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Exoskeleton arm

How to construct a smart support structure for an arm

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KTH Industrial Engineering and Management	**Bachelor Thesis MMKB 2016:40 MDAB101** **Exoskeleton arm** Christoffer Bator Rickard Svensson	
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Abstract

The purpose of this thesis was to find an optimal way to construct and control a product that could help those who suffer from muscle weakness or a muscle sickness. The device was made out of two major parts (upper arm and lower arm) which were connected through a motorized joint.

The focus was on finding a satisfying construction that could handle the forces and with the help of sensors measure movement of the users arm relative to the construction and then control it using that information.

The device needed to be fast and reliable and react to small movements to be as comfortable for the user as possible.

The result was a construction controlled by measuring the forces from the user's movement with the use of force sensors placed at the wrist. The construction managed to follow the users' arm, fast and in a satisfactory way.

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KTH Industriell teknik
och management

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Exoskelettsarm

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Sammanfattning

Tanken med detta arbete var att hitta ett optimalt sätt att konstruera en produkt som skulle hjälpa de som lider av muskel -svaghet och -sjukdom. Produkten skulle bestå av två större delar (överarmen och underarmen) som var sammanlänkade med en motoriserad led.

Fokusen låg på att hitta en tillfredställande konstruktion som kunde hantera krafterna och med hjälp av sensorer kunna mäta avståndet och rörelsen på användarens arm och förflytta konstruktionen utifrån det.

Produkten behövde vara snabb, pålitlig och reagera på små rörelser för att vara så bekväm för användaren som möjligt.

Resultatet blev en konstruktion som styrs genom att mäta tryckkraften, när användaren flyttar armen, med hjälp av trycksensorer som placeras vid handleden. Konstruktionen lyckades följa användarens arm, snabbt och på ett tillfredställande sätt.

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PREFACE

We would like to thank all the persons helping us throughout this project, starting with our supervisor Baha Alhaj Hasan for feedback and guidance. We would also like to thank all classmates, assistants and supervisors for all the help and comments. Finally, we would also like to thank Staffan Qvarnström for providing us with material and guidance.

Christoffer Bator & Rickard Svensson
Stockholm May 2016

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NOMENCLATURE

Here all the definitions and abbreviations used in the report.

Symbols

Symbol	Description
F	Force (N)
t	Torque (Nm)
K_P	The gain for the proportional part in the PID controller
K_I	The gain for the integrator part in the PID controller
K_D	The gain for the derivative part in the PID controller

Abbreviations

CAD	Computer Aided Design
FEM	Finite Element Method
(s)EMG	(surface)Electromyography
FSR	Force-Sensing Resistor
PWM	Pulse with Modulation
Rpm	Rotations per minute

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CONTENTS

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1. INTRODUCTION

This chapter contains an introduction to the project and its background.

1.1. Background

A lot of people are suffering from different types of muscle sicknesses and muscle weaknesses. To neither be able to lift everyday things nor move your body as you please is a struggle for many. The most common reason is muscle detrition due to aging, which in some degree affects all of us. Another reason is Fibromyalgia, which is a fairly common type of disease. Most people suffering from fibromyalgia feel exhausted, moving limbs and lifting things can be very painful [1]. Another common reason why a person may suffer from muscle weakness is if the muscle has been crushed, for example, in an accident. Whatever the reason is for suffering from muscle weakness those people would gain a lot from support with lifting objects.

One existing project today with the purpose of assisting lift in one arm and focuses on rehabilitation is the Titan arm [2]. The Titan arm is constructed with cables connected from a motor on the user's back to a wheel placed on the elbow of the weakened arm. A joystick in the other hand is used to control the movement of the arm. This construction is large and mechanically advanced, while the controlling part is simple and reduces the number of free hands for the user. By using a joystick, you strengthen one of the arms and make the other unable to lift or carry other items. This method is not the best as a solution were the user could control the construction with the same arm as it is mounted on would be preferable. The most optimal solution would be controlling the construction directly from the brain via the nerves, though this technology is not easily available and invasive, therefore it is not an option for this project.

At the moment the best way to control an exoskeleton arm would be with sensors to detect were the user want to move their arm and then make the arm follow the user. The struggle with this is to know how the exoskeleton best would be constructed for different sensors and which sensors that would be most suitable for this project. There are many different sensors that could be used. Some could register the movement of the arm by being in contact, others could register the distance to the arm. There are even sensors that could monitor the muscle activities instead of the nerves, without being invasive. So research is needed to find the best way to construct an exoskeleton arm.

1.2. Purpose

The project focused on how to construct a smart support structure for an arm. Sensors were used to monitor the user's movement and out of that data a controller was constructed for controlling the motor, which then moved the arm.
The main research question was:

"How should a smart support structure for an arm be constructed to register and respond to a user's movement independent of the amplitude of the movement?"

Some sub-questions that was answered were:

- "How should a mount for the sensors be constructed to effectively measure the movement of the user's arm, independent of the amplitude of the movement?"
- "How should a controller be constructed to respond to the user's movement in an effective way?"
- "How small forces can be registered by the sensors?"

1.3. Scope

To make sure that the project did not become overwhelming following limitations were set.

- The project focused only on the right arm but the construction could be modified to fit the left arm.
- The project focused on one joint and this joint was the elbow. Neither the shoulder nor wrist joints were reinforced by the structure as this would have taken too long. The thesis had to be completed during one semester.
- The structure, including the sensors, needed to be non-invasive so that the structure was easy to mount on and off the arm.
- The maximum theoretically possible lift from a support structure was not achieved from the demonstrator due to the projects budget limitation of 1000 SEK.

1.4. Method

Full size prototypes were constructed in an iterative process to find the optimal structural solution. Low cost materials were used to be able to easily change and enhance the design until a good solution was found. Then the quality of the materials was improved. CAD models were also to be constructed to test performance of materials and different design structures to ensure that the structure could withstand expected loads without having to buy expensive materials or expensive test rigs.

To be able to verify if the construction was responsive to movement it was physically tested with human movement. A servo was also used to simulate human arm movement and then the signals from the sensors and controller were monitored and compared to the signals used to control the servo. If signals from the sensors corresponded with the signals to the servo, independent of the amplitude, the system was constructed in a satisfactory way. Different constructions and controllers could be compared with each other using the simulated arm.

A computer model could have been used to calculate the correct parameters for the controller. The problem would then be to build a correct model, as many parameters were unknown and the construction was modified along the way which meant new models would have been needed. Not using this method from the beginning gave more flexibility and allowed fast changes of the construction.

2. THEORY

This chapter contains the theory of all aspect relevant to this project.

2.1. Sensors

To be able to control the structure sensors needed to be used to register the user's arm movement. The sensors needed to give accurate readings to be able to have a smooth moving structure. Research were made into a few sensor types, one of them were sEMG sensors. These sensors however were hard to get accurate from as the signals are very weak and noisy to their nature [3], they could also give positive readings of the muscle flexing without movement of the arm. Therefore, they were excluded. Using ultrasonic distance sensors were also excluded as they have a so-called blind spot on small distances and their accuracy is decided by the frequency used [4]. To get the accurate readings needed, too expensive ultrasonic sensors would have been needed. Instead two other types of sensors that seemed promising that gave analogue signals depending on the amount of movement from the user were investigated. It was the magnetic field sensors and force sensors.

2.1.1. Magnetic field sensors

Magnetic field sensors are a wide field of sensors that in different ways and amount react to magnetic fields [5]. Some that react to earth's magnetic field, some that react to weak magnetic fields, like the ones in the human brain. Then there are the ones that react to stronger magnetic fields, around 10 gauss (about the same strength as household magnets). With these sensors many other things can be analysed, for example the speed of a rotation or the distance to an object. By analysing the signal from moving a magnet within a known range from the sensor the location can then be calculated. It is this aspect that is used in this project. A downside is electromagnetic interference could be substantial in some environments.

2.1.2. Force sensors

The force sensors are sensors that react to the amount of force applied to them. One kind of force sensors is force-sensitive resistors [6]. They change resistance with the amount of force applied to them.

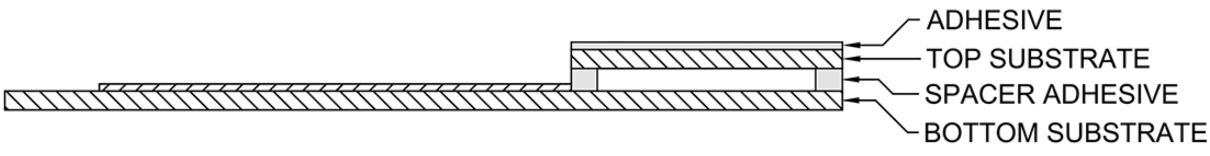

Figure 2.1. *A section view of a force-sensing resistor [6]*

The component consists of several parts that can be seen in figure 2.1. When a current is applied on the two pins on the bottom substrate there will an open circuit because they are not connected. When a force is applied on the top substrate however, the top substrate will connect the two pins on the bottom substrate through a conductive foam. With greater force applied, more of the foam will be compressed leading to a higher density which leads to lower resistance between the substrates.

2.2. Structural design of the arm

The arm needs to be light enough to not hurt the user more than the lift itself but still be able to withstand the forces and loads that will be applied to it. That can be achieved by using the right material and the right design.

The exoskeleton arm was placed along with the user's arm. To ensure that the joint of the arm and the user's arm were in the same axis the upper arm needs to be extendible. To mount the arm on the user the structure was to have some sort of straps but only to the upper arm. The user's lower arm needs to be able to move freely from the structure so that movement can be monitored. Because of the weight, the arm needed to be fastened with a strap on the upper arm and also be supported by a shoulder part, see figure 2.2.

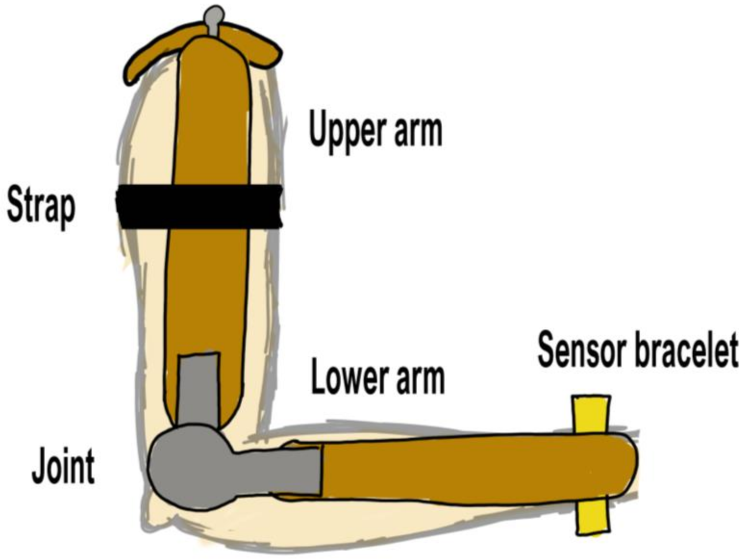

Figure 2.2 *The important parts of the structure seen on a user's arm.*

2.3. PID-controller

A controller uses an error signal to generate a control signal that can then be used to control a system, for example the speed of a motor. A PID-controller uses three parts that together generate the control signal, the Proportional part, the Integrating part and the Derivative part [7]. The proportional part multiplies the gain K_P with the error signal, the integrating part is a sum of old errors that are then multiplied with the gain K_I. The derivative part takes the changing speed of the error in consideration and multiplies it with the gain K_D. The sum of the three parts is then the control signal and by changing the gains the behavior of the system can be modified.

2.4. DC-motor control

To be able to control a motor of higher voltage than the logical circuit is able to handle, an H-bridge is needed. An H-bridge has a "low voltage side", the logical ports, were a PWM-signal is applied to control the speed of the motors and one signal to control the direction of the motors. The PWM-signal is needed to be able to control the motors with a digital signal. By changing the frequency with which the digital signal is switching between high and low signal the motors will be turned on for different periods of time but with such high frequencies that only the speed will be affected. On the "high voltage side" the voltage needed to drive the motor is supplied and then directed to the motor when the logical signal on the "low side" is high. To easier access all the connectors and get some extra features such as voltage regulators, an H-bridge is built into a motor driver card that can be used in projects.

2.5. Material

The material for the structure needs to be a lightweight material that can hold a lot of weight. The arm itself needs to be as light as possible so that the user does not get tired in the shoulder from carrying the arm for longer periods. The material for the sensor-holder does not need to be strong but it needs to be hard so that the sensors are at the same distance at all time. Due to the length of the arm the weight of the sensor holder needs to be kept as low as possible to reduce the created moment at the elbow joint. The more weight, the more of the available torque from the motor would be used just to keep the construction still. So a lower weight of the sensor holder would give more torque to the lift. In the joint a strong material need to be used due to the stress created by the torque from the motor axel, if the material is too weak or the structure to thin it may break which would cause a total construction failure.

In the arm parts it is enough to use a lighter and weaker material, as they do not need to handle as high stresses as the part connecting to the motor axle. The upper arm only needs to handle the tension from the weight which is easier to handle than the torque. The lower arm which is being bent can also be built with a weaker and lighter material as long as it is has a good fixation to the part that transfers the torque from the motor.

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3. DEMONSTRATOR

This chapter contains the problem formulation, all parts that have been used, how the work has been done and the final results.

3.1. Problem formulation

Exoskeletons can be really helpful if constructed correctly but with bad controllers or bad design it can lead to more discomfort than help. So multiple variations of an exoskeleton arm needed to be constructed to find the best solution that was neither too heavy nor badly controlled.

3.2. Software

The Arduino were programmed using Arduinos IDE. Figure 3.1 shows the flowchart of the project with the software.

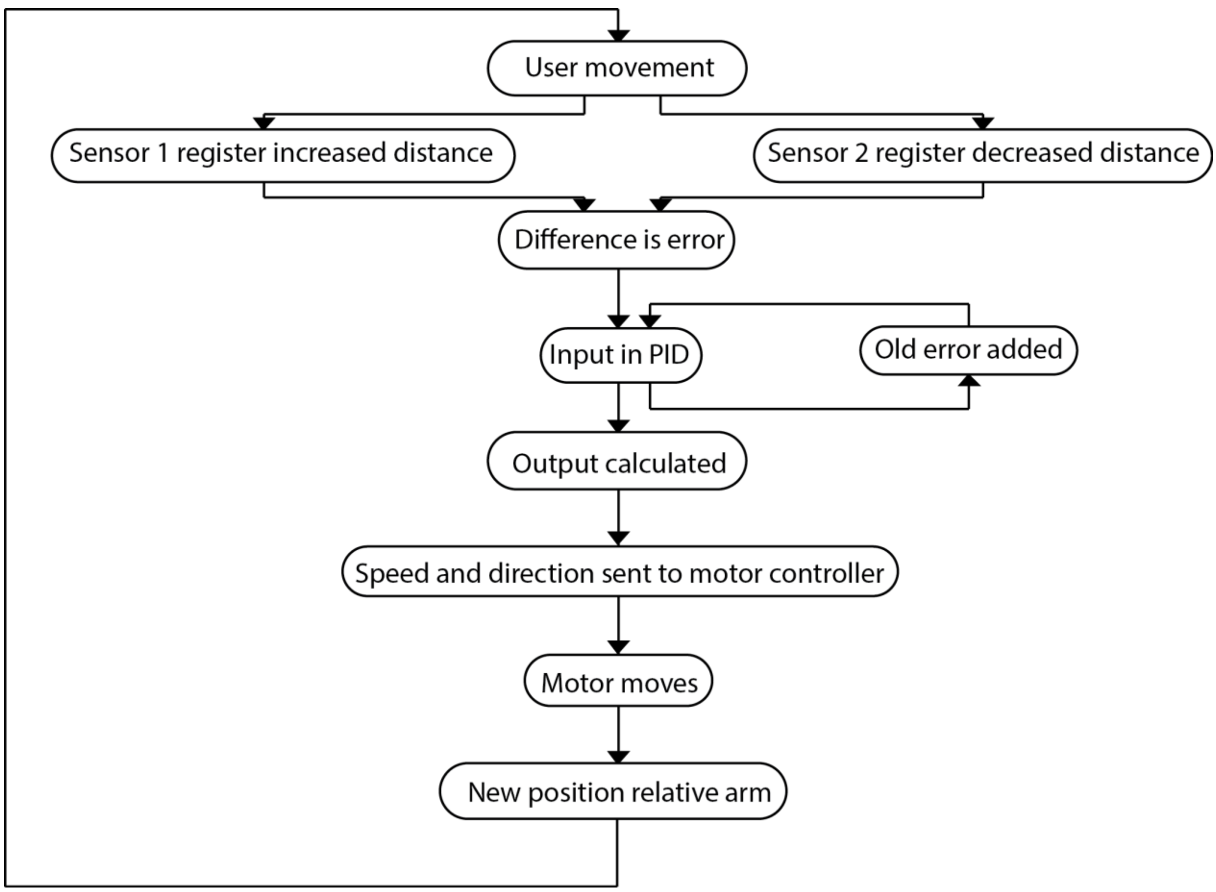

Figure 3.1. *Flowchart of the project.*

When the user moved their arm, it affected the sensors. One sensor got an increased signal and one got a decreased signal because force was applied upwards or downwards to move the arm. The signals were then processed to get rid of disturbances and then the difference between the signals was the error. This signal was sent to the controller that calculated in which direction and how much the motor should rotate to compensate for the error. The controller took the error and fed it into the PID-controller. To make sure that the I-part of the controller did not increase too much anti-windup was implemented. By putting an upper and lower limit on allowed values of the I-part the maximum signal due to constant error was limited.

When a load was applied an error occurred even if the user's arm was perfectly still because the structure was pulled down. The system then reacted to that and helped with the lifting by driving the motor.

To be able to control the motor as fast and smooth as possible the PWM frequency needed to be adjusted. The frequency was changed on pin 9 and 10 on the Arduino UNO to 3906.25 Hz. This minimized audible noises from the motor.

3.3. Electronics

To move and control the arm some electronic components were used as seen in figure 3.2 as the parts connected with wires. Number 3 shows a motor, number 4, the microcontroller and motor driver and number 6 shows where the sensors were placed.

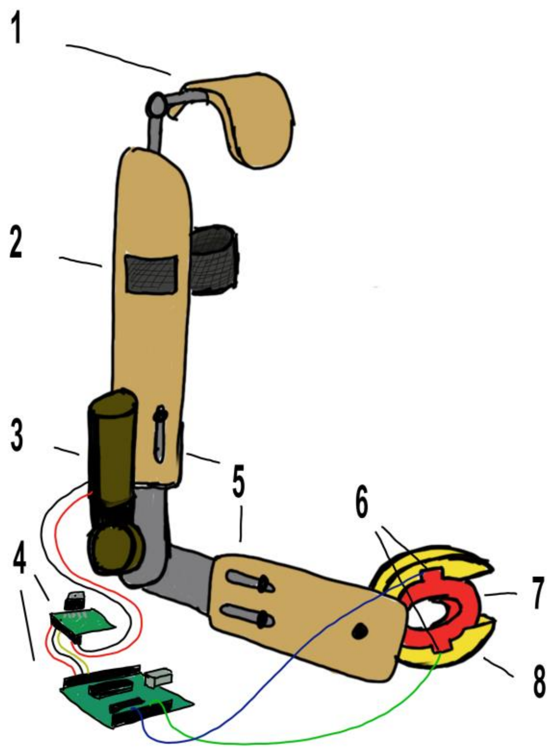

Figure 3.2. *Graphic representation of the construction. 1. The shoulder piece that reduces the load on the strap. 2 The strap that holds the construction on to the user's arm. 3 The motor. 4 The Arduino UNO (largest one) and the H-bridge. 5 The adjustment points. 6 The location of the sensors. 7 The inner ring transferring the movement to the sensors. 8 The outer ring, holding the sensors and the inner ring in contact.*

3.3.1. Microcontroller

The project used an Arduino UNO, which is a microcontroller. It was used as the main computer that did all the calculations needed to control the motor from the signals from the sensors and then sent the calculated control signals to the motor controller. It is based on the ATmega328P chip and it has a 16 MHz crystal [8]. In the demonstrator it was powered via USB but it could be powered with a 5 V battery. How it was connected in the system relative to the other parts can be seen in figure 3.3.

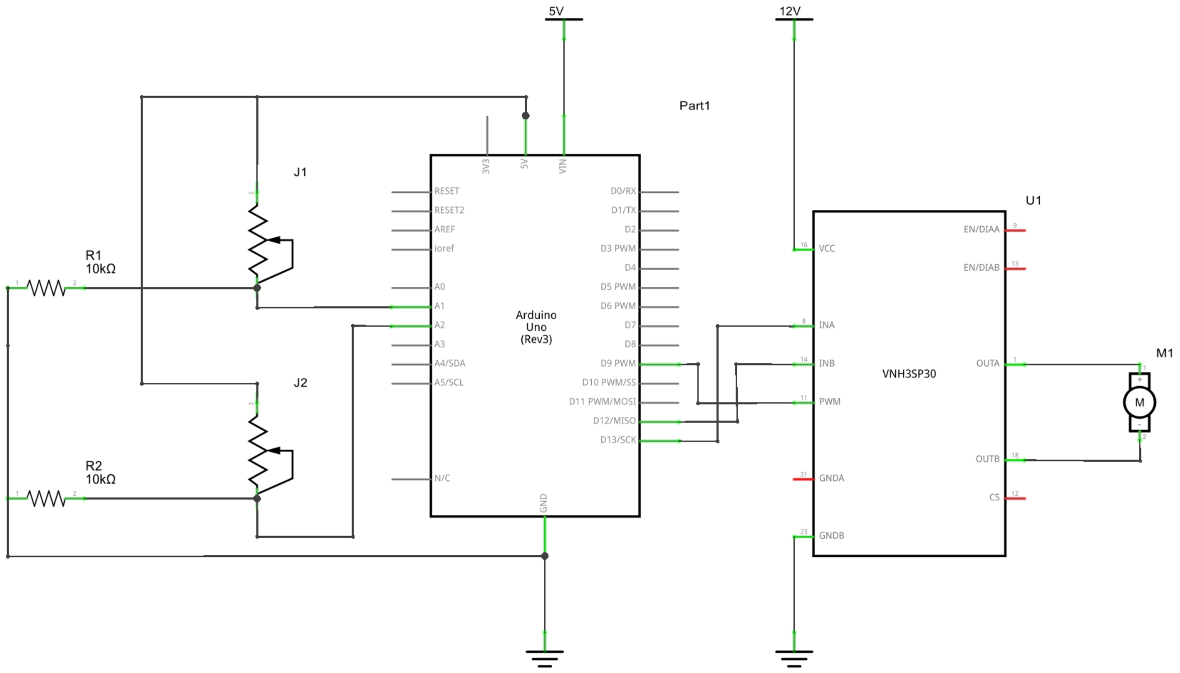

Figure 3.3 *The force sensors (J), motor driver (U) and motor (M) and how they were connected.*

3.3.2. **Sensor**

The force-sensing resistors that were used were the FSR 0.5” (12.7 mm) from Interlink Electronics. They were compact and gave a noise-free signal when force was applied directly to them. The sensors were placed in the ring, which is the yellow part in figure 3.2.

The magnet field sensors that were used were the KMZ10A from Philips. This sensor was of an analog type so it gave a gradient of values depending on the magnetic fields strength. The sensitivity was rather low though so a range of 14 steps was what was obtained from the sensors.

3.3.3. **Motor**

A DC-motor was placed on the elbow joint to lift the lower arm and any added weight. A motor with high torque and with a worm gear attached was chosen to get as high torque as possible. With the budget being limited, the strongest motor available that was of reasonable size and could be powered with a motor driver available were used. The motor can take up to 24 V with a current of 4.5 A.

3.3.4. **Motor Driver**

The motor driver that was used in the demonstrator was the VNH3SP30 from Pololu. It was capable of controlling a current of up to 9 A and voltage of 16 V [9]. It could handle higher currents without overheating but only during shorter periods. It has a max PWM frequency of 10 kHz. With a control-frequency within the audible spectrum a high frequency noise was heard from the motor when running.

3.4. Prototype development

The early concept idea was that the construction would consist of two major parts, one for the upper arm and one for the lower arm. Each part would consist of an inner part and an outer part. The upper arm parts would be linked together with hard material on one the back and straps in front. The lower arm would be linked together with a "sensing bracelet" to measure movement of the user's arm. The plan was also to have two motors, one on the inner part and one on the outer parts. That however turned out bulkier and heavier than needed and was scrapped in favor of a one sided approach. With only one side having rigid structure only one motor could be used. With the need to only mount one motor the structure lost a lot of weight but put a higher demand on the motor.

The first arm part was laser cut in Medium Density Fiberboard (MDF). This was strong and light enough for the prototype, however, it was quite porous so the motor mount was not sturdy enough to handle the torque needed to lift anything. In order to fix this and also enable the arms to be longer, two pieces of acrylic was fastened to the MDF pieces. The motor was then mounted onto the acrylic. This enabled the motor to lift the lower arm and the construction started to take shape.

The early prototype only had a strap to fit the arm on to the user. However, when you carry some weight with the construction or just wear it for a while it starts to slide down. Therefor the upper piece was extended with a shoulder piece, as seen in figure 3.2, to reduce the weight on the strap and keep the construction from sliding down the arm.

3.4.1. The sensor bracelet

The sensing bracelet first prototype was simple, consisting of a cut tube with force sensors mounted inside it, see figure 3.4. Because the sensors barely compressed rubber tips were added on top of the sensors to make then compress and get a smaller contact point to easier control where the force was absorbed.

Figure 3.4. *The paper ring prototype with the force sensor at the bottom of the inside. The other sensor is placed on the upper half of the ring.*

Here the first problem with the sensor ring was found. Due to the elliptic shape of the human arm's cross-section the pressure on the sensors were heavily dependent on the rotation of the human arm. At most rotations the sensors even lost contact with the arm. To solve this a prototype with pressure pads was developed, see figure 3.5.

Figure 3.5. *The metal ring prototype with pressure pads. Between the two metal parts is the force sensor placed.*

This proved more effective as more rotations of the arm had contact with the sensors but the pressure was still dependent on the rotation. Another problem became obvious when the signals were used to control the motor, even with the arm in the "right" rotational position. The construction was too loose and the arm could move to freely inside the ring. As the motor moved the construction in one direction it lost contact with the human arm, but before it had stopped it had slammed the other sensor into the arm. That led to a high signal to move in the opposite direction and then it repeated the process. This made the system oscillate in a constant shaking motion that was uncomfortable and useless. Even if the problem could have been soften using a controller the root of the problem was addressed and a new bracelet design was developed that were rigid and gave a constant contact with the sensor, independent of the rotation of the arm.

3.5. Simulated Arm

To measure and compare the constructions with and without PID controller a simulated arm was built. The arm was built with light wood beams, and fastened on the bracelet on one side and on a servo-motor on the other as seen in figure 3.6.

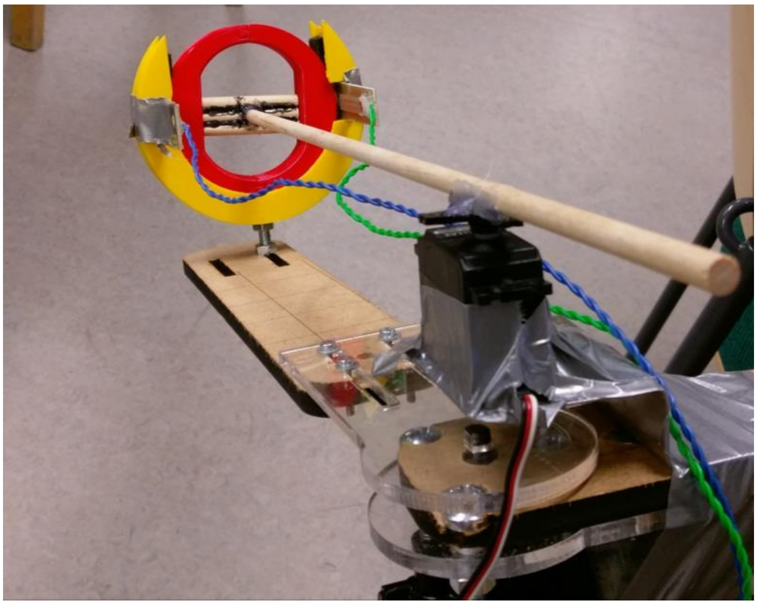

Figure 3.6. *The exoskeleton with the mounted simulated arm on it. The servo on the joint rotates the wooden beam which will result in a simulated movement at the sensors between the red bracelet and the yellow sensor-mount.*

The servo was then placed on the upper arm at the joint between the upper and the lower arm. Then three known signals were sent to the servo.

- The first was a slow and stronger signal between the values 0 and 180 as seen in the upper left graph in figure 3.7, were 90 corresponded to the zero of the servo.
- The second signal was a fast and weaker signal between the values 40 and 140 as seen in the upper right graph in figure 3.7.
- The third signal was a mixed signal between the first and the second one as seen in the lower graph in figure 3.7.

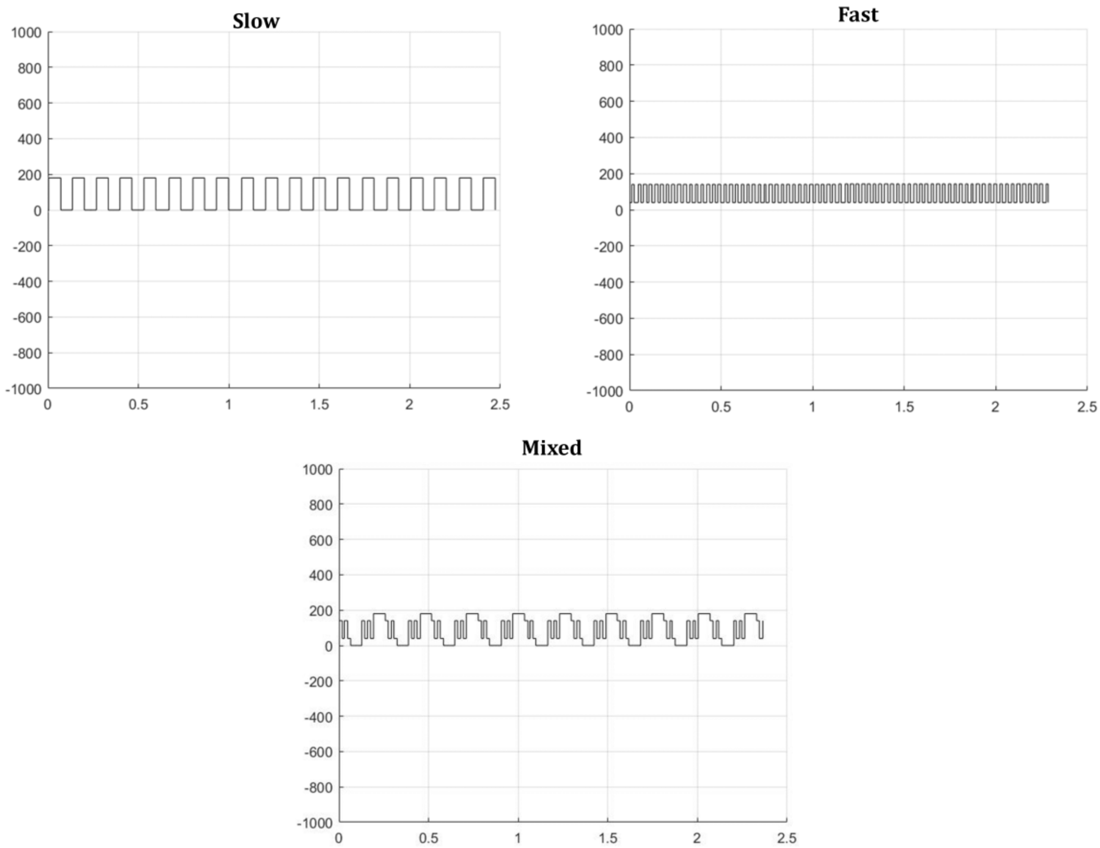

Figure 3.7. *All the signals sent to the servo-motor controllig the simulated arm. The upper left graph shows the first signal (slow) sent, the signal is between 0 and 180 and has longer periods. The upper right graph showes the second signal (fast) used, the signal is between 40 and 140 and the period is shorter. The lower graph showes the combined signal used. The y-axis is the value of the signal sent to the servo and the x-axis is the time measured in Matlab.*

3.6. Results

3.6.1. Structural Design

The project used a structure which fitted on the user's arm. The arm was based on two parts, one lower arm part and one upper arm part. The two parts fitted together in a joint at the point of the elbow, see figure 3.8. The upper part was connected with a shoulder piece that was able to reduce the weight on the strap to fasten the upper part to the user's upper arm. The shoulder piece had a ball-joint connecting the piece with the rest of the structure so that the user could move the arm as normal as possible without the shoulder piece blocking the movement.

Figure 3.8. *An image showing the demonstrator. The black part on the joint between the upper and lower arm is the motor and worm gear. The yellow part is the sensor mount.*

To ensure that the elbow and the motor driven joint were aligned, the upper and lower arm pieces had extendable parts. If the joint and the elbow would not have been aligned the structure could have moved along the user's arm and not follow it correctly which could have let to discomfort.

The construction needed to handle the torque and forces applied to it but keep the weight as low as possible so the selection of material was important. A CAD model was built and analyzed using Finite element method (FEM) to see which parts in the construction that was vulnerable. The simulations showed that the torque transfer from the motor to the lower arm was the danger zone so the motor mount, motor shaft and shaft mount on the lower arm needed to be made out of a stronger material than the rest of the construction. In the demonstrator aluminum was enough to handle the forces. The forces on arm parts will be lower so they can be made out of plastic.

3.6.2. **Sensor Holder**

The holder was based on two parts, one ring to be fitted on the arm and one open ring to hold the ring and the sensors in contact. The open larger ring seen as yellow in figure 3.8 allowed the red smaller ring to rotate freely inside, which in turn allowed the user to rotate the lower arm. The larger ring was then fitted to the lower arm, seen in figure 3.8, to register when the smaller ring moved. When the smaller ring moved up or down inside the large ring, the sensors on the inside of the large ring registered pressure from the small one.

The smaller ring was fitted on the arm by sliding the two half together, see figure 3.9. Because the smaller ring always had the same outer diameter it fitted inside the larger open ring. This made the red ring the only part necessary to be customized for the user and in turn lowered the prize for an eventual costumer.

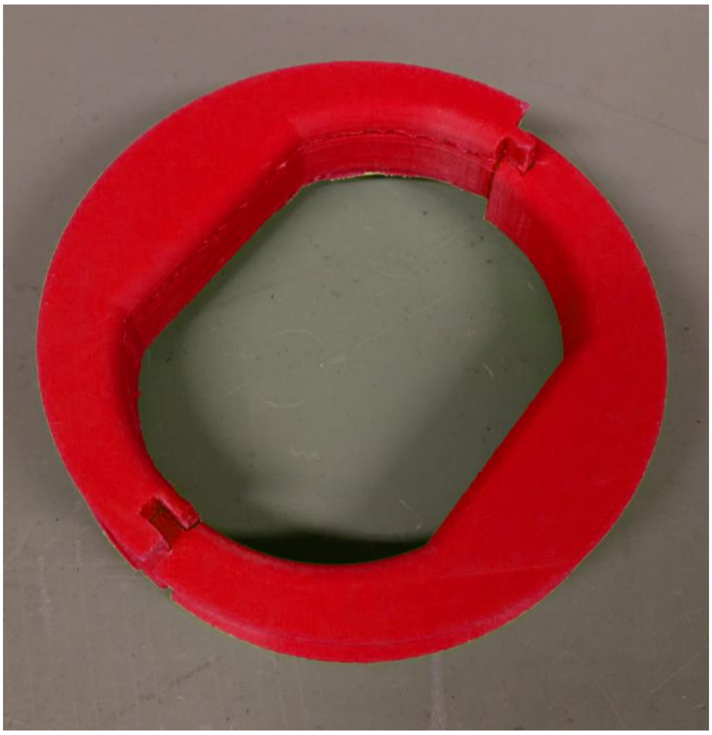

Figure 3.9. *The bracelet transferring movement from the user's arm to the force sensors mounted on the yellow sensor holder seen in figure 3.8. The two halves are identical and slide together.*

3.6.3. **Performance**

To test the performance of the system and check the improvement that had been made the three test signals from figure 3.7 were all fed to the simulated arm with three different systems. First the slow signal was fed into it and the resulting signals from the sensors and the signal to the motor were sent into Matlab can be seen in figure 3.10.

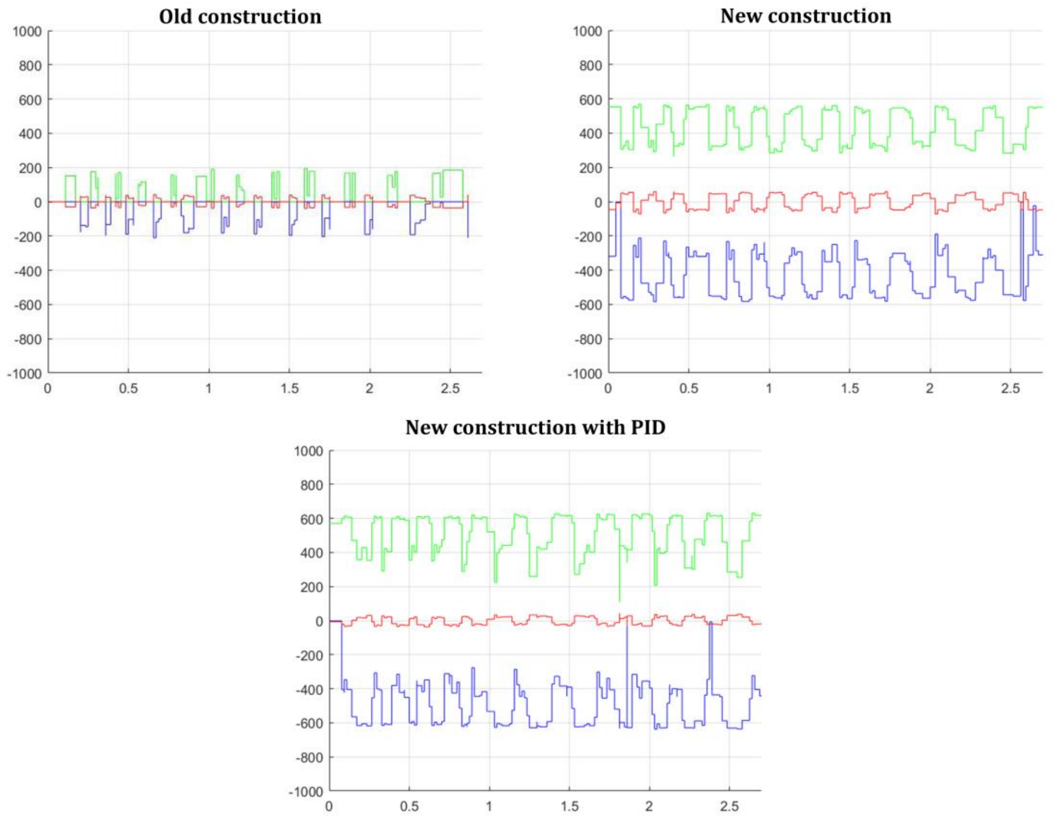

Figure 3.10. *The green signal shows the up-sensors measuring and the blue shows the down-sensor. The red signal is the output-signal for the motor. The upper left graph shows the signal response to the slow signal with the old construction and without the PID controller. The upper right graph shows the signal response to the slow signal with the new construction and without the PID controller. The lower graph shows the signal response to the slow signal with the new construction and the PID controller. The y-axis is the value of the signal sent to the servo and the x-axis is the time measured in Matlab.*

The first system was the old construction without the PID controller, this showed a bad control signal seen as red in the left graph in figure 3.10. Even though the input signal never was zero the graph shows a time between all measured signals were both the sensors seen as green and blue were zero. This shows that the sensors is not in contact all the time with the human arm.

The second system was the new construction without the PID controller. As seen in the right graph in figure 3.10 there is always a signal measured from both the sensors and also a continued output signal to the motor. The motor signal follows the measured signals from the sensors directly which gave an aggressive controller for the system.

The third system was the final system with the new construction and the PID controller. This system showed a good output signal as seen in the lower graph in figure 3.10, the signal follows the input from the sensors but under controlled forms. The amplitude in the graph is lower and switching direction was not as direct as in the previous one.

The next tests were conducted with the second signal, the fast changing, being fed into the simulated arm. This time the old construction was too bad to give any result at all and, therefore, it has no figure to show.

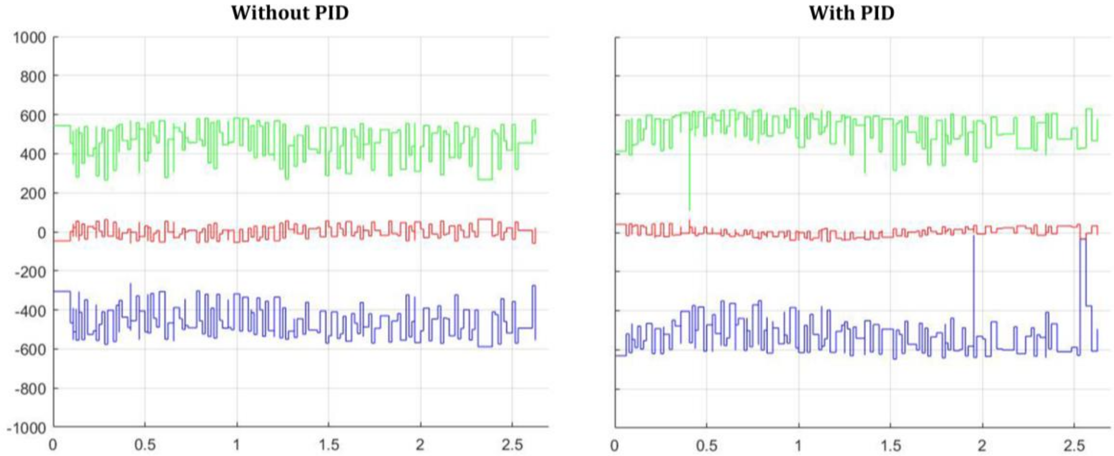

Figure 3.11. *The green signal shows the up-sensors measuring and the blue shows the down-sensor. The red signal is the output-signal for the motor. The left graph shows the signal response to the fast signal with the new construction and without the PID controller. The right graph shows the signal response to the fast signal with the new construction and the PID controller. The y-axis is the value of the signal sent to the servo and the x-axis is the time measured in Matlab.*

This test, on the system with the new construction gave the result seen in the left graph in figure 3.11. The new construction was able to measure the fast and weaker signal but without the PID controller the output signal once more followed the measured signals too closely. The test on the third system with the new construction and the PID controller gave once more a smooth and good output signal as seen in the right graph in figure 3.11.

The third test conducted, shown in figure 3.12, was on the third mixed signal on the new construction with the PID. The result from the test shows how the system was able to control the arm even with a varied signal in a smooth and controlled way.

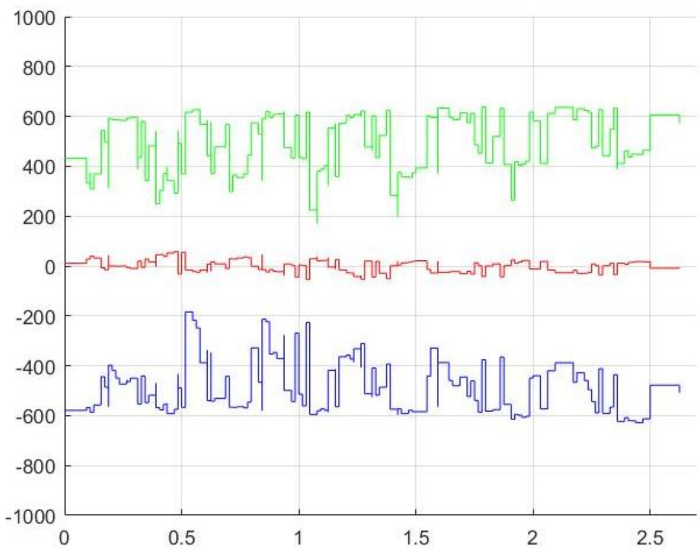

Figure 3.12. *The green signal shows the up-sensors measuring and the blue shows the down-sensor. The red signal is the output-signal for the motor. The signal response to the mixed signal with the new construction and the PID controller. The y-axis is the value of the signal sent to the servo and the x-axis is the time measured in Matlab.*

Finally, a test on a user was made with the new construction and without the PID controller. When the user tried to hold the arm still the construction started oscillate as seen in figure 3.13, bouncing up and down on the user's arm.

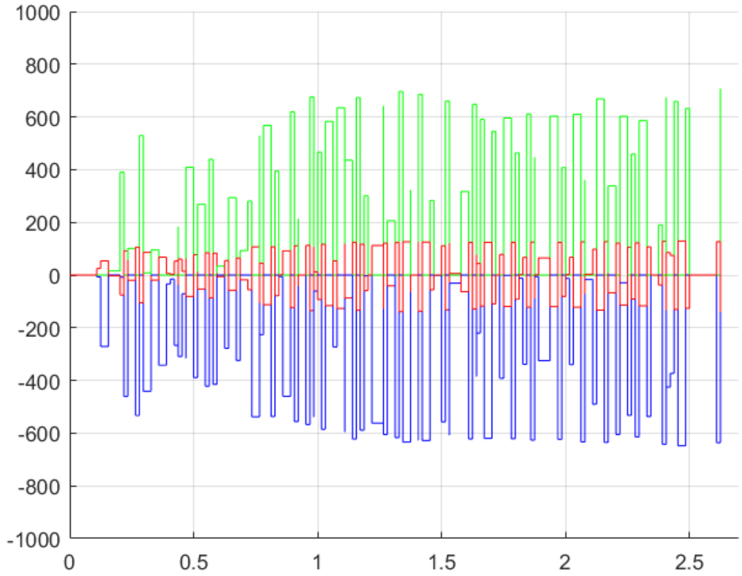

Figure 3.13 *Signals from the sensors and to the motor with the new construction and without the PID. The green signal shows the up-sensors measuring and the blue shows the down-sensor. The red signal is the output-signal for the motor. The y-axis is the value of the signal sent to the servo and the x-axis is the time measured in Matlab.*

To finally test the sensitivity of the fully constructed system dynamometers were used to measure the amount of force needed to provoke a reaction from the sensors. Different thresholds were set and then the dynamometers were pushed at the bracelet and when the sensor reached the threshold the value on the dynamometers were read. It can be seen in table 3.1 that the three test shows about the same result. A test with compression was also performed; the results however, were ambiguous.

Table 3.1 *The results from the test using dynamometers*

Sensor threshold	Measurement 1 (mN)	Measurement 2 (mN)	Measurement 2 (mN)	Compression (mm)
50	110	115	110	~0.1
100	200	220	220	~0.5
150	300	300	300	~0.3
300	450	450	450	~0.2

If the force is divided with the threshold the first three thresholds give an approximate sensitivity of 2.13 mN/step. The theoretically highest signal that the sensors could give was 1023, the highest gotten signal from the sensors however was 960.

4. Discussion and Conclusions

This chapter contains a discussion on the results and the conclusions of the research.

4.1. Discussion

The choice to have the motor on the arm instead of on the back put a higher demand on the motor as it needs to be light and at the same time strong. If it would have been mounted on the back a heavier motor could have been used as it is easier to have a "backpack" with motors and gears. However, this construction would have been bigger as the user would have to wear a backpack while our construction is only an arm. Hypothetically, by optimizing every body parts exoskeleton, a combination of parts could be used to fit a user's need.

When comparing the available magnetic field sensor and the force sensor that the accuracy and signal resolution of the force sensor was substantially better so the force sensors were chosen as the sensor type to use and develop around. The problem with the force sensors that were used however was that they barely compressed which made it harder to get a good fitting to get good readings. So the solution of adding rubber tips made the sensors able to compress so that it could be placed under small pressure to always get readings from the movement, instead of getting "grey zones". In these zones the user would move but no signal would be given.

The importance of the rigidity of the sensor bracelet cannot be understated. It can clearly be seen in the upper left graph in figure 3.10 with the old construction that was not in contact all the time because there is a gap between the green and the blue sensors signals. This will lead to a loss in accuracy and make the system susceptible to oscillations. The oscillations could also hurt the user if the motor was too strong, especially when the system was lacking a controller. When the new construction was implemented a change in the response could be seen as in the upper right and the lower graphs in figure 3.10, even though, the sensors were the same. The system was in constant contact with the arm and always gave signal which improved the response to the movement so it could register small movement, compared to the old construction that could not. The new bracelet also limited the movement sideways from the arm in a way the older bracelet had not.

When implementing the PID-controller a change in the behavior could also be seen as the problem with oscillations was drastically reduced. The problem seen in figure 3.13 was hard to generate even when actively trying to. This because the PID was used to dampen the system with small P and I parts.

The sensitivity tests on the system showed that the system had a high sensitivity to forces and that it slightly decreases with the amount of force applied. So it was sensitive enough to react to even very small forces when the user moved their arm. When testing the sensitivity to a distance needed to move to reach the threshold it proved hard to get good readings. It was because of the distance needed depended on how compressed the sensor was when the measuring started. The measurements are therefore not with as high accuracy as it would have been preferred. They do however show that the movement is somewhere within 1 mm which is good enough to register small changes in the position of the user's arm.

4.2. Conclusions

The importance of a good sensor arrangement and sensor mounting was found to be greater than expected as it greatly affects the end result. It also proved to be more difficult to fulfill than expected. The bracelet construction proved successful and gave good results independent of the amplitude of the movement.

From the demonstrator a few important aspects that need to be considered when constructing a smart support structure for an arm were learnt:

- A light structure, to minimize the load on the user and different components, also to maximize the usage of the motor.
- Constant contact or constant input from the sensors measuring the movement of the arm, for avoiding "grey-zones" in the input for the controller, also to cover the whole movement relative to the construction.
- The elliptic shape of the arm needs to be considered when using different types of sensors.
- The construction needs to be adaptable for different people, the length from the shoulder to the joint and from the joint to the wrist differ allot from person to person.
- When placing one motor at the elbow joint, the size of the construction can be decreased but puts a higher demand on the motor.
- The forces from the motor puts the material close to the joint under higher stress, demanding a more rigid structure and stronger material, but further away from the joint a weaker material could be used to save weight.
- A high sensitivity to movement can be achieved.

5. RECOMMENDATIONS AND FUTURE WORK

This chapter contains recommendations towards more detailed solutions and ideas for future development.

5.1. Recommendations

Depending on the amount of budget, a stronger motor would be highly recommended as the demonstrator only helped with approximately 1 kg of lift at the hand. A motor with more torque would be able to lift more and therefore help the user more. A motor driver with higher maximum PWM frequency would be preferable as the high frequency noise from the motor could be completely removed with a higher frequency.
Also with higher budget more expensive materials could be used and therefore a more effective weight to strength ratio could be achieved. For a construction able to lift more weight steel or titanium alloy is recommended in the joint and axis to handle the stress.
When trying to build something similar it is very important to get a good fit when using the force sensors and that the mounting is rigid. As they are sensitive to movement, both wanted and not, a good construction is key to a good movement of the controlled construction. It would have been preferable to be able to have sensors that slightly compresses without having to add the rubber tips. If other sensor types would be used, then the points in the conclusion should be taken into consideration when constructing the sensor mount.

5.2. Future work

The sensing technology in the system is applicable on other joints, such as the knee, shoulder or wrist. Modification on the driving mechanism would be needed in case of the shoulder and wrist as they have more degrees of freedom. Including the hand and wrist in the structure would be a great improvement as this would allow the user to use their own hands to grab objects and thereby be able to get support when lifting a greater range of objects.
Research into construction of light and effective power source, like battery packs would be a good idea as the construction now is bounded by wires. A battery pack would make the construction wireless and allow the user a greater range of movement when wearing the structure.

A full body construction would be able to help some users more than an arm can. Some user thou, might prefer a lighter construction and therefore only one body part is enough.

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