Faculty of Health Science and Technology (HST)

Surrogate pointing device for cognitive sensory feedback

Mai Kristiane Thomsen

Biomedical Engineering
4th semester Master

Study overview (titelblad)

Education: Cand.polyt (biomedical engineering)

Educational institution: Aalborg University

Project: Master thesis

Project title: Surrogate pointing device for cognitive sensory feedback

Author: Mai Kristiane Thomsen (Studynr.: 20115740)

Study group: 10414

Main supervisor: Eugen Romulus Lontis, lontis@hst.aau.dk

Number of pages: 63

Synopsis:

One of the challenges within the field of prosthetics is to restore the missing sensory function that comes with an amputation. Throughout the years several techniques have been designed and tested to provide amputees with sensory feedback as a replacement for the lost function. This study seeks to design a surrogate pointing device for cognitive sensory feedback for a simple two-dimensional movement.

A screen cursor was adapted as pointing device in target reaching tasks in response to the centre-out task being controlled by a human subject through an analog joystick. The sensory feedback was implemented as non-invasive vibro-tactile sensations projected onto the skin of the subject, i.e. imitating the cursors movement on the screen.

The experiments were conducted in five trials, slowly enhancing the learning curve for the subject, before tests were conducted where the subject had to solely rely on the vibration feedback as orientation of the cursors movements. The results showed a steep learning curve when the visual feedback was taken away. Furthermore, it proved that small targets (target<10x10) were almost impossible to reach with the proximity of the feedback given.

Results further showed that a combination of visual and sensation feedback proved effective in the target reaching tasks and could even reduce the efficacy by almost 3 second.

Mai Kristiane thomsen

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1.0 Introduction

1.1 Prostetic Devices

The development of prosthetic devices has significantly improved in functionality, look and size. Some even resembles an actual human hand with individual controllable fingers and joints. They have flexibility in movement and a stable, robust human-machine interface with different control strategies for grasping functions. In other words, prosthetic devices now days can look and move resembling a human hand. However such devices are yet to have any kind of somatosensory feedback implanted. Meaning, operating a prosthetic device is relying on visual feedback. [1, 2] This is causing amputees choose a lower developed and lower functional body-powered prosthetic over a highly evolved electrically-powered hand prosthetic. Because, with a body-powered device the amputees are provided with intuitive kinesthetic feedback through the control along with their individual visual feedback.

Researchers have been looking into recreating or fixing the deficit of the motor and sensory system in patients suffering from amputations or spinal cord injuries, and studies have shown that the motor function can be restored through using active prosthetics. This field of improving motor function keeps developing, along with ideas for restoring the missing sensory feedback. One example is through the phantom digit map - Some amputees are left with sensation areas on the stump or along the remaining limb (phantom digit map). However reading these mappings and reaching them for stimulation can be quite challenging, because these mappings are never the same due to the fact that every amputation is always different. [3] However when located and tested, these mappings may be a potential monitor guide for rehabilitation of peripheral injuries, and can be used as target areas of stimulation to restore the missing sensory feedback. [4–6] However some amputees do not have this phantom digit map left after the amputation, while other mappings are yet to challenging to stimulate. This raises the question, if there is an alternative way to provide a sensory feedback mechanism which do not rely on the sensory cortical mapping?

Other studies have used (invasive or non-invasive) vibrating or cutaneous electric pulses in attempts to substitute for the loss of sensation. This by changing amplitude or frequency in response to changes in the position or force of the prosthesis, in which the grasping force is controlled. [7] Tactile feedback is the main factor that grasping relies on, which means that prosthetic devices would have a better function using closed-loop control. To achieve this, the prosthetic should be able to use both exteroveptive and proprioceptive information; respectively referring to detection of physical interactions with the environment, and sensing the joint-position in space. Thirdly, the prosthetic device needs to make a transformation of this information to the user. [8] This should then be perceived in the stump connected to the prosthetic device via some type of tactile sensory feedback.

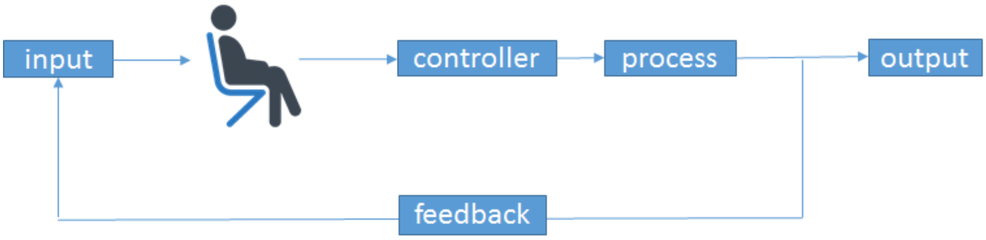
1.2 Sensory Feedback

Sensory feedback is feedback provided within the sensory systems where information from sensory receptors is returned along the afferent pathways so the brain can monitor the consequence of actions. These consequences are all a part of learning and controlling movements, both essential for motor control and thereby an important part in creating a full-functional prosthetic. Sensory feedback is received by sensory receptors in the body, when stimulated, these receptors pass information to the CNS via action potentials. This is all a connection of the sensory pathways which describe the afferent division of the nervous system. [3] In healthy people this process happens all the time. However, after a traumatic loss of a limb the process is broken, and although each part of the body has its own receptors and corresponding sensory pathway, the pathways going to the missing limb are compromised and do no longer function in the same way, causing amputees to suffer from, not only, loss of movement but also loss of sensation. Some are even suffering from phantom limb pain (pain in the missing limb). In theory, this pain is a state of panic, recognised by the brain, because the path of the sensory system is broken due to the amputation. The pain can be located in any part of the missing limb because every finger on a human hand has its own area of activation. These areas extends to the central cortex via labelled lines. Which is interpreted as one long line of sensation. In theory, it could be possible to remove the pain by recreating or fixing the sensory feedback system, which these labelled lines also indicate. Theoretically, if a stimulation is made along one of these lines, it would be possible to produce a false sensation somewhere along the line and mimic sensations felt in the (missing) hand and fingers. [3, 9]

1.3 Initial problem

The current study seeks to implement a system which allows for adaptation of a new sensation-type feedback mechanism using non-invasive vibro-tactile stimulation as a substitute for sensory feedback. When vibratory stimulations is applied to the skin, the fast-acting mechanoreceptors (Meissner's and Pacinian corpuscles) are activated. Where the afferent fibres innervating these receptors fire at a rate proportional to the frequency of the stimulus. [7] This will in theory create a simultaneously sensation of vibration along with the stimulation and is the main reason for applying vibro-tactile stimulation over mechano- and electro-tactile. These would activate different mechanoreceptors which typically model the stimulus amplitude with the firing rate. [7]

Based on the labelled line theory and previous successful studies on using vibro-tactile stimulation as feedback this initial problem of this study aims to implement a sensory feedback mechanism for control of a visual object via a simple feedback loop as illustrated in figure 1.1.



Figur 1.1: An example of a feedback control system; the feedback given is through non-invasive tactile stimulation, based on human control of a process, giving an output movement of the system.

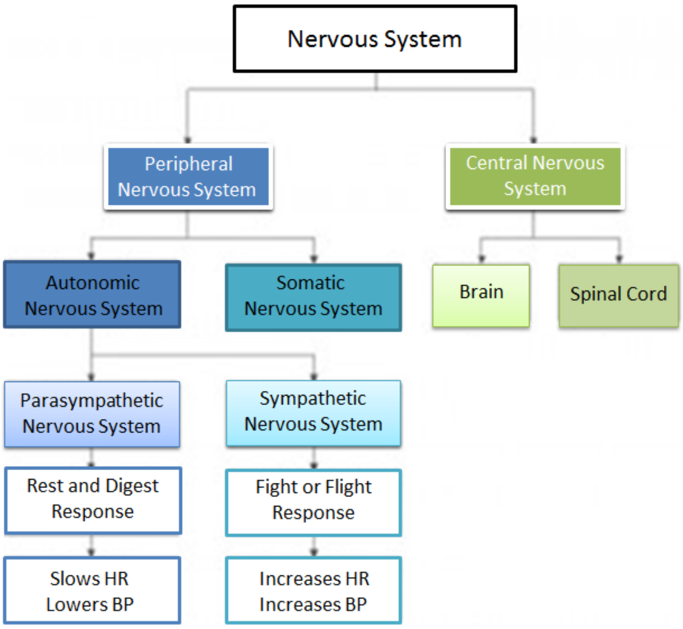
Del I

Problem Analysis

2.0 Sensory Pathways

Sensory feedback is provided within the sensory system where information form sensory receptors are returned along the afferent pathways, to the brain which can monitor the consequences of actions. [3] The sensory system is a part of the nervous system responsible for processing sensory information. As mentioned the sensory system consists of sensory receptors, neural pathways, and parts of the brain that are involved in sensory perception. [3]

2.1 The Nervous System



Figur 2.1: The nervous system is divided in to two main groups; the CNS and the PNS, where PNS can further divides into a somatic and an autonomic part, and the autonomic is divided further into a sympathetic and parasympathetic part of the nervous system (created by author from Martini [3]).

The nervous system includes all neural tissue in the body; brain, spinal cord, receptors in the complex sense organs (eye, ear), and nerves that link the nervous system with other systems of the body. [3] When we look at the nervous system, we can divide it in two ways; according to anatomical or functional perspective. A schematic division of the two perspectives is illustrated in Figure 2.1. [3]

2.1.1 The Anatomical Division of the Nervous System

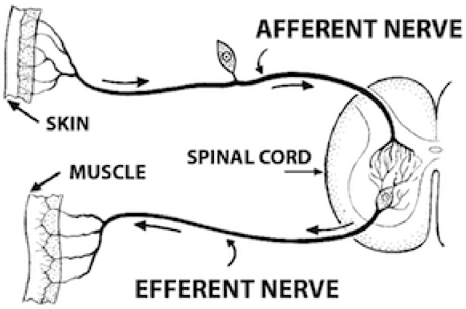
The central nervous system (CNS) and the peripheral nervous system (PNS). [3] The CNS consists of the brain and spinal cord. Its responsibilities is to integrate, process, and coordinate sensory data and motor commands. [3] The other part is the PNS. It includes all neural tissue outside of the CNS. Its responsibilities is to deliver sensory information to the CNS and carry motor commands received here from to the peripheral tissues and systems. These motor commands or sensory information's are carried by bundles of axons, called peripheral nerves. The nerves connecting to the brain are called; the cranial nerves, and connecting to the spinal cord; the spinal nerves. [3]

2.1.2 The Functional Division of the Nervous System

An afferent and efferent part, each with different functions. The afferent part brings sensory information to the CNS from receptors in the peripheral tissue and organs. The receptors are sensory structures that detect changes in the environment (internal or external) or respond to specific stimulus. [3] The efferent part carries motor commands from the CNS to the muscles, glands, and adipose tissue. From the effectors, the target organs which respond by doing can further be divided into somatic and autonomic components. [3]

2.2 The Somatic Nervous System

The somatic nervous system (SNS) is the part of the peripheral nervous system that controls the skeletal muscle contractions; voluntary and involuntary contractions (reflexes). This by conducting informations about nerve impulses, received by the afferent fibers, delivered from the CNS and passing these impulses on to the efferent fibers that are responsible for muscle contraction. The SNS includes the pathways from the skin and skeletal muscles to the CNS. It is also described to be involved with activities that include consciousness. [3]



Figur 2.2: An illustration of the communication between the two-neuron sequence [3]

It can be divided into a two-neuron sequence; The first include the upper motor neurons, with a cell body located in the precentral gyrus of the brain (Brodman Area 4). Here it receives a stimuli to control voluntary skeletal muscles. The stimulus is then carried, by the upper motor neuron, down the corticospinal tract and synapses in the ventral horn of the spinal cord to the alpha motor neuron (a lower motor neuron). The upper motor neuron releases acetylcholine from its axon terminal knobs and these are received by nicotinic receptors on the alpha motor neuron. The alpha motor neurons cell body then sends the stimulus down its axon via the ventral root of the spinal cord and proceeds to its neuromuscular junction of its skeletal muscle. Here it releases the acetylcholine from its axon terminal knobs, received from the upper motor neuron, to the muscles nicotinic receptors, resulting in stimulus to contract the muscle. In other

words, the SNS includes all neurons connected with the muscles, sense organs and the skin. This part of the nervous system deals with sensory information and controls the movement of the body. [3]
From this we can gather that restoring sensory feedback is connected to the afferent communication - from body to brain and spinal cord and lies the communication of information within the nervous system.

2.2.1 The Sympathetic Nervous System

The sympathetic nervous system is the part of the autonomic nervous system (ANS) which activates the fight or flight response, ie. is mostly activated under sudden stressful circumstances. This response causes the pre-ganglionic sympathetic fibers (ends in the adrenal medulla) to secrete acetylcholine, this then again activates the secretion of adrenaline (epinephrine) and to a lesser extend it activates the secretion of noradrenaline (norepinephrine). Because of this, the response acts primarily on the cardiovascular system and is mediated directly via impulses that are transmitted through the SNS. [3]

2.2.2 The Parasympathetic Nervous System

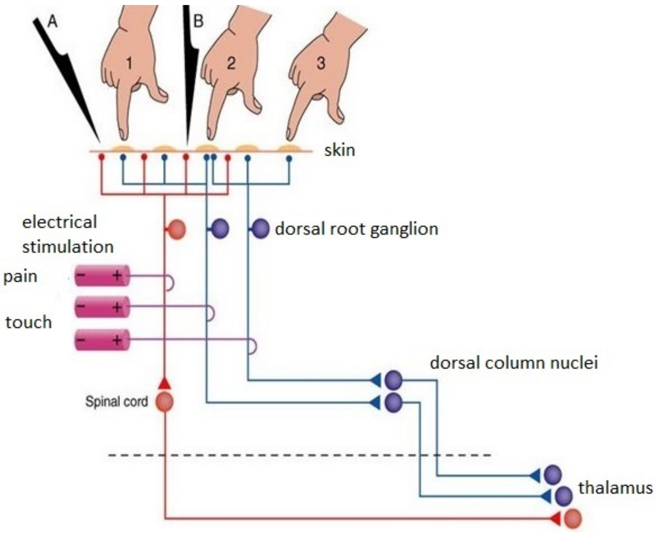
The parasympathetic nervous system is the part of the ANS which conserves energy as it slows the heart rate, increases intestinal and gland activity, and relaxes sphincter muscles in the gastrointestinal tract - hence this part of the ANS is referred to as the rest and digest system or feed and breed. This is in other words the counteraction to the sympathetic system. Following, that after a high stress situation (ie. fight or flight situation) the parasympathetic system has a form of backlash reaction that balances out the reactions by the sympathetic system. [3]

3.0 Sensory Receptors

Sensory receptors monitor specific conditions in the body or in the external environment and when they are stimulated, each receptor passes information to the CNS through action potentials. These travel along the axon of a sensory neuron and are a part of the sensory pathways. These sensory pathways make, together with the sensory receptors and sensory neurons, the afferent division of the nervous system. [3]
Each receptor has a unique characteristic function. Receptors of touch are very sensitive to pressure but relatively insensitive to chemical stimuli. This kind of receptor feature is the receptor specificity. The specificity can result from the structure of the receptor cell or from the presence of accessory cell(s) or structures that shield that specific receptor from other stimulus. [3]
The receptive field, the area monitored by a single receptor cell, is like a detection field and whenever a sufficiently strong stimulus arrives within this field, the CNS will receive information about it to detect the location of the stimulus. This also means that the larger the receptive field, the harder it will be to locate a stimulus. [3] The simplest receptors are the dendrites of the sensory neurons. Free nerve endings are the name of the branching tips of the dendrites. These are not protected by accessory structures. They extend through tissue can and show a little receptor specificity, which means they can be stimulated by many different stimulus. For example free nerve endings that respond to tissue damage and provide pain sensations can be stimulated by chemical stimulation, pressure, temperature changes, or a trauma. Though all arriving stimulus can take many forms the sensory information about the stimulus is sent to the CNS only in the form of action potentials (electrical events). [3]
The transduction begins when a stimulus causes a change in (trans)membrane potential of the targeted receptor cell. This change is referred to as the receptor potential and is either a graded depolarization or hyperpolarization. The stronger the stimulus, the larger is the receptor potential. [3] Any receptor potential that causes a depolarization of the plasma membrane will bring the membrane closer to the threshold. [3]
A depolarizing receptor potential in a neural receptor is called a generator potential. Change in membrane potential alters the rate of neurotransmitter release at the synapse, while receptor cells develop graded receptor potentials in response to stimulation. The result is a depolarization or a hyperpolarization of the sensory neuron. [3]

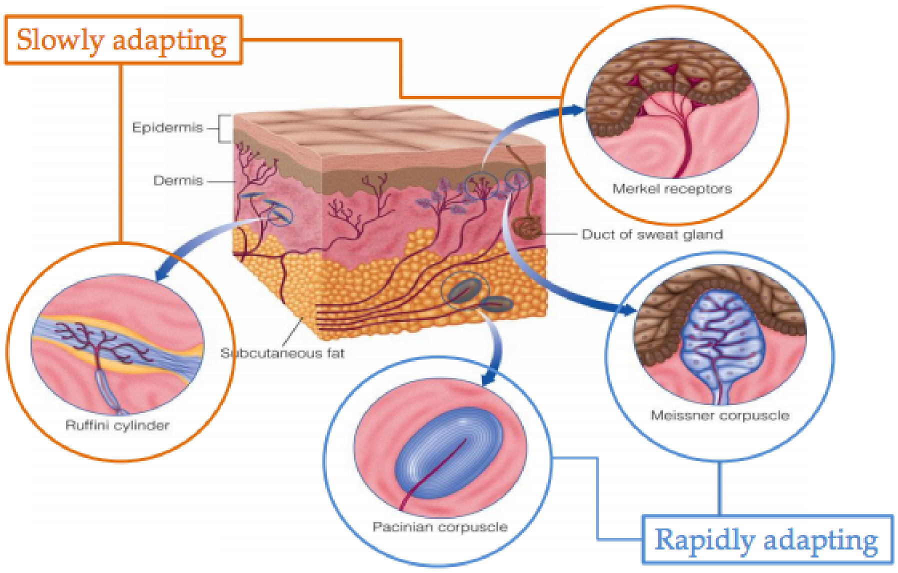
3.1 Labelled line

Sensory information arriving at the CNS is routed according to the location and nature of the stimulus. Along the sensory pathways, a series of neurons relays information from the receptor to the neuron at the specific site in the cerebral cortex. The link between the peripheral receptor and the cortical neuron is called a labelled line, as illustrated in Figure 3.1. Each line consists of axons which carry information about the modality or type of stimulus. The CNS interprets this modality on the basis of the labeled line over which it arrives. This would result in one lone line of sensation meaning that it would not be possible to detect the difference between a true sensation and a false one generated somewhere along that line. [3]
This strengthens the initial problem and in theory makes it possible to reproduce a false sensation somewhere along the line in order to mimic sensations felt in the hand and fingers.



Figur 3.1: An example of the labelled lines in the somatosensory system.The two dorsal roots (blue) sends peripheral axons as part of a touch receptor. Activating the neurons of touch by direct touch of the skin or stimulation along the axon produces a sensation of light touch at a defined location. Stimulation of both axons produces the same sensation but with different localization. **Copyright ©2002, Elsevier Science (USA)**

3.2 Anatomy of Receptors



Figur 3.2: An example of the labelled lines in the somatosensory system.The two dorsal roots (blue) sends peripheral axons as part of a touch receptor. Activating the neurons of touch by direct touch of the skin or stimulation along the axon produces a sensation of light touch at a defined location. Stimulation of both axons produces the same sensation but with different localization. **Copyright ©2002, Elsevier Science (USA)**

Functions of grip and touch are served by the complex organ of the human hand. Here the mechanoreceptors can be categorized into two areas of function; the ones associated with joints and muscles providing the central nervous system (CNS) with information about movement and position of hand and fingers, and the ones located within the skin and subcutaneous tissues. In addition, there are numerous free nerve endings, these are reacting to thermal and/or painful stimuli. These are generally referred to as polymodal nocieptors and are located in the connective tissue of the locomotion apparatus as well as in the skin where some even enter the epidermis. [10]
Morphologically, these are non-specific structures around the "free"nerve endings and can be seen as terminal branches of the afferent fibers, this in contrast to the different types of mechanoreceptors. [10]

3.3 Mechanoreceptors

Now looking into the mechanoreceptors, these can be of the joints, of the musculararture, and of the connective tissue between skin and muscle fascia. The joints are surrounded by mechanoreceptors in the connective tissue, this forming the joint capsules. [10]
The first type of mechanoreceptor in focus of this study - Ruffini corpuscle - is found in the outer fibrous layer of the joint capsules. These corpuscles consists of one or several cylinders. These are formed by flat perineural cells and are supplied by a myelinated axon. On entering the cylinder it looses its myelin sheath and branches several times. Functionally, the Ruffini corpuscles are found to have a high sensitivity respond to stretching of the collagen fibres. Discharge patterns of the action potentials are slowly adapting throughout the maintained stimulation with very regular interspike intervals. [10]
The second type of mechanoreceptor in focus of this study - Pacinian corpuscle - is the largest type of mechanoreceptors. The myelinated axon of this receptor looses its myelin sheath on entering the inner part of the corpuscle. Here the axon ends in the centre of the corpuscle with a ball shaped thickening. Functionally, the Pacinian corpuscles are found to have the optimum sensitivity when stimulated by vibration in the frequency range of about 200Hz and vibration amplitudes below $0,1\mu m$. [10]

4.0 Problem Definition

The brain utilizes a rich supply of feedback from multiple sensory modalities in order to control movemenst in healthy individuals. These afferent pathways, as well as their efferent counterparts, can be compromised by a disease or injury, resulting in significant impairments and reduced quality of life. As mentioned, one of the most vexing problems in the field of upper extremity prosthetics is the inability to substitute for the loss of sensation. Encoding sensory feedback in prosthetics would theoretically mean that the prosthetic hand would no longer just resemble a real human hand from looks and detailed movement but also from sensations about movement and position. Thereby, restoring or creating sensory feedback would, in theory, make it possible to induce perception and touch. [2]
To create the missing afferent feedback, the flow of sensory information is in focus. Ideally, a prosthetic should be instrumented with artificial sensors able to recreate proprioception along with different modalities of touch, pressure, vibration, and temperature. The simplest and most common sensory modality methods employ electro-, mechano-, and vibro-tactile feedback to activate the tactile sense. Feedback from proprioceptors is essential for an accurate execution of movement.

Feedback mechanisms are most often inplemented in brain-machine interfaces (BMI), which is a technology that offers a way of restoring functionality of movement by allowing for control of a device using the brain. Most current BMI implantations make use of visual feedback for closed-loop control, and it is suggested that additional feedback modalities may lead to improvements in control.
Previous studies working with sensory feedback have focused on restoring the missing feedback of sensation, whereas this study seek to create a new sensory feedback type. This by looking into feedback modalities like mechano-, electro- and vibro-tactile sensations in combination with visual feedback as suggested by A.J. Suminski, 2010 [11]. Implementing something new means a new way of control, i.e. a new way of learning. This is to be taken into consideration with the sensory feedback in order to be able to use it.
The study [11] further looked into behavioral tasks in humans and monkeys through random target persuit tasks - controling a cursor in a two dimentional space. This idea is being adapted into the current study, by implemeting a surrogate pointing device. This device is to give both visual and sensory feedback.
Another study by L.R. Hochberg et al., 2006 [12] focused on neuronal ensemble control of prosthetic devices by using neural cursor control. Here they measured the activity of neurons in the primary motor cortex during neural cursor control in both monkeys and human with spinal cord injuries. To compare the neural activity they had the participant preforming a step-tracking centre-out task using the neural cursor. The data from the centre-out task were used to evaluate speed and accuracy of the cursor control. [12]

Combining the two studies mentioned above would create a platform of implementing a tactile modality as sensory feedback and using this along with visual feedback to evaluate speed and accuracy within target tracking and/or target reaching tasks, also related to the centre-out task.
By this, the study seek to investigate the following problem definition;
How to implement and evaluate a surrogate pointing device for cognitive sensory feedback, using vibro-tactile sensations and the basic setup of the centre-out task?

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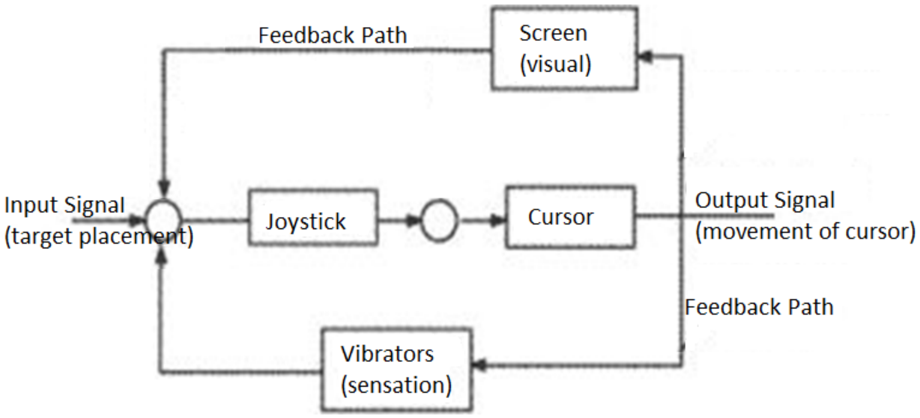
Problem Solution

5.0 System Design

Grip and touch are both results of some kind of movement, and every movement is based on some kind of prediction. The concept of motor prediction was first considered by Helmholtz [13] when trying to understand how humans localise visual objects. In general, prediction refers to estimating a future state of a given system - in this case the human body - and the extend to which the CNS can influence these future states covers a continuous range. [14]
Considering limb motion - a dynamic of multi-joint motion - the relationship between the motor command given and the behaviour executed is based on a complex system. If this complexity is broken down to a simple dynamic movement of the index finger - opening and closing to reach the thumb - then the motion can be related to a joystick movement. [14]
Motor predictions and state estimations are deeply related to the use of these predictions in sensory-motor control. Knowledge of the body state - positions and velocities - is fundamental for accurate motor control. Theoretically, the body state can be estimated based on sensory information and/or based on motor commands. However, using solely sensory information can lead to large errors, especially regarding fast movements and thereby cause instability. Likewise for a solo use of motor commands. Here the estimate is made ahead of the movement, giving a better result in terms of time delay. However, if the forward model is not perfectly accurate, the estimate will drift over time, again generating cause for errors.
In motor control, a forward model can be used to predict the sensory consequences of the actions. In perception of action, multiple forward models can be used to make multiple predictions and, based on the correspondence of these predictions and the observed behaviour, they can interferer in which of the controllers to be used in order to generate the observed action. [14] Solving drawbacks of using one or the other of the mechanisms for motor prediction can be done by combining the two and hereby specifying the importance of sensory feedback, when controlling movements. In addition to state estimation, predictions allows for filtering of the sensory information, i.e. the sensory predictions can be derived form the state prediction and used to cancel the sensory effects of a movement. [14]

Adapting this physiological feedback mechanism into the system, will mean that the movement of a limb is simplified to the movement of a pointing device with a 2D orientation. This pointing device is being implemented as a cursor on a screen being controlled via a joystick. The sensory feeback is implemented as non-invasive vibro-tactile stimulations following the movement of the cursor, giving the subject using the system two feedback channels - visually and through sensation. The functional block diagram of the system is illustrated in Figure 5.1.

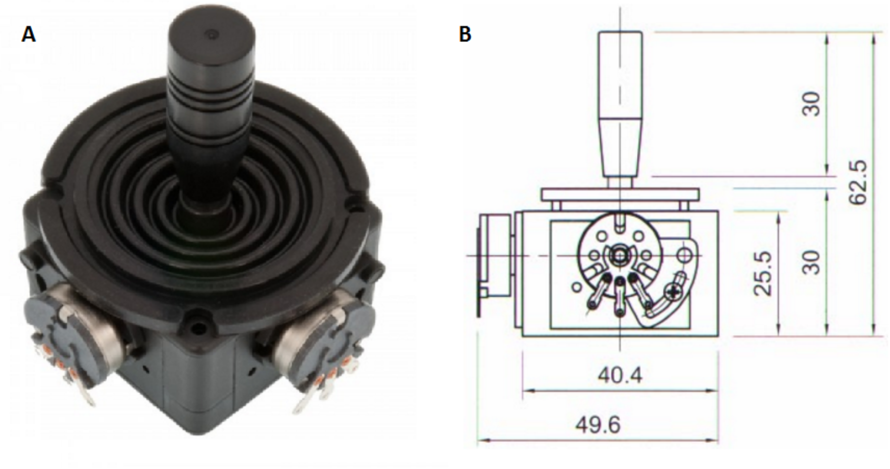
The software implementations for the system has been made in MATLAB with use of Psychtoolbox. The complete code (with comments) can be found in the Appendix IV.



Figur 5.1: Illustration of the systems functional block diagram, where the human subject gets a visual input of target placement and based on this information the subject is moving the joystick, controlling the cursor to reach this target. The cursors movements are projected onto the skin via vibrations as sensation feedback.

5.1 Joystick Control

The joystick has a six wire connection, as illustrated in Figure 5.2 **A**. These represent the 2-axle controls and are respectively connected to the USB-6001 DAQ card (implemented inside a black box) delivering an output of 0-5V as indication of activation on either the horizontal or vertical channel.

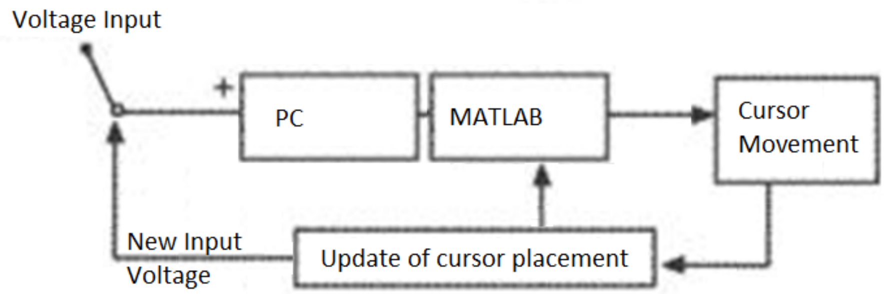


Figur 5.2: Illustration of the joystick build with measurements and details. Picture **A** shows the visual body of the joystick which has been implemented in the black-box system for the joystick. Picture **B** shows the detailed measurements of the joystick, implemented within the black-box.

The joystick can as maximum deliver an output of 5V and the control of the joystick can be compared to an x-y coordinate system, where the x-axis corresponds to horizontal movements (also given as right and left). Likewise is the y-axis corresponding to vertical movements (also given as forward and backward). This means, if the output is greather that 3V that will be considered a movements to the right, if the output is lower than 2 it will be considered a movement to the left and likewise for the vertical movements. A movement in the obliquely direction is determined by both channels, i.e. an output on both the x and y. This is all represented in the code which can be found in the Appendix IV

5.2 Surrogate Pointing Device

The pointing device is implemented as a cursor on a screen and can be seen as a limb (prosthetic) or other object to be controlled. The goal of implementing a surrogate pointing device is to allow for control of this pointing device under a set of circumstances and/or for target reaching purposes.
There is no hardware implementation of the this compartment, the software implementation of the cursor is illustrated in the Appendix IV.



Figur 5.3: Illustration of the functional block diagram for the pointing device, where the cursor movement is implemented with in the code in MATLAB. This movement is dependent on the voltage input and its current position.

The joystick is delivering an output of 0-5V which is given as an input digit to the computer and MATLAB code. This input is determing in wich direction the cursor is to move from its current position. Moreover the speed of the cursor is implemented in the code and is not given by the joystick control.
The cursor speed is defined as 10 random velocities (1-10) moving according to number of pixels per "press". This was optimized later on in the experimental setup.

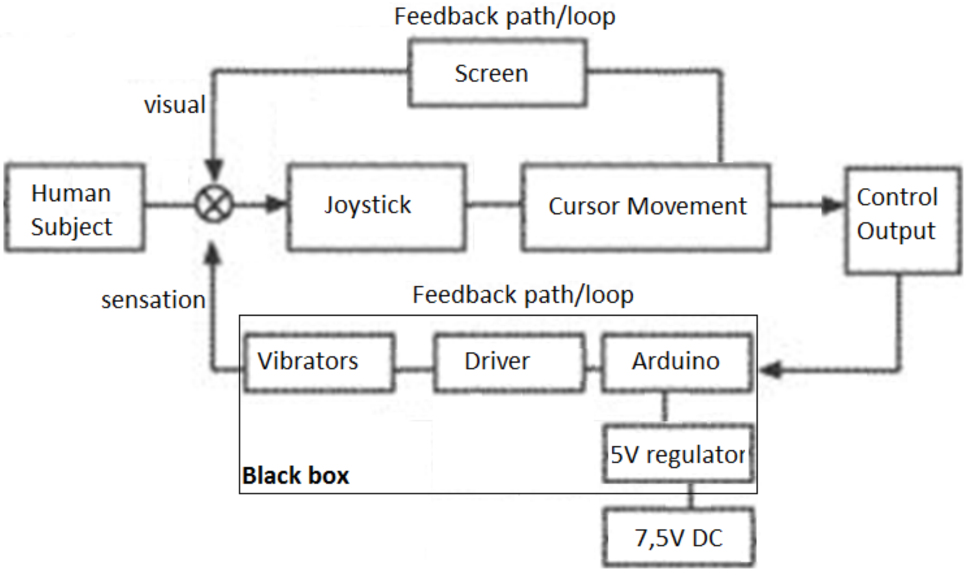
The visual setup for the poiting device was implemented as a dot indication on the screen. A circular shape with a size of 5x5 pixels on the computer window. The cursors inital position has been implemented to in the centre of the window.

5.3 Cognitive Sensory Feedback

The main component to the system is the cognitive sensory feedback mechanism. When looking at the body's physiology, the proprioceptors provide information about orientation of the body relative its placement with respect to gravity, its movement relative to the external medium, along with movements and forces in localised regions of the body. Muscle spindles are primarily responsible for position and movement sense, Golgi tendon organs provide the sense of force and the vestibular system provides the sense of balance. [3, 10]
For voluntary movements, feedback from proprioceptors can regulate the generation of motor command by correcting errors based on negative-feedback loops. This will provide timing on the ongoing movement and (if necessary) initiate commands required at a later time within the movement sequence to

adjust the further movement. This by using provided signals from the planning of the movement based on information about the starting position to set parameters of the feedforward commands. This feedback type is further required to modify motor commands slowly in response to alterations in the biomechanical properties of the limb. [3, 10]

By adapting the physiology from the proprioceptors to the system, it is possible to implement the desired cognitive sensory feedback mechanism. This is done by building a setup using vibro-tactile stimulation. Figure 5.4 illustrates the the functional block diagram for the vibrator connection, i.e. the cognetice sensory feedback system.



Figur 5.4: Illustration of the functional block diagram for the cognitive sensory feedback. The black box showes the vibrator connection.

As illustrated in the figure above, the control output functions as input to the vibrator connection. Within in this connection is 3 important components.

5.3.1 Arduino NANO 3.0

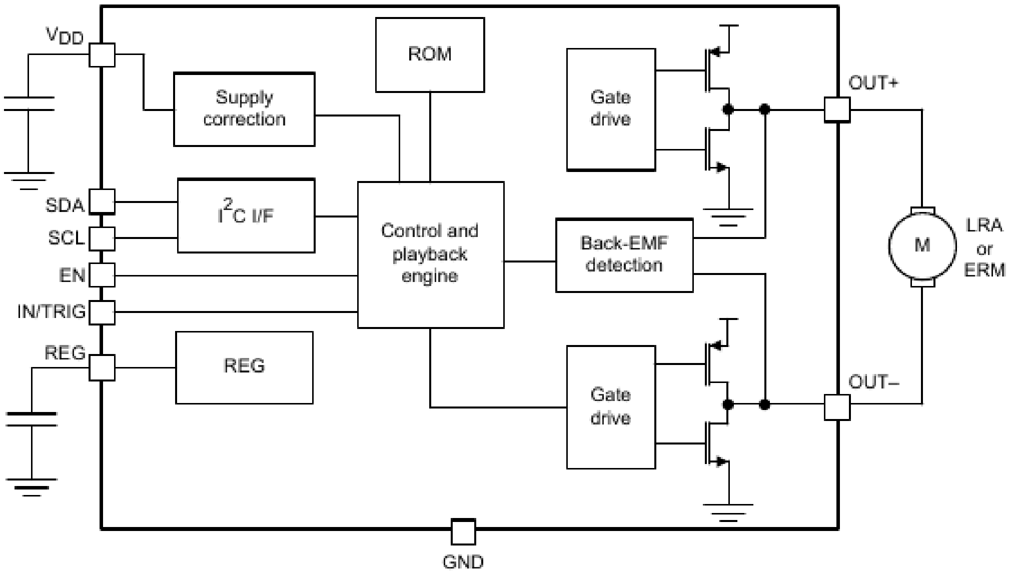
The first connected component is the Arduino wich is connected to the computer, i.e. MATLAB and the control input, through a USB. The Arduino used is an Arduino Nano 3.0 [15]. This Arduino type lacks a DC power jack and a Mini-B USB cable connection. The input voltage limit level is at 6-20V, which fits perfectly with the external battery supply of 7.5V DC connected to a 5V regulator. The Arduino can provide or recieve 40mA DC current per I/O pin and have 14 digital pins, which all can be used as input or output depending on the function used. The pins all operate at 5V, which again calls for the external battery supply when the power supply from the computer would not be enough. The 5V regulator is implemented to ensure the voltage input to the system circuit does not go above the maximum level of voltage supply. For the driver the maximum input voltage supply is 6V.
Specialized pin functions can be found in the Arduino Nano produck overview [15] and the code implemented for the Arduino can be found in the Appendix IV.

5.3.2 Haptic Driver

The second component is the DRV2605 Driver from Texas Instruments [16]. This component was added to ensure the Arduino is not sourcing all the current for the vibrators. The component is a haptic driver that relies on the back-EMF produced by an actuator to provide a closed-loop system. This provides flexible control of linear resonance actuator (LRA) and eccentric rotating mass (ERM) actuators over a shared bus or input signal.
Implementing a haptic driver means...
The functional block diagram of the DRV2605 haptic driver is illustrated in Figure 5.5. As illustrated the driver runs on a I^2C controlled digital playback engine which gives a real-time playback mode. The driver is furthermore induced with a smart loop architecture which is a patent pending control algorithm. This allows for the following features;

- Automatic Overdrive Breaking (ERM/LRA)
- Automatic Resonance Tracking (LRA)
- Automatic Actuator Diagnostic (ERM/LRA)
- Automatic Level Calibration (ERM/LRA)

The allowable feedback provides automatic overdrive and breaking creates a simplified input waveform paragrim as well as reliable motor control and consistent motor performance. A further description of this smart loop architecture can be found in the online usermanual for the DRV2605 haptic driver.

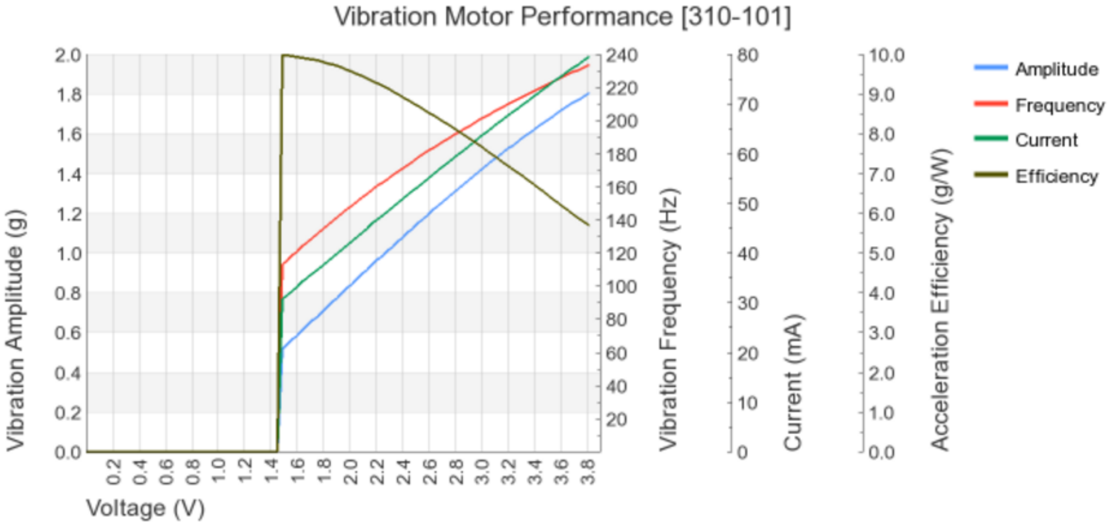


Figur 5.5: Illustration of the functional block diagram DRV2605 haptic driver.

Five vibrators are connected to the vibrator system via DIN-stick, with the idea of creating a visual presentation of a coordinate system, with a centre and maximum/minimum of the x,y axes.

5.3.3 Vibrators

The third component consists of the 5 vibrators. Each of them has a range of 0-255 values, i.e there are in theory 255 intensity settings for every vibrator. The 255 values are build from binary digits or bits, where 8 bits equals 1 byte, and one bit consists off of 0-255 values.
Increasing the voltage induced will also cause an increment in both amplitude and frequency for the vibrators, as illustrated in Figure 5.6 given from the user manual for the vibrators.

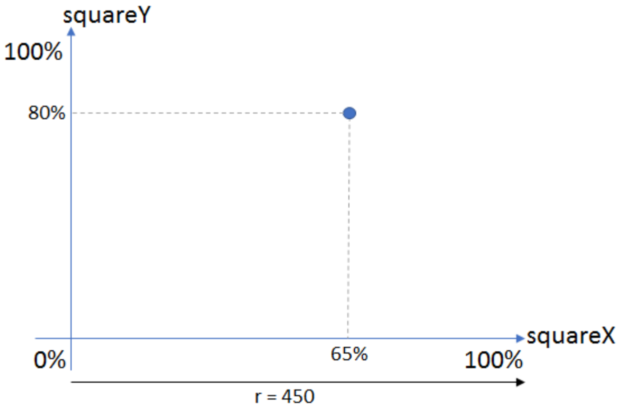


Figur 5.6: I. The transmission of aerodynamic forces on control surfaces or rotor blades to cockpit controls as also the transmission of cockpit control forces to the aircraft control surfaces or rotor blades. II. A process in an electrical circuit or control system in which some energy from output of the system or circuit is fed back into the input. A system using a feedback system is called a closed-loop system. III. The return of a portion of the output of a device to the input. Positive feedback adds to the input, and negative feedback subtracts from the input. IV. Information, such as progress or results, returned to an originating source. [Source: User manual for vibrators]

The figure further shows that the power consumption/current consumption should be around 60mA to have the highest efficiency. The usermanual for the vibrators further states that the power consumption should be at a maximum of 100mA, i.e. it must be ensured that the cicuit will drive at a maximum of 100mA. Another detail from the figure is the vibration frequency and amplitude which respectively should be around 200Hz and 180g for the highest efficiency.
The vibration intensities are dependent on the cursor position, i.e. the closer to the centre (with the four vibrators placed as max and min of the horizontal and vertical movement directions) the lower vibration intensity for the four outer vibrators. Opposite response for the centred vibrator, i.e. indicating how fare away from the centre the cursor is.
Figure 5.7 illustrates how these calculations were made. For vibrators placed at 100% on the x and y axes, the intensities are calculated from the cursor position as shown in the figure. The window range of the visual presentation has 450 pixels from the centre to each of the four vibrators giving the radius. The intensity range goes from 55-255 values giving a total range of 200, hence 2 intensity increasement per percentage. This gives the equation;

$$intensity = |cp/r * 100| * 2 + value_0 \tag{5.1}$$

calculating the intesity for eighter x or y, where cp is the responding cursor position and $value_0$ is an indication of the starting intensity value, i.e. 55. This is calculated for both the x and y axes for all active vibrators.



Figur 5.7: The x and y axes represents the minimum and maximum percentage delivery of vibration, indicated by the x0 and y0 placement of the cursor.

6.0 System testing

System testing is conducted on software and hardware of an integrated system to evaluate its compliance with the specified requirements. This means, that a system can be tested and require no knowledge of the inner design of the code or logic, also known as black-box testing. In general, system testing takes inputs of all the components (after passing integration testing) and seeks to detect defects within the components as equals and in the system as a whole. The integration testing is made throughout implementation. Here each component is tested when connected to the system. The purpose of integration testing is to detect any inconsistencies between the software units that are integrated together or in the connection to the hardware. This integration testing is a part of the verification state, as illustrated in Table 6.1.

Tabel 6.1: Different phases of the system test, divided into verification (conducted during / after implementation) and validation (conducted at after implementation).

Compartment	Joystick Control	Pointing Device	Sensory Feedback
Verification phase 1	The hardware implementation is undergoing verification - is it functioning according to the specifications, i.e. does it deliver a voltage output according to activation of channels?	There is no hardware implementation of this compartment	The hardware implementation is undergoing verification - is it functioning according to the specifications, i.e. is i possible to activate the vibrators and change their vibration intensity?
Verification phase 2	The software implementation is undergoing verficiation - is it functioning according to the specifications, i.e. is the control freely and as wanted?	The software implementation is undergoing verification - is it functioning according to the specifications, i.e. is the cursor illustrated as desired?	The softwareimplementation is undergoing verification - is it functioning according to the specifications, i.e. is the intensity changing with the cursor position?
Validation	The complete implementation of the joystick control is undergoing validation - is the software fit for use and does it satisfy the system need, i.e. can the joystick be used for control of the cursor?	The complete implementation of the pointing device is undergoing validation - is the software fit for use and does it satisfy the system need, i.e. can the cursor move freely on the screen according to control?	The complete implementation of the sensory feedback is undergoing validation - is the software fit for use and does it satisfy the system need, i.e. can the vibrations mimic the cursors movements, acceptably?

System testing is performed on the entire system in the context of fulfilling the purpose of the system. It does not only test the design, but also the behaviour. It is also intended to test up to and beyond the bounds defined in the software/hardware requirements specification(s) - specified in Table 6.1. This complete system testing is specified as being the validation of the system.

6.1 Joystick Control

The joystick is implemented as a tool for control of a pointing device, hence the specifications for this compartment of the system follows a usable control mechanism with little to no delay in cursor movement versus joystick movement. Furthermore a correct control is disable, i.e. when the joystick is moving on

the horizontal channel, the cursor should move accordingly, likewise for the vertical channel and the obliquely.
The specifications proved to be fulfilled when using the joystick as control mechanism for the surrogate pointing device.

6.2 Pointing Device

The pointing device was fairly easy to specify. The cursor had to be visible on screen, hence given a size of 5x5 pixels and willing to be controlled by the joystick.
The software setup allowed for free and smooth control of the pointing device.

6.3 Sensory Feedback

The sensory feedback mechanism was implemented as vibro-tactile stimulations through vibrators placed on the skin. The purpose of implementing vibrators was to create a cognitive sensory feedback mechanism, hence the vibrators were to mimic the cursors movements, i.e. giving the user feedback about the cursor position at all times.
The tests showed that further specifications had to be made to the sensory feedback compartment of the system. One specification was that the placement of vibrators had to comply with a minimum distance of 4 centimetres between each vibrator. If not fulfilled the vibrations will influence each other and the skin receptors will not be given the correct information, hence the sensations will not mimic the cursors movements.
Testing the cognitive sensory feedback also means testing the individual vibrators. What are their intensities, i.e. at what frequency are they vibrating and how is this corresponding to the 55-255 digital bits being induced by the system?

- Power Consumption; maximum of 100mA; most efficient at 60mA
- Vibration Frequency; most efficient at 200Hz
- Vibration Amplitude; most efficient at 180g
- Current input; most efficient at 2,6V

Del III

Experiments

7.0 Experimental Design

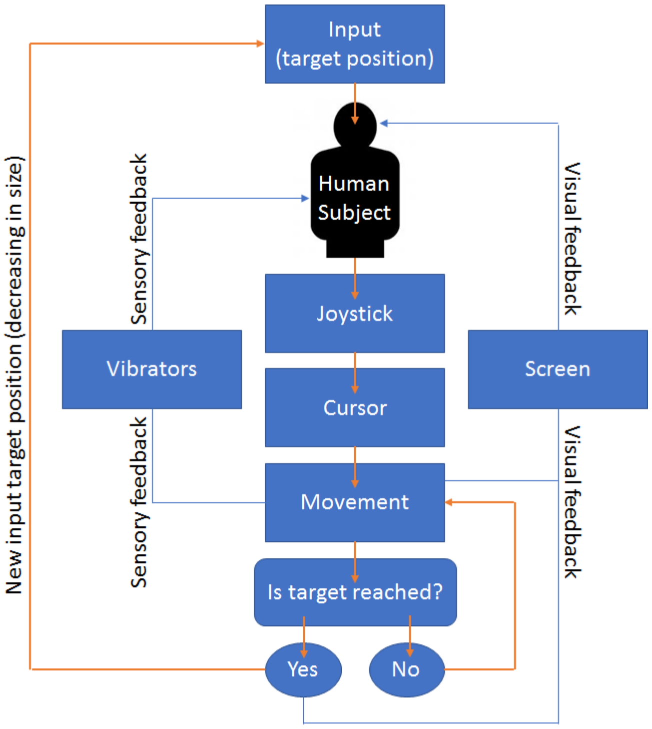
In the section of System Design chapter 5 page 19 the three compartment were designed and implemented. The joystick is controlling a cursor, moving and being visually presented on a screen, while every movement of the cursor is delivered as a output from the computer to the vibrators. The idea is essentially, that the vibrators will be attached to a subject, controlling the joystick and manoeuvring the cursor by feeling/sensing the movements being reflected onto the skin, where the vibrators will be attached.
Therefore, the three components will, in the following section, be combined in a system setup that will allow for conduction of experiments on a number of subjects with the goal of testing how applicable the use of this surrogate pointing device for cognitive sensory feedback is.

The purpose of an experiment is to test a hypothesis and draw a conclusion. When a scientist has a question about the world or a fact that they wish to prove, they do this by conducting experiments. The hypothesis, in case of this study, is that vibro-tactile stimulation can be used as cognitive sensory feedback. This will be tested through experiments, where subjects will control a surrogate pointing device by moving a joystick for target reaching and tracking purposes.

The idea of implementing targets has been widely used across all fields of engineering. Employing a new feedback mechanism equals identifying and implementing a learning process and measuring the performance. In doing that, setting targets and goals are the best way to ensure strategies for improvement.
In order to do so, a system setup has been created for the experiments.

7.1 System Setup

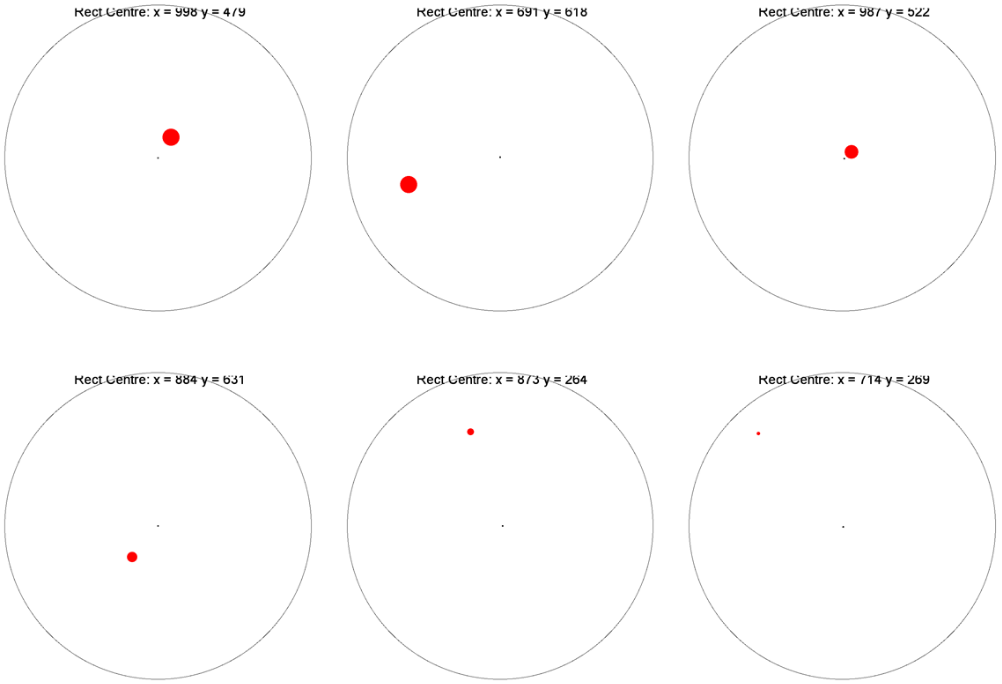
The joystick control, cursor movement and vibration feedback is connected through visual presentation of target reaching tasks. As illustrated in figure 7.1 the human subject is given an input information about target position (visual feedback). Based on this information the subject moves the joystick to control the cursor (5x5 pixels) illustrated on the screen. The cursors movements are reflected onto the skin of the subject via vibro-tactile stimulation.



Figur 7.1: A flow diagram of the system functions. The subject is essentially controlling everything from the point of which they are given an input information about the task at hand. From here the subject influences the joystick, which influences the cursor, giving an output of movement until the statement of; *Is taret reached?* is true. Then a new input is given and the loop repeates itself. If the statement is false, the cursor movements continue until this statement changes.

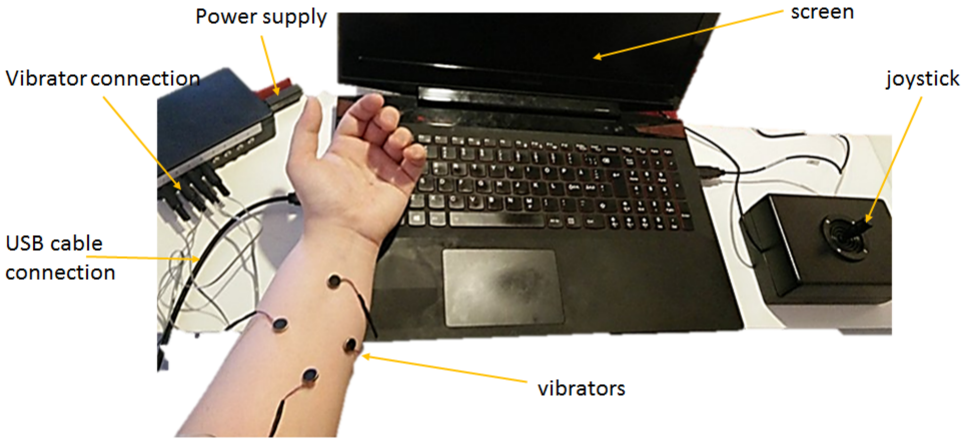
The task at hand is to detect and reach the round targets presented on the screen. Every time the subject points to the target, the cursor will be default relocate to the centre of the screen and a new target will immediately appear in a new random location. Moreover the size of the target will decrease from 50x50 pixels to 5x5 pixels. Six random targets will appear for every trial set.
The targets being presented on the screen is illustrated in Figure 7.2.

In order to document the learning curve of using this surrogate pointing device for cognetice sensory feedback, the cursor movements (x,y positions) are saved in a matrix along with the target location and size. Moreover the time in which it takes to reach each target is saved along with the total runtime for every trial set.



Figur 7.2: A representation of the 6 random targets which will appear throughout the experiments. 6 targets per trail set.

7.2 Experimental Setup



Figur 7.3: A picture of the experimental setup which was used on all 10 subjects. [Photo by author] The subject is seated on a chair with access to the control joystick and both visual and sensation feedback from respectively a computer screen and vibrators attatched to the skin of the subject.

The test subject is operantly trained to control a cursor on a screen in a two-dimensional workspace using a two channel controlable joystick. The subject is placed on a chair infront of a table with a joystick, a computer screen and a resting place for the arm of the subject. The subjects dominant arm is placed to control the joystick while the other arm (non-dominant) is placed on the resting place and have four vibrators connected onto the skin of the underarm.

The subject has direct visual access to the computer screen where the cursor is presented. Visual feedback is available via visual cursor projection onto the screen. The position of the cursor is controlled by the joystick, which is essentially controlled by the subject, i.e. coordinates of the visual cursor are determined by the joysick movements in response to the two channels (horizontal and vertical).

The experimental setup is illustrated in Figure 7.3.

7.3 Experimental Protocol

10 subjects will participate in the experiment which is based on target reaching tasks. Each of these tasks are projected visually onto a computer screen allowing for visual feedback to the subject connected to the system, described in detail in the section above.

The complete experiment contains five trials each with three to six trial sets. Every trial is build as a stepping stone to full system use. This meaning for every trial the difficulty increases - allowing for a stepwise increasing learning curve. The intension is to give the subject a steep learning curve from the beginning of each trial, hence for every trial the subject is given a new additional challenge, as the system opens up for more and more features to be taken into account for every trial.

- Trial 1: (1 trial set) Goal; to gain knowledge of the joystick control - learn to maneuver the joystick in order to move around the cursor for random target persuit tasks
- Trial 2: (3-6 trial sets) Goal; to gain knowledge of the vibro-tactile feedback mechanism - learn to sense the vibrations in response to the cursor movements
- Tiral 3: (3-6 trial sets) Goal; to gain knowledge of the vibro-tactile feedback mechanism - learn to sense the vibrations in response to the cursor movements, now with an additional change of cursor speed for every trial set
- Trial 4: (3-6 trial sets) Goal; to gain knowledge of the vibro-tactile feedback mechanism - learn to sense the vibrations in response to the cursor movements, now with partial visual cursor projection onto the screen
- Trial 5: (3-6 trial sets) Goal; to fully adapt/control the surrogate pointing device using cognetive sensory feedback - be able to maneuver the joystick sololy in response to the feedback given

7.3.1 Description of Trial 1

The first trial of the experiment has 1 trial set, i.e. 6 target reaching tasks before advancing to the second trial level.

The subject has full control of the joystick and thereby the cursor movements for the given target reaching tasks. Though the subject will have no sensation feedback at this level, i.e. the goal of this level is only gain knowledge about the joystick control. This by learning to maneuver the joystick for cursor control in response to the random target persuit tasks.

The cursor will move at a constant speed for this trial set, defined as 3 pixels per "press". This speed is considered as a medium from a set of 10 speeds. The targets will decrease in size every time a new taret is projected, going from 50x50 pixels to 5x5 pixels.

7.3.2 Description of Trial 2

The second trial fo the experiment has a range of 3-6 trial sets, i.e. 6 targets will appear in every trial set for the target reaching tasks before advancing to the third trial level.
As for the first trial level, the subject has full control of the joystick and thereby the cursor movements for the given target reaching tasks. Furthermore the subject will recieve sensation feedback through vibrations onto the skin of the non-dominant arm, i.e. the goal of this level is to gain knowledge of the vibro-tactile feedback mechanism. This by learning to sense the vibrations in response to the cursor movements (same goal as for trial 3 and 4).

As for the first trial level, the cursor will move at a constant speed for this trial set, defined as 3 pixels per "press". This speed is considered as a medium from a set of 10 speeds. And likewise will the targets decrease in size every time a new taret is projected, going from 50x50 pixels to 5x5 pixels.

7.3.3 Description of Trial 3

The third trial for the experiment has a range of 3-6 trial sets, i.e. 6 targets will appear in every trial set for the target reaching tasks before advancing to the fourth trial level.
This trial level is build as an upgrade of trial 2, meaning the subject still has full control of the joystick and thereby the cursor movements for the given target reaching tasks, along with recieving sensation feedback through vibrations onto the skin of the non-dominant arm, i.e. the goal of this level is to gain knowledge of the vibro-tactile feedback mechanism. This by learning to sense the vibrations in response to the cursor movements (same goal as for trial 2 and 4).

As for the previous trial levels, the targets decrease in size every time a new taret is projected, going from 50x50 pixels to 5x5 pixels. However on this level there will be a random change in cursor speed. The speed will be constant within every trial set (a total of 3-6 trial sets) but vary with each new trial set from a total set of 10 different speeds. The random cursor speed is calculated from Equation 7.1.

$$speed = \frac{\sqrt{(squareX^2 - 960) - (squareY^2 - 540)}}{2000} \tag{7.1}$$

7.3.4 Description of Trial 4

The fourth trial for the experiment has a range of 3-6 trial sets, i.e. 6 targets will appear in every trial set for the target reaching tasks before advancing to the fifth trial level.
This trial level is build as an upgrade of trial 3, meaning the subject still has full control of the joystick and thereby the cursor movements for the given target reaching tasks, along with recieving sensation feedback through vibrations onto the skin of the non-dominant arm, i.e. the goal of this level is to gain knowledge of the vibro-tactile feedback mechanism. This by learning to sense the vibrations in response to the cursor movements (same goal as for trial 2 and 3).

As for the previous trial levels, the targets decrease in size every time a new taret is projected, going from 50x50 pixels to 5x5 pixels. Building on the previous trial, the cursor speed on this level will still be changed randomly with every new trial set, though constant within every trial, calculated from Equation7.1.

7.3.5 Description of Trial 5

The fifth and final trial for the experiment has a range of 3-6 trial sets, i.e. 6 targets will appear in every trial set for the target reaching tasks before the experiment is completed.

This is the final trial where all features are activated. Hence the subject still has full control of the joystick and thereby the cursor movements for the given target reaching tasks, along with recieving sensation feedback through vibrations onto the skin of the non-dominant arm.

As for the previous trial levels, the targets decrease in size every time a new taret is projected, going from 50x50 pixels to 5x5 pixels. Building on the previous trial, the cursor speed on this level will still be changed randomly with every new trial set, though constant within every trial, calculated from Equation7.1.
The last and most special feature for the system is added in this last trial; an invisible cursor. I.e. the will no longer be visible on the screen. The goal of this trial is thereby for the subject to fully adapt/control the surrogate pointing device using the build in cognetive sensory feedback. By this the subject must be able to maneuver the joystick sololy in response to the sensory feedback delivered as non-invasive vibro-tactile stimulation.

8.0 Presentation of Results

The experiments were based on adaptation of a new sensory feedback type, i.e. learning to sense/percieve a cursors position via non-invasive vibro-tactile sensory feedback. The results of the experiments are presented in two ways in response to the evaluation of performance and learning curve from the system.

The experiments run in five trials each with 3-6 trial sets as presented in the experimental protocol in the section above. 6 trial sets are presented from Trial 4 and 5 in the tables below 8.1 8.2.
These results are taken from subject 3 and have been selected due to the fact that the results of subject 3 is closest to the average calculated across all 10 subjects. An example of a full table result presentation for subject 3 is available in the Appendix 10.1.

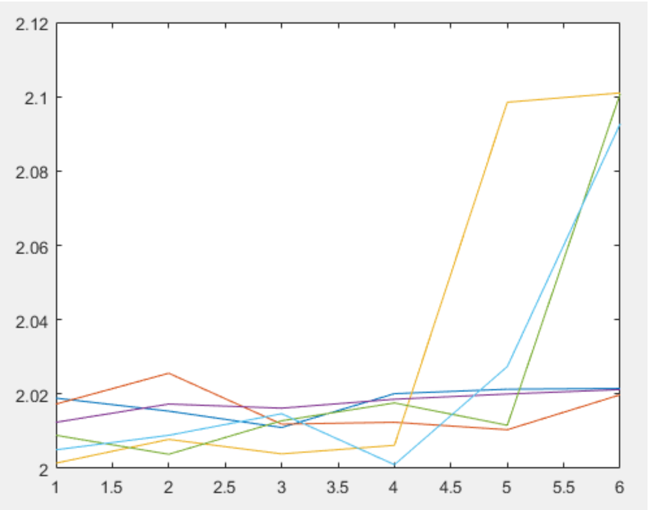
Tabel 8.1: Experimental results from subject 3 of Trial 4. The table illustrates the target placement and time used to reach each target for all 6 trial sets.

Subject 3	**Trial 4**						
	Number	**Size(pixels)**	**Placement (x,y)**	**Time (sec)**		**Placement (x,y)**	**Time (sec)**
Trial set 1/6	1	50x50	837,322	2,0189	**Trial set 2/6**	765,383	2,0173
	2	40x40	927,292	2,0154		907,784	2,0256
	3	30x30	845,318	2,0110		746,296	2,0119
	4	20x20	837,322	2,0201		717,471	2,0124
	5	10x10	916,786	2,0213		1156,733	2,0104
	6	5x5	803,734	2,0215		1114,695	2,0198
Trial set 3/6	1	50x50	824,750	2,0014	**Trial set 4/6**	969,790	2,0124
	2	40x40	1159,389	2,0078		1188,438	2,0173
	3	30x30	894,781	2,0039		1042,776	2,0162
	4	20x20	820,333	2,0062		1198,463	2,0186
	5	10x10	723,619	2,0985		1183,428	2,0200
	6	5,x	1207,581	2,1010		1177,416	2,0212
Trial set 5/6	1	50x50	1047,774	2,0089	**Trial set 6/6**	900,392	2,0050
	2	40x40	830,327	2,0038		846,511	2,0089
	3	30x30	940,291	2,0128		878,392	2,0147
	4	20x20	1116,344	2,0176		1019,725	2,0010
	5	10x10	1038,303	2,0116		1173,736	2,0274
	6	5x5	875,427	2,1008		1145,294	2,0927

Tabel 8.2: Experimental results from subject 3 of Trial 5. The table illustrates the target placement and time used to reach each target for all 6 trial sets. NAN is used as a indicator whenever the subject took more than 6 minutes to complete a target.

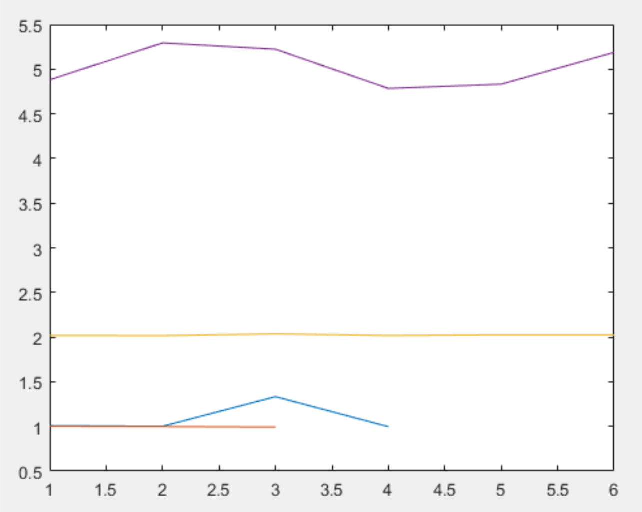
Subject 3	**Trial 5**						
	Number	**Size(pixels)**	**Placement (x,y)**	**Time (sec)**		**Placement (x,y)**	**Time (sec)**
Trial set 1/6	1	50x50	1052,483	5,0326	**Trial set 2/6**	765,383	5,8700
	2	40x40	1198,780	4,7300		907,784	5,0078
	3	30x30	876,296	nan		746,296	5,0039
	4	20x20	837,322	nan		717,471	nan
	5	10x10	916,786	nan		1156,733	nan
	6	5x5	917,193	nan		1114,695	nan
Trial set 3/6	1	50x50	756,338	5,0124	**Trial set 4/6**	1025,709	5,0098
	2	40x40	970,748	4,0201		1189,438	4,0050
	3	30x30	764,269	5,9186		867,322	5,0176
	4	20x20	771,417	5,9412		873,269	4,0998
	5	10x10	1165,733	nan		961,139	nan
	6	5,x	1141,659	nan		1171,768	nan
Trial set 5/6	1	50x50	916,512	5,0139	**Trial set 6/6**	765,649	5,6721
	2	40x40	846,392	4,0733		891,237	4,2509
	3	30x30	819,725	4,0756		876,932	5,0087
	4	20x20	1019,294	5,0988		1091,572	5,0184
	5	10x10	854,725	5,8992		935,673	5,9903
	6	5x5	953,178	nan		918,293	nan

To illustrate if there is a difference in the time used for the subject throughout the whole trial and the individual trial sets, the 6 trial sets for Trial 4 are plottet against eachother, as illustrated in Figure 8.1.



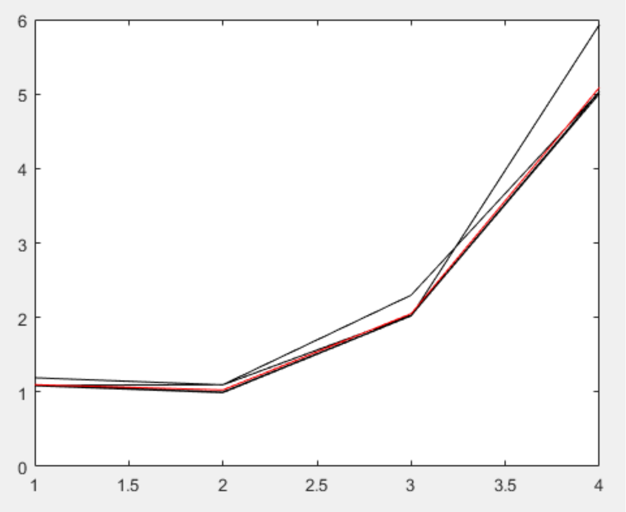
Figur 8.1: MATLAB plot illustration of subject 3 in Trial 4 of the target reaching tasks.

The results of Trial 2 and 3 are presented in the Appendix 10.1, where Trial 1 has been excluded because this was a training level and results from this trial were undocumented. The results from 8.1 indicates an increasement in the time used to reach the targets in response to the target decreasing in size.
To get a clear indication of the learning development through Trial 2-5 the results (subject 3) from the four trials are plottet together in Figure 8.2.



Figur 8.2: MATLAB plot illustration of Trial 2-5 for subject 3 of the target reaching tasks. The purple line is Trial 5, the yellow line is Trial 4, the red line is Trial 3, and the blue line is illustrating Trial 2.

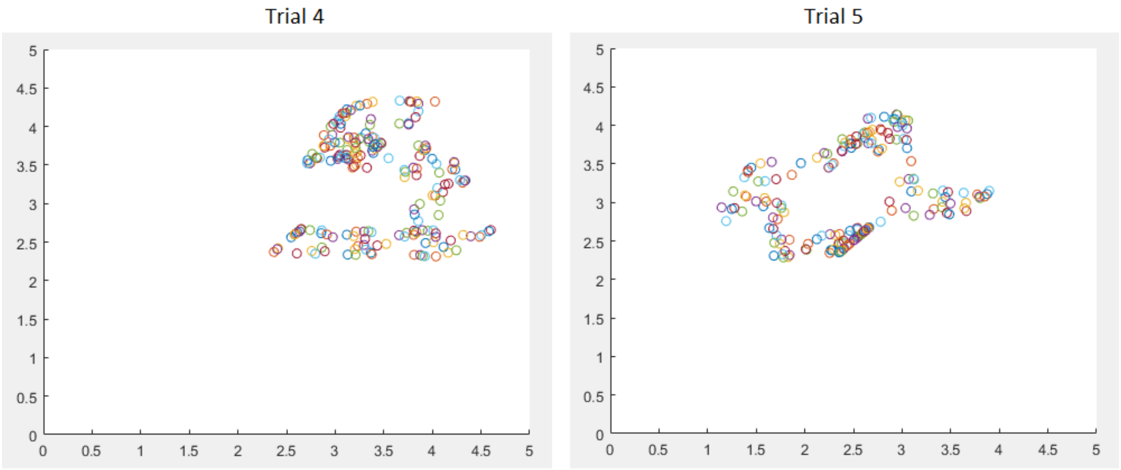
Figure 8.2 indicates that the average time used in trials 2 and 3 are approximetly the same, whereas Trial 4 and 5 have higher time values, though still somewhat stable.
However to get a better indication of the learning curve produced by all 10 subjects, the average results for each trial is plottet for every subject in Figure 8.3. The results here indicates an increasement in the time used to complete the target reaching task when targets decrease in size.



Figur 8.3: MATLAB illustration of all 10 subjects plottet from a average across trials 2-5.

Results from the 10 subjects are plottet from Trial 2-5 by calculating the average time used per trial set per subject. Each subject is illustrated with a black line, created from the average of each subjects trial sets, i.e. the four punkts are made from 3-6 average calculations, responding to the number of trial sets per trial. The red line indicates the overall average, hence the average time calculated across all 10 subjects.

Figure 8.4 is an illustration of the cursor movement from Trial 4 and 5 based on the x,y cursor positions saved through the trials. The plots are based on an average of the combined cursor movements from subject 3. This to get an indication of how accurate the cursor movements are in response to the centre-out task.



Figur 8.4: MATLAB illustration of all 10 subjects plottet from a average across trials 2-5.

8.1 Performance Evaluation

A performance evaluation is essential to look into how easily adabtable the system is and how well the test subjects can performe under a number of predetermined conditions.
The performance evaluation conducted in this study is based on the mathmathics of Fitts' law for evaluation of performence within target tracking tasks.

8.1.1 Fitts' law

Fitts' law is a one-dimensional speed-accuracy model of human movement, though the model is often applied to two-dimensional target acquisition tasks, like for the system at hand. [17]
The law states that the time, MT, it take to move and select a target of a defined width, W, placed at a distance, A, is as shown in 8.1:

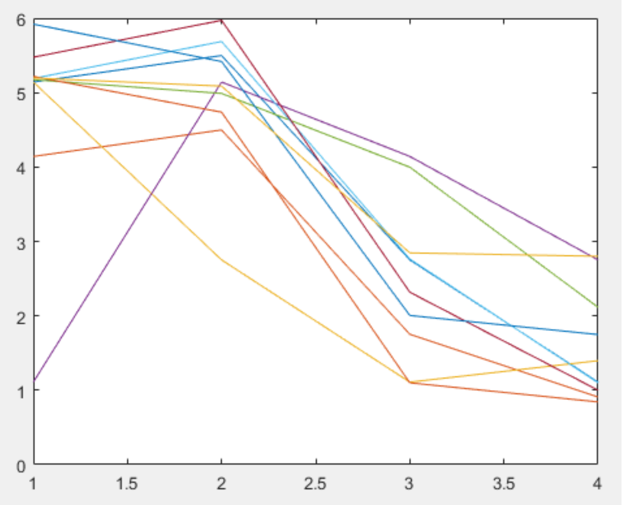
$$MT = (a+b)log_2(\frac{2A}{W}) \tag{8.1}$$

where a and b are constants defined through linear regression. W indicates the accuracy in which the target is reached. The log-term indicates the index of difficulty, ID and is measured in bits, and with MT measured in seconds that makes the unit for a to be in seconds and for b to be in seconds/bit. The reciprocal of b is the index of the performance, IP, measured in bits/seconds, which is the human rate of information processing for the movement task. [18].
Evaluation of performance in point detection is complex, since there is a difference between the classes of devices as well as within each class. The most used evaluation methods are speed and accuracy. Speed, as illustrated above in 8.1 is usually measured in movement over time. Accuracy is usually measured as an error-rate. The study by I.S. MacKenzie et al., 1992 [19] have extended Fitts' law to fit two-dimensional

tasks and use the ISO 9241-9 standard to assist in evaluating pointing devices. [19,20] The target selection tasks are evaluated by 'throughput' (THP) measured in bits per seconds (bps) illustrated in 8.2:

$$Throughput = \frac{ID}{MT} \quad where \quad ID = log_2(\frac{A}{W_e} + 1) \tag{8.2}$$

A study by E.R. Lontis et al., 2009 [20] evaluated the THP along with the tracking task, which was measured by the time on target, defined as the ratio between the time from the pointer was inside the target and the total time required to move to the target.



Figur 8.5: MATLAB plot of the performance evaluation of all 10 subjects. Based on the mathmatics of Fitts' law 8.2.

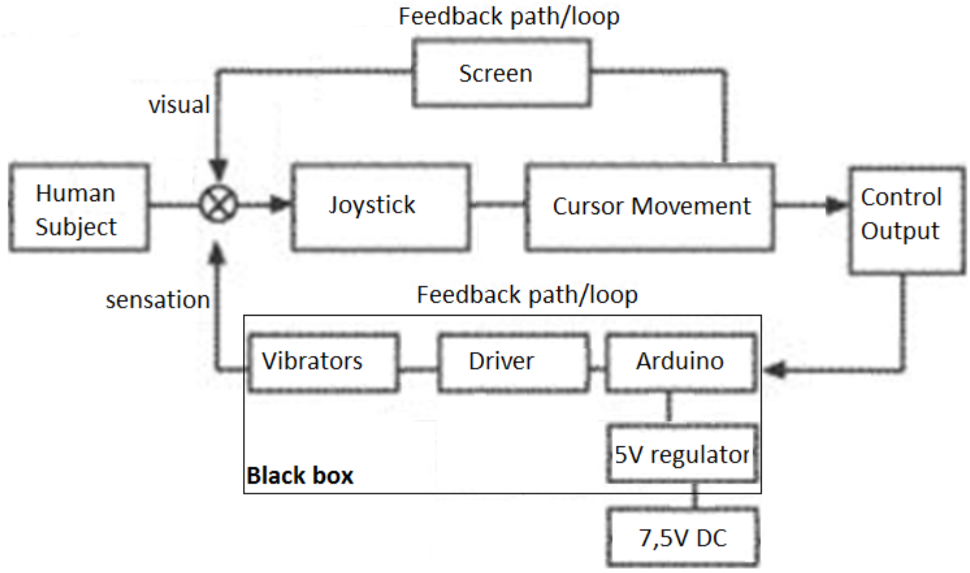
The current study is looking into target reaching tasks, as opposed to target tracking tasks which is taken into account when calculating the *throughput*, MT and ID. The throughput is also refered to as the index of performance, IP, which is calculated from Equation 8.2. It is essentially performance evaluated from the index of difficulty, ID, and movement time, MT. The movement time has already been given by the the results of the experiment, these time calculations are inspired from Equation 8.1. The width of the target is easily given by the experiment, and the distance to the target has been calculated via the target placement notations. With the assumption made; 1 pixel equals 1mm. This gives an average calculated across all each of the four trials for all 10 subjects as illustrated in Figure 8.5.

9.0 Discussion

One of the challenges within the field of prosthetics is to restore the missing sensory function that comes with an amputation. Throughout the years several techniques have been designed and tested to provide amputees with sensory feedback as a replacement for the lost function. This study seeks to design a surrogate pointing device for cognitive sensory feedback for a simple two-dimensional movement.

9.1 System

The system consisted of three compartments; the control, the surrogate pointing device and the cognetive feedback mechanism. These were combined through target reaching tasks, presented visually on a screen. The full system setup is illustrated in Figure 9.1.



Figur 9.1: Illustration of the functional block diagram for the cognitive sensory feedback. The black box showes the vibrator connection.

A screen cursor was adapted as pointing device in target reaching tasks in response to the centre-out task being controlled by a human subject through an analog joystick. The sensory feedback was implemented as non-invasive vibro-tactile sensations projected onto the skin of the subject, i.e. imitating the cursors movement on the screen. The following section will look into improvements to be added in each of the compartments, starting with the control.

9.1.1 Joystick Control

The control mechanism was implemented as a an analog joystick. Other options could be to use a computer mouse, keyboard, or trackball etc. The joystick was chosen because it allowed for a free horizontal, vertical and rotational control. Moreover the joystick was easily manipulated in a way so the pressure applied to the joystick did not affect the speed of the movement. This speed was solely dependent on the configurations of the code.

9.1.2 Surrogate Pointing Device

The surrogate pointing device was implemented as a digital cursor presented on a screen. In doing so, it allowed for complete control, whereas an analog pointing device (such as a prosthetic) would constantly give a visual feedback to the subject. However the movement feedback might have been more lifelike and more smoothly adaptable.

9.1.3 Cognetice Sensory Feedback

The cognetive sensory feedback was implemented as non-invasive vibro-tactile sensations through vibrators placed on the underarm of the subjects. The system setup allowed for 8 connected vibrators, however only 4 vibrators were connected. This because initial tests gave a clear indication of the minimum distance between the vibrators. Were two or more vibrators active at the same time with intensities greather than 90, then a minimum of 4 centimeters was necessary. If placed closer, it proved impossible to detect which of the vibrators were actually vibrating, hence the orientation value would be lost. Using all 8 avaliable vibrators would thereby mean that the size of the subject underarm had to be taken into consideration for vibrator placement.

A way around this could be to implement a different tactile feedback mechanism. Options could be mechano- and/or electrical stimulateion as sensory feedback. However implementing non-invasive electrical stimulation as feedback for the system at hand would be more or less impossible. The beauty of vibro-tactile stimulations is its abuility activate great receptors in the human skin. Furthermore vibrations are easily manipulated to create a moving sensation just by a change in intensity, whereas electrical stimulation, to create the same sensation, would have to stimulate from one electrode to another. And mechano-tactile stimulation on its own would leave to little of an impression, however in combination with either vibration or electrical stimulation, it could mean reaching receptors deeper within the skin tissue for a more clear sensation.

9.2 Results

The experiments were conducted in five trials, where the results of Trial 4 and 5 are of interest. Here the subject had to solely rely on the vibration feedback as orientation of the cursor movements.

The experiment was structured in a way to slowly progress the learning curve of using vibro-tactile sensory feedback as guidelines for detecting the cursor movement. The experiments gave an overview of the time used for every trial as well as the time and accuracy within reaching each target.

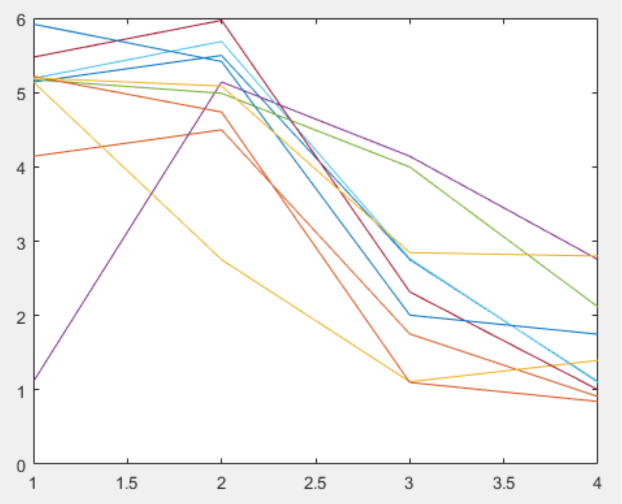
The ideas is that each trial would get harder and harder, hence have a lower accuracy rate and possibly take longer an possibly be less efficient. This along with an induced difficulty within each level with the targets getting smaller requiring for higher accuracy. With that follows the hypothesise that with higher accuracy comes longer trials, hence the movements have to be smaller and controlled in detail when reaching targets with small diameters, as compared to reaching targets of larger diameters.

The results showed a steep learning curve when the visual feedback was taken away. Moreover, in Trial 5 where the subjects had no visual feedback of the surrogate pointing device and had to solely rely on the

vibro-tactile feedback for orientation, the target detection and reaching tasks proved almost impossible for the smaller targets (target<10x10). None of the 10 subjects managed to reach target 6 which was the smalles target with its 5x5 pixels.
This lead to implementation of a new condition in the experiments, saying if the subjects took longer than 6 seconds to reach a target, this target was considered unsuccessful (marked in the table as nan - for not a number). Results further showed that a combination of visual and sensation feedback proved effective in the target reaching tasks and could even increase the efficacy by almost 3 second.

9.3 Performance Evaluation

The index of performance was calculated from MT, the time in which it took to reach each of the individual targets, and ID, the index of difficulty - calculated for the six different target widths and the mean distances to each of these targets. The calculations were made for all 10 subjects and is presented in Figure 9.2.



Figur 9.2: MATLAB plot of the performance evaluation of all 10 subjects. Based on the mathmatics of Fitts' law 8.2.

As the results show, each of the 10 subjects performed equally in the different trials. This means that regardless of the person using the system, the performance level will be more or less the same, i.e. the experimeltal design has succeeded - resulting in an equal learning curve for all subjects.
Now looking at the values, it is indicated that the subjects performed better in Trial 4 and 5 than for Trial 2 and 3 which is not the case. However the means for the two trials in question have been calculated based on fewer inputs, simply due to the fact that the subjects did not succeed in reaching all targets. Looking at the values will thereby give a false representation of their individual performance.

10.0 Conclusion

The aim of the study was to implement and evaluate a surrogate pointing device for cognitive sensory feedback, using vibro-tactile sensations and the basic setup of the centre-out task. Looking at the 10 subjects combined and overall performance, the results indicate that the system can infact be applied as a cognetive sensory feedback mechanism for controlling a surrogate pointing device, though it is reccomended to use the feedback system in combination of visual feedback.
What does this mean for the future of prosthetic devices? Having a fake sensory feedback mechanism to be implemented as orientation of the prosthetic device movements gives almost endless possibilities. The feedback can be implemented as a way of learning to control the new mechanical part of the body, or as an indicator of the pressure applied for grib force. In theory fake stimulations can be given as an indication of warning, i.e. is the prosthetic doing something inwhich the amputee should feel pain if done by a human limb?

Del IV

Appendix

```
%forces the toolbox to continue despite error in screens
Screen('Preference', 'SkipSyncTests', 1);

% Clear the workspace and the screen
sca;
close all;
clearvars;

%Here we call some default settings for setting up Psychtoolbox
PsychDefaultSetup(2);
% Get the screen numbers
screens = Screen('Screens');
% Draw to the external screen if avaliable
screenNumber = max(screens);
% Define black and white
white = WhiteIndex(screenNumber);
black = BlackIndex(screenNumber);
% Open an on screen window
[window, windowRect] = PsychImaging('OpenWindow', screenNumber, white);
% Get the size of the on screen window
[screenXpixels, screenYpixels] = Screen('WindowSize', window);
% Query the frame duration
ifi = Screen('GetFlipInterval', window);

%The avaliable keys to press
escapeKey = KbName('ESCAPE');
%Loading the joystick channels

%initialize the DAQ-card
s = daq.createSession('ni');
addAnalogInputChannel(s,'Dev1', 0, 'Voltage');
addAnalogInputChannel(s,'Dev1', 1, 'Voltage');

%Loading the vibrators
%initialize the serial port
if exist('ser')
    fclose(ser);
    clear(ser)
end
ser = serial('COM3');
ser.BaudRate = 115200;
ser.Terminator = 13;
fopen(ser);

%Get the centre coordinate of the window
[xCenter, yCenter] = RectCenter(windowRect);

%Definition of the cursor
baseRect1 = [0 0 5 5];
% Set the intial position of the square to be in the centre of the screen
squareX = xCenter;
squareY = yCenter;
%Definition of the speed - depending on the velocity
speed = randi(10,1,1) * (sqrt((squareX^2-960) - (squareY^2-540))/2000);
pixelsPerPress = speed;

%Definition of the circle
% Make a base Rect defined pixels
baseRect3 = [0 0 900 900];
baseRect = [0 0 898 898];
```

```
% Define colors
red = [1 0 0];
blue = [0 0 1];
green = [0 1 0];

%Defining the target (dot)
% The color of the target
dotColor = white;
rectColor = red; %defined as red=[1 0 0];
angle = round(rand(1)*360); % The angle in which the target appear
% The outer circle that the target can appear in
radius = 250;
Xpos = 960+radius*sin(angle);
Ypos = 540+radius*cos(angle);
% The coordinates for the dot
dotXpos = Xpos;
dotYpos = Ypos;
dotSizePix = 5; % Size of the dot
%baseRect4 = [0 0 50 50];
trial=5;    %for wanting 6 targets in one runtime
k=trial*10;
baseRect4 = [0 0 k k];
% Set the intial position of the target to be in the centre of the dot
targetX = dotXpos;
targetY = dotYpos;

%Sync us and get a time stamp
vbl = Screen('Flip', window);
waitframes = 1;

%Maximum priority level
topPriorityLevel = MaxPriority(window);
Priority(topPriorityLevel);

%This is the cue which determines whether we exit the demo
exitDemo = false;

intervaltime = nan;
iTime=1;
%cursorPos = cell(100,6);
n = 1;
stopToc = 0;
cursorPosTimeTic = tic;

%Loop the animation until the escape key is pressed
while exitDemo == false
    % Check the keyboard to see if a button has been pressed
    [keyIsDown,secs, keyCode] = KbCheck;

    %      cursorPosTimeTic = tic;
    %      tElapsed = toc(cursorPosTimeTic);
    %         if tElapsed > 0.1
    %             cursorPos(n,iTime) = {centeredRect1(2:3)};
    %             n = n+1;
    %             cursorPosTimeTic = tic;
    %         end

    % Depending on the button press exit the demo
    if keyCode(escapeKey)
```

```
        exitDemo = true;
    end

    % JoystickControl
    % Setup datascan for joystick
    data=s.inputSingleScan;
    ch1=data(1);
    ch2=data(2);
    if ch2 > 3
        squareX = squareX + pixelsPerPress; %right
    elseif ch2 < 2
        squareX = squareX - pixelsPerPress; %left
    elseif ch1 > 3
        squareY = squareY - pixelsPerPress; %up
    elseif ch1 < 2
        squareY = squareY + pixelsPerPress; %down
    end
    if ch1 > 3 && ch2 < 2
        squareY = squareY - pixelsPerPress;
        squareX = squareX - pixelsPerPress;
    elseif ch1 > 3 && ch2 > 3
        squareY = squareY - pixelsPerPress;
        squareX = squareX + pixelsPerPress;
    elseif ch1 < 2 && ch2 < 2
        squareY = squareY + pixelsPerPress;
        squareX = squareX - pixelsPerPress;
    elseif ch1 < 2 && ch2 > 3
        squareY = squareY + pixelsPerPress;
        squareX = squareX + pixelsPerPress;
    end

    % Center the cursor on the centre of the screen
    centeredRect1 = CenterRectOnPointd(baseRect1, squareX, squareY);
    % Center the circles on the centre of the screen
    centeredRect3 = CenterRectOnPointd(baseRect3, xCenter,yCenter);
    centeredRect = CenterRectOnPointd(baseRect, xCenter, yCenter);
    % Center the target on the center of the dot
    centeredRect4 = CenterRectOnPointd(baseRect4, targetX, targetY);

    % Cursor detection for vibration - the vibrations must mimmic the cursor movements
    % Calculating the %-intensity of x and y
    intX = abs(((squareX-960)/450)*100); %abs is taking the aboslute value
    intY = abs(((squareY-540)/450)*100);
    %vib0 = ();

    %Making sure that every percentage 0-100 is taken into account
%     while intX<101 && intY<101
%         if keyCode(escapeKey)
%             exitDemo = true;
%             break
%         end
        %vibrators 1-4 are given intensity X or Y in response to their axes
        %and added by 55 because that is the off set
        %multiplied by 2 because that is the interval of bits

        if (intX > 101)
            intX = 0;
        end
        if (intY > 101)
            intY = 0;
```

```
        end

        vib2 = intX*2+55;
        vib4 = intX*2+55;
        vib1 = intY*2+55;
        vib3 = intY*2+55;
        %vib0 = vib0*2+55;
%     end
    str = [];
    % Get the centered position of the cursor
    [squareX, squareY] = RectCenter(centeredRect1);
    if squareX>510 && squareX<960 && squareY>91 && squareY<540
        str = ['$' num2str(vib1,'%03d') ',' num2str(000,'%03d') ','...
            num2str(000,'%03d') ',' num2str(vib4,'%03d')];
    elseif squareX>510 && squareX<960 && squareY>540 && squareY<991
        str = ['$' num2str(000,'%03d') ',' num2str(000,'%03d') ','...
            num2str(vib3,'%03d') ',' num2str(vib4,'%03d')];
    elseif squareX>960 && squareX<1410 && squareY>91 && squareY<540
        str = ['$' num2str(000,'%03d') ',' num2str(vib2,'%03d') ','...
            num2str(vib3,'%03d') ',' num2str(000,'%03d')];
    elseif squareX>960 && squareX<1410 && squareY>540 && squareY<991
        str = ['$' num2str(vib1,'%03d') ',' num2str(vib2,'%03d') ','...
            num2str(000,'%03d') ',' num2str(000,'%03d')];
    end

    fprintf(ser,str);

    % Get notification when target is reached
    %Find the centered position of the target (rect)
    [targetX, targetY] = RectCenter(centeredRect4);
    %See if cursor is inside the target (rect)
    inside = IsInRect(squareX, squareY, centeredRect4);
    %If the cursor is inside the target...

    tic;
    if inside == 1 %true
        rectColor = green;              %was succesful
        k=trial*10;                     %k indicates pixels of the target
        baseRect4 = [0 0 k k];          %setup for the target
        trial=trial-1;                  %trials=5 giving us 6 targets
        angle = round(rand(1)*360);     %defining the angle inwhich the target will appear
        radius = 250;                   %constant radius (of the total circle)
        Xpos = 960+radius*sin(angle);   %defining the targets random x position
        Ypos = 540+radius*cos(angle);   %defining the targets random y position
        targetX = Xpos;
        targetY = Ypos;
        Screen('DrawDots', window, [dotXpos dotYpos], dotSizePix, dotColor, [], 2); %drawing
the target to the screen
        Screen('FillOval', window, rectColor, centeredRect4);   %filling the drawing (the
target)
        %center the cursor to the centre position of circle
        squareX = xCenter;
        squareY = yCenter;
        fprintf(ser,'$000,000,000,000');
        pause(1);

        if iTime < 7
            intervaltime(iTime)=toc;    %the time for each sucess
            iTime=iTime+1;
        else
```

```
            stopToc = 1;
            %                  break
        end

    elseif inside == 0 %not true
        rectColor = red;    %waiting for succes
    end

    % Draw the circles to the screen
    Screen('FillOval', window, black, centeredRect3);
    Screen('FillOval', window, white, centeredRect);

    % Draw the cursor to the screen
    Screen('FillOval', window, black, centeredRect1);
    % Draw the target (dot) to the screen
    Screen('DrawDots', window, [dotXpos dotYpos], dotSizePix, dotColor, [], 2);
    Screen('FillOval', window, rectColor, centeredRect4);

    % Show the target position on the screen
    line1 = ['\n Rect Centre: x = ' num2str(targetX) ' y = ' num2str(targetY)];
    DrawFormattedText(window, line1, 'center', 100, black);
    %line2 = ['\n Cursor position: x = ' num2str(squareX), ' y = ' num2str(squareY)];
    %DrawFormattedText(window, [line1 line2], 'center', 100, black);

    % Flip to the screen
    vbl  = Screen('Flip', window, vbl + (waitframes - 0.5) * ifi);

end
% Clear the screen

%clean up
release(s);
fprintf(ser,'$000,000,000,000');
pause(1)
fclose(ser);
delete(ser);
clear ser;

sca;
```

Tabel 10.1: Results from Trial 2, subject 3

Subject 3	**Trial 2**						
	Number	**Size(pixels)**	**Placement (x,y)**	**Time (sec)**		**Placement (x,y)**	**Time (sec)**
Trial set 1/6	1	50x50	890,300	1,0121	**Trial set 2/6**	1153,382	1,0031
	2	40x40	824,750	1,0098		824,750	1,0025
	3	30x30	760,690	1,0100		867,308	1,0062
	4	20x20	746,669	1,0097		1065,767	1,0008
	5	10x10	1128,726	1,0032		722,465	1,0003
	6	5x5	1193,630	1,0009		997,293	0,9989
Trial set 3/6	1	50x50	1038,302	1,0023	**Trial set 4/6**	720,471	0,9997
	2	40x40	755,398	1,0008		853,314	0,9924
	3	30x30	1051,307	1,0004		1119,733	0.9973
	4	20x20	867,308	1,9978		717,600	0.9962
	5	10x10	775,708	1,9985		1156,695	0,9978
	6	5,x	1073,317	1,0013		1065,313	0,9994

Tabel 10.2: Results from Trial 3, subject 3

Subject 3	**Trial 3**						
	Number	**Size(pixels)**	**Placement (x,y)**	**Time (sec)**		**Placement (x,y)**	**Time (sec)**
Trial set 1/6	1	50x50	721,314	0,9990	**Trial set 2/6**	724,624	0,9994
	2	40x40	867,471	1,0017		849,764	0,9986
	3	30x30	1111,689	1,0010		931,292	0,9891
	4	20x20	893,601	1,0001		746,411	1,0019
	5	10x10	1133,697	1,0013		978,789	1,0024
	6	5x5	1042,319	1,0015		1015,296	1,0004
Trial set 3/6	1	50x50	1202,470	0,9913			
	2	40x40	710,550	0,9990			
	3	30x30	949,790	0,9886			
	4	20x20	867,308	0,9937			
	5	10x10	1114,347	0,9930			
	6	5,x	755,679	0,9916			

Tabel 10.3: Results from Trial 4, subject 3

Subject 3	**Trial 4**						
	Number	**Size(pixels)**	**Placement (x,y)**	**Time (sec)**		**Placement (x,y)**	**Time (sec)**
Trial set 1/6	1	50x50	837,322	2,0189	**Trial set 2/6**	765,383	2,0173
	2	40x40	927,292	2,0154		907,784	2,0256
	3	30x30	845,318	2,0110		746,296	2,0119
	4	20x20	837,322	2,0201		717,471	2,0124
	5	10x10	916,786	2,0213		1156,733	2,0104
	6	5x5	803,734	2,0215		1114,695	2,0198
Trial set 3/6	1	50x50	824,750	2,0014	**Trial set 4/6**	969,790	2,0124
	2	40x40	1159,389	2,0078		1188,438	2,0173
	3	30x30	894,781	2,0039		1042,776	2,0162
	4	20x20	820,333	2,0062		1198,463	2,0186
	5	10x10	723,619	2,0985		1183,428	2,0200
	6	5,x	1207,581	2,1010		1177,416	2,0212
Trial set 5/6	1	50x50	1047,774	2,0089	**Trial set 6/6**	900,392	2,0050
	2	40x40	830,327	2,0038		846,511	2,0089
	3	30x30	940,291	2,0128		878,392	2,0147
	4	20x20	1116,344	2,0176		1019,725	2,0010
	5	10x10	1038,303	2,0116		1173,736	2,0274
	6	5x5	875,427	2,1008		1145,294	2,0927

Tabel 10.4: Results from Trial 5, subject 3. NAN is used as a indicator whenever the subject took more than 6 minutes to complete a target.

Subject 3	**Trial 5**						
	Number	**Size(pixels)**	**Placement (x,y)**	**Time (sec)**		**Placement (x,y)**	**Time (sec)**
Trial set 1/6	1	50x50	1052,483	5,0326	**Trial set 2/6**	765,383	5,8700
	2	40x40	1198,780	4,7300		907,784	5,0078
	3	30x30	876,296	nan		746,296	5,0039
	4	20x20	837,322	nan		717,471	nan
	5	10x10	916,786	nan		1156,733	nan
	6	5x5	917,193	nan		1114,695	nan
Trial set 3/6	1	50x50	756,338	5,0124	**Trial set 4/6**	1025,709	5,0098
	2	40x40	970,748	4,0201		1189,438	4,0050
	3	30x30	764,269	5,9186		867,322	5,0176
	4	20x20	771,417	5,9412		873,269	4,0998
	5	10x10	1165,733	nan		961,139	nan
	6	5,x	1141,659	nan		1171,768	nan
Trial set 5/6	1	50x50	916,512	5,0139	**Trial set 6/6**	765,649	5,6721
	2	40x40	846,392	4,0733		891,237	4,2509
	3	30x30	819,725	4,0756		876,932	5,0087
	4	20x20	1019,294	5,0988		1091,572	5,0184
	5	10x10	854,725	5,8992		935,673	5,9903
	6	5x5	953,178	nan		918,293	nan

Litteratur

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