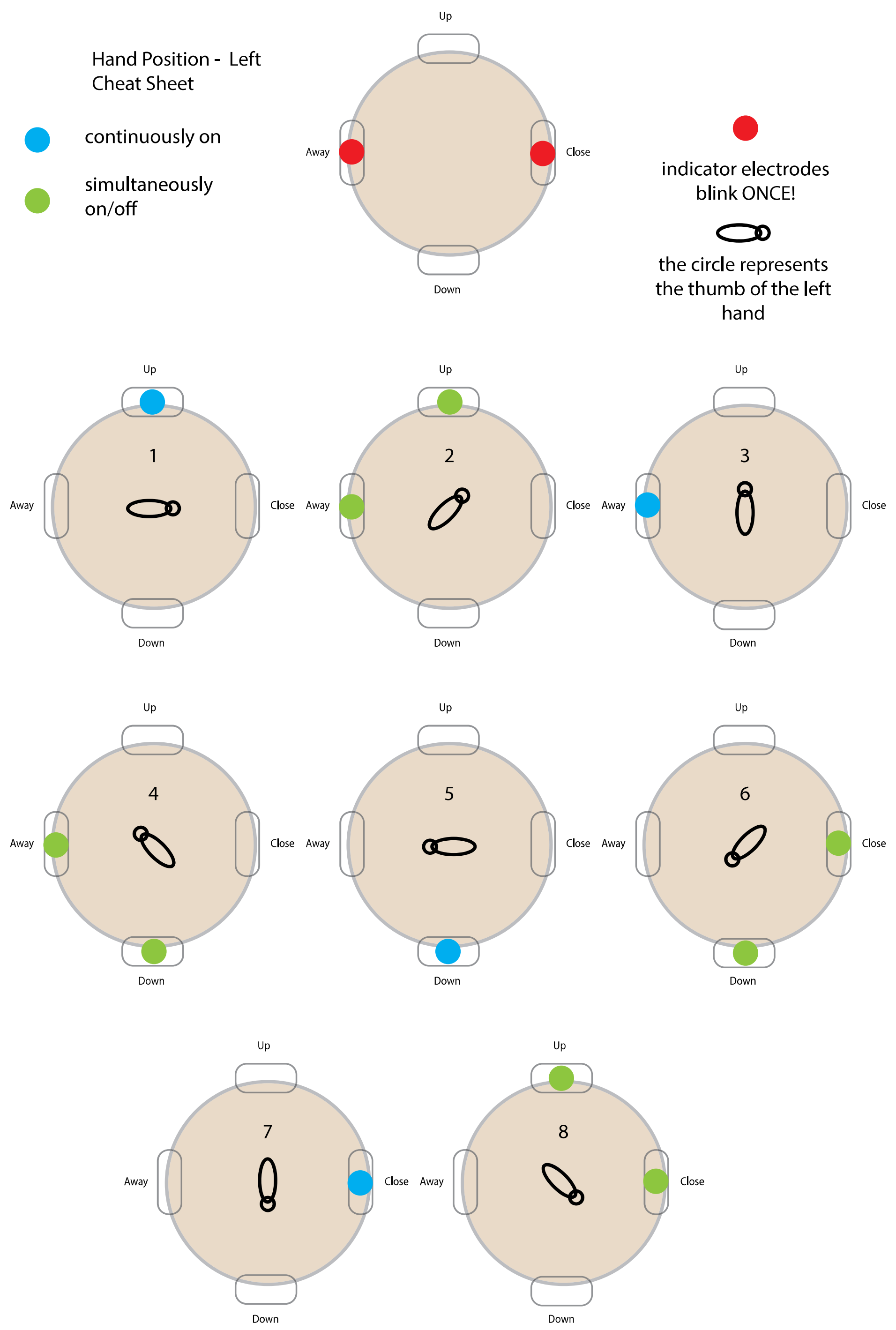

FIGURE A.2: Hand Position Cheat Sheet - Left Hand

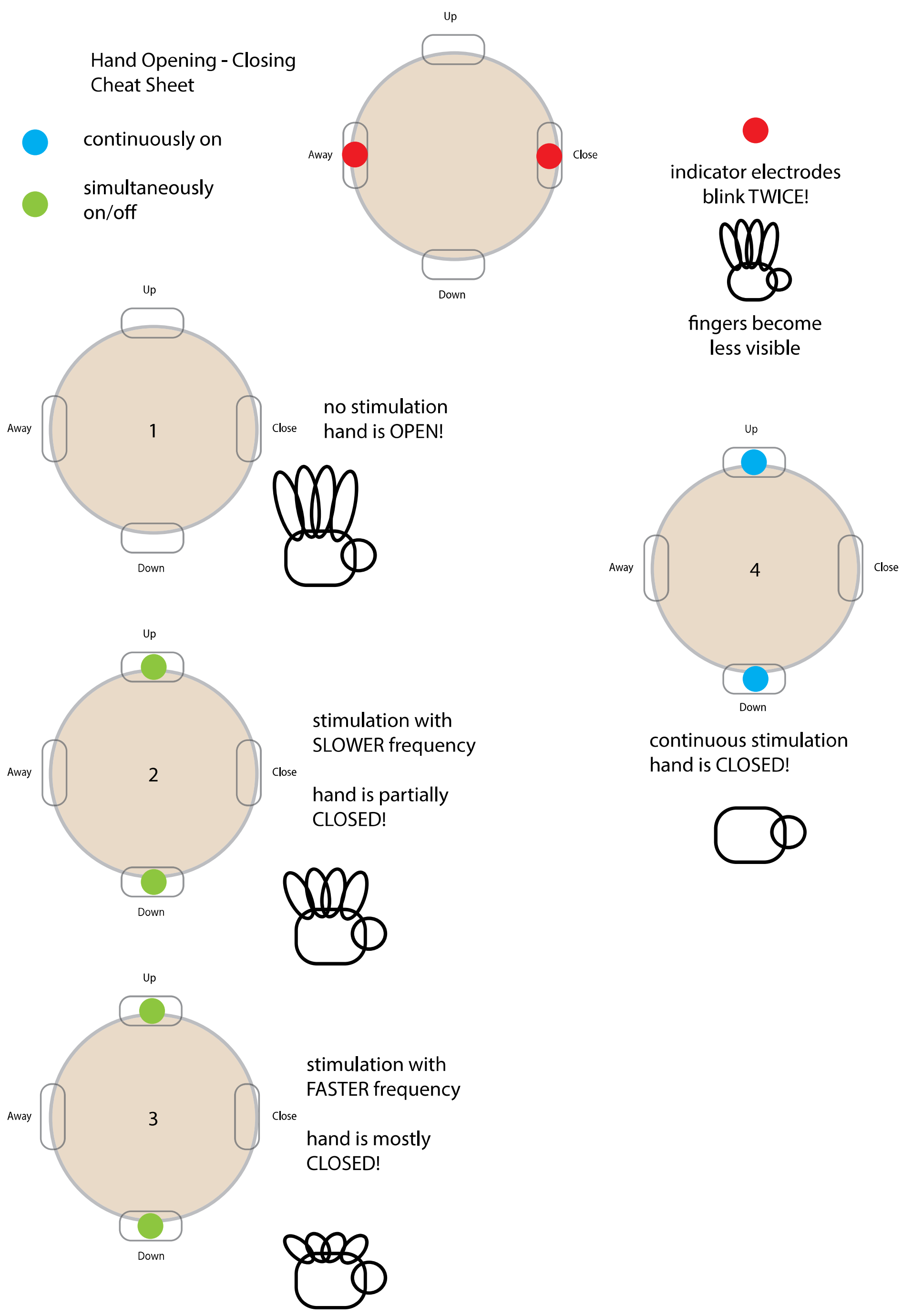

FIGURE A.3: Hand Opening-Closing Cheat Sheet

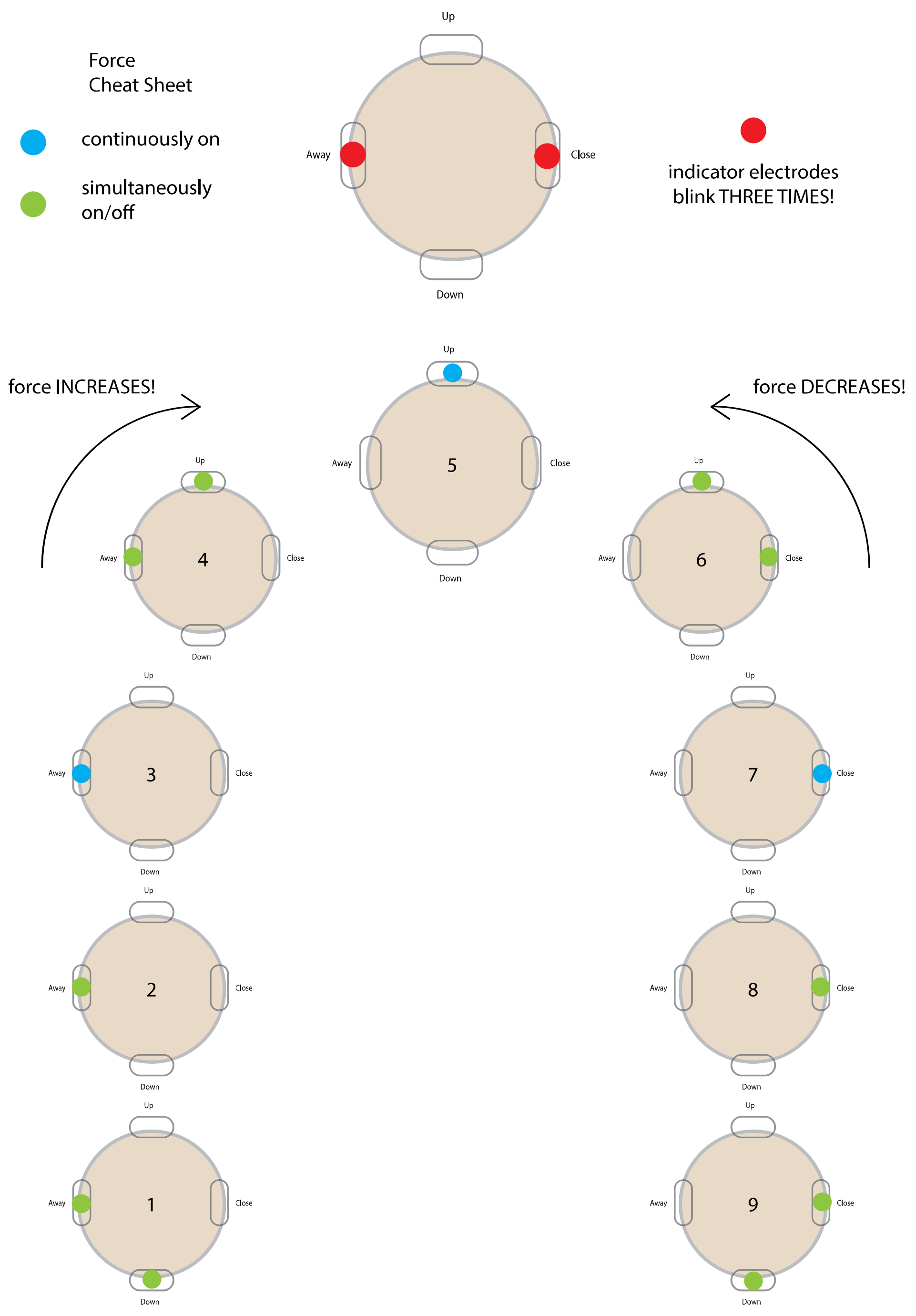

FIGURE A.4: Force Feedback Cheat Sheet

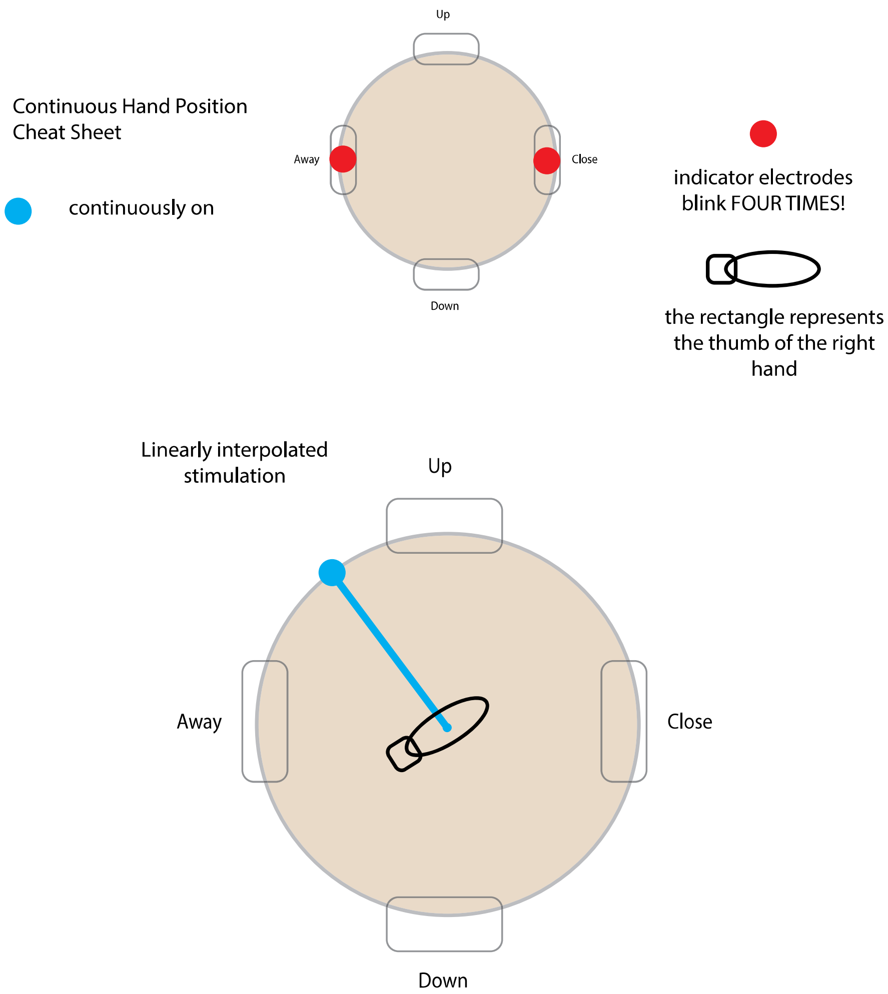

FIGURE A.5: Continuous Hand Position Cheat Sheet

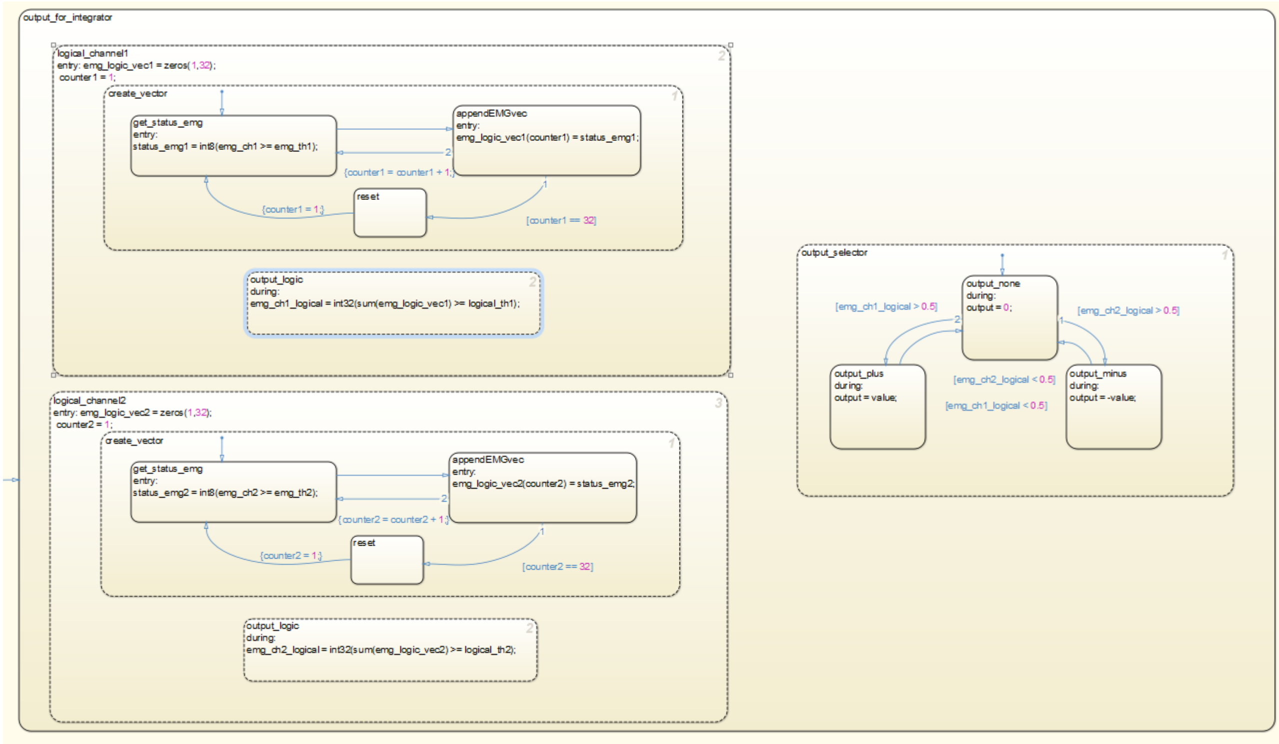

FIGURE A.6: EMG-Logic Classifier

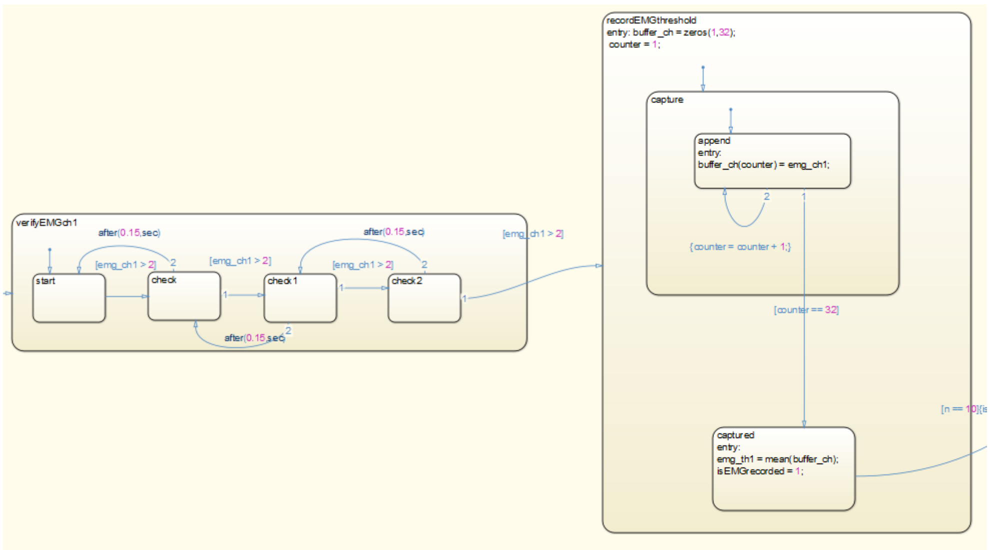

FIGURE A.7: EMG-Logic Threshold Values

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