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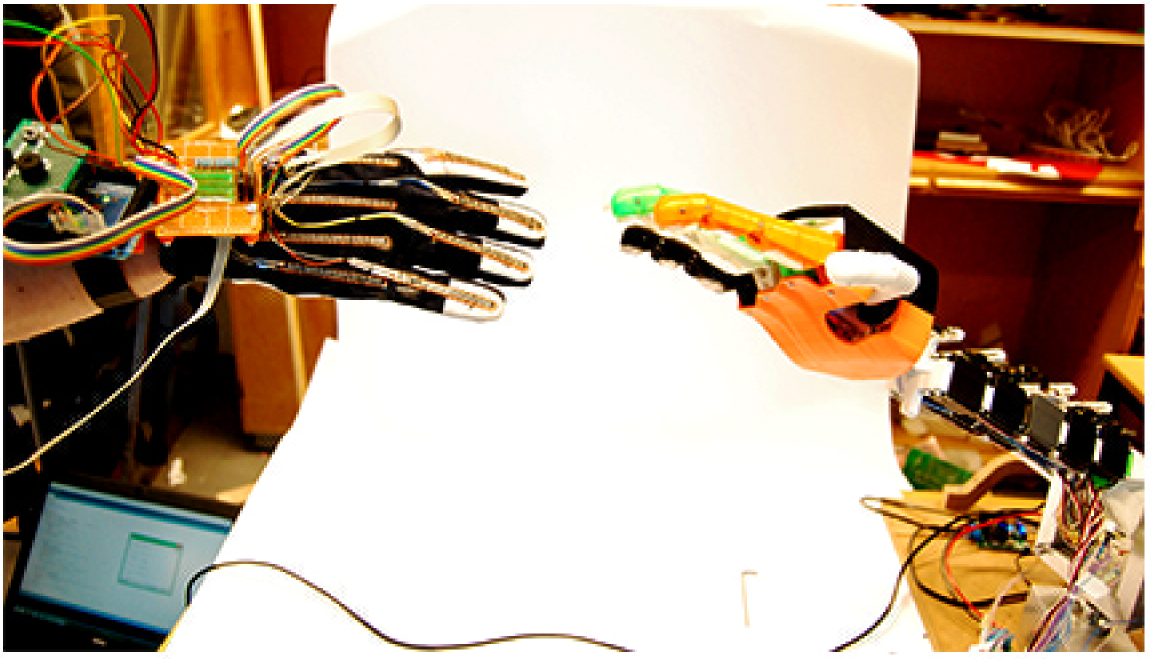

Design of an Anthropomorphic Robotic Arm

Letting human intuitiveness influence the design and control of robotics

Bachelor thesis

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Foreword

The following report is a bachelor thesis, carried out at the institution *Signal and systems* at *Chalmers University of Technology.* The project was performed during the spring of 2014 in *Gothenburg* by six engineering students. The students originate from three different programs; *Electrical engineering*, *Automation and Mechatronics* and *Mechanical engineering.*

The achieved results of this project would not be feasible without some valuable help from others. Therefore we would like to show our appreciation by both mentioning and thanking those who have assisted us:

Göran Stigler who, with several inputs on design factors, helped us optimize the printable parts for successful 3D-printing.

Jan Brageé and *Reine Nohlborg* who showed a great interest in and helped us with the design and construction of the prototype.

Our adviser *Victor Judéz* and our examiner *Jonas Fredriksson* for their inputs and advice during the process of the entire project.

Abstract

This thesis examines the feasibility of designing and manufacturing a wirelessly controllable anthropomorphic robotic arm for use by a human operator to remotely perform operations in potentially hazardous environments.

The primary objective was to prototype a robotic hand, with an intuitive wireless control interface, able to seize a cylindrical object of maximum weight 500 g and subsequently lift, rotate and reposition it, as well as performing ditto operations while pinching a smaller object such as a rubber eraser. For the purposes of the project, budgets of 7000 SEK for components and materials were provided by *Chalmers University of Technology*.

Early on it was decided that 3D-printing would be used to the greatest possible extent to minimize small-scale production costs as well as facilitate construction. Electronics prototyping boards from *Arduino* were used, one to read data from a control interface consisting of two *Invensense* motion sensing modules and a glove equipped with resistive flex-sensors sown onto the fingers. Another *Arduino* was used to distribute instructions to the electromechanical components comprising the robotic arm proper; namely, an array of servos operating strings to contract and expand the fingers, a servo to rotate the forearm around its axis, and a servo to pivot the arm to its sides, as well as a geared DC-motor for raising the robotic arm, equipped with a rotary potentiometer on its axis to provide angular position data for a closed-loop PID control system. To enable communication between control interface and robotic arm two *Xbees* were used.

Grip data was ultimately not implemented due to the pressure sensors proving fragile and thus breaking during the process of attachment. A strength test was successfully fulfilled by manipulating a cylindrical object weighing 1 kg, and a similar test, aimed at assessment of dexterity, was successfully performed through manipulation of a small rubber eraser by holding it between thumb and finger.

To sum up the report the goals regarding the desired functions were achieved as the arm could be controlled in a suitable way and manipulate the defined objects. As for the list of criteria and desiderata, 23 criteria's out of 27 and 9 desiderata out of 16 is to be considered accomplished.

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Appendix

1 Introduction

The human hand may be the most practically utilizable part of the human being. With five independently operating fingers, including the renowned opposable thumb, it offers unparalleled versatility and precision in the manipulation of physical objects. Since man started using tools, a wide range of paraphernalia have been created specifically to be operated by the human hand; from hammers and levers made to amplify applicable torque or force, to polearms and shields created to distance early humans from danger.

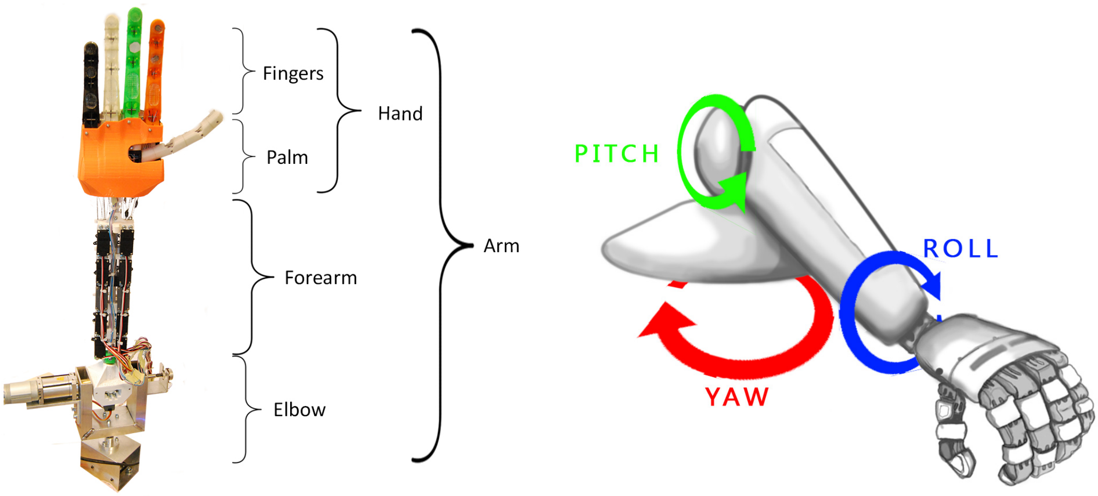
Even today, tools are created with the aim of more efficiently amplifying the user's capabilities while minimizing the risk of injury to the hand or body.

In modern industries there are plenty of robots and robotic gripping tools which have the function of moving and operating different objects and instruments. Although these robot designs have proven effective while integrated in the production industry, limitations make them viable only for predefined movements or objects. This to optimize the robot for a specific part in the manufacturing process or for a specific product, leading to a greater difference between robot and man and thus the robots have to be developed with a specific tool as reference or the other way around. Conventional tools need a new design and expensive processes regarding analysis to make the robot functional for each new possible application. The controls also have an interface that the common man needs education for to understand.

By making a robotic hand using the human hand as a reference these problems could be solved. Giving the robot equivalent capability regarding movement, function, versatility and design. Tools originally developed for the human hand will also be usable by the robotic hand. In the process of finding new areas for robots to practice in, the human hand works fine as a model for a universal tool. There is no need for a manual or a course to understand the potential areas of use for a robotic hand, which gives even novices the possibility to offer new assignments to the robot. By using materials and a design which gives the robot a resistance to dangerous environments, it can operate in areas otherwise unreachable to man while maintaining ease of operation.

In conclusion, a robotic hand with the same capabilities as a human hand, and with a similar design, would be effortlessly adaptable to our society and its potential limited only by our own imagination.

In order to separate different terms in this report, regarding different parts on the robotic arm, an explanatory picture can been seen in Figure 1a. Figure 1b explain terms for different movements.



(a) Different terms for the robotic arm

(b) Directions which the arm can move in

Figure 1: Concept and actual arm with explanation of different parts and movements

1.1 Purpose

The main purpose of this project is to prototype a hand-like tool suited for harsh environments. Ideally the tool should be used as a wireless duplicate of the operator's hand. However, the idea of building an exact copy of the human hand was disregarded due to its complexity. For the design, it was necessary to understand the key functions and anatomy of a human hand. It was decided that this "tool" or robotic hand should be able to grip, lift and rotate an object, similarly to the human hand. In order to lift an object the hand would have to be expanded to a complete forearm including elbow with the ability to rotate around a vertical axis through the elbow joint, see Figure 1b. Since the robotic hand was meant to be used in harsh environments, it had to be controlled from a distance where the operator's safety could be guaranteed.

In short, the finished product should be a robotic arm, with the key features and functionality of the human hand, arm and elbow, which wirelessly mimics the gestures of the operator's movements.

1.2 Objectives of the project

The idea of this project was to create a robotic arm, for manipulation of physical objects, as well as creating an interface between the device and operator which is as simple and intuitive as possible. To reach this some partial objectives had to be fulfilled, these are presented in Figure 2. The objectives are created for guidance throughout the project but also as verification of the completed product.

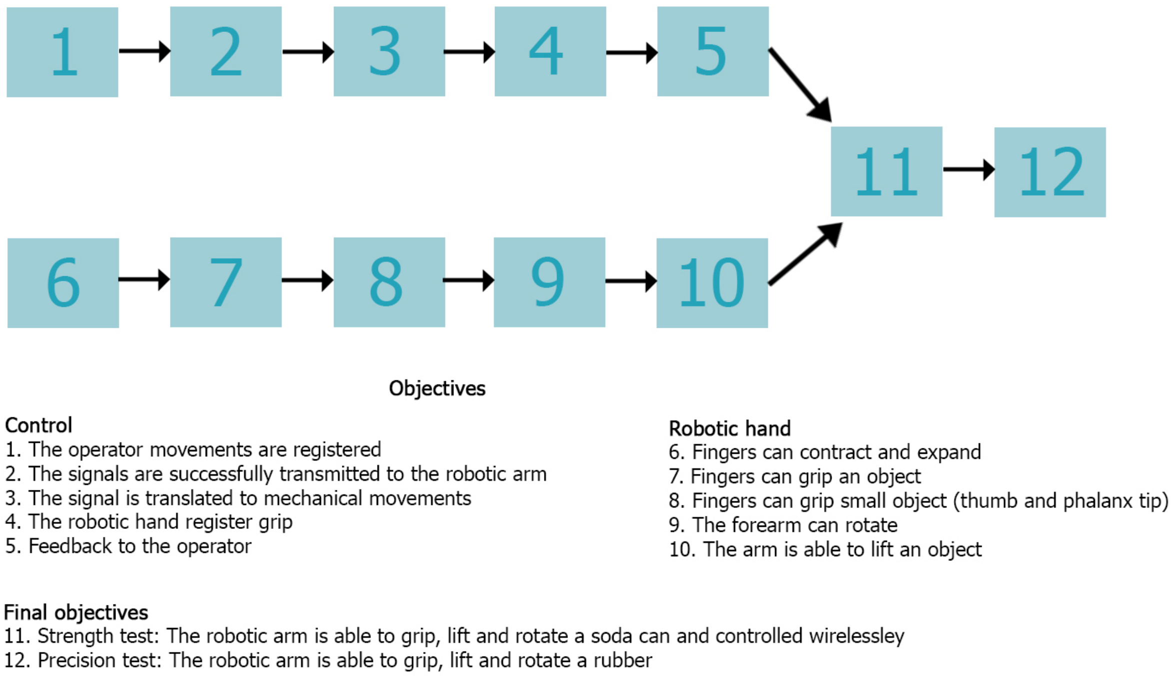


Figure 2: Partial objectives that was set early in the project

1.3 Requirements of the finished product

Exceeding the basic idea, certain requirements were set for the performance of the robotic hand. These were set cooperatively through discussion regarding what is possible to realize with respect to the collective level of expertise and resources. Even requirements which seemed impossible at the time was added to the list of desiderata, see Appendix A, in order to be implemented if possible.

For this project, two goals for the robotic hand were set in terms of different objects to lift. The geometry of the first test-object should be cylindrical with a diameter of 54 mm; during the lift, all five fingers should be in contact with the object. The robotic hand should then be able to lift and rotate the described object. The second test-object should involve a "pinch" function. Using the pinch function, the robotic hand should be able to grab, lift and rotate a rectangular parallelepiped object of size 60 x 20 x 10 mm and a maximum weight of 100 g.

Another goal for the robotic arm was to be able to lift and manipulate an object, weighing up to 500 g, in any of the hand-positions re-creatable by the system. Thus, all calculations assumed a weight of 500 g, although the possibility of raising this weight limit to 1000 g was also evaluated.

1.4 Limitations

A budget of 5000 SEK was provided for the project in its entirety, thus limiting the quality of components and materials used. In order to widen the budget range, the remains from a similar project last year was utilized. Since this was a bachelor thesis at *Chalmers* all projects, working in the workshop provided by *Chalmers*, had a construction budget of 2000 SEK provided for them. This limit was never passed and therefore the cost of construction material was never calculated further. This also applies for the 3D-printed materials in this project. As for the time frame of the project, six students would allocate approximately 400 hours during the span of four months of work each, completely devoted to project work. A budget is illustrated in Appendix D.

As stated in the section *Purpose* the robotic hand should be able to perform the most important movements of a human hand. Therefore the abilities of spreading the fingers or bending only the top joint of a finger, which are less functional and very complex, was dismissed for the complete product. Since the robotic hand is supposed to act like a human hand it seemed pointless to make it more flexible than a human hand. Therefore, no fingers are able to bend their joints more than 90°.

During industrial or laboratory work with the robotic arm it would be an advantage for the operator to feel what the robotic fingers feels. However; the process of making the feedback act as a sense of pressure or strain for the operator as well was thought of as extremely hard. Due to the expected complexity of this operation and the lack of time, it was decided that the control interface would not have this feature. Instead, a possible solution seemed to be visual feedback.

Even though the robotic arm may use some of the functions that are located in the upper arm of the human body it still consists of only a hand, a forearm and an elbow. The project was therefore not designed nor built further than the elbow. Since the arm is robotic, one could imagine that it would be stronger than a human arm, but the stronger the robotic arm is the bigger and more powerful parts are required. Since powerful parts are more expensive than less powerful parts, the funding of this project was insufficient to build a robotic arm that strong. Therefore the project limited the strength of the arm to a level were it is not able to lift nor handle more than 1000 g. Also, the robotic arm will only be used in indoors environments in non-harsh environments.

As known, the human thumb is very flexible and can move in several dimensions. The robotic thumb, however, can move between the “handshake” and “can-grabbing” position and from those positions only be able to bend in two degrees of freedom. The wrist is considered stiff and therefore not able to tilt in respect to the forearm. The forearms ability to rotate around its own axis was however implemented. These limitations were set to simplify the construction while still keeping the robotic arm similar to a human arm.

1.5 Feasibility studies

Before a project can start there is usually some source of inspiration giving basic knowledge and defining problems and background. Therefore searches for documentation about robotic hands have been done that explain several approaches to solving the problems defined in the problem section of this report. This research, along with literature studies, must be done to prevent unnecessary work; there is no need to "reinvent the wheel".

Last year (2013) a similar project was conducted [1]. The goal with that project was to create a robotic hand that could grip an object as well as rotate around its own axis. The complete product of that project was later donated for this year's robotic arm. It is however important to understand that the project evaluated in this report is a stand-alone project and not a continuation on last year's robotic hand; although important knowledge was obtained from the mentioned report.

By review the report for the previous project [1] the conclusion was that there were a desire for a more compact design using a smaller amount of material. Many of the electronic devices and some of the mechanical designs could be used or improved to a new complete design. Another report from 2013 [2] shows a construction not entirely adequate for the purposes presented in this report. The signal processing, however, was designed in a way suitable for implementation into this project.

Also, open source material was reviewed as an inspiration source which offered several solutions to the design including CAD-files. There were no specific source that was used but by reading about other's solutions, one were given several inputs on how to create a functional robotic arm.

1.6 Disposition

The disposition of this report may differ from the common convention regarding how a technical report is structured. As the traditional template may be suitable for projects with a more investigative process, the pattern of this report better suits a project with focus on the building and evaluation. The following sections describe the path from concept generation to evaluation of objective.

Section 2 presents the various possible solutions that were evaluated and why the final solution was chosen. The following Section 3 uses calculations and simulations to explain the possibility of the chosen solution while Sections 4-6 discusses the electrical and mechanical aspects of the prototype. Testing of partial objectives are presented in Section 7 and finally the project and its results are discussed and conclusions are made; these are presented in Section 8 and 9 respectively.

2 Concept Generation - from idea to concept

To ensure that all demands of the robotic arm, along with its desired features, were taken into account, a requirement specification was formulated for the project. All requirements needed to be unambiguously verifiable in order to confirm whether or not they are fulfilled at the end of the project. The set of requirements were also used as basis for selection among generated solutions for realization. These solutions are explained later on in this section.

A list of desiderata was also created for use in the screening of concepts. The screening was done by iteratively comparing desiderata and ranking them by importance. The results of this screening were used for the comparison of several complete solutions.

For the complete list of requirements, desiderata, and the importance ranking of the desiderata, see Appendix A.

The screening process was done in several steps, each step decreasing the list of possible solutions. This was a very important and a crucial part of the project as many important decisions were made here. These decisions had an impact on everything from design parameters to choice of actuators and features.

2.1 Generation and selection of promising solutions

To make the generation of solutions manageable, a function analysis was devised, highlighting the different problems and simplifying the generation of ideas. For this a flowchart was formed over the complete system with all the partial functions included, as can be seen in Figure 3.

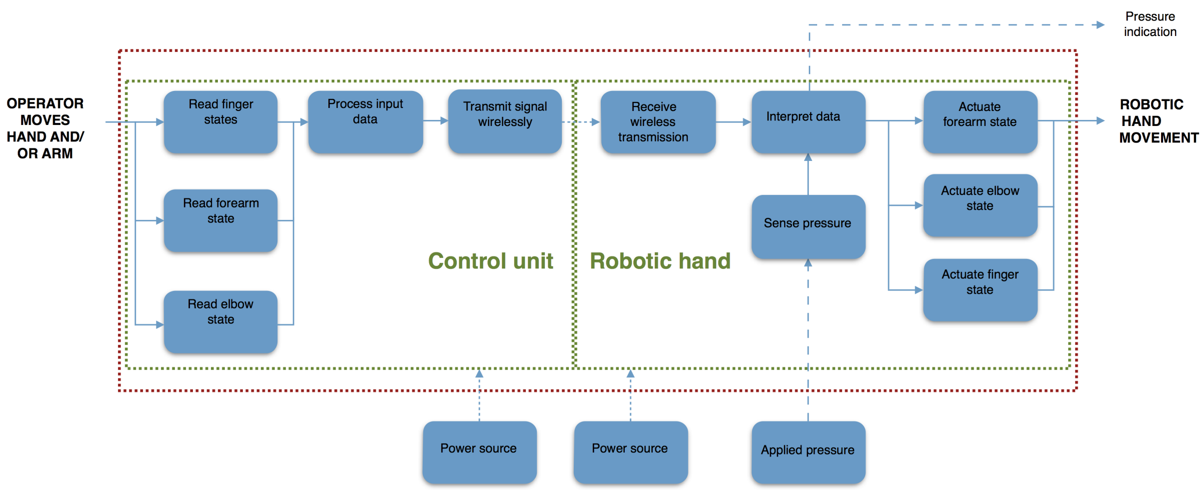


Figure 3: Function analysis of the robotic arm that illustrates the idea and is the basis for the generation of concepts

As an array of solutions was generated for each partial function satisfying each requirement placed upon the robotic arm, a screening had to be conducted to determine which solutions were plausible for the project. Partial solutions were removed if deemed too expensive, too time-consuming, too complex to implement or considered conflicting with requirements. For a complete list of these partial solutions see Figure 4.

Subsequently to partial solution screening, seven complete concepts were constructed using unique combinations of partial solutions for every function identified in the function analysis, although some functions in the analysis are split to make the concepts more detailed. Each partial solution, in all complete concepts, was required to be compatible with all of the other partial solutions to ensure the viability of every complete concept. Some partial solutions were dependent on those chosen for another problem. In particular, the solution chosen for transmission of data must be the same as for reception of data.

For the purpose of designing the complete concepts a morphological matrix was constructed, containing all available partial solutions for their respective problem, and with each cell comprising a graphic representation of the partial solution. This morphological matrix is displayed in Figure 5 showing concept 2, 3 and 4 which were deemed superior of the seven concepts, all of the seven concepts can be seen in Appendix B.

Function 1 Read finger state:
1.1
    1.1.1 Glove with flex sensors
    1.1.2 Glove with slide-potentiometer with string
    1.1.3 Glove with pressure sensors on the inside of the fingers
1.4 Reading through camera
1.5 Myoelectrical reading of muscles
1.6 Piezoelectric materials

Function 2 Read forearm state (rotation):
2.1 Flex sensor
2.2 Slide-potentiometer with string
2.3 Pressure sensors
2.4 Reading through camera
2.5 Myoelectrical reading of muscles
2.6 Harness and potentiometer
2.7 Gyroscope and accelerometer

Function 3 Read rotation around elbow:
3.1 Flex sensor
3.2 Slide-potentiometer with string
3.3 Pressure sensors
3.4 Reading through camera
3.5 Myoelectrical reading of muscles
3.6 Harness with potentiometer
3.7 Gyroscope and accelerometer

Function 4 Read elbow state (angle):
4.1 Flex sensor
4.2 Slide-potentiometer with string
4.3 Pressure sensors
4.4 Reading through camera
4.5 Myoelectrical reading of muscles
4.6 Harness and potentiometer
4.7 Gyroscope and accelerometer
4.8 Rotational potentiometer with string

Functions 5 Interpreting readings:
5.1 Microcontroller
5.2 Personal Computer

Functions 6 Send wireless signals:
6.1 Xbee radio transceiver module
6.2 Internet
6.3 Construct antennas
6.4 Bluetooth LE

Functions 7 Receive wireless signals:
7.1 Xbee radio transceiver module
7.2 Internet
7.3 Construct antennas
7.4 Bluetooth LE

Function 8 Interpreting readings:
8.1 Microcontroller
8.2 Personal Computer
8.3 Mobile phone

Function 9 Reading of the grip:
9.1 Pressure sensor
9.2 The difference between the operators and the robotics fingers

Function 10 Actuators forearm, rotation:
10.1 Servo
10.2 Stepper motor
10.3 DC-motor with feedback
10.4 Hydraulic
10.5 Pneumatics

Function 11 Actuators elbow angle:
11.1 Servo
11.2 Stepper motor
11.3 DC-motor with feedback
11.4 Hydraulics
11.5 Pneumatics

Function 12 Actuators rotation around elbow:
12.1 Servo
12.2 Stepper motor
12.3 DC-motor with feedback
12.4 Hydraulics
12.5 Pneumatics (too much noise)

Function 13 Actuators fingers outer phalanges:
13.1 Servo
13.2 Stepper motor
13.3 DC-motor with feedback
13.4 Hydraulics
13.5 Pneumatics
13.x Power transistion
    13.x.1 Strings
    13.x.2 Strut
    13.x.3 In joint

Function 14 Actuators fingers inner phalanges:
14.1 Servo
14.2 Stepper motor
14.3 DC-engine with feedback
14.4 Hydraulics
14.5 Pneumatics
14.x Power transition
    14.x.1 Strings
    14.x.2 Strut
    14.x.3 In joint

Function 15 Pressure indication:
15.1 Light-emitting diode array 5x5
15.2 Speakers
15.3 Number indicator
15.4 Dimmable light
15.5 Digital display

Function 16 Power source robotic arm:
16.1 Electricity grid
16.2 Combustion engine with/without generator
16.3 Batteries
16.4 Solar cell

Function 17 Power source control unit:
17.1 Electricity grid
17.2 Combustion engine with/without generator
17.3 Batteries
17.4 Solar cell

Figure 4: List of every function and their partial solutions

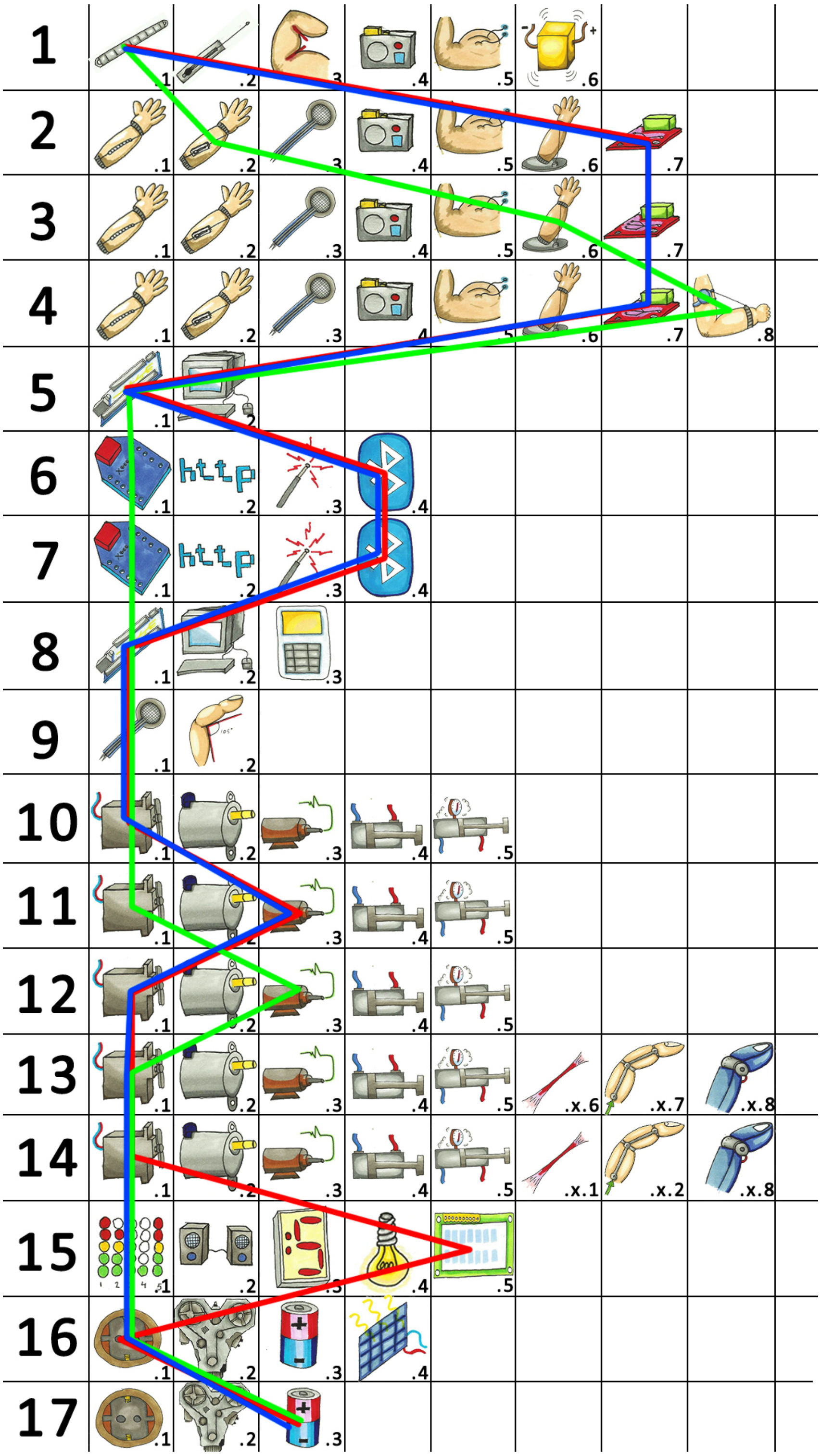


Figure 5: Morphological matrix, visual presentation of possible partial solutions. Red line is concept 2, green line is concept 3 and blue line is concept 4.

Additional screening was conducted to rule out complete concepts deemed inferior with regard to the degree of satisfaction in respect to the project requirements. This screening was performed using a *Pugh matrix*, see Appendix C, in which a concept is chosen as a reference and then comparing the other concepts to the reference. With subsequent iterations omitting clearly inferior concepts and, if necessary, setting new reference concept. However, the screening was judged inconclusive due to the differences in expected performance being small to insignificant.

Following these results, a new screening was conducted using a kesselring matrix, see Appendix C table 9, which takes regards to the degree of satisfaction of the project desiderata. This screening was performed using a decision matrix with the degree of satisfaction defined in a five-point scale ranging from zero to four. The resulting degree of satisfaction for each partial solution was multiplied with the weight of each respective desideratum to produce a technical number later used to compare the concepts.

2.2 Reasoning behind solution ranking using *Pugh-matrices*

This section describes the reasoning behind using the solution rankings in the *Pugh matrices* which would narrow down the selection from seven to three superior concepts. As noted in the previous section, the desiderata were ultimately used to rate the seven original concepts as the requirement ranking produced inconclusive results.

The use of strings connected to servos mounted on the robotic forearm to control the outer phalanges of the fingers was considered superior to the use of double shaft servos mounted directly in the finger joints, primarily due to the potential size increase of the hand when accommodating servos in each joint, which was undesirable according to desideratum 1.12 *Maximum size 1.5 times as big as a human hand.* Servos in each joint was also considered to breed louder operation due to inferior insulation possibilities and due to the possible cascading of offsets in position which may occur with more servos. Movement of the inner phalanx of the fingers using servos with connected struts or in-joint servos was considered superior to servos with connected strings, due to the possibility of strings snapping, as well as the potentially higher gripping strength produced by servos in joints or by rigid struts.

Several important desiderata were related to precision in the robotic arm positioning with regard to the reference, i.e. the operator's arm position. An armature of slide-potentiometers was considered more precise than slide- or rotational potentiometers mounted directly on the operator's arm. However, the utilization of a triple-axis gyroscope as well as accelerometer was found to be able to produce more precise results than any other concept, as well as being much lighter and more portable than the alternatives, thus satisfying another desideratum concerning maximum weight of the control unit, 4.4 *Maximum weight of*

Two desiderata concerning wireless performance were set; namely, the ability to communicate at greater range than 40 meters, and the ability to communicate well through a wall. The 2.4 GHz *Xbee* module was found to have better indoor performance, i.e. communication at close range in a cluttered environment, than Bluetooth technology, although Bluetooth was found to have a greater maximum range.

2.3 Evaluation of three concepts rated superior

Three concepts were selected as superior options since their respective scores were significantly higher than those of the other concepts. The superior concepts were 2, 3 and 4, and were largely similar in design. All three utilize flex sensors mounted on the fingers of a glove to read the operator's finger states, a microcontroller to interpret signals, pressure sensors for reading gripping force in the robotic hand, a servo to rotate the forearm, a DC-motor with added feedback to control the elbow angle of the robotic arm, as well as the electrical grid and batteries as power sources for the robotic arm and control unit respectively.

The dissimilarities were as follows: concept 2 utilizes a slide-potentiometer with strings attached to read forearm rotational angle, a stationary harness with attached slide-potentiometers, connected to the operator's arm by strings, to read the rotation of the upper arm, and a rotational potentiometer to read the operator's elbow angle; in contrast, both concept 3 and concept 4 use triple-axis gyroscopes and accelerometers to detect all of the aforementioned movements.

For the wireless communication, concept 2 uses a 2.4 GHz *Xbee* radio transceiver module, as previously documented in one of the year 2013 project reports [1], while both concept 3 and concept 4 use Bluetooth LE (Low-Energy) transceivers. To rotate the robotic arm around the vertical axis through the elbow joint, concepts 2 and 3 both use a single servo while concept 4 uses a DC-motor with added feedback.

All three concepts use servos to control each finger joint; however, the methods used differ. Concept 2 uses a smaller types of servos directly embedded in all three joints per finger, thus no extra transmission between the servos through shaft and the phalanx as the axis is directly attached to the phalanx. Concept 3 uses servos attached to the forearm with strings wired around servowheels. These strings connects the servos to its corresponding phalanges, 2 servos control each finger: one for the inner phalanx and one for the two outer phalanges. Concept 4 uses the same solution as concept 3 regarding the outer phalanges, concerning the inner phalanx concept 4 uses supporting struts to amplify the torque applied to the joints, as documented in another project report from 2013 [2].

To indicate contact between the robotic hand and a held object, concept 2 indicates grip data on a digital display, while both concept 3 and concept 4 use a five by five array of RGB-LEDs.

These three concepts were considered very similar which made it hard to pick one of them as a final concept. It was therefore decided that they were going to be combined. The partial solution that was the strength of each concept was taken into this final concept to make it even more superior. And so, a final concept had been put together and it was decided that this was the one that was going to be realized. The final concept was given the name *Wireless Intelligent Toolset for Computerized Handling*, or *WITCH*, and is presented and motivated in detail in the following sections.

2.4 Short introduction to the chosen concept

Before this report proceeds a short introduction of the final concept is presented. At this point in the project a decision was made to prioritize desideratum 3.4. *Most custom made parts created by a 3D-printer* because of the simplicity of creating a prototype not only construction wise but also to make the arm as anthropomorphic as possible. The final concept consists of the following partial solutions:

Read finger state

With consideration to the similar project conducted last year this particular solution was contemplated as very successful, therefore this project uses a glove with stitched flex sensors.
1.1.1 Glove with flex sensors

Reading elbow state

This was done by using an electronic device with gyroscope and accelerometer. This option was chosen because of the high resolution and good repeatability the device enables, although it is one of the more complex options as large amount of data needed to be handled.
2.7 Gyroscope and accelerometer
3.7 Gyroscope and accelerometer
4.7 Gyroscope and accelerometer

Interpreting readings

In order to interpret readings, implement the transfer function for mapping and handle the wireless signals, a microcontroller development board of the brand *Arduino* was chosen.
5.1 Microcontroller
8.1 Microcontroller

Send and receive wireless signals

It seemed wise to choose a wireless transceiver that works well with the chosen microcontroller, therefore the *Xbee* module was implemented which is a component which also is created by the brand *Arduino*.
6.1 Xbee radio tranceiver module
7.1 Xbee radio tranceiver module

Reading of the grip

With intention of perceiving the grip of the robotic hand, using pressure sensor attached to each finger seemed to be the best solution compared to the other suggestions.
9.1 Pressure sensor

Actuators forearm

The estimating of the torque needed could only be approximated at this stage, but the torque required for the lifting of the elbow was approximated to be much higher than the rotation of the wrist and rotation around the elbow axis. This could be estimated because the rotational movements only have to overcome the moment of inertia and not any actual load.

10.1 Servo
11.3 DC-motor with feedback
12.1 Servo

Actuators fingers

Since the fingers needs a high resolution in its movements and was not considered to handle any heavier load, it was considered wise to use servos as the controlling actuator. Regarding the use of strings, the purpose of the hand; *To be as humanlike as possible*, played a big part when the decision was made to use tendonlike strings instead of struts. Even though struts was ranked higher due to its mechanical properties it was declined as it was judged to fail the imitation demand of the human hand.

13.1 Servo with strings
14.1 Servo with strings

Pressure indication

This problem had many plausible solution, but the chosen one seemed like the most effective with respect to time, cost and the fairly easy implementation .

15.1 Light emitting diode array 5x5

Power source

Since the robotic arm may use quite large amount of current it seemed wise to use the electricity grid for this, mainly because it would be cheaper and the supply could be borrowed for free. Regarding the control unit no large currents were to be present and the unit was designed to be attached to the human arm, therefore a small battery was considered sufficient enough and which also allow better freedom of movement.

16.1 Electricity grid
17.3 Batteries

3 Simulations, Measurements and Calculations

The following section presents the results from all simulations, calculations and measurements conducted to design the system with respect to the requirements from the list of criteria and desiderata, see Appendix A. All simulations and calculations were made in *Matlab*.

3.1 Simulation of finger movement

To make the fingers move there are two servos attached with strings to each finger, one string for the inner phalanx and one string for the two outer phalanges. As the servos start to rotate, the string attached for contraction winds up on the wheel attached to the servo and the string controlling expansion starts to unwind; when the servos rotate in the opposite direction the reaction is inverted. Through this the mechanism can make the finger contract or expand depending on the direction of the servos. By simulating this operation, a transfer function can be obtained stating the relation between the angle in each joint of the finger and the angle sent to the servo. Figure 6 illustrates the bending of a finger for a specific servo-angle.

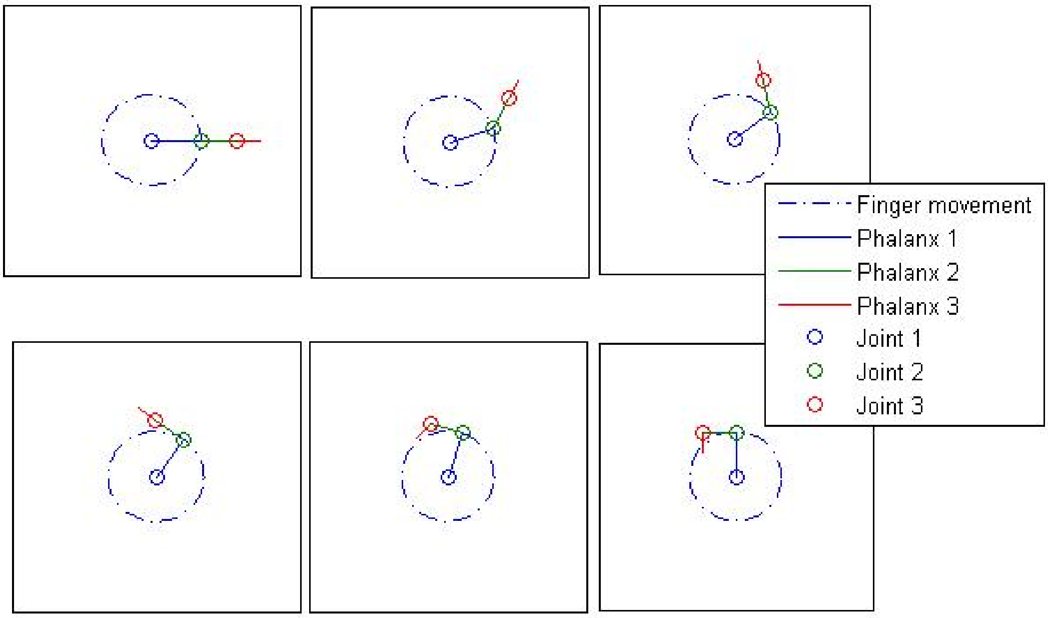


Figure 6: Illustration of finger movement

Each joint needs 90° of freedom around its axis. In combination with the length from the middle, L_1 for inner joint and L_2 for middle and outer joint, of the finger which the strings attachment is placed the length that the string needs to alter to move each joint 90° can be determined. This length needs to correspond to the length altered by the servo. Therefore its important to define the transmission between a servo and its respective joint/joints. Calculation of length L_3 is done accordingly:

$$L_3 = R_1 * \alpha \; [mm]$$

where R_1 is the radius of the first servo wheel steering the inner phalanx and α stands for the current angle position of this servo. R_1 was set to 7 mm since these wheels were already obtained from the robotic hand of 2013 [1]. Due to the maximum turning angle of a servo being 180° (or π radians), the biggest possible transmission is 22 mm. The second servo wheel for the other two phalanges also has a radius of $R_2 = 7\ mm$ and as it contracts the phalanges using a ring, see Section 4.10 for a detailed explanation, the calculations differ. The current angle position of this servo was set as β. As the second servo starts to move, the middle joint starts to bend. The system needs to be designed so that when the second joint reaches 90° it stops and the outermost phalanx starts to bend. While both phalanges move the string transmission is equal between servo and phalanx, but as the outer joint starts to bend the alternation doubles. Lenghts L_4 and L_5 were calculated by:

$$L_4 = \frac{2 * R_2 * \beta}{3} \; [mm]$$

$$L_5 = \frac{R_2 * \beta}{3} \; [mm]$$

See Figure 7 for an explanation of the variables when the finger is fully expanded. In Figure 7 L_4=L_4m and L_5=L_5m, which is their maximum.

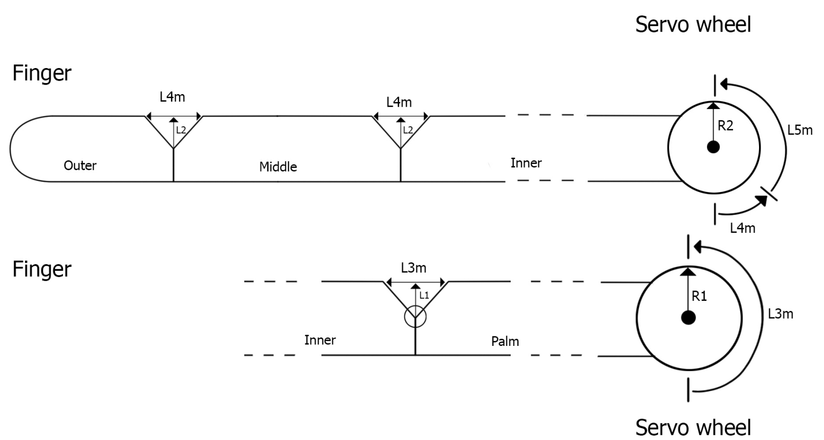


Figure 7: Explanatory picture of the variables used through out the calculations

Since two third of β maneuvers the middle joint and the one remaining thirds maneuvers the outer joint it is important to design servos and string position in joints so $90°$ can be achieved in each joint.

Through calculations, using α and β as π, the max lengths computes as $L_3m = 22\ mm$, $L_4m = 10.5\ mm$ and $L_5m = 21\ mm$. Knowing these lengths, the transfer functions between servo angle and joint angle can be determined:

$$Y_i = \frac{\pi}{2} * \frac{L_i}{L_{im}}\ [rad]$$

The $i = 3, 4, 5$ indicates which joint the function corresponds to while Y is the joint angle in radians.These lengths, L_1,L_2,L_3m,L_4m and L_5m which can be seen in Figure 7 also needs to take in consideration when designing the fingers. With:

$$L_1 = L_3m\ [m]$$

$$L_2 = L_4m + L_5m\ [m]$$

L_1 and L_2 are calculated which is the length that the string will change in the two outer joints.

3.1.1 String offset caused by inner phalanx angle

As each finger is controlled by two servos it had to be investigated if the servos can work independently of each other. Both servos can rotate and move a part of the finger individually but this does not make them independent.

Assuming that servo one controls the inner phalanx while servo two controls both outer phalanges, as the servos uses strings lead through the phalanges to bend the finger they are affected by alteration in the string. If servo two starts to move the outer phalanges, servo one is unaffected since the string of servo two is lead through the first phalanx without moving it and therefore the string of servo one remains untouched. But once servo one starts to rotate the whole finger starts to move and as the strings between servo two and the outer phalanges are lead through the inner phalanx their path length alters.

When the finger contracts or expands due to the movement of the inner phalanx there will be an offset between the servos. To prevent the strings to be slack servo two needs to compensate for servo ones movements. Meaning that when the finger extracts servo two needs to rotate more than servo one. Likewise servo two has to rotate the same amount of degrees more than servo one when the finger contracts.

To calculate the right amount of compensation regarding the counter move the radius in the lower joint of the first phalanx were needed which is $R_p = 1.55\ mm$. With this along with the radius for the servo, $R_s = 7\ mm$, and:

$$A_1 = \frac{\pi}{2} * R_p\ [mm]$$

$$A_2 = \frac{160 * \pi}{180} * R_s\ [mm]$$

the total alteration of the string for outer phalanges regarding either servo one, $A_1 = 2.44\ mm$, or servo two, $A_2 = 19.55\ mm$, were calculated.

As the size of the alternation depends on the alternation of degrees in the servos. This needed to be taken in consideration in the calculations. Therefore the alternation were recalculated to represent the alternation of the string per alternation of degrees in the steering servo. By using:

$$Ag_1 = \frac{A_1}{160}\ [m/^\circ]$$

$$Ag_2 = \frac{A_2}{160}\ [m/^\circ]$$

these two alterations, Ag_1 and Ag_2 could be calculated.

$A_g1 = 0.01525\ mm/^\circ$ shows the relation between servo one and the string while $A_g2 = 0.122\ mm/^\circ$ shows the relation between servo two and the string. With these two known and by using:

$$O_f = \frac{Ag_1}{Ag_2}$$

the offset, $O_f = 0.125$, between servo one and two were calculated.

In other words, whenever servo one contracts the inner phalanx its movement needs to be taken in considerations for the movement of servo two; meaning that for every degree servo one turns servo two needs to compensate with turn one-eighths degrees.

3.2 Sensor measurements - characteristics and linearity

One important and successful aspect from the robotic hand of 2013 [1] is the flex sensors. These resistors change value depending on the angle of which they are bent.

Measurement of these sensors showed that most flex sensors varied between around $25k\Omega$ and $70k\Omega$. One of the sensors were also measured every 10th degree; for confirmation of the resistance's linearity. The result from the linearity study is shown in Figure 8.

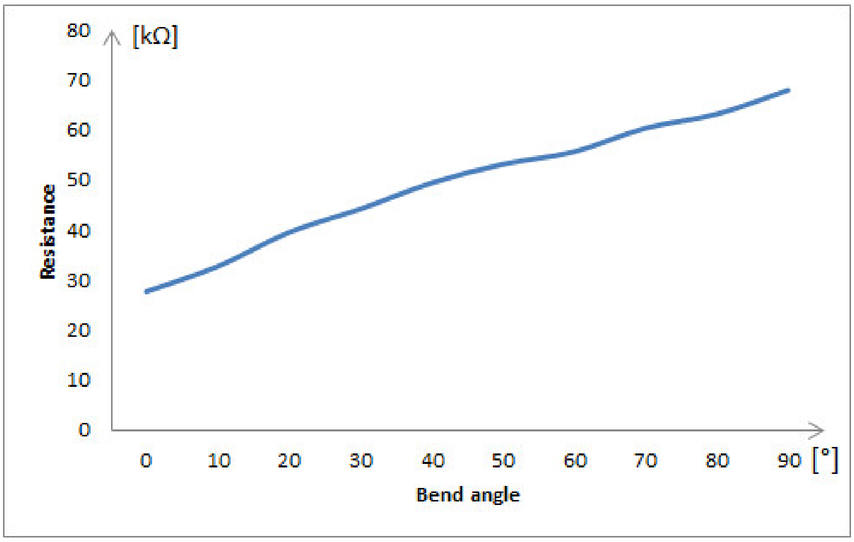


Figure 8: Mean from three measurements on one flex sensor

A quick measurement of the pressure sensors showed that they varied between almost unlimited resistance without pressure and 50 $k\Omega$ with relatively high pressure applied.

3.3 Dimensioning of servos and DC-motor

In this section the dimensioning of servos and the DC-motor is discussed using calculations, and including information from the design of the robotic arm such as its length and weight. For an illustration of the arm's movement see Figure 1b.

3.3.1 The pitch movement

Necessary information for calculating the required torque for the pitch movement where: The weight of the robotic arm, its length, its radius, in this case the arm would be approximated to the form of a cylinder, and the object's weight and position. The weight of both the robotic arm and the object applies a torque in two ways. One torque comes from the weight as the arms length works as a lever and the other torque is the moment of inertia. With:

$$M_1 = \Sigma m_i * g * L_i \ [Nm]$$

the torque from the weight, M_1, was easily calculated with the given values, where $m = weigth,\ g = gravitational\ constant,\ L = weigth's\ distance\ from\ elbow.$

Using:

$$I = \Sigma m_i * L_i^2 \ [kgm^2]$$

the moment of inertia, I, was calculated.

With:

$$M_2 = I * \dot{\omega}_p \ [Nm]$$

and the minimum necessary angular acceleration, $\dot{\omega}_p$, that is needed, the torque, M_2, for the pitch movement is obtained. According to the requirement specifying a maximum delay of one second between operator's movement and the movement of the robotic arm; the robotic arm needs to move from 0 to $\pi/2$ radians in one second. It has been approximated that the arm has to have constant acceleration to the position $\pi/4$ radians and then retard in the same manner to $\pi/2$. Using this approximation it was possible to calculate the angular speed: The angular speed was calculated to $\pi/2 \ rad/s$ and the angular acceleration was calculated to $\pi \ rad/s^2$.

By adding M_1 and M_2, the total torque, M_l, needed from the DC-motor is obtained.

3.3.2 The roll movement

The same information as in the calculation of the pitch movement is needed for the roll movement. To calculate the moment of inertia for the robotic arm, I_2, the arm was approximated as a cylinder, thus can:

$$I_1 = \frac{1}{2} * m_1 * r^2 \ [kgm^2]$$

be used to calculate it. The angular acceleration, $\dot{\omega}_r$, will be twice as fast as for the pitch movement since the roll movement has to rotate π radians instead of $\pi/2$. The moment of inertia from the object, I_2, is calculated with:

$$I_2 = m_2 * r^2 \ [kgm^2]$$

The center of gravity for the object has been approximated to be located 5 cm from the forearms axis which is the forearms radius.

$m_1 = weight\ robotic\ arm,\ m_2 = weight\ object,\ r = radius\ of\ arm$
Adding I_1 and I_2 together produces the total moment of inertia, I.

Torque, M_1, from the moment of inertia regarding the arm were calculated:

$$M_1 = I * \dot{\omega}_r \ [Nm]$$

and the torque, M_2, from the objects weight itself was calculated:

$$M_2 = m_1 * g * r \ [Nm]$$

and this torque had to be added to the total torque as well.

By adding these two torque together the total torque, M_{rw}, needed for the roll movement was calculated.

3.3.3 The yaw movement

As seen in:

$$M_{re} = \frac{I_l * \dot{\omega}_y}{2}\ [Nm]$$

the moment of inertia will be same as for the pitch movement, and is the only data needed to take into consideration since this movement is perpendicular to the force of gravity. The angular acceleration for the yaw movement, $\dot{\omega}_y$ will also be the same the angular acceleration as the pitch movement, due to the same quantity of radians of this movement.

3.3.4 The fingers and the thumb movement

For these movements the weight of the object which the hand grasps, the dimension of the fingers and thumb, and the coefficient of friction between the material of the finger and surface of the object are needed. The force needed to hold the object in the air which the hand grasps has been approximated as being evenly distributed on all four fingers and the thumb since the hand will be completely closed thus directing the force from each finger into the palm; by using:

$$N_f = \frac{m * g}{A * \mu}\ [N]$$

the force applied on a finger are obtained.

This force and the length of lever in fingers transmits into the lever of the servo and torque needed from the servo, M_{servo}, can be calculated:

$$F_s = \frac{N_f * L_{finger}}{L_{joint}}\ [N]$$

$$M_{servo} = F_s * R_{servo}\ [Nm]$$

The procedure is the same for the thumb as for the fingers to obtain the torque for the thumb servo.

3.3.5 Minimum torque needed for the actuators

The result of these calculation is that the following minimum torque is needed from the DC-motor and servos, with a safety factor of 1.25 are show below. This safety factor was made because no consideration regarding friction or skewness was taken.

DC-motor for the pitch movement: 13.3 Nm

Servo for the roll movement: 0.65 Nm

Servo for the yaw movement: 1.62 Nm

Servo for finger: 0.21 Nm

Servo for thumb: 0.28 Nm

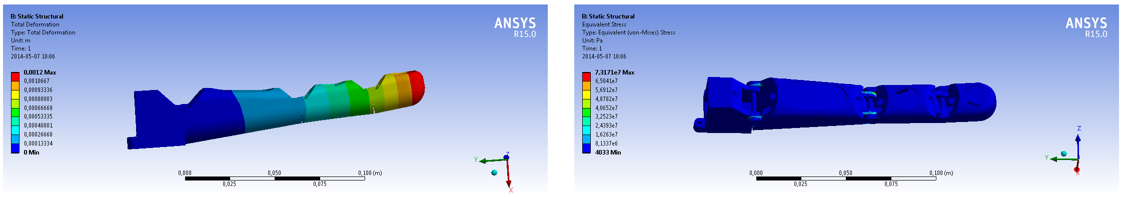
As mentioned before, the Figure 1b illustrate the arm's movements.

3.4 FEM - analysis of materials and design

So far the calculations argue what characteristics the actuators need to have along with how the finger motion occurs. To fully prove that the concept works, in theory, a calculation had to be done considering the material and its design. To prevent critical fractures and sudden damage simulations in *Ansys* were done. *Ansys* is a computer program that calculates the strength in materials using the *Finite Element Method* (FEM). In these calculations approximations had to be made to get the calculation to a level which matched the available knowledge about *Ansys* in the project. That being said these calculations need further analysis to be complete, but they give enough data to prove an estimated durability of the design.

3.4.1 Deformation and stress - finger

The most critical moment regarding the finger was assumed to be if the hand grips an object with just two fingers. To calculate the stresses and deformations of the finger, two simulations with 1.0 kg as load was done. The load was approximated as a widespread force attached on the same area as the pressure sensor. The first one shows the deformation, see Figure 9a, and the second the stress, see Figure 9b, to the finger if it carried the load with the palm facing upwards.

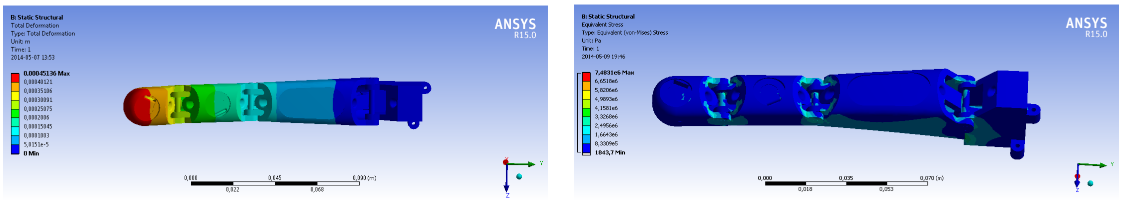


(a) Finger deformation (b) Finger stress

Figure 9: Analysis of a horizontal finger receiving 1 kg load

The result shows that the maximal deformation moved the tip of the finger around 1 mm which is barely detectable with the eye, neither does it affect the function concerning grip. The stresses concentrate around the joints were plastic meets metal and indicate not surprisingly the most vulnerable area. As the *Tensile strength* for ABS is around 40 MPa [3] and the most critical stress lies around 73 MPa, the finger would start to deform if the load of 1 kg was placed one finger's most outer phalanx, thus this needed to be avoided.

As the finger were considered to be one of the more important parts a second calculation was done where the palm was placed vertical, see Figures 10a and 10b.



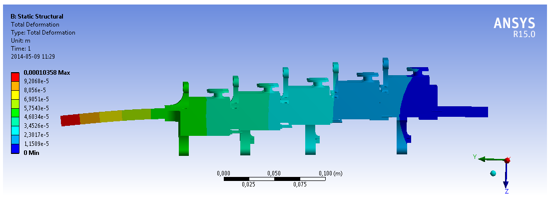
(a) Finger deformation (b) Finger stress

Figure 10: Analysis of a vertical finger receiving 1 kg load

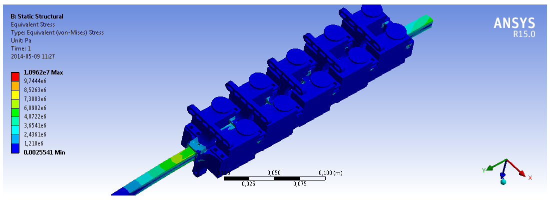
The total deformation with the maximum at the tip of the finger were around 0.5 mm, even less than for the first calculation so no big deformations were to be found. The stress seemed to stay around 7.5 MPa which is in the permissible limit. It was important to take in consideration that the manufacturing process of the finger is 3D printing and *Ansys* probable count the manufacturing to be casting which gives a more solid design, but as the numbers are so low this is still a valid result.

3.4.2 Deformation and stress - forearm

The forearm contains several important parts regarding movement of the fingers. To prevent the servos connected to the forearm to absorb force from the load they were attached to an aluminium beam with the *Tensile strength* of 300 MPa. In the calculation the load was approximated to 1 kg while the other end said to be fix supported. The result are presented in Figures 11a and 11b.



(a) Forearm deformation



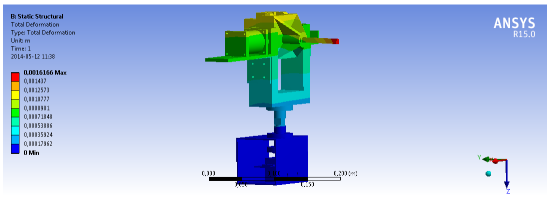
(b) Forearm stress

Figure 11: Analysis of the forearm receiving 1 kg load

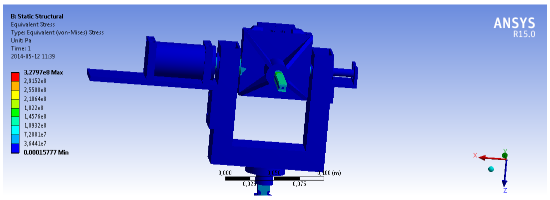
As the deformation, see Figure 11a, is around 0.1 mm at the very end of the beam it does not affect the design in any critical way. By examine Figure 11b it was acknowledge that the beam carried most of the load preventing the servos and the connecting plastic parts to take any serious damage. The highest stress, which emerges in the beam, was 12 MPa and are within the boundaries for any damage. Further examine of the result regarding stress showed that a few zones, where the servos were attach to one another, developed stress. As the servos and its belonging mounts are much more fragile and built in plastic, the conclusion was that if the hand received too much load it was at one of these zones the fracture would emerge.

3.4.3 Deformation and stress - elbow

A simulation for the elbow was also done to get at picture of critical areas. Here the forearm along with the hand were removed and replaced with a 3 kg load and a bending moment of 10 Nm corresponding the loss of length for the lever. The result are presented in Figures 12a and 12b.



(a) Elbow deformation



(b) Elbow stress

Figure 12: Analysis of the elbow receiving 3 kg load

As most of the elbow were designed in metal it was not a surprise that the deformation is almost non-existing for that low amount of load. The deformation is around 0.1 mm and was therefore disguarded. When the stress was evaluated there were some areas that was more vulnerable, partly the different mounts for the axes along with the axes itselves and partly the areas around the pins in the elbow module. As the module was designed in ABS plastic it was crucial that the stress was kept lower than 40 MPa [3], the maximum stress for the elbow emerges in the steelaxes but the stress in the module was calculated to have a maximum stress around 36 MPa, with other words the elbow would withstand the stresses but it is close to break and could need a better design.

4 Implemented Digital Electronics

To give reality to the concept several electronic parts such as sensors, actuators and power sources was chosen for different tasks and are described below. Also the schematics for the electronics are described.

4.1 The *Arduino* electronics prototyping platform

Everything from the reading of sensors to the control of the DC-motor is done using two *Arduino* boards. An *Arduino* board is an open-source hardware unit composed of a microcontroller with its pins broken out to headers creating an easy to use prototyping unit combining the compact size of a professionally manufactured circuit board and surface soldered components, with the flexibility of a breadboard. *Arduino* boards also include supporting hardware such as voltage regulating components to ensure that the board may be driven with a wide range of power supplies, and, usually, a USB port for programming it. The *Arduino Mega* is one of various *Arduino* platforms, and, compared to the other platforms, the *Mega* has a greater number of pins supporting Pulse Width Modulation (PWM), general purpose input output (GPIO) pins and analog digital converter (ADC) pins. A great advantage with *Arduino* boards as compared to using the microcontrollers directly is that the onboard microcontrollers come preconfigured with a boot loader which simplifies writing of new programs; additionally, another advantage is the amount of software libraries freely available. In short, *Arduino* is a viable and relatively low-cost option for hardware and software prototyping. Two *Arduino Mega* boards were obtained for the purposes of this project and they are placed on the robotic arm and control interface respectively.

4.2 Reading of finger state - glove with attached flex sensors

The final solution uses a glove with attached flex sensors to analyze the movement of the operator's hand. This solution was chosen because it was easily implemented and it has been successfully executed in a similar project [1]. Flex sensors vary their resistance depending on the degree of which they are bent; since these sensors are sown on to the glove, their resistance changes depending on the bending of the operator's fingers. These sensors are then connected in series with a fix resistance in order to vary the voltage from between the resistors to the ground; which is read and utilized for the control of the robotic fingers.

The glove has two flex sensors for each robotic finger, except the thumb; one for reading the motion of the joint by the knuckles and one for the motion in the other two joints. As the inner phalanx of the robotic thumb was designed for only two positions, a button was implemented for switching between these positions.

4.3 Reading of forearm, upper arm and elbow movements - gyroscope and accelerometer

By using a gyroscope and an accelerometer the design achieved a much more precise reading compared to solutions containing potentiometers or flex sensors, while still being one of the cheapest solutions. The gyroscope and the accelerometer is able to record movement in any direction as well as angle around any axis in a three dimensional space, which made this solution optimal for these movements.

4.4 Interpreting readings and controlling actuators - microcontroller

For the interpreting of readings and controlling the actuators, two microcontrollers were evaluated: (1) *ATmega328* (mounted on an *Arduino Uno* board) and (2) *ATmega2560* (mounted on an *Arduino Mega* board). These controllers were selected because of their simplicity and robustness, both when it comes to simple and cheap hardware but also because there is a lot of existing libraries which led to a lot of saved time and allowed this project to focus on the design of the whole hand and not on how the interpreting had to be done. Both microcontrollers support 5 V logic levels and relatively large current drawn directly from GPIO pins, 40mA per pin. Ultimately two boards equipped with *ATmega2560* microcontrollers on *Arduino Mega* boards were used owing to their larger memory registers and greater amount of GPIO pins. The *Arduino Mega* board for the control unit was mounted on a custom-made holder and fitted with hook and loop fastener for attaching onto the operators arm.

4.5 Wireless transmission - *Xbee*

One of the many components that works well with the *Arduino* board is the *Xbee*: *Xbee* is a wireless communication unit that can establish wireless communication as well as transmit and receive information. Although it proved more difficult to use this unit than expected; the available library and documentation made it easier to use *Xbee* than several other wireless units. Two other important reasons behind the choice of *Xbee* was the *Arduino Wireless SD* shield which easily connects the unit to the *Arduino* in the correct way, and the available *Xbee* unit from last year's project [1]. The signal transmitted by the *Xbee* has a frequency of 2.4 GHz and the component has the ability to establish a communication of 30 m indoors and up to 100 m outdoors.

4.6 Reading of the grip - pressure sensor

For the measurement of the pressure the robotic hand applies to an object several pressure sensors, of the brand *Interlink Electronics FSR-400*, was chosen since this method is less expensive and fairly easy to use compared too many other solutions. Similar to the behavior of flex sensors the resistance of the pressure sensors is altered depending on the amount of pressure applied. By utilizing a resistor in series with the sensors, the *Arduino* is able to read the amount of pressure applied by recognition of occurring the voltage change.

4.7 Pressure indication - RGB-LEDs - concept

Due to the complexity of making the pressure on the robotic fingers act as a strain or pressure on the operator's hand, the pressure feedback from the robotic hand to the operator was implemented as visual feedback. For this RGB-LEDs was used; these have the ability of changing color. Therefore the LEDs glow green when a little pressure is applied, yellow at medium pressure and red when maximal pressure is applied. This makes it possible to see if all fingers are in contact with the object as well as how the load is distributed between the fingers. Thou to broken sensors this was not implemented in the finished prototype.

4.8 Actuators roll and yaw movement - servo

As the center of gravity for the forearm along with the hand and its load was approximated around the axis of rotation, the actuators only require to overcome the friction and the moment of inertia. As plain bearings was used for the axis of both rotations, friction losses was reduced and the contribution considered insignificant since the torques for these rotations then only had to work against the moment of inertia. Therefore it was decided that servos would suffice for both these tasks.

4.9 Actuators pitch movement - DC-motor with feedback

The calcutations in Section 3.3.5 show that a large torque is required for the pitch motion. Due to this; it was decided that a servo would not be sufficient. Therefore a DC-motor with an epicyclical gearbox was used. The *Banebots P60 gearbox* with a gearing of 256:1 and the *Banebots RS-555 brushed DC-motor* is used. Since the motor itself has great rotational speed but quite low torque; attaching the gearbox to the motor greatly increases the torque but lowers the rotational speed, as a result the arm moves with a controlled motion.

Each of the servos contain a control circuit in order to steer them to the right angle, the DC-motor on the other hand lacks this circuit. This means that the torque of the DC-motor depends on the direction of the current through it and the amplitude of that current. Since the current through the DC-motor is dependent on the voltage one could vary the voltage to control the DC-motor, but there is a better way: Through PWM it is however possible to simulate a changing current by continously turning the power on and off. With an H-bridge, it is also possible to control the direction of the current through the flip of a switch. In this project a *Pololu Dual VNH5019* Motor Driver Shield for *Arduino* was utilized; this unit has the ability to control the direction of the current using an H-bridge as well as PWM-control the DC-motor using transistors. An *Arduino* library already exist for this motor driver which makes it easy to operate through the *Arduino*. It can also withstand the highest current the controlled DC-motor may use.

For the *Arduino* to be able to regulate the motor, it was necessary to install a feedback operation. A rotary sensor, which changes resistance depending on the angle of its axis is therefore connected to the axis of the gearbox. Utilizing the feedback and the mentiond motor driver it is possible to control the motor using the *Arduinos* built-in PID-regulator.

4.10 Actuator for finger phalanges - servo and strings

Following the same reasoning as for the roll movement, servos was a good solution for the bending of the fingers. As mentioned earlier a similar project was conducted last year [1]. The final product from that project has been preserved and was utilized for building this year's robotic arm. Since this year's project built a different robotic arm than the one from last year, only the servos were reused for economic reasons as calculations proved them suitable.

For the inner phalanx movement a servo mounted in-joint or connected with a strut was considered the best solutions. However this solution involves severe complexity and is space consuming. The decision was made to use strings that would work like the human tendons for the inner as well as for the outer phalanges.

Each servo both contract and expand their respective phalanges. Since one servo controls both the middle and the outer phalanges a ring connect the servo to the phalanges according to Figure 13. The strings going to the phalanges are not tied to the ring making the movement more adaptive. When the middle phalanx movement is obstructed the most outer starts contracting/expanding.

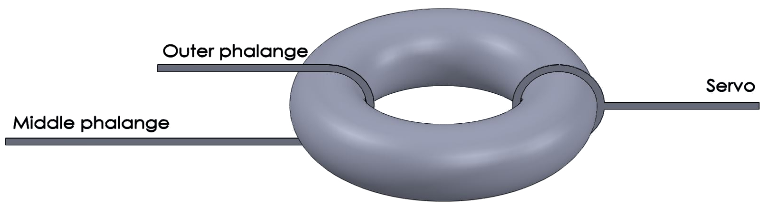


Figure 13: Concept of servo connection with middle and outer phalanges

To fully make the design with strings and servos work, the strings had to be tense, otherwise the string can jump off the servo wheel which makes it impossible to control the corresponding finger. To make the process of straining the strings as simple as possible small plastic directors were designed, see Figure 14.

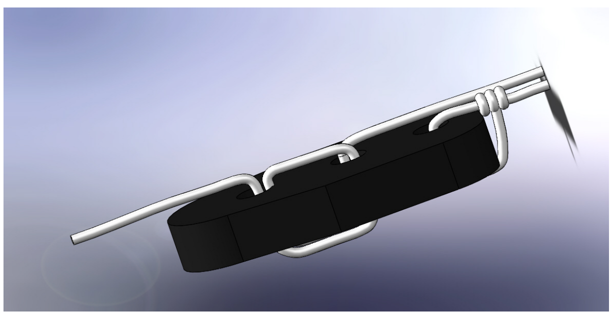


Figure 14: Directors for straining the strings

These directors made it possible to strip the servo of its mount as the string was tightened by pulling the director along the string and then put the mount back, the friction between the strings and the director was considered big enough to make them stay in place. As there are several knots on each string these tighten up as the strings take up force while bending the fingers. With other words the directors was needed to keep the strings tense.

4.11 Power source for the robotic arm and control unit

The robotic arm receives its power from a DC power supply connected to the electricity grid. There are two reasons for this; one is that the robotic arm is stationary and therefore does not have any need of a battery and the other is that the combined power required for both servos and DC-motor is too large for a battery. The control unit on the operators arm is not stationary and does not require as large amount of power so a battery is sufficient.

4.12 Electrical schematics

In Figures 15 and 16, are the schematics of the robotic arm circuit and the controller unit circuit. These show how sensors, motors, and microcontrollers are connected.

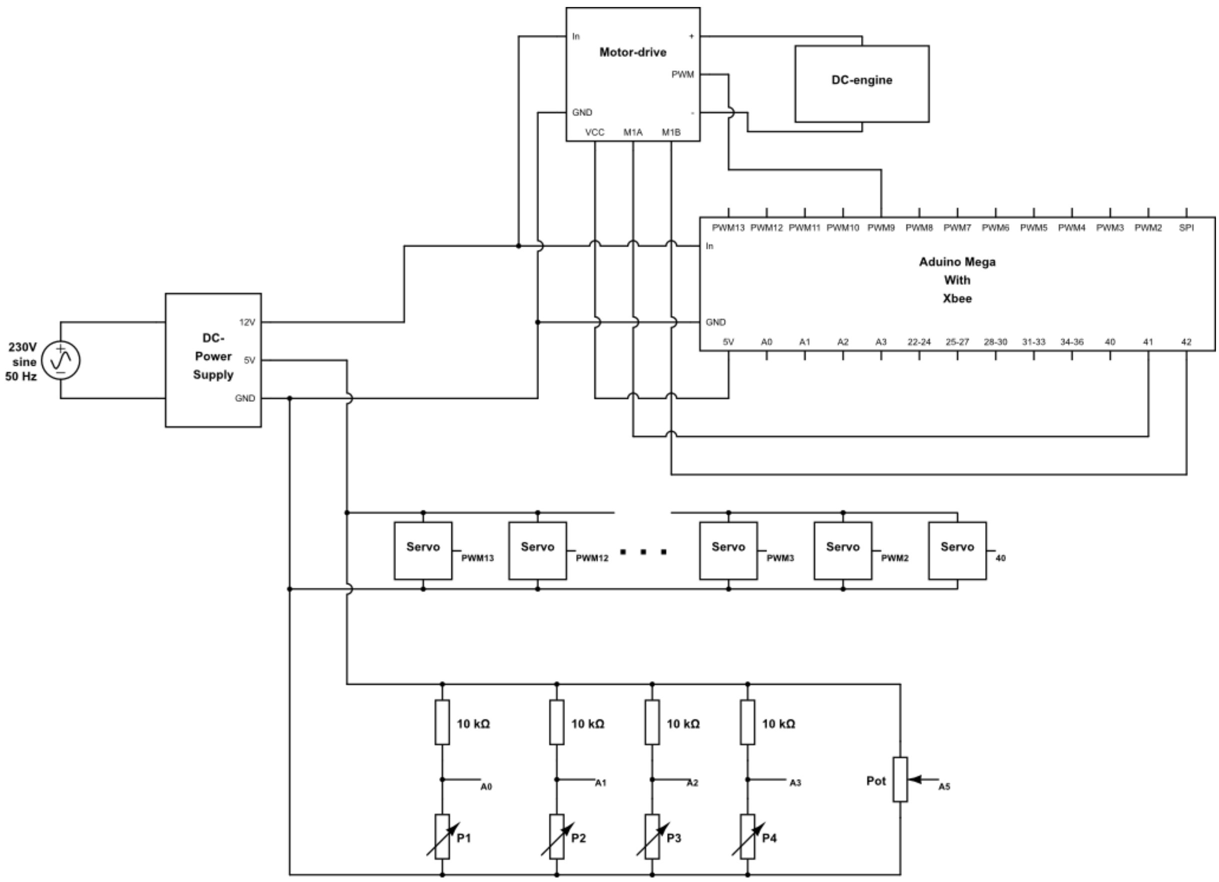


Figure 15: Schematics of the robotic arm

To the far left in the schematic of the robotic arm, shown in 15, is an illustration of the DC power supply, which delivers both 12 V and 5 V. The 12 V output is connected to the *Arduino* and the motor driver, the power is then delivered to the DC-motor. The 5 V output supplies the power for the servos that controls all the movement but the pitch rotation. It also applies a necessary voltage to the resistances and pressure sensors as well as the potentiometer that reads the angle of the arm. In order to control the direction of the current through the DC-motor, two digital pins on the *Arduino* is connected to the motor driver. Since the speed of the DC-motor is controlled through PWM, the motor driver is also connected to a PWM output on the *Arduino*.

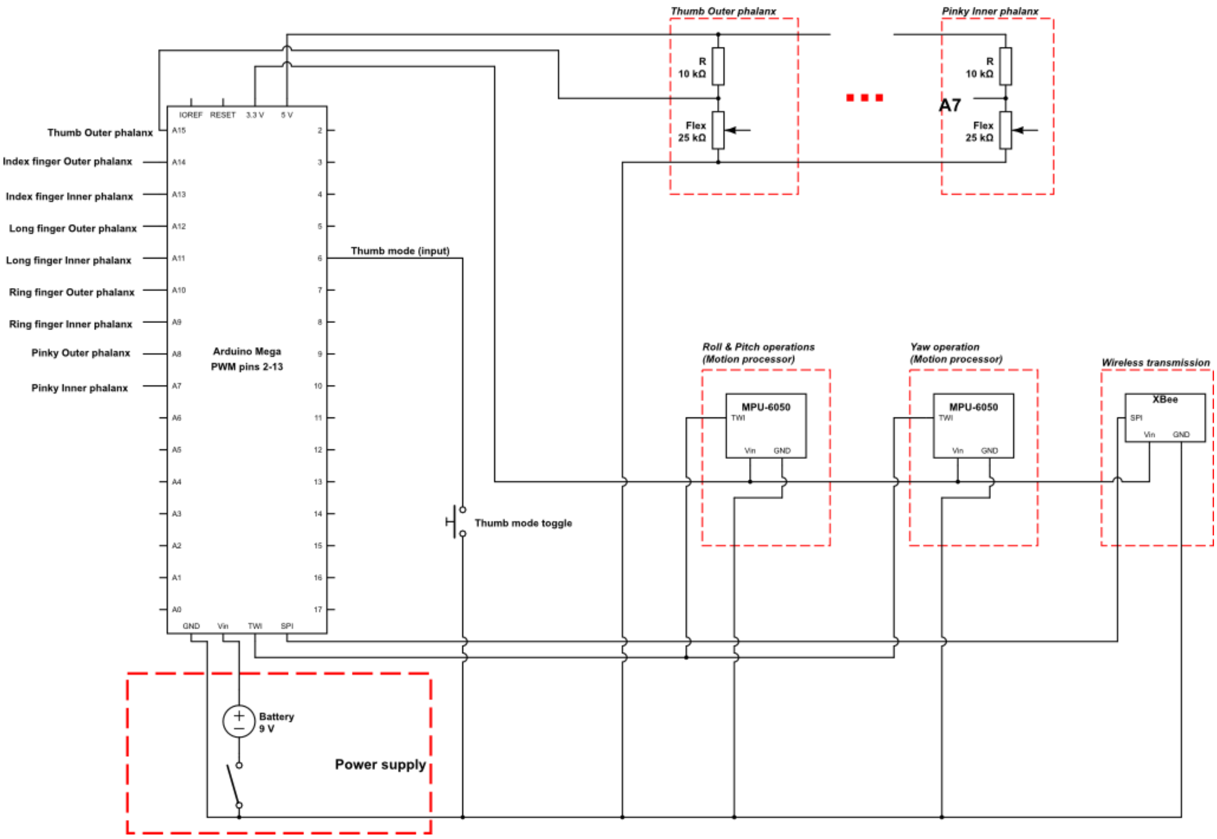


Figure 16: Schematics of the controller unit

A schematic of the control unit illustrating components and wiring is displayed in 16. On the left side of the schematic, a representation of the *Arduino Mega* connection headers is displayed with flex sensor connections indicated by the analog digital converter pins lining the left side. Lining the right side of the *Arduino Mega* are GPIO pins, one of which is connected through a momentary pushbutton to ground. Pressing the button triggers a switch between can-grabbing and handshake positions. Below the *Arduino Mega*, the battery is displayed with a switch symbol to indicate that it is simple to remove power quickly. On the right side of the schematic the connection principles for flex sensors, on the top half, and the motion sensing and wireless communication modules, on the bottom half, are illustrated. Note that Two-Wire Interface (TWI) in reality corresponds to two connections (SDA for data and SCL for clock) and SPI to three (MISO for data in, MOSI for data out and SCK for clock); however, to avoid cluttering the schematic these connections were represented as single wires.

5 Software Configuration and Signal Interpreting

To control the solution several programmable units were installed. How these were configured and how the interpreting of sensors is handled is presented in this section.

5.1 *Xbee* - the wireless communication device

For the *Xbee* units to be able to communicate with each other some necessary configurations had to be done. In order to configure *Xbee*, one had to establish a serial communication with them and the computer through USB and utilize a software called *XCTU*. Once confederated, the two *Xbees* are able to transmit information between one another in Application Programming Interface (API) mode. In this mode an *Xbee* has the ability to transmit packets containing an array of data to the other *Xbee* which also sends a confirmation signal upon receiving the package. For this project only two *Xbee* units were used since the only necessary wireless transmission was between the control unit and robotic arm, however; in this mode it is possible to create a network of *Xbee* units which means it would be possible to control several robotic arms with one control unit.

5.2 Implementation of motion sensing technology

Identification of operator arm movements is accomplished using motion sensing technology. The motion sensor *MPU6050* from *Invensense* was chosen because it combines both a triple-axis serial output accelerometer and triple-axis serial output gyroscope on a single, low-cost chip. Hardware serial interface support eliminates the need for connecting each sensor axis to a different analog digital converter and also allows both sensors to be connected to the same data bus, minimizing the amount of cables which must be connected. The sensor manages signal processing automatically with an adjustable sample frequency of up to 1 kHz for accelerometer output rate and 8 kHz for gyroscope output rate. Data is accessed by the microcontroller through a serial TWI where one wire is used by the master to set the clock rate and the other for two-way data transmission. For advanced applications, the *MPU6050* incorporates an independent Digital Motion Processor (DMP) which may be configured to automatically calculate orientation data, thus taking a load off the connected microcontroller; however, for the calculations utilized in this project it was not deemed necessary. Using the *ATmega2560* microcontroller, the code used for motion sensing occupies only about 9 % (24 out of 258 kB) of program storage space and global variables occupy about 13 % (1.1 out of 8.2 kB) of dynamic memory, leaving a major part of space available for other code.

For communication with the *MPU6050* a series of available user created libraries are available. A C programming library for serial TWI, simplifying data acquisition and initializing of peripherals, called the *I2C Device Library* [4] supports communications with the *MPU60X0* device class and was used in conjunction with the *FreeIMU library* [5] which provides basic filtering and conversion of acquired raw data to orientation data in quaternions. Quaternion orientation data is then converted using standard formulae to Euler, or roll, pitch and yaw, angles.

Two *MPU6050* chips on breakout boards were used, one mounted on the operator's forearm and one on the upper arm. Usage of two separate chips was chosen as opposed to a single chip setup due to the fact that gyroscope data is subject to drifting; therefore, accelerometer data is used to provide a ground reference since the earth's gravitational pull has a constant direction and size. However, with a single chip mounted on the lower arm, one angle lacks a ground reference, namely the rotation of the arm around the vertical axis through the operator's elbow joint. That is, the gravitational vector will be parallel to the axis of rotation, giving no valid reference to correct gyroscope drift for this angle.

To solve this problem, the second chip is mounted on the operator's upper arm, which during normal use is slightly tilted forward. The upper arm rotation angle around its axis is uniform to the rotation of the lower arm around its vertical axis and, since the arm is tilted, the rotation axis will not be parallel to the gravitational pull vector while still providing the correct angular data. In short, a dual sensor setup eliminates all effects of gyroscope drift by providing valid constant ground references for each result.

5.3 Reading of pressure and flex sensors

By connecting one of the *Arduino's* analog pins between a flex sensor and a fix resistor, a voltage which differs with the bend can be read. The read voltage is then transformed into a variable with a value between 1023 and 0, where 1023 equals a voltage of 5 V to ground and 0 means a voltage of 0 V to ground. For the pressure sensors; this value was supposed to set different digital pins high depending on its size and thereby shifting the color of a RGB-LED, this was however not implemented for reasons which is explained further on in this report. For the flex sensors on the other hand the read value is translated to an angle for its specific servo to rotate to.

At the start of the program, and after each reset, the flex sensors are calibrated by reading both the voltage-value when the operators hand is closed and when it is open. These readings are then used for the mapping of each read value during the control of the fingers; this means that the read values when the operator's hand is closed represents the servo-angles when the robotic hand is closed and likewise for the values of the open hand. Thereby each reading of the flex sensors are mapped to the correct angle of their respective servo for the bending of that phalanx. For example; if the calibrated value of an open hand is set to 700 and the calibrated value of a closed hand to 400, a reading of 600 would indicate that the servo should rotate to the angle representing a 30° bending of that phalanx.

5.4 PID-regulation of the DC-motor

As mentioned in Section 4.9 the *Arduino* contains a built-in PID regulator which is used for the control of the DC-motor. An *Arduino* library for the mentioned PID regulator already exists and is therefore used for this purpose. Since the angle of the robotic arm is accessed through the rotary sensor, this serves as input for the regulator. The setpoint is set to the angle of the operators arm received from the control unit while the output of the regulator sets the speed of the motor.

Since the gravitational torque on the gearbox varies with the angle of the robotic arm, the output limits of the regulator is set to be linearly dependent on the input. As for the coefficients of the regulator, i.e. K_p, K_i and K_d, were through testing set to: $K_p = 3$, $K_i = 0.2$ and $K_d = 0.2$. Although these values may have been optimized through calculations and simulations, this method was chosen due to the lack of time.

For the motor driver an *Arduino* library is used as well. The various functions in this library makes it possible to assign the pins *Arduino* used to control the direction of the current as well as the PWM. There is also a method designed for setting the speed and direction of the motor; this method takes one argument between -400 and 400 where the amplitude of the argument sets the speed of the motor and the sign determines the direction.

6 Design of the Prototype

This prototype was not tested in hazardous environments because of the cost of money and the limited amount of time. Although this prototype can show that such implementation is plausible. The following sections describes the different parts of the concept.

6.1 Control unit

As mentioned in Section 4, several motions from the operator are measured using different sensors. As transmission from operator to the robotic hand had to be wireless and there was a desire to let the operator move as freely as possible, the sensors was placed on holders along with flex sensors on the glove which made it possible to be carried around by the operator, see Figure 17.

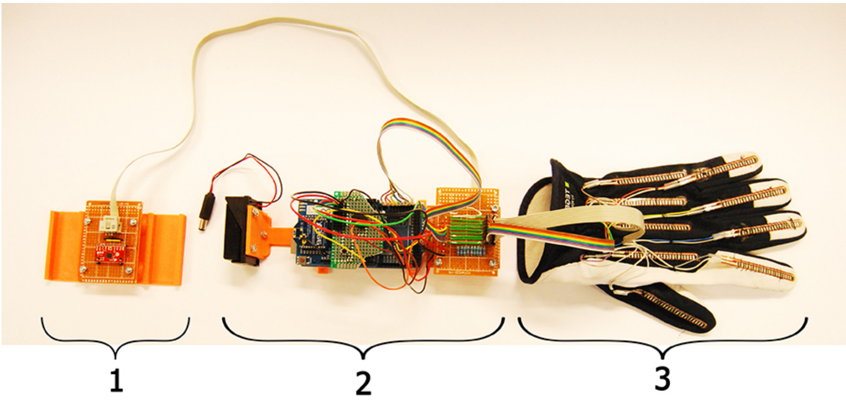
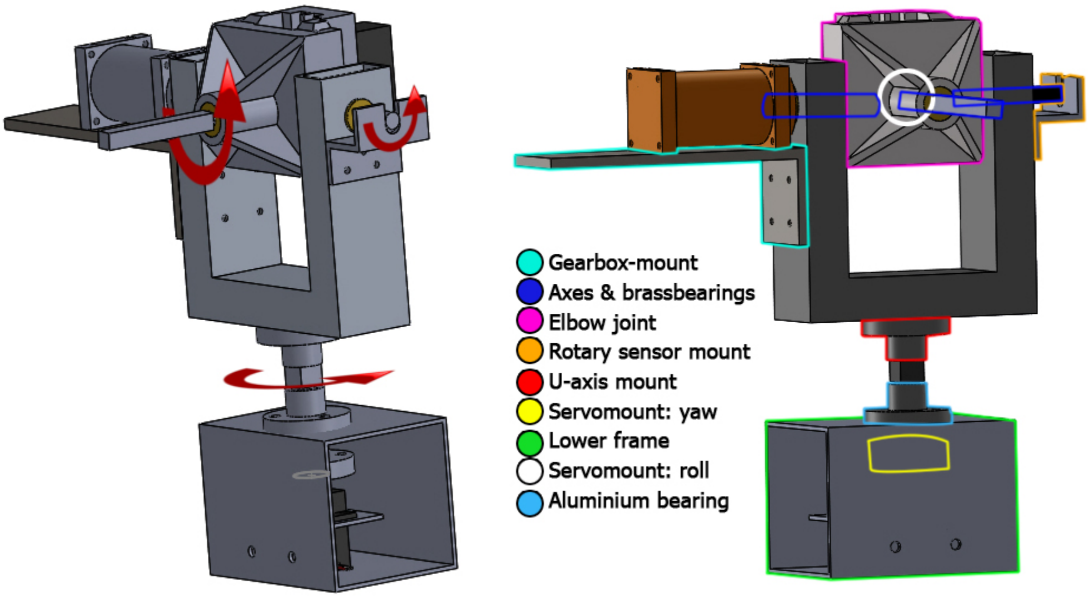


Figure 17: The operator control unit

The control unit contains three sections as the movements origin comes from different sources and the unit had to be divided to be able to register all degrees of freedom. The first board, section (1) in Figure 17, carries the sensor for yaw movement and it is kept in place around the operators upper arm. The second board, section (2) in Figure 17, contains the core of the module as it holds the microcontroller which manage the signals obtained by the sensors. A button is also mounted here to switch the thumbs position. The sensor regarding roll and pitch movement is also placed on this board along with the modules power source and a link of resistors. The third part, section (3) in Figure 17, contains the glove with the flex sensors which are vital for operating the fingers on the robotic arm.

6.2 Robotic Elbow

An elbow design to satisfy the requirements, desiderata and degrees of freedom regarding the different rotations of the arm; pitch, roll yaw, was accomplished using several joints which can move independent of each other. To make the complete arm sturdy the elbow consist mostly of aluminum and steel but also some 3D-printed material. See Figure 18a and Figure 18b for two illustrations of the complete design of the elbow.



(a) Concept of the elbow's degrees of freedom

(b) Model of the robotic elbow with highlighted custom made components

Figure 18: Concept of the robotic elbow

6.2.1 Axes and bearings

The servos and motor that control rotation of the joints in the elbow is attached to rotating axes with corresponding mounts. These mounts, see Figure 19, was constructed both to be able to be attached between the axes and the servo mount and between the axes and their supporting parts, see red outlines in Figure 18b.

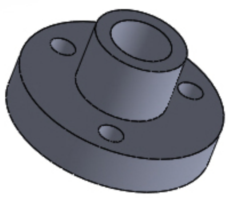


Figure 19: Model of mount designed for servos and axes

As the elbow must endure the total weight of the robotic arm, along with the elbow itself and possible load, the axes was forced to receive some of the load as well. By using bearings, the blue outlines in Figure 18b, the friction in the joints is reduced and the bearings receive the radial load, thus preventing damage to the operating servos and motors along with the rotary sensor. The bearings are plain bearings consisting of a silver steel axis and a brass bearing, see Figure 20.

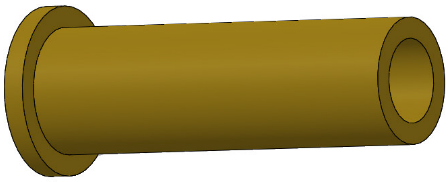
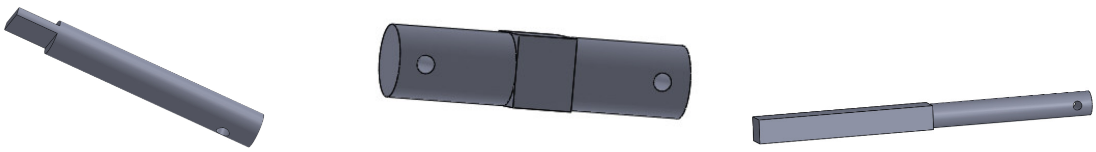


Figure 20: Model of a brass bearing implemented around some axes

The silver steel axes for the elbow are illustrated in Figures 21a-21c. Figure 21c illustrate the axis between elbow and forearm. The first half has a rectangular cross section and the second part has a circular cross section. The circular section works as a part of the plain bearing for roll movement while the rectangular part was designed to mount the forearm along with the elbow. In Figure 18b these can also be seen as the blue outlines.



(a) Model of axis; from elbow joint to rotary sensor (b) Model of axis for yaw movement (c) Model of axis for roll movement

Figure 21: The different axes for the elbow

6.2.2 Design of the robotic elbow

The elbows more supportive parts consist mainly of aluminum apart from the mount supporting the servo for the roll movement, see Figure 22, which consist of 3D-printed ABS-plastic. It was chosen to be made in 3D-printing because of its complexity and as show in Section 3.4.3. This part can be seen in the middle of the Figure 18b with pink outlines

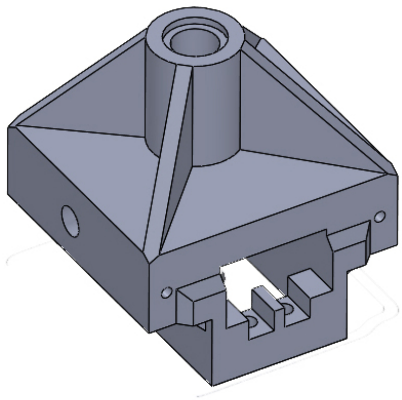
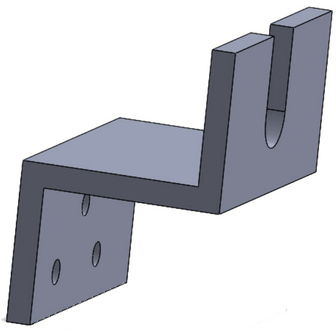
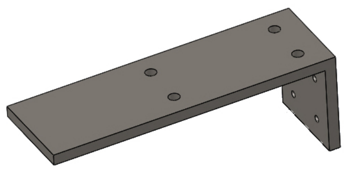


Figure 22: Model of the elbow joint for printing in ABS-plastic

The plastic joint has two silver steel axes which are led through the U-formed support and is attached to a rotary sensor on one side, see orange outlines in Figure 18b, and the epicyclical gearbox on the other, see turquoise outlines in Figure 18b. The epicyclical gearbox and the rotary sensor is kept in a static position by using two supporting attachments, see Figure 23a and 23b. Not illustrated in Figure 18 is the DC-motor, which is kept in place by the gearbox.



(a) Model of mount for rotary sensor



(b) Model of mount for gearbox and motor

Figure 23: Supporting attachments on the U-mount

Aside from the supporting elbow part presented in Figure 22 there is one more part that was constructed using 3D printing and that was the extra mount that concatenate the wrist axis with the servo controlling the roll movement, see Figure 24 and the white outlines in Figure 18b:

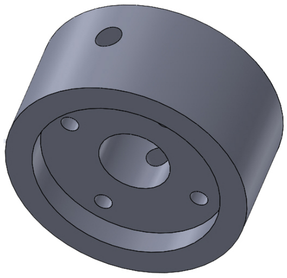


Figure 24: Model of the mount that concatenate servo and wrist axis, to be printed in ABS-plastic

Underneath the U-formed support an axis was attached using one of the earlier mentioned mounts. The axis was then attached to the servo controlling the yaw rotation.

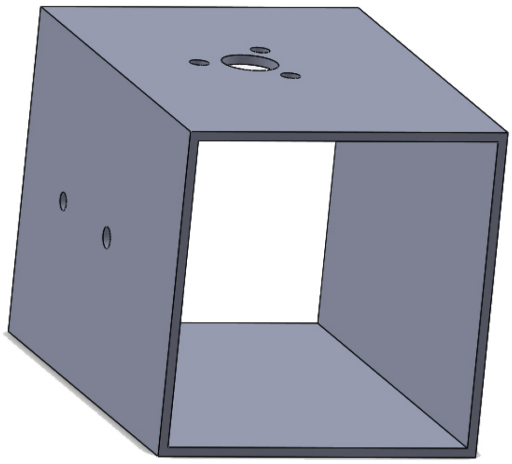


Figure 25: Model of the lower frame, to be made in Aluminum

By using a square shaped aluminum profile, see Figure 25, a servo holder and two of the earlier mentioned mounts, the servo is kept steady. One of the two mounts acts as a bearing along with the axis as it consists of *7075 aluminum alloy*. The square shaped profile, the green outlines in Figure 18b, was also designed to be fixed to the supporting ground in order to give the whole robotic arm stability.

This elbow design satisfy all requirements and desiderata regarding degrees of freedom as all the three desired rotations are included.

6.3 Robotic forearm

The robotic forearm contains all actuators needed for the hand to operate. It does not only provide stability for the arm but also lead the strings from the operating servos to their respective phalanges.

6.3.1 Design of the robotic forearm's core

A hollow aluminum beam with dimensions $10x10$ mm constitutes the basic structure of the forearm. This was chosen because the calculations made in Section 3.4.2 shows that this structure are able to uphold most of the load applied on the robotic arm.

6.3.2 Arrangement of servos in the robotic forearm and design of servo holders

From the list of criteria, see Table 7 Appendix A, there was several aspects to consider when arranging the servos. The most important ones in this section was requirement 1.12 *Maximum size 1.5 times as big as a human hand*, 3.1 *exchangeable parts with standardized tools* and 3.4 *Most custom made parts created by a 3D-printer*.

After measuring a human arm, with the criteria in mind, the final solution was chosen to the one shown in Figure 26. This solution arranges the servos in two arrays, each holding five servos. Each pair of servos has an offset from each other in order to let the strings move smoothly within the forearm. This solution was also adequate for the 3D-printer since the solution was built up by many small parts, all surrounding the aluminum beam for maximum strength.

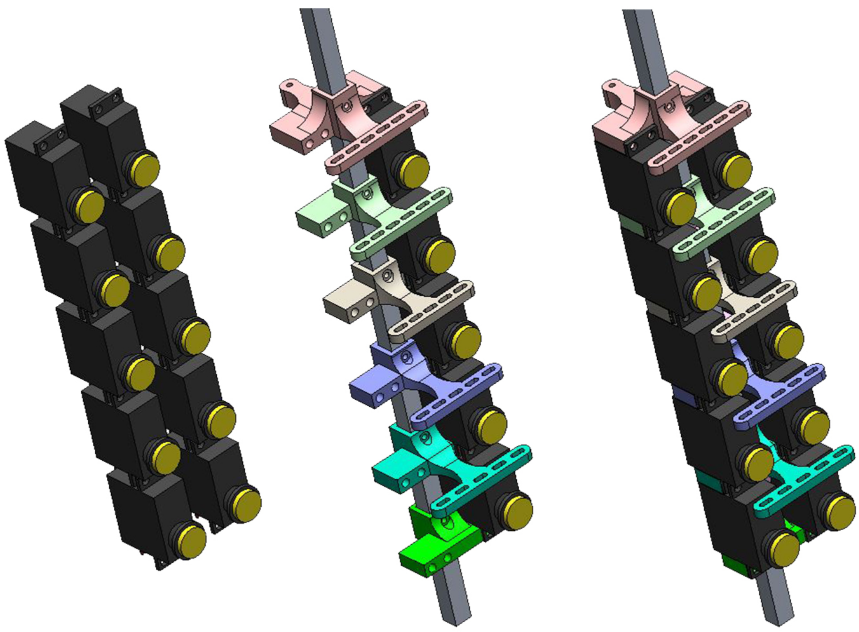


Figure 26: Concept of servos arranged in a 2x5 array, from just servos to fully assembled forearm

In order to attach the servos to the aluminum beam, custom made holders were created for every pair. The mounts also had arms that stretch out in front of every servo with several holes so that the strings would be able to run smoothly, guided by the mounts. See Figure 27 for a concept design.

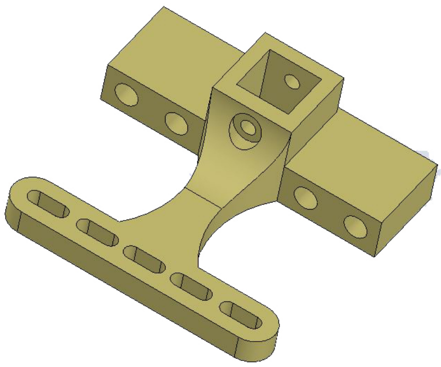
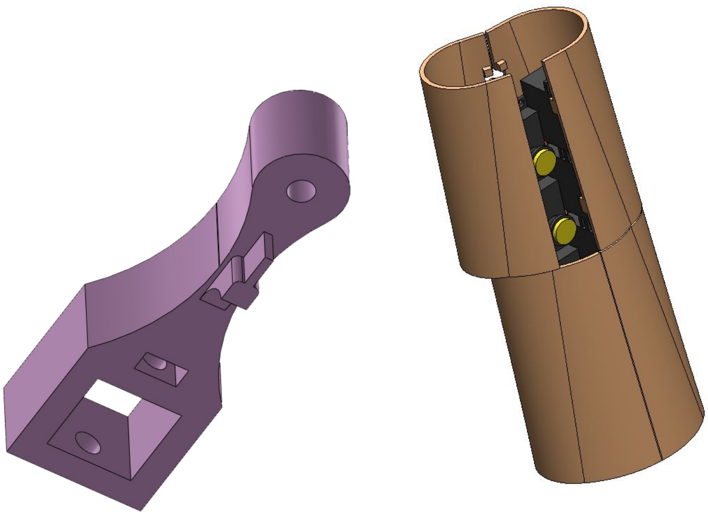


Figure 27: Concept of the servo holder and the arm which guides the strings

6.3.3 Casing of the robotic forearm - concept

To aid the visual similarities between the robotic arm and a human arm, a casing for the forearm was designed. Due to higher priorities and limited time it was never implemented. The casing of the forearm was intended mainly for aesthetic purposes, and had no direct mechanical function nor any criteria to be considered other than 1.12 *Maximum size 1.5 times as big as a human hand* and, preferably, 3.4 *Most custom made parts created by a 3D-printer.* Therefore a simple design but one that looks something like the human forearm were chosen. Dimensions of the casing were very close to the human forearm. However, due to the size of the servos, and that the forearm must not be longer than 300 mm, the radius close to the palm had to be bigger than the human measures. The casing had two features: (1) the holes on the back which created a hinge when a pin were inserted, and (2) small pockets at the front which had room for small magnets which would keep the casing closed. See Figure 28b for a detailed view of the casing.

In order to attach the casing to the rest of the arm, "hinge arms" were designed. Their only function was to hold the casing and create a hinge function. This would have been done by inserting an aluminum pin with diameter of 3 mm into the holes, see Figure 28a.

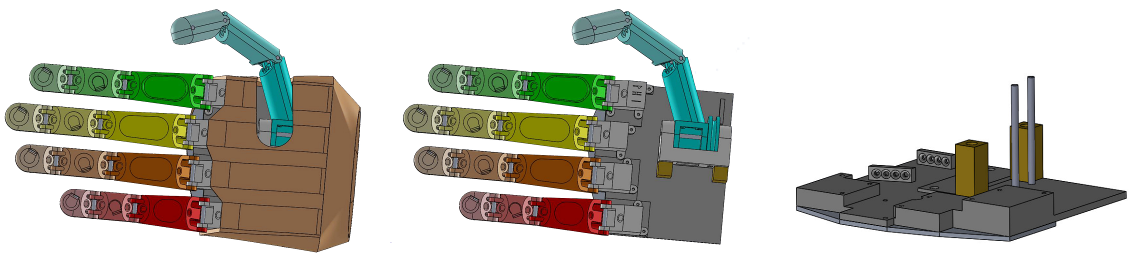


(a) Concept of the hingearm (b) Concept of the casing

6.4 Robotic hand

To keep a close resemblance to the human hand, the robotic hand was required to have four fingers and an opposable thumb. The placement of the fingers on the actual hand was not defined, but to maintain the intuitiveness of the control and functionality of the robotic hand they were placed with a offset from each other in two dimensions, see Figure 29a-29c.

In Figure 29c four different parts are illustrated; two identical metal cuboids (yellow in the figure) which acts as spacers between the beam that were placed on top of them and the mounting and reinforcement plate. The reinforcement plate is visible at the very bottom of Figure 29c and consist of aluminum. The mounting plate have several ledges used to create the offset needed between the fingers. Also, to accommodate for the thumbs movement, guide holes for the strings are extruded from the plate. To guide the strings for the thumb two holes were made in the mounting plate to keep the two axes in place together with mounts in the palm, creating a 90° bend for the strings.



(a) The whole hand (b) The hand excluding palm and backhand (c) Mounting plate, spacers and reinforcement plate

Figure 29: Concept of the robotic hand

To rearrange the strings to accommodate them for their paths to their respective finger a guiding plate, see Figure 30, was mounted between the servos and the hand. Since every finger have four strings controlling the phalanges there are four holes in the guiding plate for each finger.

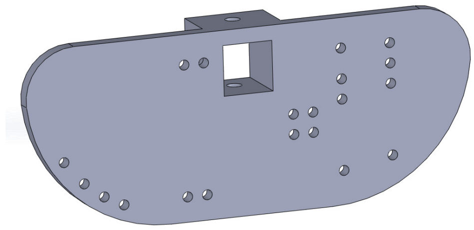
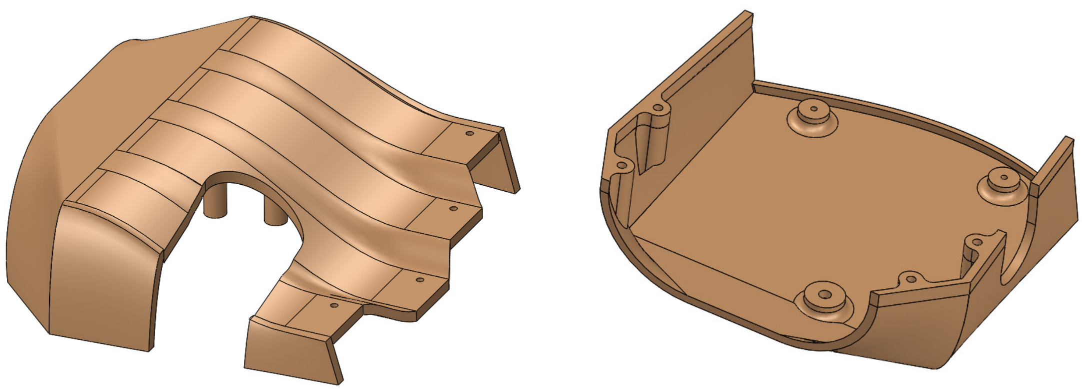


Figure 30: Model of the guiding plate, to be printed in ABS-plastic

6.4.1 Palm and backhand

The palm was designed to help the fingers maintain a good grip of a cylindrical object, see Figure 31a. It is also removable to simplify maintenance of the strings and electrical wires going from the robotic fingers to the robotic forearm and further down to the *Arduino*. Two mounts are extruded from the underside for support of the axes guiding the thumbs strings, visible through the hole accommodating the palm for the thumbs movement. Four holes close to the fingers keep the palm fixed to the hand with the help of screws and the finger mounts.

To maintain the similarity of a human hand, a backhand, and the sides connecting it with the palm, was implemented on the robotic hand. The backhand creates a protective cover for the bolts and gives support to the palm, see Figure 31b. The four holes at the edges have corresponding holes in the palm and are fitted with pins keeping the two parts fixed in two dimensions.



(a) Model of the palm

(b) Model of the backhand

Figure 31: Models of the palm and backhand, to be printed in ABS-plastic

6.4.2 Robotic fingers

The design for the robotic fingers were limited by the chosen concept and several entries in the list of criteria, see Table 7 Appendix A; 1.2 *Same number of joints in the robotic fingers as in human fingers*, 1.3 *Feel whether the robotic hand is in contact with an object* and 1.12 *Maximum size 1.5 times the size of a human hand*.

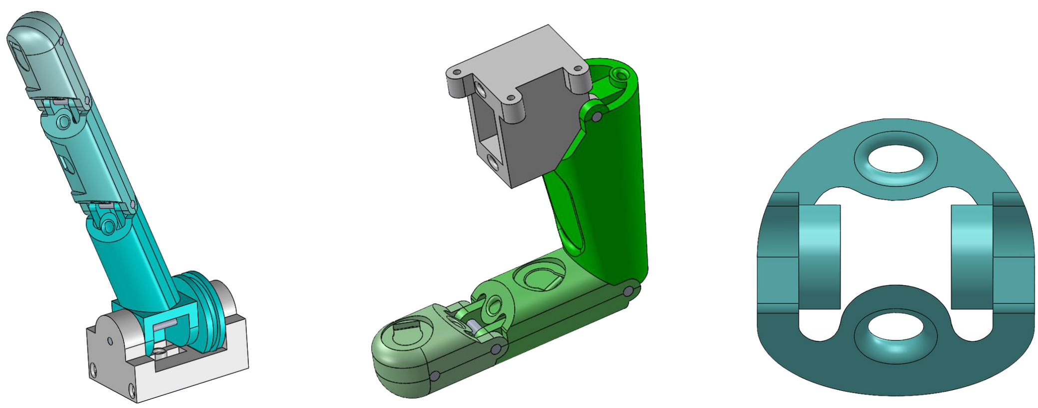
Both outer phalanges are connected to the same servo while the inner is controlled by a single servo. To fully make use of the servos rotation range, discussed in Section 3.1, the distance from the phalanges axes of rotation and the channel for the strings vary between the outer and inner phalanges, see Figure 32b, making the length the strings contract/expand optimal for their corresponding servo.

A mount for the finger is visible as the grey block making it possible to fix it to the hand. To create friction between the fingers and the object the hand is grasping, a friction pad with rubber like properties was mounted on each finger. A socket was implemented to accommodate the fingers for ease of construction. Another function of the friction pad is to evenly distribute force on the pressure sensors mounted in the socket beneath. Every finger has pockets for two pressure sensors, one on each of the outer phalanges. The friction pad are also acting as protection from sharp objects. However did the majority of the sensors broke during construction and due to limited resources no replacements were installed.

The thumbs phalanges was designed in a similar way; the two outer phalanges are controlled by the same servo and each have a pressure sensor beneath a friction pad. However the sockets produce a slight angle, see Figure 32a, relative the normal of the surface to optimize contact area.

A block at the inner end of the thumbs inner phalanx, see Figure 32a, gives it the ability to move between the can-grabbing and handshake positions. A limb similar to the outer phalanges makes an angle of 70° with the inner block and also has a slight rotation around its own axis to resemble a human thumb.

In Figure 32c, a single middle phalanx is presented. The view is from the outer phalanx and shows the string channels, the hollow area which contain electric wires to the pressure sensors and the joints joining the outer and the middle phalanx.



(a) Model of the thumb (b) Model of a finger (c) Model of a phalanx

Figure 32: Models of the different finger parts, to be printed in ABS-plastic

6.5 Board for prototype testing

The arm by itself is not stable enough for testing without being mounted on a more static structure. Therefore a wooden board, see Figure 33, was designed to withhold the substantiality necessary for the hand to operate. As the hand uses a DC power supply as a source of power and several electronic devices for different tasks, the wooden board suits as an area on which these devices are mounted aside of the actual robotic arm making it easy to move around.

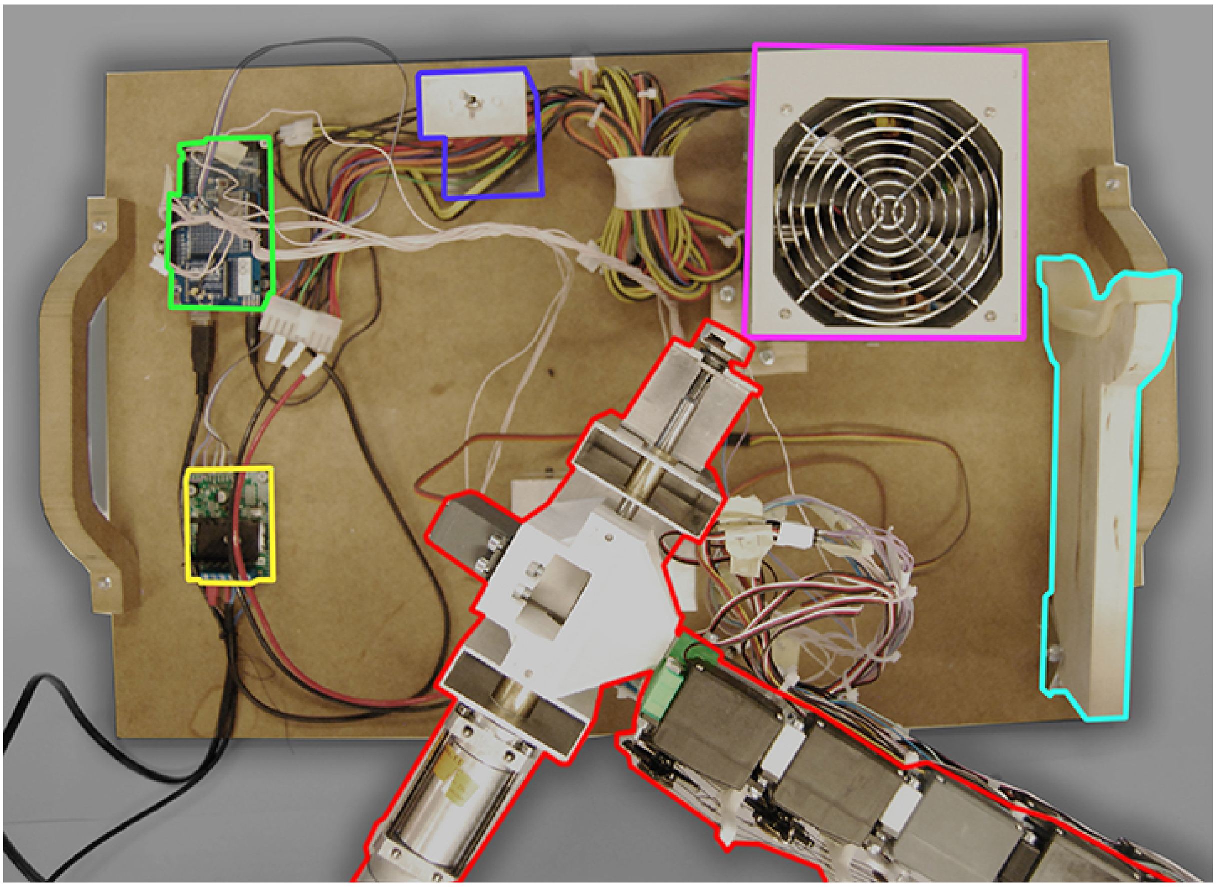


Figure 33: Picture of the testing station

Referring to Figure 32, in the upper right corner the DC power supply (pink) is attached and in the lower corner an arm (turquoise) for supporting the robotic arm when it is on standby preventing any unnecessary wear on the mechanical parts. Moving towards the middle on the upper side a switch (blue) is placed, this is crucial and serve as an emergency stop to shut down the whole system if unexpected movements should occur which could damage the arm something in its surrounding. The lower side contains the actual robotic arm (red). Continuing towards the left side, in the lower corner the motor driver (yellow) for the DC-motor is visible and in the upper corner the *Arduino Mega* (green) is placed.

7 Evaluation of Objectives

In this section the result of testing the partial goals, which were set at the beginning of this project, will be presented and validated. Another important aspect is how well the system meets the requirements and desiderata, which both will be evaluated below.

7.1 Test result regarding partial objectives

The partial objectives of this project are illustrated in Figure 34. Some of the goals can be achieved separately, but mostly the arrows in the picture describe the order of testing. Objectives regarding control and robotic arm was tested independent of each other, thus the numbers does not illustrate the order of testing apart from the final two objectives. The partial objectives marked in red in the figure failed.

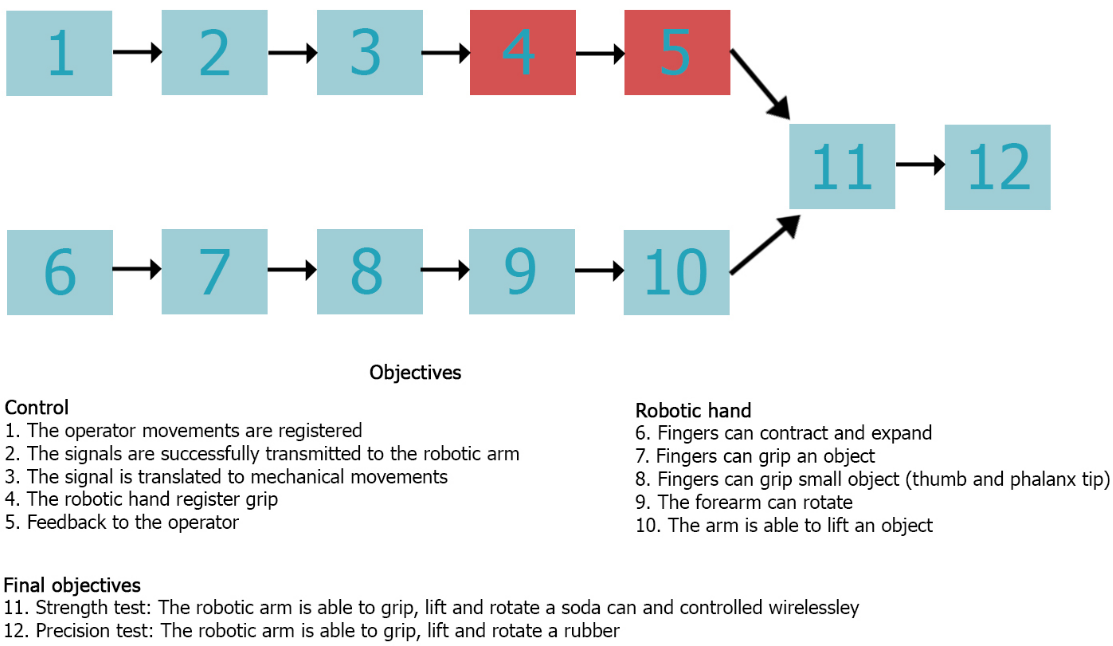


Figure 34: The twelve objectives that were created at the start of the project, red objectives were not completed

1. The operator movements are registered

As the flex sensors change resistance when bent, it is possible to map their changes to angles of the servos, using a transfer function. These angles are then sent to the servos to make them move, meaning the robotic fingers can imitate the movements of the operator's fingers using a calibration method. This test was performed successfully and proved that the concept was achievable.

2. The signals are successfully transmitted to the robotic hand

By using the wireless *Xbee*-modules for *Arduino*, data was successfully transmitted. The basic test of the wireless communication was conducted by defining a list of elements and sending that list from one *Arduino* then receiving and printing that list from the other *Arduino*.

Whilst performing a test of the finger movements, a range test was conducted. The results from this test proved that the controller and the robotic arm can communicate on a distance of approximately 10 m. It also verified that they can communicate through a window 10 m away.

3. **The signal is translated to mechanical movements**

   From Section 3, a transfer function was retrieved which translates the registered angle from the operator's finger movement to the required angle of the servos. After the information from the flex sensors are sent, the *Arduino* on the robotic arm translates it to an angle and then uses this transfer function to send the information to the servos. This was tested by a comparing calculated values and obtained values from the *Arduino*, which were the same and therefore the test was successful.

4. **The robotic hand register grip**

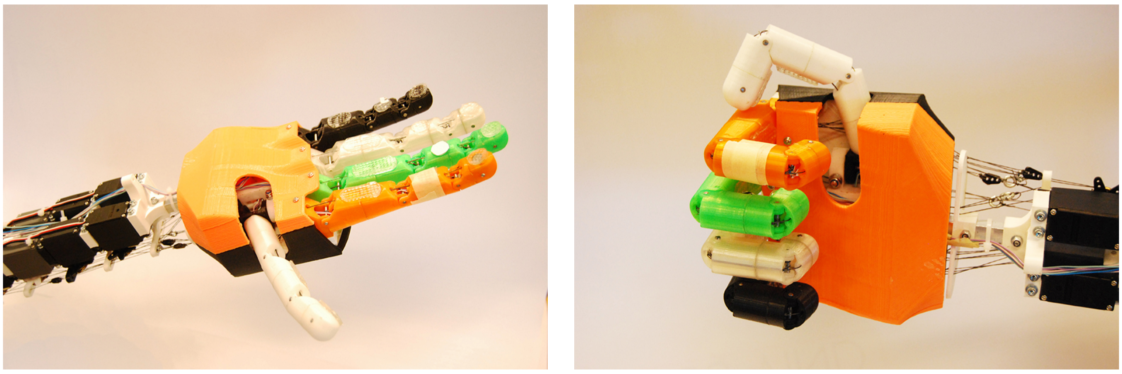
   The hand was only partially able to register the grip. Mainly due to the fact that the majority of the pressure sensors broke during construction. With four sensors left, which are attached on the index finger and the thumb, it was possible to detect when these fingers made contact with an object and when the pressure of the grip changed. Although, because there are so few sensors left working, it was decided not to implement this function but instead prioritize other objectives.

5. **Feedback to the operator**

   As feedback to the operator is depending on reading of grip this objective could not be verified and therefore considered failed.

6. **Fingers can contract and expand**

   As shown in Figure 35 the mechanics in the assembled fingers as well as the thumb are working perfectly. The robotic hand can both grip with all fingers and the thumb as well as pinch something small using one finger and the thumb. The thumb can also switch between the two modes; can-grabbing and handshake.



(a) Fingers fully expanded

(b) Fingers fully contracted

Figure 35: Objective six: Fingers can contract and expand

7. **Fingers can grip an object**

   The motion of gripping a soda can was performed successfully as can be seen in Figure 36 and the objective was therefore considered accomplished.

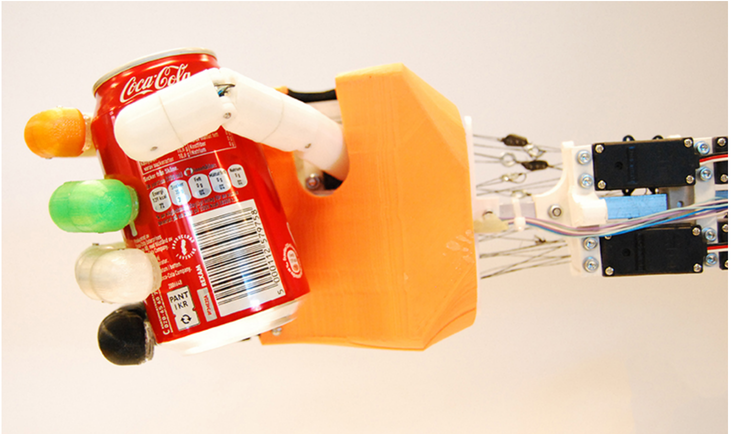


Figure 36: Objective seven: Fingers can grip an object

8. **Fingers can grip small objects (thumb and phalanx tip)**
   A small rubber eraser was used to verify the pinch grip and precision of the robotic hand. Testing was considered successful, and the objective thus accomplished, as is evident from Figure 37.

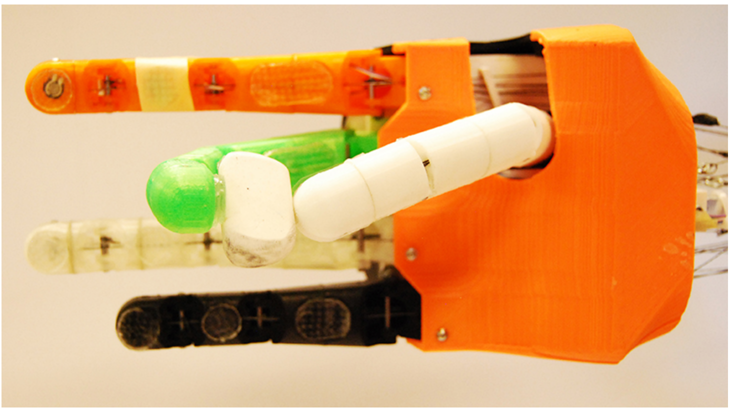


Figure 37: Objective eight: Fingers can grip a small object (thumb and phalanx tip)

9. **The forearm can rotate**
   This is a simple test of the servo controlling the roll rotation of the robotic forearm. As the operator rotates his arm the robotic arm also rotates, as can be seen in Figure 38 thus proving the objective accomplished.

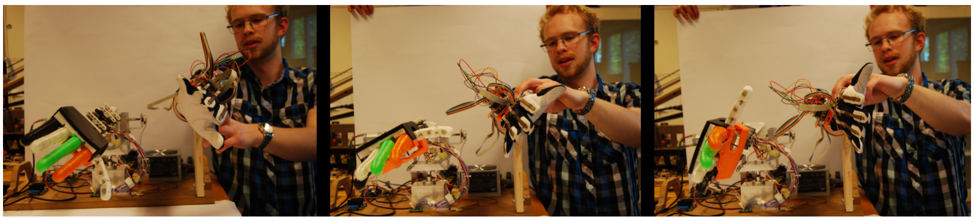


Figure 38: Objective nine: The forearm can rotate

10. The arm is able to lift an object

By using a PID-regulator function in the *Arduino*, and a rotary sensor as feedback, the speed and direction of the DC-motor could be controlled. This test proves that the mechanics and electronics are working in interaction with the control unit.

11. Strength test: The robotic arm is able to grip, lift and rotate a soda can and be controlled wirelessly

This is the first test that proves that the arm is functioning as it should in its whole. To demonstrate this a short video was recorded, and frames taken from this video lined up after each other. They are presented in Figure 39 and proves that the test was accomplished. A can was however not used, although instead two *50 cl* bottles filled with water was, which proves the lifting capacity of 1 *kg*. It is also approximately the same shape as a *33 cl* soda can.

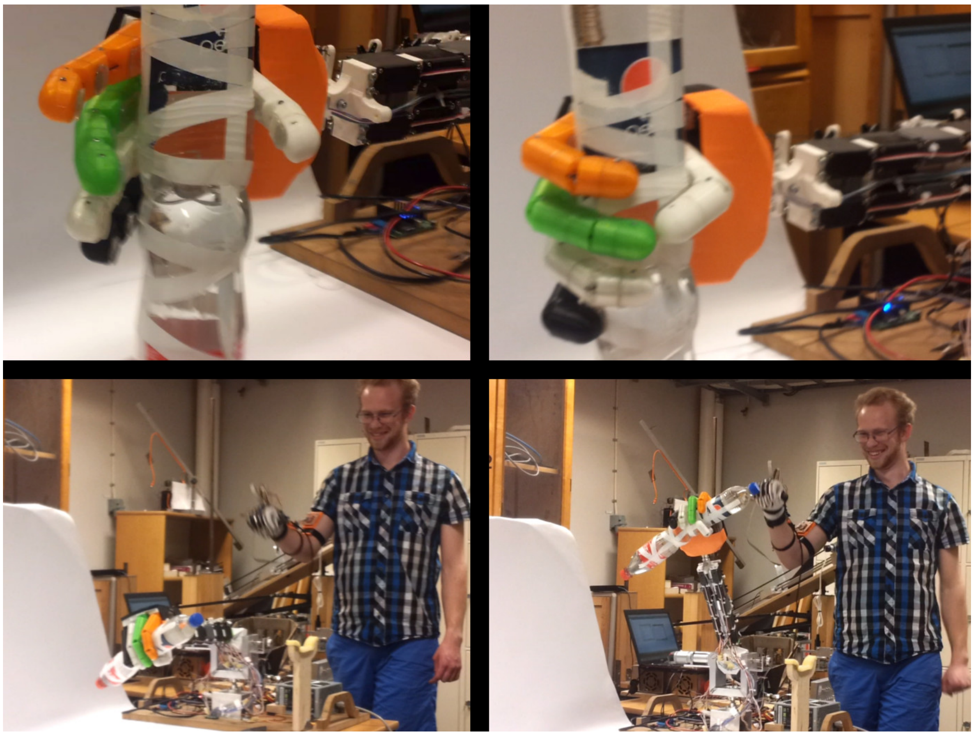


Figure 39: Frames taken from a video which shows the robotic arm grasping two 50 *cl* water bottles filled with water and then rotating and lifting it.

12. Precision test: The robotic arm is able to grip, lift and rotate a rubber

The last test would see if the robotic arm had the desired precision as it attempts to pinch, lift and rotate a small rubber eraser. Figure 40 shows the hand holding a rubber which proves that the robotic arm is able to grip and hold small objects. Although not shown in the figure, the robotic arm is able to both lift and rotate the rubber as desired.

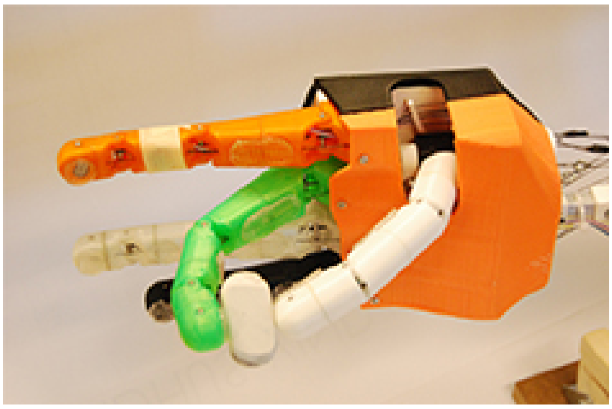


Figure 40: objective twelve

7.2 Check against the list of criteria

A check against all requirements, (R) and desiderata, (D) were made to determine if they were accomplished, for a compact list check Appendix A Table 7.

7.2.1 Successful requirements and desiderata

Function/Design

1.1. Four fingers, one thumb, (R) Figure 40 proves this requirement was successful.

1.2. Same number of joints in the robotic fingers as in human fingers, (R) As seen in Figure 35a the robotic fingers have the same number of joints as human fingers.

1.4. Be composed of an elbow, a forearm and a hand, (R) The whole arm can be seen in Figure 1a and consists of all previously mentioned parts.

1.5. Maximum size 2 times as big as a human hand, (R) The most critical distance is the one from palm to backhand, as it is almost 71 mm. Measurements have shown this requirement successful as a human hand is around $40 - 50$ mm for the same distance.

Should be able to:

1.6.1. Grip cylindrical objects with a diameter of 54 mm**, (R)** Although most tests were conducted using a bottle and the diameter originates from a soda can Figure 36 show the robotic arm holding a soda can.

1.6.2. Grip parallelepiped's with measurements 10 x 60 x 20 mm**, (R)** These measurements originates from a rubber eraser and Figure 37 conclude this requirement successful.

1.6.3. Lift cylindrical objects weighing up to 500 g **independent of the hands position, (R)** Although Figure 39 shows the arm lifting 1 kg it proves the ability to lift 500 g as well.

1.6.4. Lift parallelepiped's weighing up to 100 g **independent of the hands position, (R)** Even though Figure 37 does not show the arm moving the rubber eraser around, it concludes this requirement successful.

1.6.5. Rotate forearm 180° around its own axis, (R) No pictures were taken as the roll movement were in one of its end points but Figure 38 shows a angle rotation of close to 180°.

1.6.6. Move the forearm from parallel with the floor to perpendicular with the floor, (R) Figure 1a and 38 shows the arm in the respective positions.

1.7. Simple installation (standardized tools), (R) No custom made tools were created for the assembly or construction of different parts in the robotic arm.

1.8. All rotations and bending should be independent of each other, (R) All rotations are independent of each other. After implementing the compensation evaluated in Section 3.1.1 the bending of fingers are also independent of other movements.

1.9. The robotic arm should not have a length greater than 0.6 m, (R) Partially complete depending on definition. From the elbow joint up till the fingertip of the middle finger the criteria is complete. But the distance from base plate to the same finger the distance is greater than 0.6 m.

1.10. The robotic arm should be able to do a yaw movement (90°)**, (D)** As shown in Figure 42a-42c Appendix E the arm is possible to do a yaw movement.

1.11. Lift cylindrical objects weighing up to 1000 g independent of the hands position, (D) As shown in Figure 39 this test was successful.

Performance

2.1. Maximal latency, 1 second, (R) The results presented in Table 1 indicates that the hardware registered the movements and produced the desired signals on time, see Appendix E for footage of the test.

Operator start	**Robotc finger start**	**Response time**	**Successful R**	**Successful D**
0 + 91	273 - 91	273 ± 91	Yes	Yes

Operator finish	**Robotc finger finish**	**Response time**	**Successful R**	**Successful D**
455 - 91	1001 - 91	546 ± 91	Yes	No

Table 1: Response time for bending of a finger, all times are in [ms]

2.2. Minimizing control errors in the robotic arm to a limit where the ability to lift and grip won't be compromised, (R) As no object were dropped due to control errors during testing this requirement is proven successful.

2.3. The angle difference between the operators fingers and the fingers of the robotic hand can not be more than; 15°, (R) Since the majority of the results presented in Table 2 are within the allowed offset, the test was successful. For footage of the test, see Appendix E.

Check	Offset [°]	Successful	
		R	**D**
1	8.79	Yes	Yes
2	12.96	Yes	No
3	29.40	No	No
Mean	17.05	No	No

Table 2: Bending of a finger

2.4. Angular offset in roll movement maximum; 20° from reference, (R) As all results in Table 3 are within the allowed offset the requirement was proven successful. For footage of the test, see Appendix E.

Check	Offset [°]	Successful	
		R	**D**
1	3.99	Yes	Yes
2	1.90	Yes	Yes
3	16.47	Yes	No
Mean	7.45	Yes	Yes

Table 3: Roll movement

2.5. Angular offset in pitch movement maximum 20° from reference, (R) All results presented in Table 4 were within the allowed offset and the requirement is proven accomplished. For footage of the test, see Appendix E.

Check	Offset [°]	Successful	
		R	**D**
1	5.93	Yes	Yes
2	7.49	Yes	Yes
3	5.77	Yes	Yes
Mean	6.40	Yes	Yes

Table 4: Pitch movement

2.7. Regulate pressure on object in hand automatically, (D) Failed due to lack of time and broken pressure sensors.

2.9. Angular offset in roll movement maximum 10° from reference, (D) As shown in Table 3 a majority of the results were within the allowed offset and proves this desideratum successful. For footage of the test, see Appendix E.

2.10. Angular offset in pitch movement maximum 10° from reference, (D) All results presented in Table 4 is within the allowed offset and concludes this desideratum successful. For footage of the test, see Appendix E.

2.11. Angular offset in yaw movement maximum 10° from reference, (D) The yaw movement was a highly prioritized desideratum, and as shown in Table 5 the precision desired is met. For footage of the test, see Appendix E.

Check	**Offset** [°]	**Successful**
1	7.51	Yes
2	6.11	Yes
3	14.11	No
Mean	9.24	Yes

Table 5: Yaw movement

Environment

3.1. Exchangeable parts with standardized tools, (R) All parts are exchangeable without any customized tolls.

3.2. Constructed with environmentally friendly materials, (R) No hazardous materials have been used in the construction of the robotic arm.

3.4. Most custom made parts created by a 3D-printer, (D) As all parts not requiring great strength or durability is 3D-printed this, desideratum is declared fulfilled.

Control

4.1. Wireless control with a range of 10 m, (R) The range for controlling the robotic arm exceeds 10 m.

4.2. Real-time control, (R) As all signals from the control unit is sent close to immediately to the robotic arm, control is considered to be in real-time.

4.4. Maximum weight of the control unit, 1 kg, (R) The weight of the control unit does not exceed the limit of 1 kg.

4.7. Maximum weight for the control unit, 0.5 kg, (D) The weight of the control unit does not exceed the limit of 0.5 kg.

4.9. Wirelessly controllable separated by a wall, (D) The Operator could stand in another rum with a concrete wall between him and still be able to control the robotic arm

7.2.2 Unsuccessful requirements and desiderata

Function/Design

1.3. Feel when the robotic hand is in contact with an object, (R) The pressure sensors where to few to show a good enough representation of the grip so this was not fully implemented. Thou if connected to a computer it could be seen that there was a change of resistance from the pressure sensors that where left on the fingers.

1.12. Maximum size 1.5 times as big as a human hand, (D) Due to the distance from palm to backhand is greater then 1.5 of a human hand this desideratum was not accomplished. However were all other dimensions within this criteria.

Performance

2.6. Maximal latency, 0.5 seconds, (D) This desideratum was not completely achieved as the values commute to much. However is it within the allowed latency with regard to the deviation.

2.8. Angular offset in finger joints maximum 10° from reference, (D) With the result presented in Table 2 it is concluded that this desideratum failed a majority of the test. For footage of the test see Appendix E.

Environment

3.3. Not create sound over 70 *dB* at a distance of 1 m, (R) No measurements were below the allowed limit as can be seen in Table 6.

Check	**Level** [dB]	**Successful**	
		R	**D**
1	93	No	No
2	92	No	No
3	94	No	No
Mean	93	No	No

Table 6: Sound level

3.5. Not create sound over 50 *dB* at a distance of 1 m, (D) Since requirement 3.3. failed this desideratum failed as well.

Control

4.3. Controlled with one hand, (R) Failed due to the button mounted on the main board switching the thumb between "handshake"- and "can-grabbing" position.

4.5. Roll, pitch, yaw and finger movement must be independently controlled, (R) The pitch and roll movement is not completely independent of each other if the arm is standing right up.

4.6. Learn movements, (D) Failed due to lack of time.

4.8. Wireless control with a range of 40 m, (D) Test proved this desideratum unsuccessful as the operator could not control the robotic arm from over 40 m.

4.10. Controllable over Internet, (D) Failed due to higher priorities and the choice of Xbee.

8 Discussion

In this section the result of the testing is analyzed regarding level of achievement. More contextual aspects as design parameters and chosen solutions are also discussed as well as problems encountered and potential improvements to the design.

8.1 Evaluation of test results

After reviewing many of the test results, one can speculate if too many features were desired regarding degrees of freedom resulting in characteristics such as response time, precision and feedback were lower prioritized. Overall desired functions like gripping, rotating and lifting worked fine but the precision could be improved upon as well as the calibration process could be more precise. The existing design with gyroscopes and accelerometers gives the design these desired features and is a suitable way of reading the operator's movements. If a gyro was tilted 90° it lost its reference, causing the roll and pitch movements not to be independent of each other. Yaw movement, on the other hand, was unaffected by this restriction since this movement was read by a separate MPU6050 unit. Even though the reading of one rotation was affected by another rotation, the gyro was able to keep its reference and this could be compensated for within the code - up to 90° that is.

8.1.1 Finger movement

The fingers had an offset between the robotic hand and the operator hand which was greater than the demanded 15° in one of the three tests, see Appendix E. This is most likely a result of the placing of strain sensors on the control unit. Partly they did not follow the operator's move of the fingers to their normal end positions. But they are also placed in such way that they influence on another, thus if the operator moves for instance the middle finger it influence both the contiguous fingers. To eliminate this source of failure the strain sensors need to be place in such way that they read signals independent of the other finger motions. Also as the operators hands differ, the unit might need a function that alter the size or signal recording in a more precise way then the existing calibrating as the flaw more likely depends on the design of the hand rather than the program.

8.1.2 Roll, pitch and yaw movement

Regarding the mimic of the operator, the robotic arm had some offsets as the angles in the robotic arm did not correspond to the operator. The difference was held within the tolerated boundary, 10°, when the movements of the elbow was examined, see Appendix E. This prove that the gyro along with the accelerometer was sufficient for this solutions regarding accuracy.

The robotic arm had some problems executing small movement because the actuator first had to overcome the moment of inertia, both concerning acceleration and retardation, which made it hard to regulate. During early testing of the movement the arm sometimes made unexpected movements. Therefore a more reliable code was implemented with safety features included in order to stop the robotic arm from damaging itself or its surroundings. As the robotic arm performs some of the quicker movements, some indication regarding weak framework could be noticed in the elbow section. The elbow swings especially when it preform the yaw movement. These motions needs to be better regulated to be smoother, alternatively the framework needs a new and more robust design.

8.1.3 Sound level

The desired maximum sound level of 70 dB was exceeded mainly by the epicyclical gearbox. Either the gearbox needs to be better greased to reduce the sound or a designed to make less sound. If the sound which origin from the gearbox is absent the volume should stay below the desired boundary.

8.1.4 Control unit

Demonstrably the control unit contains all the necessary equipment to measure the operators movement even though it may lose the reference which is discussed earlier in this section. But due to its complexity and dimensions it was experienced a bit artless and restricted the degrees of freedom a bit too much. The board holding the microcontroller and sensors could be developed to either be sew on a clothing which follow the body movements better or be minimized in size.

8.1.5 Response time

The response time closely fulfil the desiderata but as the uncertainty are to major the response time need to be more stable and a bit lowered. The problem lies within the signal processing as the hardware are sufficient for the task of measuring quick and precise. The code processing the data and transfer it needs some evaluating to make it more streamlined. There could be some unnecessary loops which could be handled in different approaches making the program faster. The regulation regarding the difference between the set point and the existing point need further analysis to make it more precise with the best applicable PID values.

8.1.6 Pressure sensors - exposed of fatigue

The pressure sensors used proved to be fragile and therefore six of ten broke during the construction phase. It was discovered late that they broke, and because of limited time and money no new sensors were installed. The main reason for the sensors breaking was limited space in the fingers, causing the sensors to be bent back and forth during installation and also in some cases during finger movement, ultimately breaking the sensor.

8.1.7 Controlled with one hand

Because the thumb only move between two static positions a button were added to the control unit. This button is unreachable by the hand the control unit is attached on forcing the operator to press it with the other hand. It should not be hard to implement another way of switching between the positions, however the decision were made to use a button to avoid unnecessary coding problems since several other daunting more important tasks had to be solved.

8.2 Encountered problems

During the course of the project some original solutions proved to be insufficient for the problem they were supposed to solve. Some of these solutions were replaced with other more promising solutions. Other solutions were not replaced and the problem still remains, since it had a low priority.

8.2.1 Inadequate tightening of strings

A method using small plastic pieces, directors, with three holes were used to tighten the strings, as described in Section 4.10. Close to the end it was discovered that the friction wasn't enough to stop the strings from loosen up. To solve the problem the directors were removed or used to extend new strings while the servos got a plate underneath the servo wheel with several holes in it on different distances from the center. Allowing a small pin to be moved around until a hole is found that tense up the string.

8.2.2 String compensation for inner phalanx movement

Before the solution presented in, Section 3.1.1, with the servos programed to compensate for the offset of the phalanx the intention was to use springs to keep the strings tense. A finger mounted on a test rig with its strings going through a spring proved this solution effective. However when implemented on the robotic arm the strings seemed to create too much friction in all of the guiding holes causing the spring to extend instead of the finger contracting.

8.2.3 Implementation of a kill switch

After some close calls while testing different programs for the robotic arm it was determined that a kill switch was needed. This due too the fact that switching off the DC power supply did not cause a direct stop of the arm's movement since the power supply holds a significant amount of electric energy in inductors and capacitors. The kill switch were connected to chosen ground cables making it important to connect different cables to the right connector on the DC power supply so the circuit can be broken.

As it turned out the electrical energy was stored longer then desirable as the switch was turned off. This caused the prototype to do uncontrollable motions when the switch was turned back on even when the DC power supply was turned off. A temporary solution to this was to install a fan which was always connected to the power supply. When the kill switch breaks the circuit, the fan uses the stored energy in the coils preventing twitching and unexpected movements when the circuit is closed again.

8.2.4 Available resources during construction

One of the most limiting resources turned out to be the 3D-printing. Since the printers were handled by a single employee with more tasks than just 3D-printing and there was several other bachelor thesis projects also that needed parts there were a long waiting time to get parts. At the end parts were instead printed on a private 3D-printer owned by one of the project members.

All of the metal and wood work were conducted in the prototype workshop. Limited number of spots per day, machines and instructors caused the work to be quite ineffective and therefore dragged out the construction phase of the project. Thou the constructions got an early start which result in additional help from the instructors and much access to the machines because the prototype workshop was not that crowded in the begning .

8.3 Suggestion of improvements

By doing this kind of projects new knowledge and experience are obtained. Therefore it is obvious that several ideas of improvements are considered. Improvements that would greatly affect either performance, price, complexity or wanted features are discussed in this section.

8.3.1 Usage of counterweight or spring

As testing indicates the force the DC-motor needs to apply on the arm while lifting or lowering the arm alter. This makes the motion unstable as, for example, the lowering phase is too quick which may expose both the arm and the object being lifted to damage. A first possible solution to this is use of counterweights. This will make the center of gravity positioned in the axis of the elbow and thereby lowering the alternation of force the DC-motor needs to counter. The problem with this is that if the arm uses one counterweight the lever for the load will change as the arm rotate around the elbow axis which might be irregular with the alternation of load from the forearm. If the counterweight is split into several small pieces and placed with an offset among each other the alternation can be prevented.

Regardless of the mentioned solutions the design run to the risk of being placed on the opposite side of the forearm and as the arm moves upwards the counterweight will hit the lower frame of the ground underneath it, which result in either the arm get stuck or the counterweight can rest against the ground and still let the arm move by using a hinge. The prototype is not design to be capable of manage any greater load than 1 kg, thus the counterweight is superfluous as it is a better solution for heavier objects.

A similar solution more applicable for the smaller load is the use of a spring. This spring would be tense when the arm lies horizontally, where more torque is needed, and relaxed when the arm is vertical. Due to the approximate linearity of the force applied by the spring, the resulting torque would ensue as if a large number of small counterweights were used. A spring would also be much easier to apply on the design as it can be well integrated in the elbow without restricting its degrees of freedom.

By diminishing of the torque, by using either a counterweight or a spring, cause the elbow movement to act controlled but also enable the utilization of a servo instead. As a result the design would get smaller, partly because the DC-motor and its epicyclical gearbox is more then twice the size of a servo and partly because less electronic connections are needed as the motordrive can be erased. Along with changing from DC-motor to servo more benefits will occur. The main source of the high sound level was from the DC-motor's gearbox, without it the sound level will be much lower and it was shown in early test of reading the operator's arm that these readings was easier to implement on a servo then on a DC-motor which would have saved time.

8.3.2 Appliance of struts

After several attempts to tighten the strings along with the process of slipping the strings through the leaders between the servo and the phalanx the design with strings seemed complicated and beget annoyance. The design needs another approach to make the transmission between servo and finger simpler and more robust. If a new design is developed which enables the use of struts, the tighten process would be unnecessary which would save a lot of time and endurance, although other problems may occur. However; it is strongly recommended to investigate this further if another project would continue this project or build a similar robotic arm.

Struts could make the design considerable bigger unless they integrates in both fingers and forearm in an elegant way making the design more compact. One way of doing this is to design the fingers to integrate with each other meaning that each finger only use one connection point at the very beginning of the finger, thus the finger would contract and expand by applying force in the desired direction. In other words, the whole finger would need a design so the same motions amongst the phalanges are achieved but the applied force originate from only one actuator. This was discussed for a brief period at the beginning of this project before it was dropped due to the high rate of complexity.

8.3.3 Guidance of strings

The amount of strings that would met up at the wrist of the robotic arm was always know but the need for guidance of them was underestimated. The created servo holders, See Figure 27, has only one row of holes for guidance. This creates a risk for the stings to get tangled and at the same time it was hard to achieve an optimal guidance for the stings due to them easily coming in contact with each other which creates friction. If another row of holes would have been implemented on the mounts near the robotic hand the risk of tangle would have decreased and the guidance would have been easier to optimize.

8.3.4 Improvement of feedback design

As noted during various tests in the project, the design is not optimized regarding the pressure sensors. The sensors used in this project partly consist of a conductor isolated with a flat layer of plastic. As this plastic part is longer than most of the corresponding phalanges the plastic is exposed when placed in the joints, thus the bending of fingers cause fatigue in the sensor. In other words; the sensors broke after several bendings of the fingers during testing. An issue was also that it proved difficult to attach the pressure sensors in the right place because they had to be soldered to the cables when the flat plastic layer almost was inside the finger, and once the sensors were in place they were hard to remove.

The pressure sensor are vital to the feedback function, therefore either the fingers need a new design allowing the sensors to be placed in such a way that they avoid fatigue or other sensors needs to be obtained which are more adaptive to the existent finger design. One should also make it feasible to first solder them to the cables and then attach them to the finger making easier to get them in place.

9 Conclusion

The main purpose for this project was to build an anthropomorphic robotic arm that is able to grip, lift and rotate a cylinder shaped object and to pinch, lift and rotate a small rubber eraser. This was deemed accomplished as objective 11 and 12 in Section 7 was conducted successfully. The simulations in Section 3 shows which torques is needed by the operating actuators and together with the validation of the material strength using *Ansys* the design was proven to work in theory. When tests were done it showed that it worked in practice as well.

Regarding the custom made parts of the robotic arm, 3D-printing technology appeared to be an excellent manufacturing process fitted for this kind of technical problem. It allowed a high customizability and great freedom when designing the arm. The material properties is sufficient enough for the design meaning it has enough strength within the desired amount of used material. 3D-printing is also very efficient regarding cost and time.

The list of criteria was mostly satisfied which section 7.2 discusses. There were a few solitary mishaps but the only significant was the inadequate design regarding pressure sensors. This is also the most critical improvement discussed along with the stretching process of strings.

The gyro along with the accelerometer gives the design the desired features and a suitable way of reading the operators movements. Even if the control unit is attached alongside the main part of the operators arm the steering, see Section 6.1, is intuitive and allow the operator to freely move the arm almost naturally without impediment. Some restrictions was discovered as the gyro lost its reference if it was carried in a certain way. To make it more flexible evaluation needs to be done considering how the different coordinates depend on each other.

As for the list of criteria and desiderata, 23 criteria's out of 27 and 9 desideratum's out of 16 is to be considered accomplished. For the full evaluation see section 7.

To sum up the report the goal regarding the desired functions was achieved as the hand could be controlled in a suitable way and manipulate the defined objects as stated in Section 1.2. As this project only designed and evaluated a prototype, no analysis regarding harsh environments was done, but with a suitable protection which could capsule the vulnerable electronic equipment the prototype is considered to work in these kind of environments.

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A List of Criteria

Table 7: List of criteria

Nr.	Description	R/D	Importance
1.	**Function/Design**		
1.1.	Four fingers, one thumb	R	-
1.2.	Same number of joints in the robotic fingers as in human fingers	R	-
1.3.	Feel whether the robotic hand is in contact with an object	R	-
1.4.	Be composed of an elbow, a forearm and a hand	R	-
1.5.	Maximum size 2 times as big as a human hand	R	-
1.6.	*Should be able to:*		
1.6.1.	Grip cylindrical objects with a diameter of 54 mm	R	-
1.6.2.	Grip parallelepiped's with measurements 10 x 60 x 20 mm	R	-
1.6.3.	Lift cylindrical objects weighing up to 500 g independent of the hands position	R	-
1.6.4.	Lift parallelepiped's weighing up to 100 g independent of the hands position	R	-
1.6.5.	Rotate forearm 180° around its own axis	R	-
1.6.6.	Move the forearm from parallel with the floor to perpendicular with the floor	R	-
1.7.	Simple installation (standardized tools)	R	-
1.8.	All rotations and bending should be independent of each other	R	-
1.9.	The robotic arm should not have a length greater than 0.6 m	R	-
1.10.	The robotic arm should be able to do a yaw movement (90°)	D	11
1.11.	Lift cylindrical objects weighing up to 1000 g independent of the hands position	D	7
1.12.	Maximum size 1.5 times as big as a human hand	D	5
2.	**Performance**		
2.1.	Maximal latency, 1 second	R	-
2.2.	Minimizing control errors in the robotic arm to a limit where the ability to lift and grip wil not be compromised	R	-
2.3.	Angular offset in finger joints maximum 15° from reference	R	-
2.4.	Angular offset in roll movement maximum 20° from reference	R	-
2.5.	Angular offset in pitch movement maximum 20° from reference	R	-
2.6.	Maximal latency, 0.5 seconds	D	13
2.7.	Regulate pressure on object in hand automatically	D	10
2.8.	Angular offset in finger joints maximum 10° from reference	D	14
2.9.	Angular offset in roll movement maximum 10° from reference	D	12
2.10.	Angular offset in pitch movement maximum 10° from reference	D	8
2.11.	Angular offset in yaw movement maximum 10° from reference	D	9
3.	**Environment**		
3.1.	Exchangeable parts with standardized tools	R	-
3.2.	Constructed with environmentally friendly materials	R	-

Table 7: List of criteria

Nr.	**Description**	**R/D**	**Importance**
3.3.	Not create sound over 70 dB at the distance of 1 m	R	-
3.4.	Most custom made parts created by a 3D-printer	D	15
3.5.	Not create sound over 50 dB at the distance of 1 m	D	4
4.	**Control**		
4.1.	Wireless control with a range of 10 m	R	-
4.2.	Real-time control	R	-
4.3.	Controlled with one hand	R	-
4.4.	Maximum weight of the control unit, 1 kg	R	-
4.5.	Roll, pitch, yaw and finger movement must be independently controlled	R	-
4.6.	Learn movements	D	3
4.7.	Maximum weight for the control unit, 0.5 kg	D	6
4.8.	Wireless control with a range of 40 m	D	2
4.9.	Wirelessly controllable separated by a wall	D	5
4.10.	Controllable over Internet	D	1

Table 8: Importance of desiderata

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ	Importance
1	x	-	-	-	-	-	-	-	-	-	+	+	+	0	0	0	-6	5
2	+	x	+	+	+	-	-	-	+	-	+	+	+	+	+	+	7	11
3	+	-	x	-	-	-	-	-	-	-	+	+	+	+	+	+	-1	7
4	+	-	+	x	+	-	+	+	+	-	+	+	+	+	+	+	9	13
5	+	-	+	-	x	-	-	+	+	-	+	+	+	+	+	+	5	10
6	+	+	+	+	+	x	+	+	+	-	+	+	+	+	+	+	13	14
7	+	+	+	-	+	-	x	+	+	-	+	+	+	+	+	+	9	12
8	+	+	+	-	-	-	-	x	-	-	+	+	+	+	+	+	3	8
9	+	-	+	-	-	-	-	+	x	-	+	+	+	+	+	+	3	9
10	+	+	+	+	+	+	+	+	+	x	+	+	+	+	+	+	15	15
11	-	-	-	-	-	-	-	-	-	-	x	+	-	+	-	+	-9	4
12	-	-	-	-	-	-	-	-	-	-	-	x	-	+	-	+	-11	3
13	-	-	-	-	-	-	-	-	-	-	+	+	x	+	+	+	-5	6
14	0	-	-	-	-	-	-	-	-	-	-	-	-	x	-	+	-12	2
15	0	-	-	-	-	-	-	-	-	-	+	+	-	+	x	+	-6	5
16	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	x	-14	1

Desiderata

1. Maximum size 1.5 times as big as a human hand.
2. The robotic arm should be able to do a yaw movement (90°).
3. Lift cylindrical objects weighing up to 1000 g independent of the arms position.
4. Maximal latency, 0.5 seconds.
5. Regulate pressure on object in hand automatically.
6. Angular offset in finger joints maximum 10° from reference.
7. Angular offset in roll movement maximum 10° from reference.
8. Angular offset in pitch movement maximum 10° from reference.
9. Angular offset in yaw movement maximum 10° from reference.
10. Most custom made parts created by a 3D-printer.
11. Not create sound over 50 dB at a distance of 1 m.
12. Learn movements.
13. Maximum weight for the control unit, 500g .
14. Wireless control with a range of 40 m.
15. Wirelessly controllable separated by a wall.
16. Controllable over Internet.

B Description of Concept

Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
1.1.1 2.2 3.2 4.8 5.1 6.1 7.1 8.1 9.1 10.1 11.3 12.3 13.1.1 14.1.1 15.1 16.1 17.3	1.1.1 2.7 3.7 4.7 5.1 6.4 7.4 8.1 9.1 10.1 11.3 12.1 13.1.3 14.1.3 15.5 16.1 17.3	1.1.1 2.2 3.6 4.8 5.1 6.1 7.1 8.1 9.1 10.1 11.3 12.3 13.1.1 14.1.1 15.1 16.1 17.3	1.1.1 2.7 3.7 4.7 5.1 6.4 7.4 8.1 9.1 10.1 11.3 12.1 13.1.1 14.1.2 15.1 16.1 17.3	1.1.1 2.2 3.2 4.2 5.1 6.1 7.1 8.1 9.1 10.1 11.3 12.1 13.1.1 14.1.2 15.1 16.1 17.3
Solution 6	Solution 7			
1.1.1 2.2 3.2 4.8 5.1 6.4 7.1 8.1 9.1 10.1 11.2 12.3 13.1.1 14.1.1 15.1 16.1 17.1	1.1.1 2.1 3.1 4.8 5.1 6.1 7.1 8.1 9.1 10.1 11.3 12.1 13.1.3 14.1.3 15.5 16.1 17.1			

Figure 41: All of the seven solutions.

Common solutions for all concepts

All of the concepts generated had some common solutions: The glove with flex sensor as a solution for the reading of finger movements. The wireless signals will in all concepts be handled by a wireless transmission module for microcontroller so called Xbee and for interpreting readings a microcontroller will be used. All of the concepts have the same actuator in the roll movement which a servo will be used for. To measure how hard the grip of the robotic hand is all concepts will use pressure sensors. Lastly, the power source to the robotic arm is an electricity grid.

Concept 1

Reading movement of the operators arm

This concept uses a slide-potentiometer with a string in order to read the roll movement and the yaw movement . The pitch movement will be read by a rotational potentiometer with a string.

Actuators

For the pitch movement actuator and the yaw movement actuator will be two DC-motors with feedback. For the finger servos will be attached to the forearm and with strings the fingers will be moved.

Pressure indication

To tell the operator how hard the grip is light-emitting diode arrays will be used.

Power source control unit

A battery will be attached to the control unit.

Concept 2

Reading movement of the operators arm

This concept will have a gyroscope and accelerometer to read all of the movements of the arm; pitch, roll and yaw movement.

Actuators

The actuator for the pitch movement will be a DC-motor with feedback as in concept 1, but for the yaw movement there will be a servo. In this concept the fingers will use actuators in form of servos which is attached in each joint.

Pressure indication

In this concept a digital display will show how hard the grip is to the operator.

Power source control unit

A battery will be attached to the control unit.

Concept 3

Reading movement of the operators arm

A slide-potentiometer with a string is used to read the roll movement. The yaw movement will be read by a stand with a potentiometer and the pitch movement with a rotational potentiometer.

Actuators

For the pitch and yaw movement there will be two DC-motors with feedback as actuators. Servos will be attached to the forearm and move the fingers with strings.

Pressure indication

To tell the operator how hard the grip is light-emitting diode arrays will be used.

Power source control unit

A battery will be attached to the control unit.

Concept 4

Instead of servos in the joint this concept will use servos with strings for the outer phalanges and struts for the inner phalanges.

Reading movement of the operators arm

This concept will have a gyroscope and accelerometer to read all of the movements of the arm; pitch,roll and yaw movement.

Actuators

The actuator for the pitch movement will be a DC-motor with feedback as in concept 1, but for the yaw movement there will be a servo. In this concept the fingers will use actuators in form of servos which is attached in each joint.

Pressure indication

In this concept a digital display will show how hard the grip is to the operator.

Power source control unit

A battery will be attached to the control unit.

Concept 5

Reading movement of human arm

All movements of the arm will be read by a slide-potentiometer with a string.

Actuators

The actuator for the pitch will be a DC-motor with feedback as in concept 1, but for the yaw movement there will be a servo. In this concept the fingers will use actuators in form of servos which is attached in each joint.

Pressure indication

To tell the operator how hard the grip is light-emitting diode arrays will be used.

Power source control unit

A battery will be attached to the control unit.

Concept 6

Reading movement of human arm

This concept uses a slide-potentiometer with a string in order to read the roll movement and the yaw movement. The pitch movement will be read by a rotational potentiometer with a string.

Actuators

The actuators will be the same as basic concept but the actuator for the yaw movement will be a step engine instead of a servo.

Pressure indication

To tell the operator how hard the grip is light-emitting diode arrays will be used.

Power source control unit

In this concept the control unit will be connected to an electricity grid.

Concept 7

Reading movement of human arm

This concept will use flex sensors for roll movement and yaw movement. For the pitch angle a rotational potentiometer with string will be used.

Actuators

The actuator for the pitch movement will be a DC-motor with feedback as in concept 1, but for the yaw movement there will be a servo. In this concept the fingers will use actuators in form of servos which is attached in each joint.

Pressure indication

In this concept a digital display will show how hard the grip is to the operator.

Power source control unit

A battery will be attached to the control unit.

C Pugh Matrices

Table 9: Pugh matrix 1: Requirement

Description	**Model 1***	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Function/appearance							
Four fingers, one thumb	0	0	0	0	0	0	0
Same number of joints in the robotic fingers as in human fingers	0	0	0	0	0	0	0
Feel whether the robotic hand is in contact with an object	0	0	0	0	0	0	0
Be composed of an elbow, a forearm and a hand	0	0	0	0	0	0	0
Maximum size 2 times the size of a human hand	0	-1	0	-1	-1	1	-1
Able to grip a cylindrical object with a diameter of 54 *mm*	0	0	0	0	0	0	0
Able to grip parallelepipeds of size 10 *x* 60 *x* 20 *mm*	0	0	0	0	0	0	0
Able to lift cylindrical objects weighing up to 500 *g* independent of hand position	0	1	0	1	1	0	1
Able to lift parallelepipeds of weight no greater than 100 *g* independent of hand position	0	1	0	0	0	0	0
Able to rotate wrist axis 180°	0	0	0	0	0	0	0
Able to raise forearm 90°	0	0	0	0	0	-1	0
Simple installation using standardised tools	0	1	0	1	1	0	1
All movement operations independent of each other	0	0	0	0	0	0	0

*Model 1 is a reference for the other solutions

Table 9: Pugh matrix 1: Requirement

Description	**Model 1***	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Performance							
Maximum latency, 1 second	0	0	0	0	0	0	0
Should not drop held objects due to control error	0	0	0	0	0	0	0
Angular offset in finger joints maximum 15° from reference	0	-1	0	0	0	0	-1
Angular offset in roll movement maximum 20° from reference	0	0	0	0	0	0	0
Angular offset in pitch movement maximum 20° from reference	0	0	0	0	0	-1	0
Control							
Wireless control within 10 m radius	0	-1	0	-1	0	-1	0
Real-time control	0	0	0	0	0	0	0
One-handed control	0	0	0	0	0	0	0
Maximum control unit weight 1000 g	0	-1	-1	-1	-1	0	0
Arm, elbow, finger joint rotation controllable independently	0	0	0	0	0	0	0
Environmental impact							
Parts replaceable without special tools or competence	0	1	0	1	1	0	1
Recycling-friendly materials	0	0	0	0	0	0	0
Noise level less than 70 dB	0	0	0	0	0	1	0
Cost							
Maximum cost of prototyping 5 000 SEK	0	-1	0	-1	-1	0	-1
Total score	0	-1	-1	0	-1	0	

*Model 1 is a reference for the other solutions

Table 10: Kesselring matrix 2: Desiderata

Function/appearance		**Model 1**		**Model 2**		**Model 3**		**Model 4**		**Model 5**		**Model 6**		**Model 7**	
Maximum size 1.5 times the size of a human hand	0.05	3	0.15	2	0.1	3	0.15	3	0.15	3	0.15	3	0.15	2	0.1
Able to lift cylindrical objects weighing up to 1 kg independent of the robotic arms position	0.07	2	0.14	4	0.28	2	0.14	3	0.21	3	0.21	2	0.14	4	0.28
Able to rotate forearm 90° around z-axis through elbow joint	0.11	2	0.22	4	0.44	4	0.44	4	0.44	4	0.44	2	0.22	4	0.44
Performance															
Maximum latency, 0.5 seconds	0.13	4	0.52	4	0.52	4	0.52	4	0.52	4	0.52	4	0.52	4	0.52
Applied pressure adjustable	0.1	2	0.2	3	0.3	3	0.3	2	0.2	2	0.2	2	0.2	3	0.3
Angular offset in finger joints maximum 10° from reference	0.14	4	0.56	3	0.42	3	0.42	4	0.56	4	0.56	4	0.56	3	0.42
Angular offset in roll movement maximum 10° from reference	0.12	3	0.36	4	0.48	4	0.48	3	0.36	3	0.36	3	0.36	3	0.36
Angular offset in pitch movement maximum 10° from reference	0.08	3	0.24	4	0.32	3	0.24	4	0.32	2	0.16	2	0.16	3	0.24
Angular offset in yaw movement maximum 10° from reference	0.09	2	0.18	4	0.36	3	0.27	4	0.36	2	0.18	2	0.18	2	0.18
Control															
Wireless control within 40 m radius	0.02	3	0.06	2	0.04	3	0.06	2	0.04	3	0.06	2	0.04	3	0.06
Wireless control through a wall	0.05	3	0.15	2	0.1	3	0.15	2	0.1	3	0.15	2	0.1	3	0.15
Controllable over the Internet	0.01	0	0		0	0	0	0	0	0	0	0	0	0	0
Maximum control unit weight 0.5 kg	0.06	3	0.18	4	0.24	3	0.18	4	0.24	3	0.18	3	0.18	3	0.18
Able to perform prerecorded movements & gestures	0.03	4	0.12	4	0.12	4	0.12	4	0.12	4	0.12	4	0.12	4	0.12
Environmental impact															
Most custom made parts created by a 3D-printable	0.15	4	0.6	4	0.6	4	0.6	4	0.6	4	0.6	4	0.6	4	0.6
Noise level less than 50 dB	0.04	2	0.08	3	0.12	2	0.08	3	0.12	3	0.12	3	0.12	2	0.08
Total score			3.76		4.44		4.15		4.34		4.01		3.65		4.03

D Budget result

The project was given a budget of 5000 SEK.

Table 11: Budget result

Object	**U/P**	**Quantity**	**Haulage**	**Total cost**	**Balance**
PLA-plastic	299.00	1	0.00	299.0	4701.0
Pressure sensors	74.60	10	49.00	795.0	3906.0
DC-motor	670.00	1	202.00	872.0	3034.0
Flex sensors	47.00	10	56.00	526.0	2508.0
Xbee and *shield*	500.00	1	56.00	556.0	1952.0
Fishing line (strings)	199.00	1	0.00	199.0	1753.0
Servos	51.00	4	30.00	234.0	1519.0
DC-power supply	290.00	1	0.00	290.0	1229.0
Motor Driver	337.50	1	185.00	522.5	706.5
MPU6050 module	349.00	1	29.00	378.0	328.5
MPU6050 module for yaw-detection	30.00	1	0.00	30.0	298.5
5V to 3V logic level translator	15.00	2	29.00	59.0	239.5
Friction pad	8.00	2	0.00	16.0	223.5

E Test results

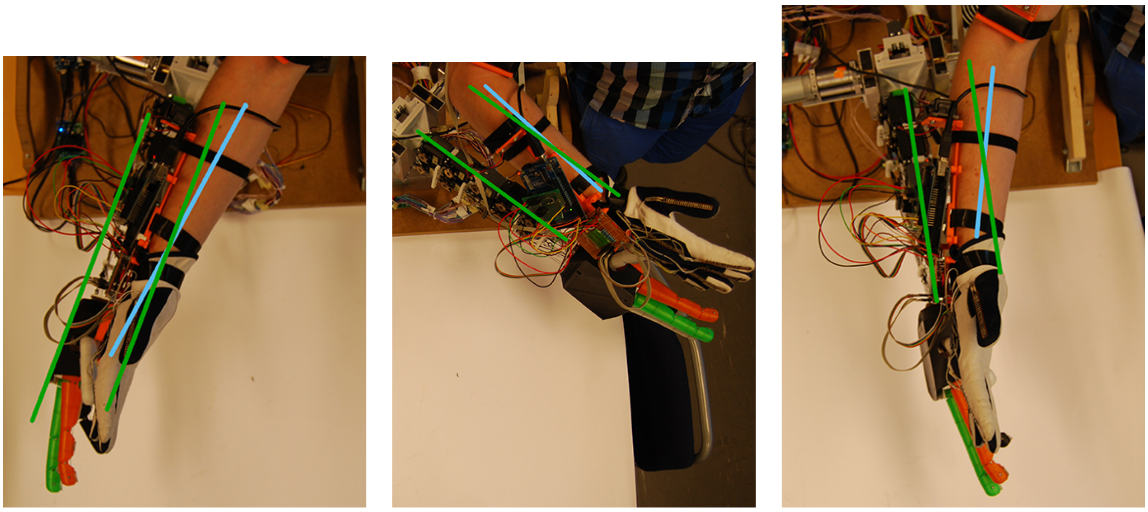
Precision

The operator was instructed to place his arm over the robotic arm and then make a roll, pitch, yaw or finger movement, depending on what test which is preformed, to another position. When the robotic arm had performed the same movement a picture was taken with both arms in it to analyze the offset that the robotic arm had from the operator's arm.

Yaw movement

Check	Offset [°]	Successful
1	7.51	Yes
2	6.11	Yes
3	14.11	No
Mean	9.24	Yes

Table 12: Yaw movement



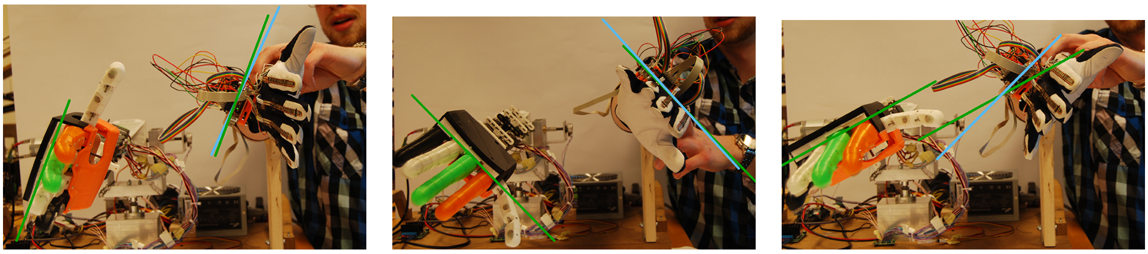
(a) Check 1 (b) Check 2 (c) Check 3

Figure 42: Checks of yaw movement offset

Roll movement

Check	**Offset** $[^\circ]$	**Successful**	
		R	**D**
1	3.99	Yes	Yes
2	1.90	Yes	Yes
3	16.47	Yes	No
Mean	7.45	Yes	Yes

Table 13: Roll movement



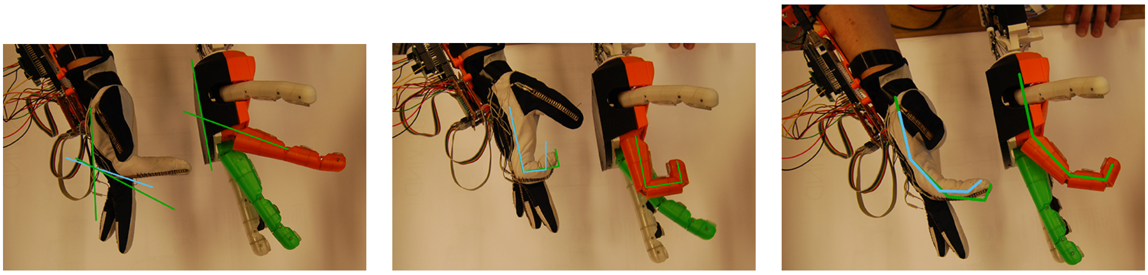
(a) Check 1 (b) Check 2 (c) Check 3

Figure 43: Checks of roll movement offset

Bending of a finger

Check	**Offset** $[^\circ]$	**Successful**	
		R	**D**
1	8.79	Yes	Yes
2	12.96	Yes	No
3	29.40	No	No
Mean	17.05	No	No

Table 14: Bending of a finger



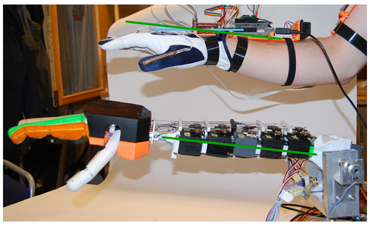
(a) Check 1 (b) Check 2 (c) Check 3

Figure 44: Checks of finger bending offset

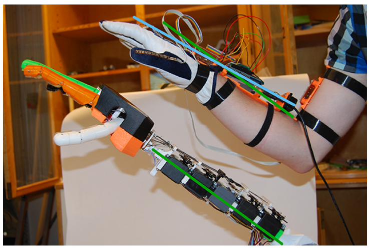
Pitch movement

Check	Offset [°]	Successful	
		R	D
1	5.93	Yes	Yes
2	7.49	Yes	Yes
3	5.77	Yes	Yes
Mean	6.40	Yes	Yes

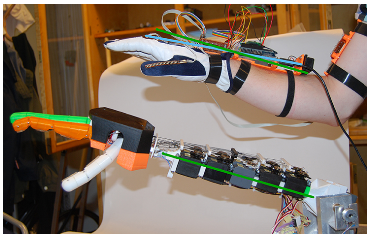
Table 15: Pitch movement



(a) Check 1



(b) Check 2



(c) Check 3

Figure 45: Checks pitch movement offset

Response time

For this test the operator place his hand over the robotic arm's hand and while the operator moved his index finger from closed to open position. Pictures where taken during the movement with a camera which had frame rate of 11 fps. This made the test have an deviation of 91 ms.

Operator start $[ms]$	**Robotc finger start** $[ms]$	**Response time** $[ms]$	**Successful**	
			R	**D**
0 + 91	273 - 91	273 $\pm$ 91	Yes	Yes

Operator finish $[ms]$	**Robotc finger finish** $[ms]$	**Response time** $[ms]$	**Successful**	
			R	**D**
455 - 91	1001 - 91	546 $\pm$ 91	Yes	No

Table 16: Response time for bending of a finger, all times are in $[ms]$

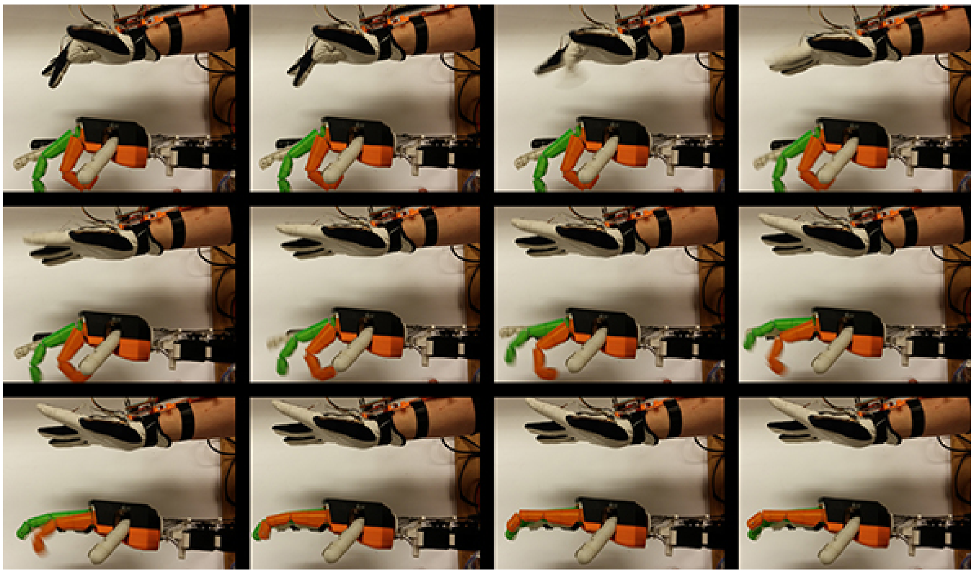


Figure 46: Photos of finger response time