CZECH TECHNICAL
UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL
ENGINEERING

BACHELOR WORK

DESIGN OF A ROBOTIC HAND

2018

TIMUR
UZAKOV

BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Uzakov Timur** Personal ID number: **453574**

Faculty / Institute: **Faculty of Mechanical Engineering**

Department / Institute: **Department of Instrumentation and Control Engineering**

Study program: **Theoretical Fundamentals of Mechanical Engineering**

Branch of study: **Study without Branches**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Design of a robotic hand

Bachelor's thesis title in Czech:

Návrh humanoidní ruky robota

Guidelines:

1) Start from an existing design of a robotic hand (fingers, palm, wrist) and design additional parts - forearm, elbow, ..., up to the shoulder
2) Create the hand (parts will be 3D printed), connect the servos
3) Program (Arduino) a simple program for basic movements, verify the design

Bibliography / sources:

[1] The Future of Humanoid Robots - Research and Applications. Edited by Riadh Zaier, ISBN 978-953-307-951-6, 310 pages, Publisher: InTech, Chapters published January 20, 2012 under CC BY 3.0 license, DOI: 10.5772/1407
[2] Mobile Robots - Control Architectures, Bio-Interfacing, Navigation, Multi Robot Motion Planning and Operator Training. Edited by Janusz Będkowski, ISBN 978-953-307-842-7, 402 pages, Publisher: InTech, Chapters published December 02, 2011 under CC BY 3.0 license. DOI: 10.5772/2304.
[3] Robot Arms. Edited by Satoru Goto, ISBN 978-953-307-160-2, 272 pages, Publisher: InTech, Chapters published June 09, 2011 under CC BY-NC-SA 3.0 license
DOI: 10.5772/677.

Name and workplace of bachelor's thesis supervisor:

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Date of bachelor's thesis assignment: **18.04.2018** Deadline for bachelor thesis submission: **15.06.2018**

Assignment valid until: ____________

doc. Ing. Martin Novák, Ph.D.
Supervisor's signature

Head of department's signature

prof. Ing. Michael Valášek, DrSc.
Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

18.04.2018
Date of assignment receipt

Student's signature

CVUT-CZ-ZBP-2015.1

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Prohlašuji, že jsem tuto diplomovou práci vypracoval samostatně s tím, že její výsledky mohou být dále použity podle uvážení vedoucího diplomové práce jako jejího spoluautora. Souhlasím také s případnou publikací výsledků diplomové práce nebo její podstatné části, pokud budu uveden jako její spoluautor.

Dne 06.06.2018

Podpis

Statement

I declare that I have worked out this thesis independently assuming that the results of the thesis can also be used at the discretion of the supervisor of the thesis as its co-author. I also agree with the potential publication of the results of the thesis or of its substantial part, provided I will be listed as the co-author.

Prague, 06.06.2018

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Signature

DESIGN OF A ROBOTIC HAND

ABSTRACT

The design of a robotic hand is a conceptualization of wrist and elbow joints, forearm and upper arm with a proposition for shoulder joint. The evolution of the hand design, from sketched proposals to a complete digital assembly, is demonstrated in this bachelor work as well as problems, which appeared during realization of the ideas, are addressed. Furthermore, a testing algorithm is written for control of each servo motor and hence each motion of the hand. Finally, conclusions are drawn and propositions for future development are given.

Contents:

Introduction

The process of creation is a vital part of people with love of engineering. Nowadays, there is a great tendency towards discovery of the artificial intelligence and its implementation in human life. Robots are becoming essential parts of advanced automated control manufacturing. They can replace heavy jobs and working in extreme or dangerous environment.

The design of a robotic hand is a stepping stone towards the whole assembly of a humanoid robot, that is desired by the department of Instrumentation and Control Engineering. There was given a design of humanoid palm with fingers, made by a student investigating the topic before me, and the task is to further develop the wrist connection, design the forearm, elbow and upper arm up to the shoulder. The consequent steps of the development are to print out the 3D models of the hand parts, assemble them and to test their effectiveness. The last part is to program the hand's motions, such as movements of fingers combined with uplifting of the forearm.

The design version that is proposed in this work could help in the development process of the human like robots. There is a plenty room for discovery and this work is only a part of the whole domain of robotism. However, it could become a source of inspiration for future generations of students, working in this field, as well as an interesting option for people with experience in domain of control engineering.

From personal point of view, there is a great advantage in the development of human like robots because they could replace unpleasant repeatable factory jobs, which can be seen nowadays with introduction of automated, but not humanlike, robotic hands. Moreover, with the development of artificial intelligence it is wonderful to see how these machines could become humanlike beings and eventually assist humanity in our daily life endeavor.

Being a part of this project and making contribution to the development of robotism is an enormous pleasure and honor to me. The challenges are to practice skills obtained from design courses, think creatively and elegantly about the design, while being able to engineer the motions and to program them.

I would like to acknowledge the faculty of Mechanical Engineering for presenting such an opportunity to improve and cooperate, express my gratitude towards erudite professors of the faculty, who introduced to me aspects of engineering. I am very thankful to doc. Martin Novak for his patience, organization and help for this work to be realized. I would like to acknowledge my family for their unconditional support.

State of the art review

Sources of inspiration

The power of creation and desire to explore are integral parts of majority of engineers. These two characters have taken us so far that by the progress of technologies it has become possible for us to realize quite abstract and previously unknown mechanism of intelligence. Due to the digital revolution we were able to harness the power of electronical computation and create machines that can perform mathematical operations: from summation and multiplication of numbers to performing and time plotting the solutions of differential equations. However, this has not become an end in history of human endeavor in the engineering, and humanity strived to invent more intelligent beings and many works were devoted towards further discovery of the capabilities of the machines.

The biggest source for inspiration for this work has become a humanoid robot produced by Honda corporation and named ASIMO. The name of the robot tells us that it is Advanced Step in Innovative Mobility. The robot was designed to freely stretch his hands and legs and move eloquently to play games such as football. According to the web page of Honda corporations [1], ASIMO can track distances and movements by the camera installed on its head. Moreover, he is built to detect faces and gestures, distinguish sounds.

Figure 1 ASIMO robot [2]

Another interesting solution of 21st century is the robot called Atlas designed by a group of engineers from the Massachusetts Institute of Technology, the United States of America – Boston Dynamics. Their specialization is on robots that behave in a similar way as animals. The unique characteristics of Atlas is that it can withstand force applied towards the machine and react to the pressure, keeping the balance and maneuverability. Moreover, this robot represents high advances in dynamics, since it can flip itself back over, while not falling. Atlas is designed with stereo vision that allows him to manipulate with the objects and orient in the environment. Further information on this wonderful robot can be obtained from the web link of Boston Dynamics. [3]

Figure 2 Atlas robot [3]

The European Union has also introduced its version of humanoid robot. This robot is named as iCub and is developed by Italian Institute of Technologies as part of the EU project RobotCub. According to the web source [4] the design was adopted by around 20 laboratories worldwide. The robot is equipped with 53 motors to move his arms and hands, legs, head and waist. Vision and hearing are also preconfigured into this robot. A unique feature of this robot, from my personal point of view, is its elegant design and configuration of the motors, that makes this robot appear as a child humanoid and his eyes resemble the eyes of a human.

Figure 3 iCub [4]

Implementation of humanoid robots

In this section of my state of art review, I would like to discuss potential implementation of humanoid robots in human endeavor. With the advancement in the field of artificial intelligence, these robots could become prior candidates for employment in industrial factories. Since they do not require human-like necessities of sleep and nutrition, these machines could increase productivity highly enough to meet the demands of the ever-increasing number of people. However, on the other side, they represent potential replacement of human labor, which is disadvantageous for many people, who rely on certain types of employment. This problem is one of the tasks of nations of the 21st century and it should be tackled very preciously.

The advantage of robots is clearly seen in automated process of car manufacturing. Robotic arms have found their implementation in the factories since roughly second half of the 20th century. These machines are primarily designed to help humanity with welding of the car body. The process is quite hazardous for humans and requires high accuracy and precision. Since majority of human beings appear to dislike repeatable jobs and tend to make mistakes, the replacement of the labor with machines is considered to be a good and productive solution. The perspective of humanoid robots in the industry is that they could weld small parts or parts that are not under automated procedure of the industrial line. This represents the advantage of human-like beings as they have more freedom in the factory.

Moreover, the robots could interact with humans and work in agreement with them. This type of solution appears in the world of electronics manufacturing. In the industry, there is a lot of work, which requires repeatable procedure to be done, such as connecting different parts together and soldering of the board. When automated, the process is reduced in time and repeatable jobs are done by human-like machines. However, an even better perspective is to employ both robots and humans in the assembly process. As they cooperate with each other, the work is done much better. This is due to the fact, that a human being can control the process of manufacturing, while not employing a repeatable job, which is done by the helpful robot. Such solution is represented by YuMi robots from the company ABB - Asea Brown Boveri Ltd., which have high maneuverability and outstanding coordination in working with people. [6]

Figure 4 YuMi® - Creating an automated future together. [6]

To further illustrate the concept, the robots are good for environments where we do not have desire to work or taking the risk that we do not want to take. One of the highly dangerous works is to disable an unnecessary bomb. This task is certainly quite risky and requires a lot of precision. The implementation of robotic arms here is definitely a good solution, since life of a human being is more valuable than of a machine, which could be reconstructed.

Robotic agents could control the environment in transportation facilities, such as airports or future Hyperloop stations. With the help of remote control, people would no longer have to take risk of an assault, but at the same time they could respond to people through machines and help them with traveling. In another case, with the development of artificial intelligence, the necessity to have contact with travelling people could be replaced by humanoid thinkable robots.

Finally, an interesting and promising future of robotics is their implementation in the space industry. The robots could play a high role in the development of space exploration by acting as builders of space stations, for example. By not taking risk, people could control the machines remotely, staying in a spacecraft, where there is plenty of oxygen and environment is relatively comfortable. Moreover, the robots could become new friends for people in outer space with the help of artificial intelligence. The robots would have access towards a pre-installed base of knowledge and thus can help astronauts with providing useful information and help them avoid, for example, psychological conflicts with each other.

Inspiration from articles

In the world today, there have been a lot of work done in the development of robotics and robotic arms especially. Many scientists have devoted their time towards investigation of mechanisms of the robotic arm and mathematical description of the arm movements. Apart from basic mechanics of rigid bodies, many mathematical implications were taken into consideration. In this section, I would like to highlight most notable information from the articles that I found through web-based scientific sources.

The first article that has raised my interest is named "Mechatronic Design of a Variable Stiffness Robotic Arm", presented in International Conference on Intelligent Robots and Systems (IROS) in Canada 2017. The article illustrates the concept of robotic arm on a rover. This design is particularly useful for robots with tasks of bomb discharging. However, in the article authors discuss the possibility of the robot to facilitate an UAV, unmanned aerial vehicle, such as drone. The robot's mission is to exchange batteries of the UAV. The design of a 3-DOF shoulder, 1-DOF elbow and 3-DOF wrist was implemented, while the required payload was set to 2 kg. The workspace for picking up the UAV was designed to be around 910 mm. Experiments done by the group confirmed the capabilities of the arm of accurate position and velocity control. The task of exchanging batteries was accomplished successfully. [7]

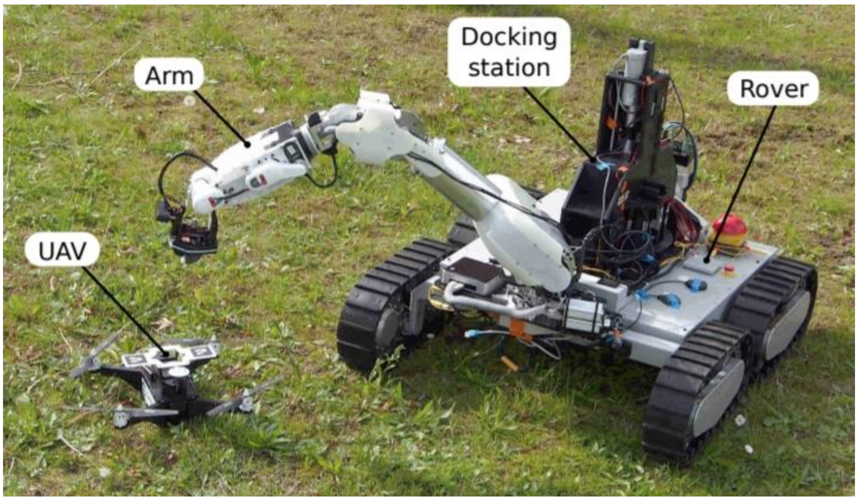

Figure 5 The SHERPA robotic arm mounted on the ground rover, together with the UAV and the docking station. [7]

Another source of inspiration is a research paper done by scientists from Pakistan on Design of a 3 DoF Robotic Arm. Here scientist discuss a possibility of a robotic arm design through utilization of a CAD software. Furthermore, they illustrate concepts of Euler-Lagrange equations for mathematical description of the system. To express the transformation of coordinates from one frame to another, scientists implemented the Denavit-Hartenberg convention, where the homogeneous transformation A_i is derived as a product of four basic transformations. The parameters as link length, link twist, link offset and joined angle are defined. The trajectories of the arm were generated, and their derivatives were computed. Finally, the graphs of torque to time functions were plotted. [8]

The educational implementation of a robotic arm was presented by researches from Brazil in their paper "Design, Manufacture and Construction of a Wireless Robotic Arm for Educational Purposes". The authors' idea is to expand horizons of students studying engineering and create stimulus for future projects. The design of a hand is done using SolidWorks® CAD software, it consists of one still and one rotating platforms, three links of the arm and a grasping mechanism, which is installed at the end of the hand. Five servos are arranged to realize arm motions. The motors are controlled by utilization of Pulse-Width Modulation signal. The selected microcontroller for the arm is Arduino Yun. The servos are connected to the microcontroller are programmed on Arduino's Integrated Development Environment. Finally, graphical user interface was developed to facilitate the education process for students. [9]

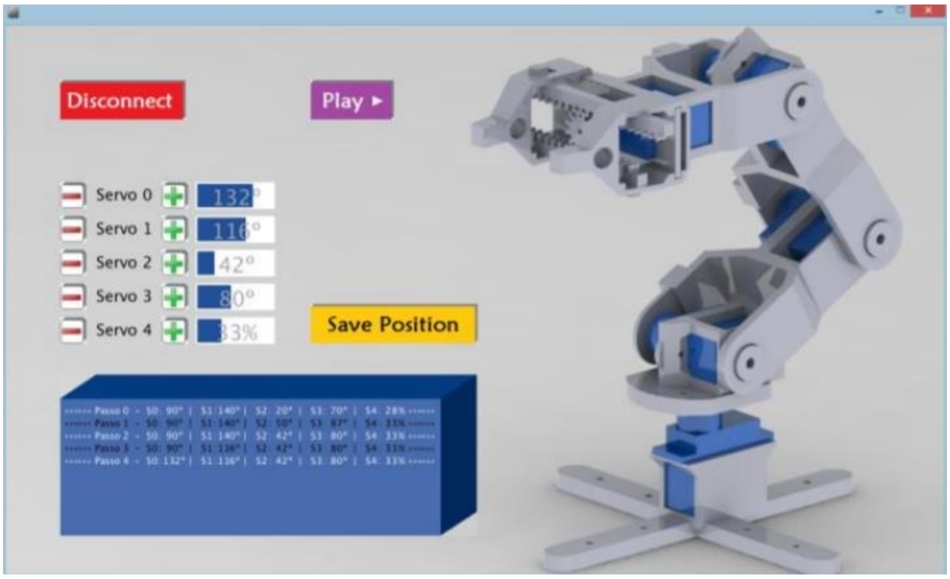

Figure 6 GUI Menu screen, Educational Robotic Arm [9]

The consideration of safety of robot arm operation and its safe interaction with human beings was discussed in the article named "Fast and "Soft-Arm" Tactics" by Anotonio Bicchi and Giovanni Tonietti. In this work scientists have designed joint-actuation mechanisms that can be guaranteed with limited level of injury. The compliance of the mechanism is varied by means of introduction of mechanical elements, such as adjustable-length leaf springs. [10]

The fifth article that I would like to discuss is the article proposed by two groups of engineers from Italy and Greece and is named “Design and Development of a Novel Robotic Platform for Neuro-Robotics Applications: the NEURobotics ARM (NEURARM)”. The biomechanics of a human arm is quite a complicated subject. However, this group of scientists has tried to mimic the catching motion of the arm. To do that they have developed a special platform for planar catching. They placed four position sensors on, respectively, the right shoulder, elbow, wrist and hand. The subject, human tester, starts from the pre-defined position, then stops a slider in front of him, and finally catches a cylinder. The motion was planar and all the data from sensors was gathered and further proceeded. To build the NEURARM platform scientist calculated the inertia, torques and power of the human hand. Hydraulic pistons instead of muscles were implemented, while load cells were used as replacement for human arm perception. The velocity of the trajectory and the trajectory itself appeared a little bit different to the measured values, however very close to the desired output. [11]

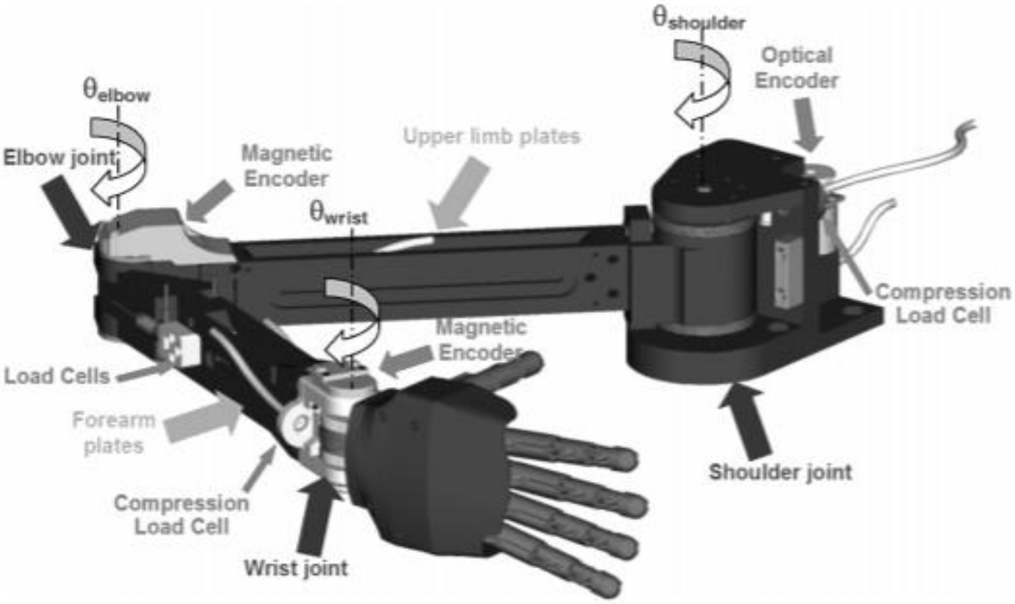

Figure 7 NEURARM planar robot arm: complete configuration. [11]

Another example of scientific work in the field of object grasping with the help of neural network training is done by a group of Asian scientists, who presented their paper on International Conference on Intelligent Robots and Systems (IROS 2014) in the United States of America. In this publication they propose a "novel" robotic arm design with high flexibility. This is done to facilitate the training and use of the recurrent neutral network model. The test is done on recognition and grasping of a box. The proposed manipulation is carried out by a mobile platform robot, NECO III, which is the third-generation robot that was developed for the navigation research. To facilitate the training, mechanical design of the robot is composed of two arms with 7 degrees of freedom, while shoulder pitch and yaw joints and elbow pitch can be moved together. The workspace of the robot is 300 by 300 mm. The payload of the hand is measured to be half of kilogram. The pan-tilt mono vision system is mounted on the robot to capture the position of the box. In result of testing, it was found out that by implementation of stochastic-continuous time recurrent neural network model(S-CTRNN) the guided trajectories could be reproduced. In future, authors imply, a more complex grasping motion could be trained by using this model. However, their design represents a more natural and faster motion of robotic arms. [12]

Kinematics and dynamics of robotic hand

Since control of many robotic arms requires knowledge of kinematics and dynamics of the system, I would like to give a brief introduction to these topics. Kinematics of a system involves the precise description of bodies and joints by utilization of geometry and geometrical time-relations, however without consideration of forces. In the book "Introduction to Robotics" by John J. Craig, the author divides kinematics of a robotic hand into two types: forward and inverse. [13] The forward kinematics is the description of end-manipulator position with respect to the base frame. It is also possible to think of the forward kinematics as of translation of manipulator position from a joint space description into Cartesian space description. The reverse operation can be applied as inverse kinematics approach. In this method, from obtain position and orientation of the end-effector of the manipulator, the sets of joint angles are calculated.

$$
{}^{0}_{1}T = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

$$
{}^{1}_{2}T = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s\theta_2 & -c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

$$
{}^{2}_{3}T = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & l_2 \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

$$
{}^{3}_{4}T = \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & l_3 \\ s\theta_4 & c\theta_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

$$
{}^{4}_{5}T = \begin{bmatrix} c\theta_5 & -s\theta_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\theta_5 & c\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.
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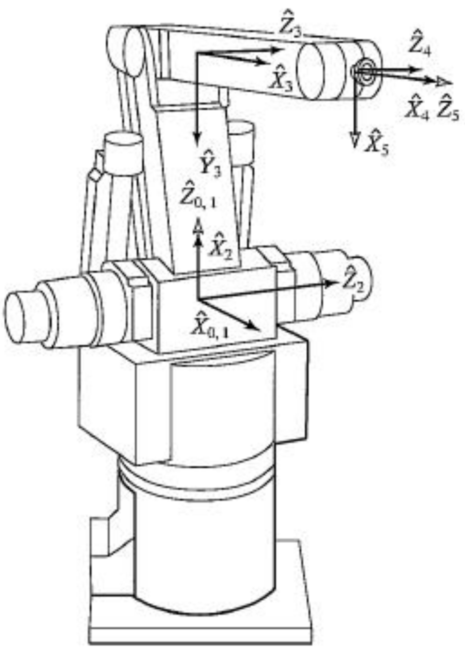


Figure 8 Assignment of link frames for the Yasukawa L-3, [13]

Forward method of calculation implies utilization of transformation matrices. An example of a kinematic description of a robotic manipulator, Yasukawa L-3, is given in the book. From the figure 8, the first transformation matrix involves rotation with respect to Z-axis, the second is rotation with respect to Y-axis, following is rotation around Z axis and linear translation on X-axis by a length of the link, the forth translation is rotation with respect to Z and linear translation by another length and the last transformation matrix is negative rotation with respect to Y. The overall transformation from base to the end-effector can be computed by multiplication of the transformation matrices.

The inverse approach implies knowledge of the end-effector parameters and the joint angles are to be computed. To have the solution it is necessary to express the end-effector matrix as product of transformation matrices from the base frame to the end-effector. Consequently, the inverse of the first, base 0-1, matrix is multiplied on both sides and a solvable equation is found. This equation is solved by implementation of trigonometric substitutions of elements of the end-effector matrix. After series of trigonometric and algebraic manipulations, the first angle is obtained. The procedure repeats until, finally, all angles are calculated.

In this work, only a brief description of the dynamics of the bodies is given. An important aspect of dynamical consideration of a manipulator system is to compute the necessary torques that must be delivered to the joints for their respective motion. One method to have the problem solved is to apply Newton's balance equation (1), stating that summation of all external forces applied to the system equals to change of its momentum. Applying this law to, for example, 3D cartesian system of a manipulator, one can arrive to a set of 3 balance equations, respective to the three chosen coordinates. To achieve moment or torque balance, one should apply Euler moment equation of motion for rigid bodies (2). The law states that the vector of 3 moment components, for example in Cartesian coordinate system, is equal to the sum of outer product of inertia tensor and angular acceleration, with outer product of angular velocity and vector product of inertial tensor and angular velocity. The previous computation methods imply the implementation of free body diagrams, which means consequent consideration of joint reactions with external forces and moments applied.

$$\frac{\partial(m\dot{x})}{\partial t} = \sum F_{ext} \tag{1}$$

$$I\dot{\omega} + \omega \times (I\omega) = \sum_{i=1}^{n} M_i \tag{2}$$

Alternatively, one can obtain equation of motions through usage of energetical methods, such Lagrange method or Reduced mass method. Both are based on Tailor series and involve concepts of kinetic and potential forms of energy with consideration of virtual work method.

Servo motors arrangement

Since most of the translation of motion is realized through implementation of servo motors in this work, it is relevant to investigate the principle of servo motor operation as well as its arrangement.

Servo motors are widely used in mechanical applications, such as robotics and CNC machining. The motors are predisposed for implementation in applications where high precision of positioning is required. It is common to distinguish between DC and AC types of servo motors, that depends on the type of power source. [14]

DC motor can be described by the following parts: the motor, position sensor, gear box and microcontroller. The motor is of direct current type and is composed of stator and rotor. Stator consists of a cylindrical frame with magnets attached to the frame's inside. Rotor contains brush, which is composed of externally coiled winding, and a shaft. The position sensor can be a potentiometer, which changes signal accordingly to the angle of motor shaft. The sensor, the motor and load, are connected through the gearbox inside the servo box. Signal is supplied by pulse-width modulation technique and then compared to the position sensor signal. The error, after that, is amplified and output signal is supplied to the motor until the error is minimized and the required position is obtained. High power applications are suitable for this type of motor. [14]

AC servo motors can be regarded as two-phase induction motors and are divided into synchronous and induction types. The stator of synchronous AC servo motor is composed of cylindrical frame and stator core, which is coiled, and the coil end is connected with a lead wire. The permanent magnet makes up the composition of the rotor of such motor, which is referred to as brushless motor. The rotor rotates synchronously within the magnetic field and since there is no current required in the rotor less heat is generated. An encoder is placed on the rotor to control the feedback and hence position. The stator of the induction type AC servo motor is similar to the synchronous type. However, the rotor of inductive motor is composed of a shaft and a core that is built of a conductor. Consequently, current is supplied to both rotor and stator, and through the interaction of produced magnetic field electrical energy is transformed into mechanical energy. It is important to note that a feedback encoder control is again applied in this type of the motor to manipulate with speed and position of the shaft. Low power applications are suitable for this type of motor. [14]

The servo motor connection consists of three wires: black - connection to the ground; red - connection to the power source; colored - connection to pulse-width modulated control signal. Small motors, frequently used in robotics, do not required external additional power source, except that of the microcontroller board. However, it is not recommended to connect motors directly to the board, since power of the microcontroller can be insufficient for a certain value of torque generated. [15]

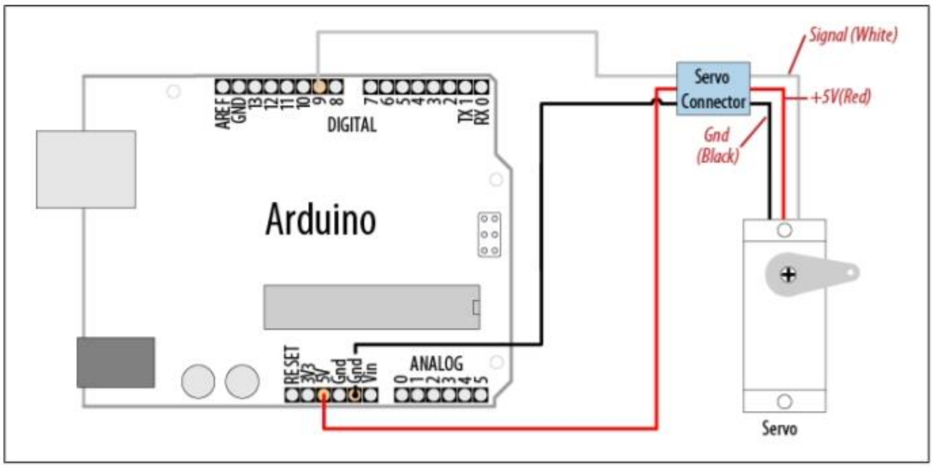


Figure 9 Servo connection to Arduino, [15]

The connection of servo with potentiometer is similar to the connection without it, however it requires a different programming code to be implemented and the potentiometer signal must be connected to one of the Arduino's analog signals. [15]

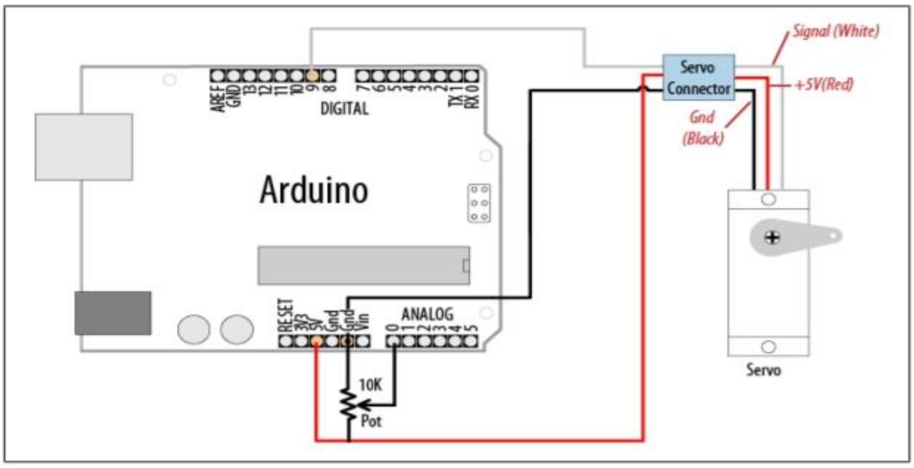


Figure 10 Servo with potentiometer connected to Arduino, [15]

Solution versions by other designers

Before proceeding to the main part of the bachelor thesis, it is important to analyze different solutions proposed by other designers, make observations and remarks of their work and to find inspiration and theoretical basis for creation of personal model. It is important to note that to investigate the concepts of robotic arms is quite a complex task, since information about joint assemblies and motors configurations and implementation is not explicitly given. However, I would like to propose it myself and illustrate the ideas behind certain examples of the robotic hands.

The first design that I have encountered from searching the web pages is a design concept proposed by researchers from South Korea and Switzerland. In the paper, Development of an Anthropomorphic Robotic Arm and Hand for Interactive Humanoids [16], authors illustrate how the development of robotic arms could proceed on. The important notice from their work is how a robotic arm could be made dexterous and how it could resemble an actual human arm. The authors imply that, for their model to be similar to human hand, the design should include seven degrees of freedom: three on the wrist, one at the elbow and three for the shoulder. Instead of using human-like ball joints, the designers rely mostly on utilization of gears and motors.

From the mechanical architecture proposed by the researchers, it can be observed that motors and frames of the hand are connected via transfer gear mechanisms, no hydraulic actuators can be seen on the picture. The three degrees of freedom on shoulder are realized by introduction of three metallic components. The first component is the end of the arm, which can be installed into the “body” of a robot, while the second one is its continuation till the rotating shaft of the arm’s pitch and the third one is the continuation till the third rotation. The motors are implemented in the three respective parts. Their combination resembles the three degrees of freedom designed for the shoulder connection. The motion of the elbow is transferred through gears from the motor installed on end of the upper arm. The purpose of such configuration could be to eliminate intersection of wires and their further destruction due to the translation of the motion. It is not quite seen from the figure, however it is supposed that the “Wrist z” motion is realized by introducing a motor in the upper end of the forearm, while “Wrist x and y” motions are generated by motors installed in the other end. Furthermore, motors controlling the motion of fingers of the hand are configured to be in the forearm compartment.

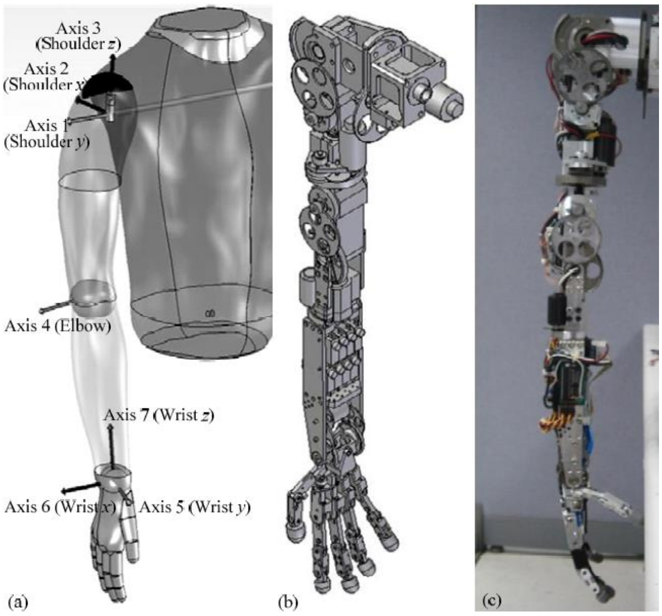


Figure 11Mechanical architecture of the anthropomorphic arm. (a) Illustration of a human arm; (b) CAD drawing of the anthropomorphic arm; (c) developed humanoid applicable robot arm. [16]

Finally, the arm meets the demands of being dexterous and human-like. However, further design is recommended to be taken to cover the components of the hand, which would make the robotic hand more appealing and better protected against external environment.

The following example, that I would like to investigate is the child robot iCub [17] and its mechanical design of the arm. The idea behind iCub is to create a robot that would be akin a 2.5-year-old child with an ability to crawl on the floor. Moreover, the task was to design a light weight solution, while at the same time meeting all requirements of infant maneuverability.

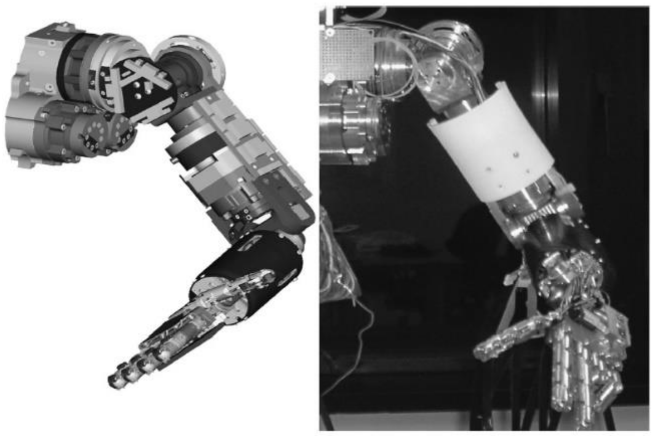


Figure 12 Arm module. iCub [17]

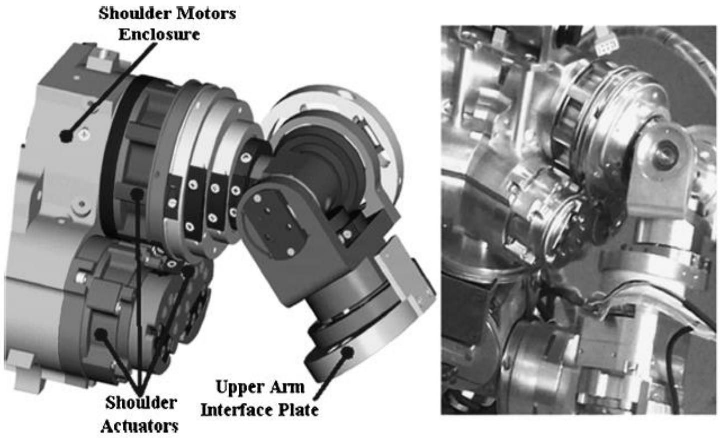


Figure 13 Shoulder mechanism, iCub [17]

The range of motion is realized by introduction of seven degrees of freedom of the arm. The shoulder mechanism is composed of three motors arranged in the enclosure and shoulder motion transfer actuators. Since motors are fixed in the base and do not move with respect to each other, the structural reduction of weight of the arm has been achieved. The driving motion of elbow is realized by a medium-power motor produced by company Kollmorgen, that occupies almost the whole compartment of the upper part of the arm. To allow the maximal possible range of movement the axis of the forearm was slightly shifted from rotational axis. The space from axis of the elbow is intentionally left free to elegantly arrange cables passing through the connection. Furthermore, 10 motors produced by a company named Faulhaber were installed in the forearm compartment. Seven of them are responsible for the hand motions, while other three are implemented for the remaining degrees of freedom. One of the three allows forearm to rotate, whereas the other two are located close to the wrist and realize wrist's flexion and abduction. The wrist is intentionally made hollow to enable hand cables to pass though.

In conclusion, the mentioned before examples of robotic arm versions represent feasible approaches towards realization of the task. Some important considerations from the designs are that the forearm should contain space for the motors, which realize motions of hand fingers, and at the same time a solution for wrist connection should be invented. There are different approaches towards the design of the shoulder and elbow connections. In this thesis I would like to propose my own version and ideas regarding the robotic arm design.

Main Part

The project of the robotic arm design has started with obtaining inspiration from the Internet and searching for possible solutions. The basis of the design was the assignment of number of degrees of freedom the arm should possess and possibility of the manufacturing. In the beginning, illustrative sketches were drawn to increase understanding and have some grasp at the model of robotic hand, how it is made and how it should be designed. Preliminary considerations were for the hand to have around 6 degrees of freedom with a pair of degrees of freedom at each joint: shoulder, elbow and wrist. Furthermore, I thought of the possibilities to realize these six motions. One of the ideas for the shoulder was to install two motors with bevel gears transmission.

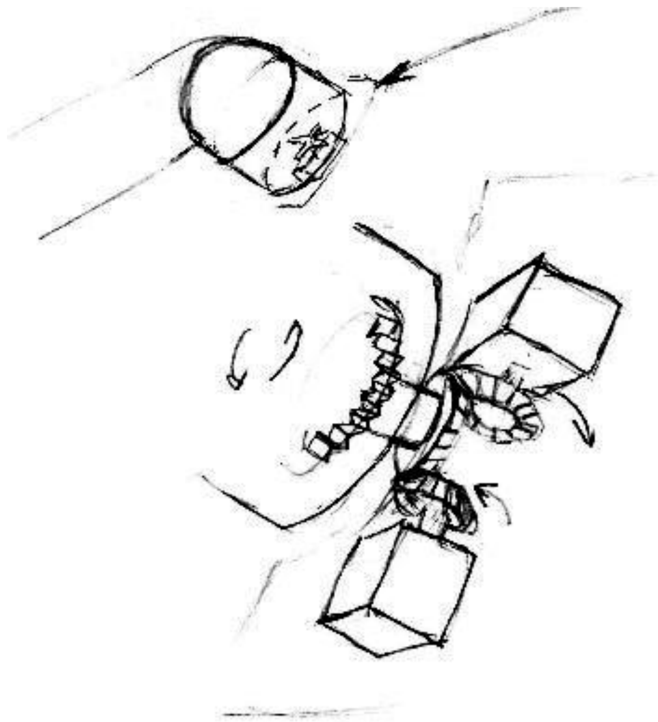


Figure 14 Preliminary shoulder sketch

The two motors instead of one single motor were considered to obtain higher torque transferred for the shoulder connection, which is supposed to have the highest loading of the entire arm. With regards to the elbow connection, it was also considered to implement a pair of motors that would enable 1 rotation of the part with gears installed to the motors and connected to the external toothed connection to the upper arm. The elbow motors were supposed to be installed in the forearm elbow end. Similar, but single motor gear transfer of motion was supposed to be implemented in the wrist connection. The twisting arm motion was replaced by three motors that would allow the rotation around connecting axes of the parts of the hand.

The first problem of the arm design is the design of wrist connection. At the first meeting, I was introduced with hand design concept provided by another former bachelor student of Czech Technical University, who researched configurations of robotic hand. [18] The robotic hand has five fingers, which are each composed of three connected finger parts. This configuration quite accurately resembles natural version of human hand. To have motion of fingers that is similar to muscles contraction, a concept based on ropes was utilized. The rope is connected from the motor through the hand up to the end of a finger, and when a servo motor operates one part of the rope is compressed, while another is stretched. The palm of the hand is composed of two parts: external and inner coverings. In external covering there is a supporting structure for another motor with bevel gear, transferring motion to thumb of the hand. Internal covering acts as a protection against external environment and makes the hand more appealing. The important characteristic of hand is that it has brick type of the end portion of the hand, through which the finger wires are routed.

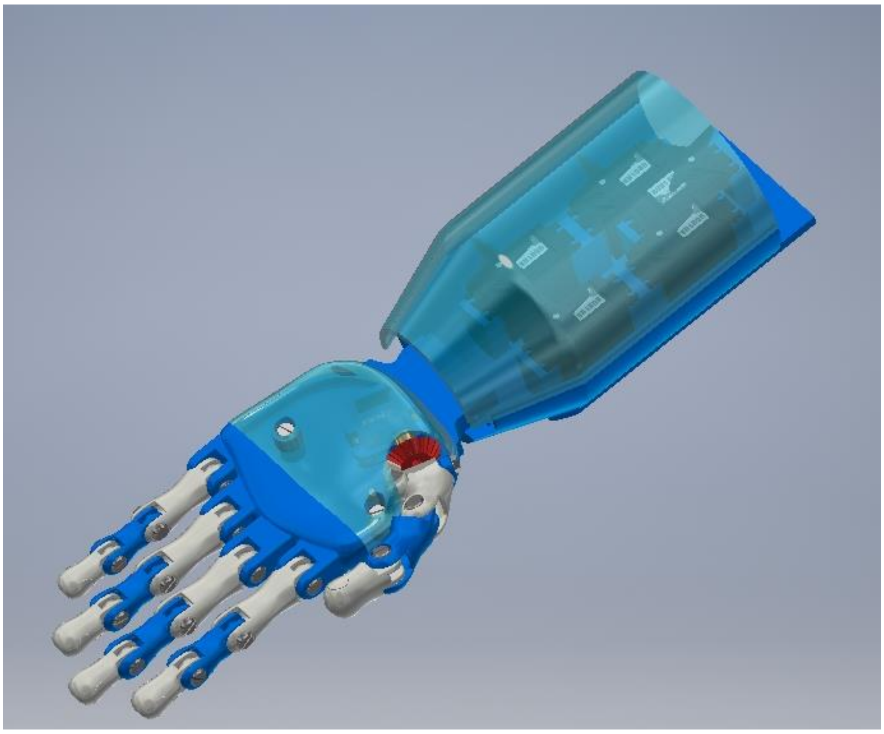


Figure 15 Hand design [18]

For the design purposes, a CAD model of the hand was given and further considerations regarding wrist connection were taken. One of the ideas was to install two servo motors on the palm side, very close to the end of the hand and to connect them to the hand through gears on the left and right sides of the hand block end. This connection would enable pitch motion of the hand. Taking into account the yaw hand motion, I considered that it would be necessary to have one motor atop the hand and connect it through a pair of gears. Furthermore, I made sketches of the whole wrist assembly for myself to have a better visualization of imagination.

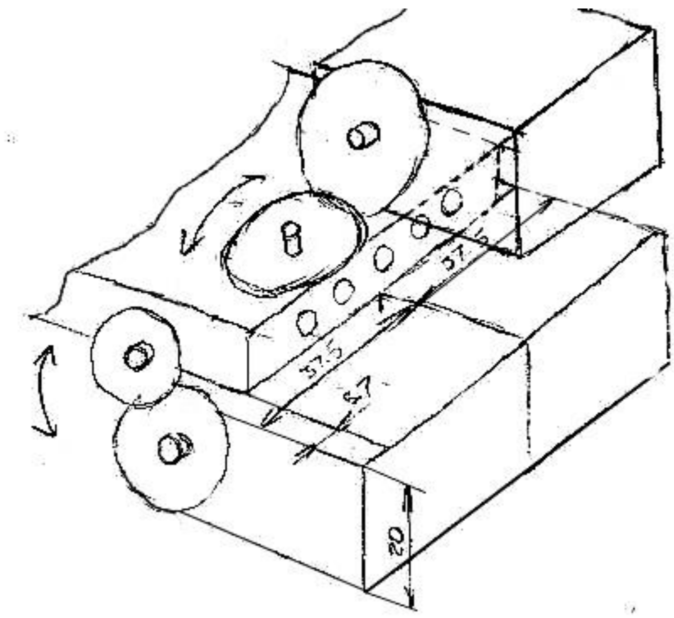


Figure 16 Wrist motor arrangement, sketch

In the designing process, I realized that for a 2 DOF wrist two separate parts should be designed that would move separately. Two “U” shaped pieces were considered and were supposed to be connected to each other through some pin connection, which is eventually after experience not a feasible solution.

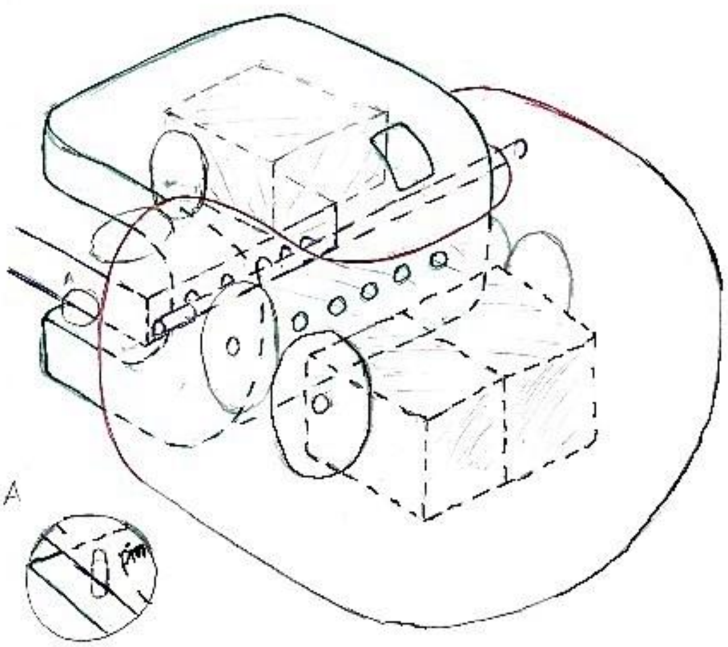


Figure 17 "U" wrist sketch

The alternative version of wrist connection appeared during a couple of days after the first version was drawn. In this new approach, I considered that it is somehow possible to mimic human like motion of wrist through introduction of a spherical joint. The initial idea of a spherical joint resembles marionette-like motion, where ropes are attached to the columns and are moved by servo motors. Alternative solutions would require more parts to be generated and solution with the sphere appeared to be quite original and elegant in its manner. The final decision was made by supervisor of the project and we decided to investigate more the spherical solution of the hand’s wrist connection.

Furthermore, it was suggested that installing two motor type of configuration would lead to a certain problem. This problem is difficulty in controlling both motors since motors could have different signal requirements as well as produced by different manufacturers. Consequently, another approach towards realization of the motions had to be taken.

Model 1

The wrist joint is designed by the spherical connection that should transfer movements from motors. These motions could be realized by implementation of ropes. Hence, there should be installed some connecting agent between cables and the sphere. In initial design, I proposed to make the sphere hollow, but with two columns and possibility for attachment of the wires to them. This design would enable two degrees of freedom, namely pitch and yaw, to be realized. The ropes, connected to the columns, would pull one of the four sides: up or down, left or right. The preliminary design of the sphere includes a rectangular hole made intentionally for the end of the palm to be fixed inside, however the method to connect the hand and sphere was not invented. The dimensions of the hand end were taken from the CAD model designed by a student before me. This allowed to grasp some preliminary concept of the size of the sphere, its appearance and sizes of the rectangular insert that should be made on the front side of the sphere.

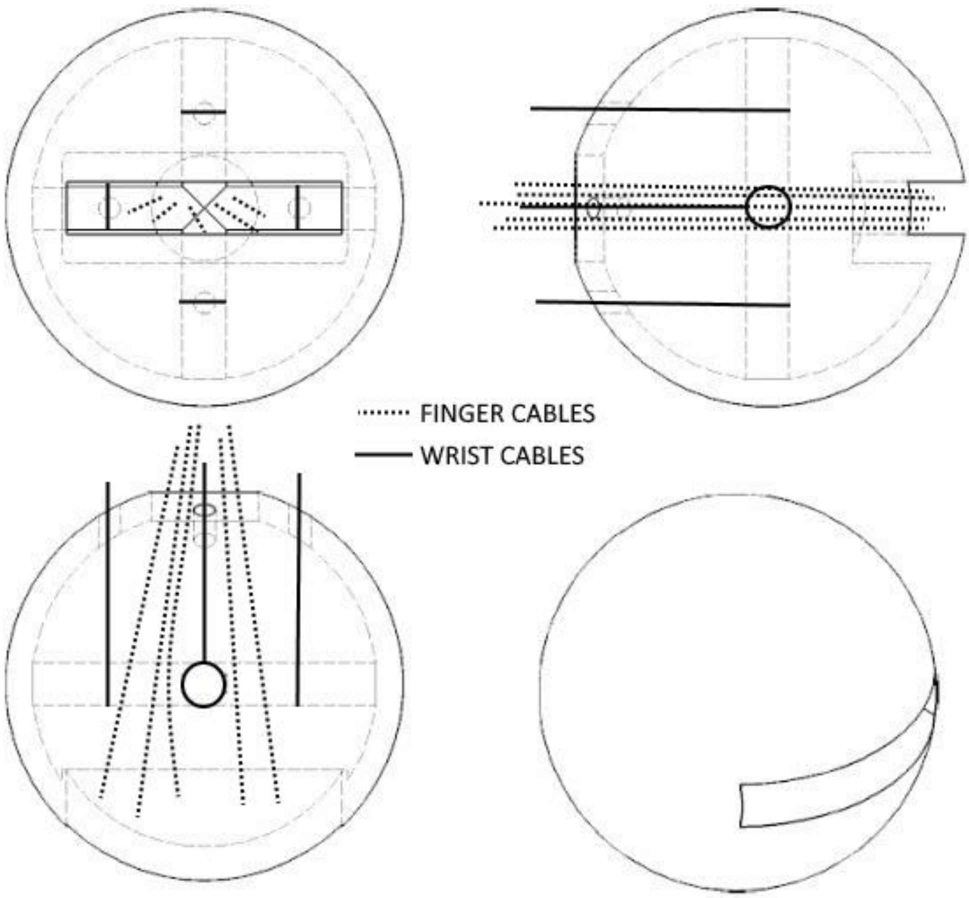


Figure 18 Spherical joint from model 1

Two simple columns without additional design of the wire connection were generated in digital model for illustrative purposes. The cables were supposed to go externally, from some motors installed before the sphere, through the connection, which is made up of four holes on the back side of the sphere. Additional hole was made on the back side of the sphere, for other five wires from fingers to be connected to their respective motors. This hole can also be used for power supply cables of a single motor installed for the motion of thumb in the hand.

Having some ideas of the spherical joint, it was further necessary to think of the possible ways how to attach the sphere to the forearm and eliminate its falling. The concept of model 1 is to restrict motions of the sphere by introduction of a connecting part with the spherical shape on the inside of it. This could be done by having two identical but separated parts. These parts are further connected to the same pats of the forearm, in a form of flange. The assembly is supposed to be done by attaching upper and lower connecting parts to respective parts of the forearm and close them with the sphere inside, thus preventing the latter from falling. The forearm of design 1 resembles the design proposed by the student before, since due to lack of experience it was necessary to investigate the alternative approach in the first place. The forearm is made in cylindrical shape with two sides of the circumference reduced to side planes.

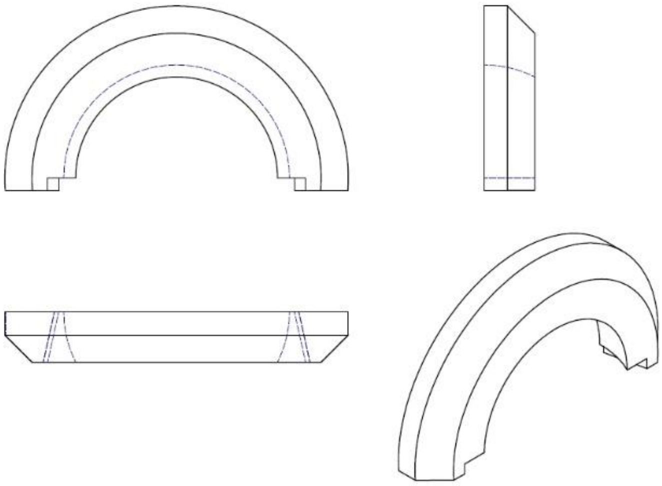


Figure 19 Wrist connecting part from model 1

No means of connection was taken into consideration since this model was just the beginning and it was necessary to have some vision for further development. The main goal of considering the design and introducing some possibilities for future work was achieved, however there is a room for improvement. After discussion with supervisor, it was suggested to have an alternative way for construction of the hand, since the first design concept appears enormous in size and not suitable for implementation as an anthropomorphic version of wrist and forearm.

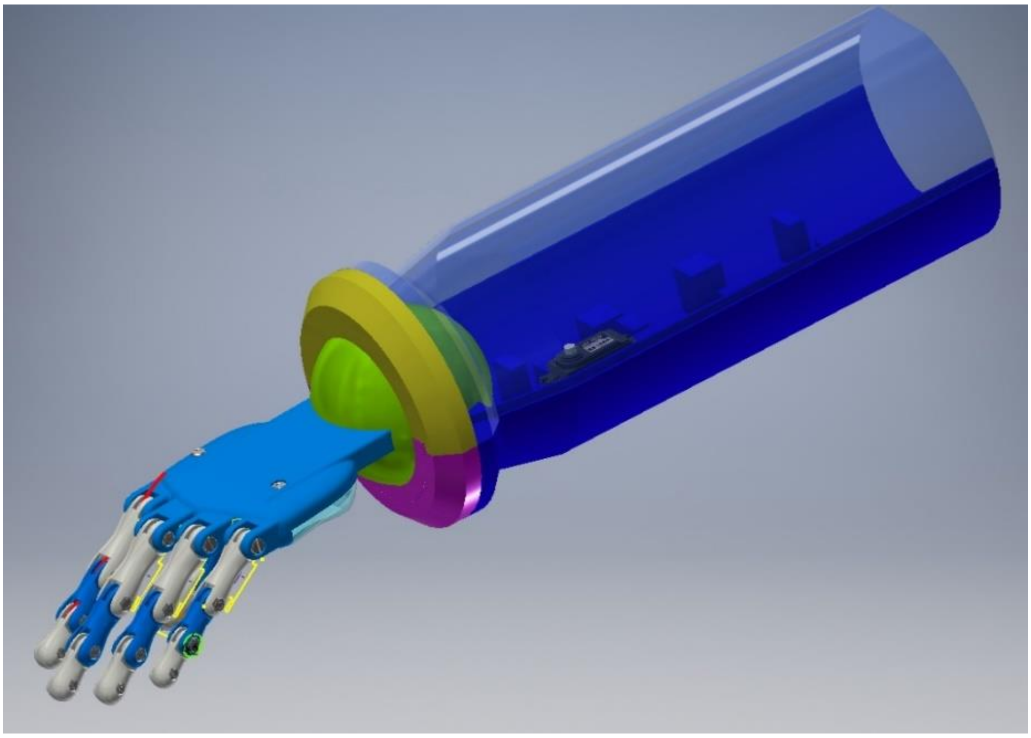


Figure 20 Model 1 Assembly

Model 2

Motion of the sphere inside the connection produces frictional losses. To compensate them, it was suggested to find a plastic ball from a shop in Prague instead of manufacturing the sphere. Initially, it was considered to purchase it from a toy shop, however toy shop investigation was not successful. After further research in stores and online, I have found a feasible solution for the required task. My idea is to use a hollow floorball. [19] The main characteristic of the ball is that it is small enough, diameter is equal to approximately 70.5 mm.

Figure 21 Floorball, [19]

Moreover, the floorball has round holes on its surface that makes it quite usable for wire routing. Besides that, it is made of flexible plastic, which is easy to work with and to modify. Consequently, the second version of the sphere was changed to match the new dimension. Furthermore, it was necessary to reduce the size of the brick end connection of the hand, since it was too large to fit inside the new size of sphere. The connecting part was changed from flange type of linking to more elegant and compact way. The approach is to implement same shape of the sphere, but with extruded section separated by an offset from the center of the sphere plane. As the result, the spherical joint would move inside the cup and would be prevented from falling.

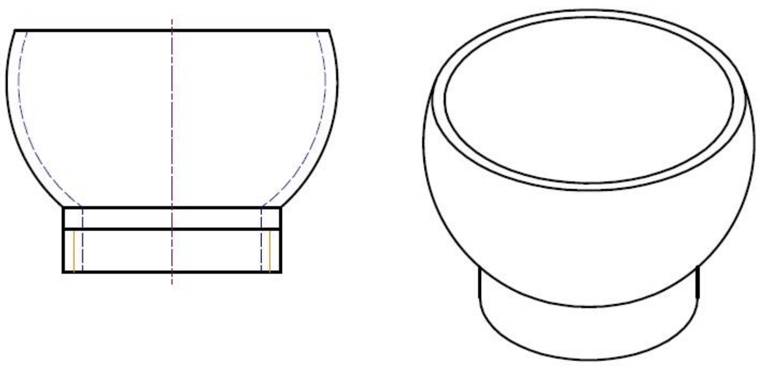


Figure 22 Cup connection of wrist, Model 2

The design of the forearm was also considered to be changed. The previous design, concerning large cylinders, was replaced by more appealing encasement. The forearm was designed using rotational generation in a CAD software. Preliminary dimensions were taken with consideration of size of servo motors and their approximate length through the entire forearm. Servo motors dimensions and models were obtained from the design of robotic hand, the name of the model is Power HD 6001 HB analog servo.

In the second project, little consideration was taken as regards to the assembly and connecting of the parts. However, it was considered to implement threading between the spherical cup and the forearm. This connection would hold the parts together, but it would make difficulties during the assembly process and cable routing.

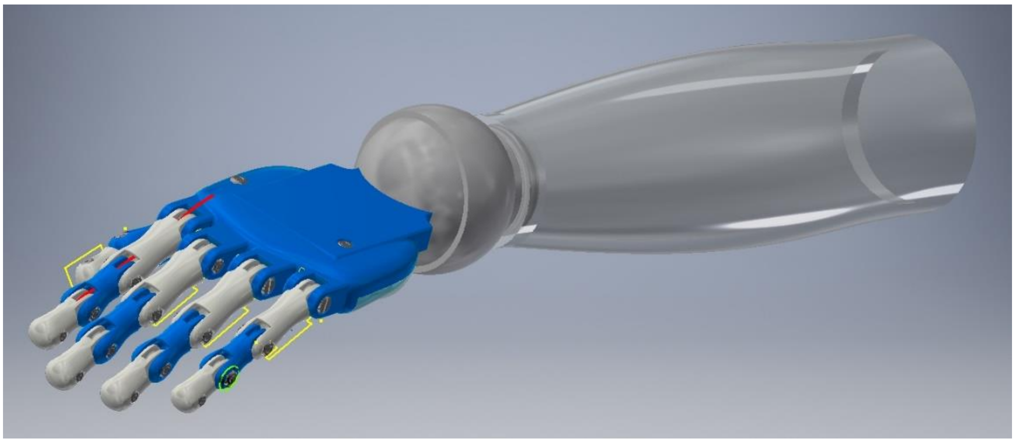


Figure 23 Model 2 Assembly

Model 3

One of the challenges represented during the third stage of arm design development is to find a certain way to connect the sphere with the hand. This link could be done in many ways. One of the ways is to generate a pressure joint between them. The disadvantage of this approach is that the link would fail dynamically, and hence the assembly would not be possible. Alternatively, it was decided to make the connection by using screw. The screws could be placed on top and bottom of the brick connection or from left and right of the joint. The first way would lead to interruption of wire cables of fingers since thickness of the brick end is not enough from top to bottom.

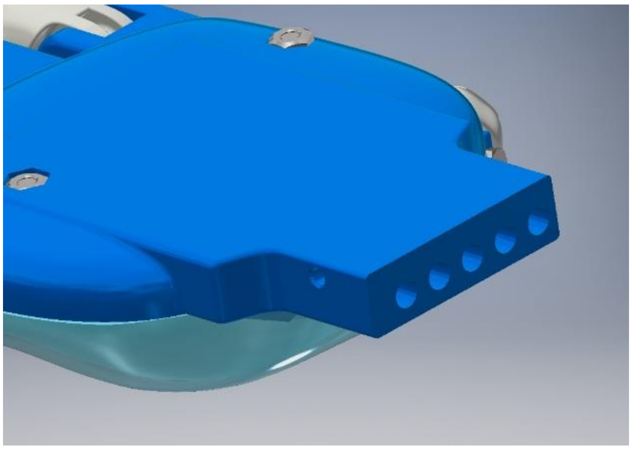


Figure 24 Hand end adjustments, Model 3

Moreover, this approach would require longer screws to be installed due to the form of the link and would lead to insufficiently strong connection. Consequently, the screws were chosen to be placed from left and from right of the brick end, due to close accessibility from the sphere to the material of the hand. Furthermore, it was decided to locate two, left and right, holes of the hand on the upper place of the side planes to have wire routing holes several millimeters apart.

Based on the decisions, the sphere was also adjusted and was introduced with compartments for screws on its sides and very closed to the rectangular cutoff. In addition, the initial design of two column 2 DOF connection was altered to have compartment for linking of motion wires. Finally, the circular hole, opposite to the rectangular one, was enlarged in order to have more space for routing of wires.

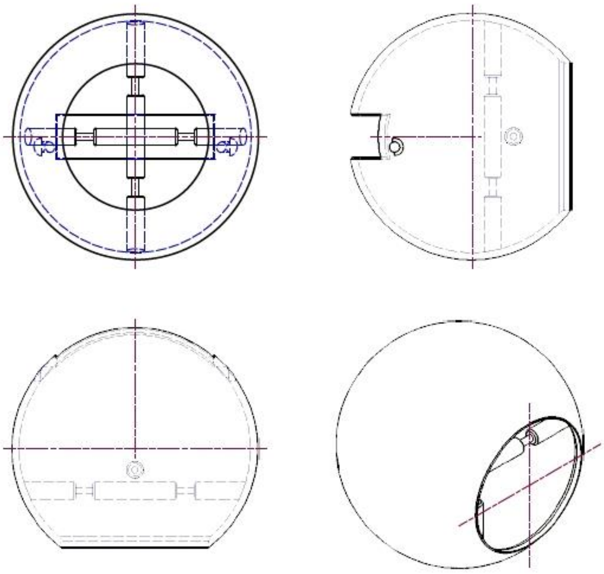


Figure 25 Sphere, Model 3

During design of the model three, the spherical cup was divided into two parts with respect to an axial plane applied. This was done to make possible the assembly of the wrist connection. Otherwise, it would not be feasible to insert the sphere into the cup, since diameter of the former is larger than cutoff of the latter. The two parts could be glued, but no glue was obviously decided to be used since assembly and disassembly would be problematic. A better possibility is to have the connection between two parts of the connecting "cup" to be linked by bolts and nuts. Consequently, the following solution (Figure 22) was designed.

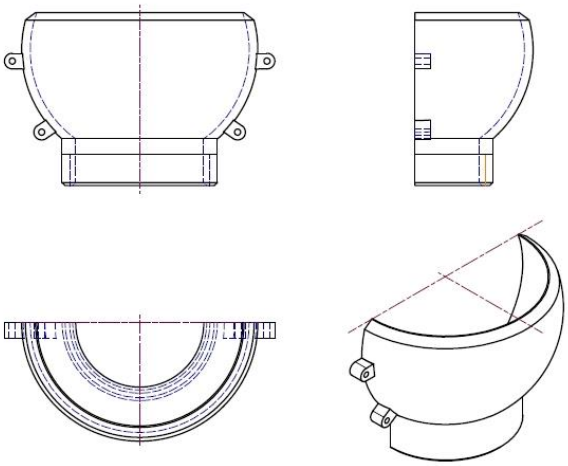


Figure 26 Half of the cup connection, Model 3

Finally, based on the approach of a student's hand design, the placement of motors in the forearm was conceptualized. The number of motors required to be installed was counted to be seven: five for fingers and two for motions of wrist. The compartment is composed of added material to the surface of the forearm by using its geometrical projection. By the extrusion to next command in the CAD software it was possible to generate a plane on the inside of the forearm, where servo motors could be installed. On that generated plane, furthermore, were created supporting blocks, by which servo motors could be fixed to the forearm. The part was split into two halves and embedded bolt-nut connections were generated along the sides of the parts. At this stage of modelling both ends of the forearm were supposed to be connected by internal threading.

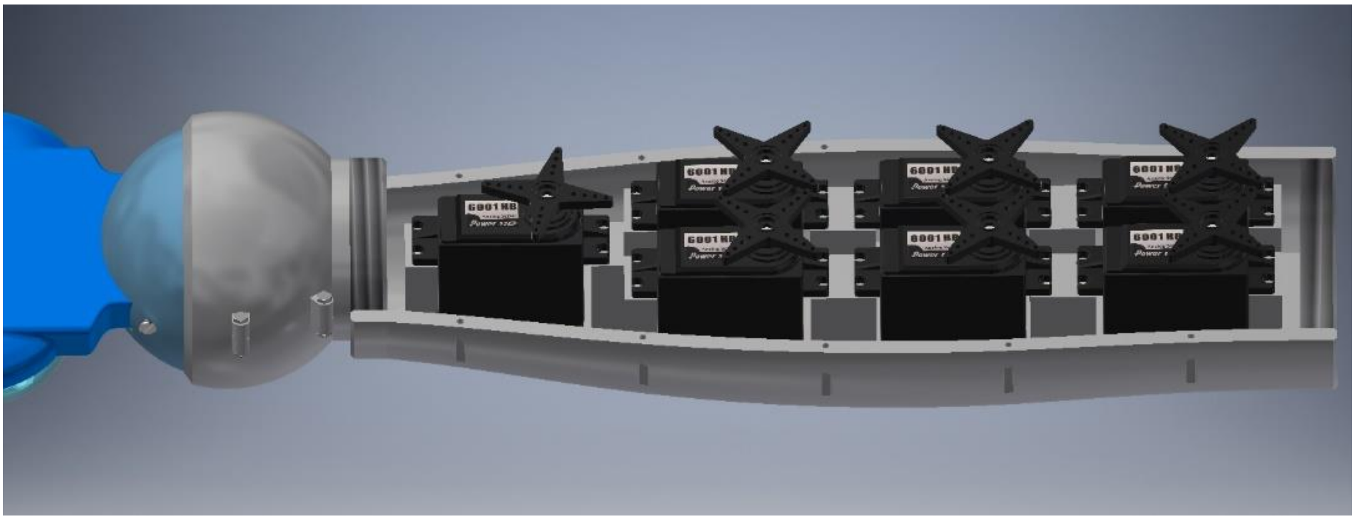


Figure 27 Model 3 assembly

Model 4

During the fourth stage of the design process only minor assembly adjustments were made. To be more precise the upper part of the forearm was generated and connected by bolts to the lower part. The design procedure for creation of digital models of the forearm was to generate the whole forearm by rotational command in the CAD software. After that the compartment for motors was made. Consequently, the design of the forearm was copied and by means of extrusion separated into upper half and the lower one. To connect the parts I decided to firstly create holes of a preliminary dimension diameter 2 mm. Precise measurement of hole positions was made and duplicated into the other half of forearm. By means a work plane that is offset from the connecting surface by 5 mm, I projected positions of holes and created larger diameter circle than of holes, cutting it to all in the direction opposite to the connecting surface. This compartment was designed for bolts to be constrained there. On the opposite half of the forearm, I proceeded with the same technique, but the projection now is of the shape of a nut, hence hexagonal and not circular. The reason behind such decision was to precisely fix nuts into the compartments and screw bolt from the other side. Eventually, it turned out not to be a good idea, due to difficulties during assembly, such as finding nuts of the size and inserting them into dimensions that are not manufactured precisely.

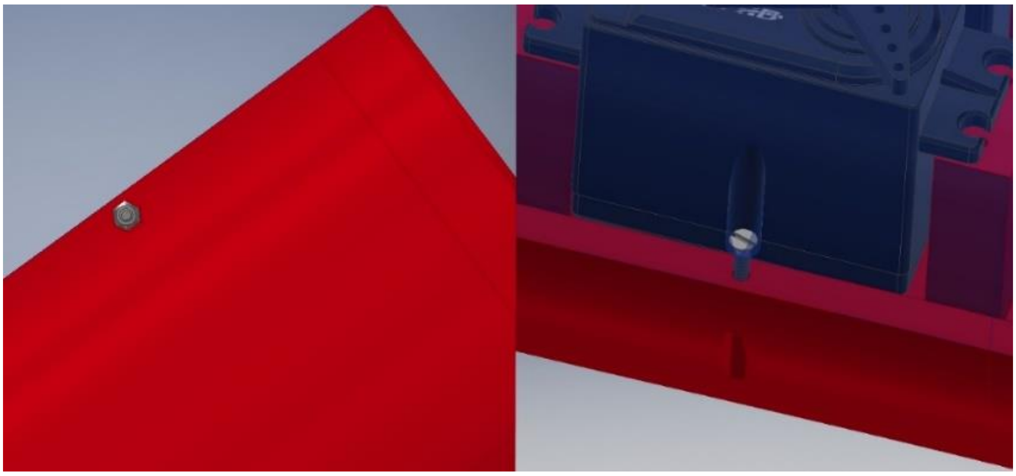


Figure 28 Connection of forearm, Model 4

Model 5

The fifth stage of development represented changes made in the sphere, further development of the connecting wrist part and implication of cable routing in the forearm. Initially, it was designed to implement two columns inside the sphere for 2 DOF wire motion connection. However, due to usage of floorball this approach was considered to be changed. The alternative method was to design a certain way that those motion wires could be attached to the sphere by bolts and nuts. Consequently, to allow the sphere to pitch and yaw, there should be 4 holes installed on the surface for connecting bolts and nuts. The challenge of the sphere design is to place those holes in such a way that they would not restrict motion of the sphere, thus reducing range of arm maneuverability. In this design, it was decided to locate three holes above the rectangular cutoff and one below it. Two of them are central one and were designed to serve for pitch motion of wrist. While the other two could be installed on the sides of ball, which would lead to block of motion. Hence, they are place above the rectangular cut and symmetrically with respect to the central top hole. These two holes would allow yaw motion of the wrist.

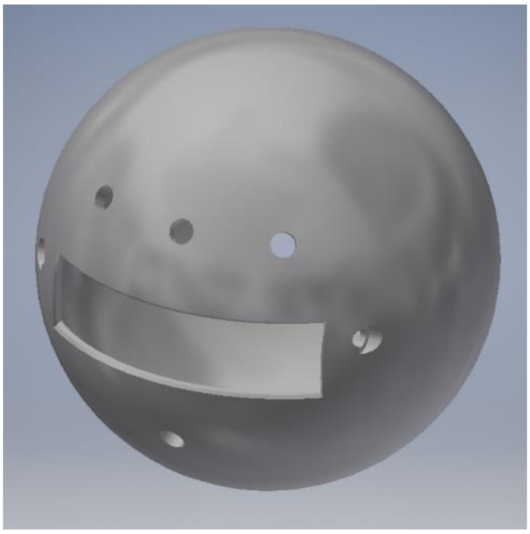


Figure 29 Sphere, Model 5

Two sphere-holding parts were modified in the fifth model. The new design concept includes bolted connection embedded inside the material. This required thickness of the parts to be slightly increased. The procedure for design of compartments for bolts and nuts is similar to the one implemented in the concept of forearm halves connection. The number of bolted connections and their compartments in the two parts of wrist joint is chosen to be four, identically to the previous version. The major change in the design of the wrist joint is the replacement of threaded connection with bolt and nut approach at the link between wrist holder and forearm. The new approach would facilitate the assembly of the wrist connection and would eliminate the problem of wire intersection of the previous model.

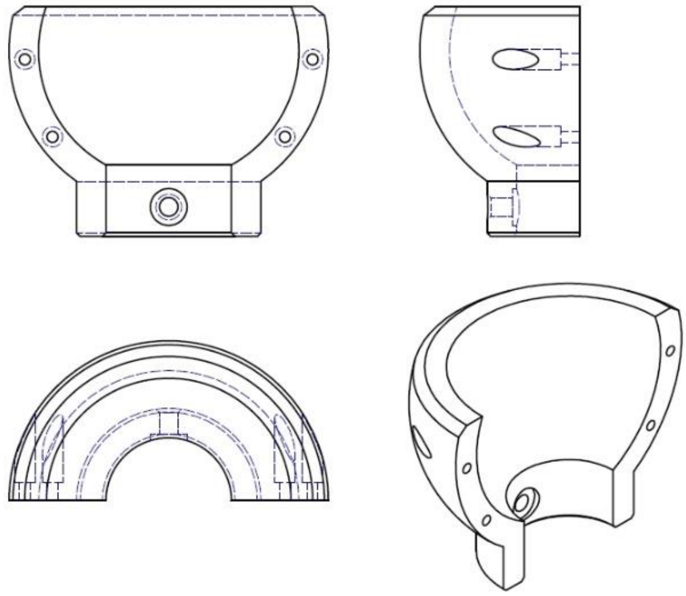


Figure 30 Half of wrist joint holder, Model 5

The following modification is the alternation of the lower part of forearm. To fix wire inside and restrict their motion, thus preventing them from intersection with each other, it was suggested to have some means of cable routing system inside the forearm. The wires could be routed by implementation of addition material with holes from the sides of the forearm compartment. However, this approach would lead to low strength capabilities of the proposed wire holdings. Consequently, I decided to introduce columns along the planar surface, where motors are constrained. Two columns, with three holes inside each one, were placed by sides of the front, and thus first, motor. Since there are seven degrees of freedom, seven wire routings were considered. The first wire would go directly to the first motor, while others would be routed to the left and right of the compartment through the columns. Furthermore, two of the six remaining cables would be connected to next pair of motors. The "top"s of motors, which serve for the realization of wire motion, are located oppositely to each other in order to eliminate possible intersection. Due to this fact, in the second and third pairs of columns, the left and right holding are slightly offset with respect to each other. The two holes are placed in the second couple of columns, whereas one wire hole configuration is used in the third set of two columns.

Furthermore, to separate 2 DOF wrist wires, I decided to design a pair of wire holders, which could be installed on opposite to "top" sides of motors. Their installation would lead wire to be directly connected to the rotational "top" part.

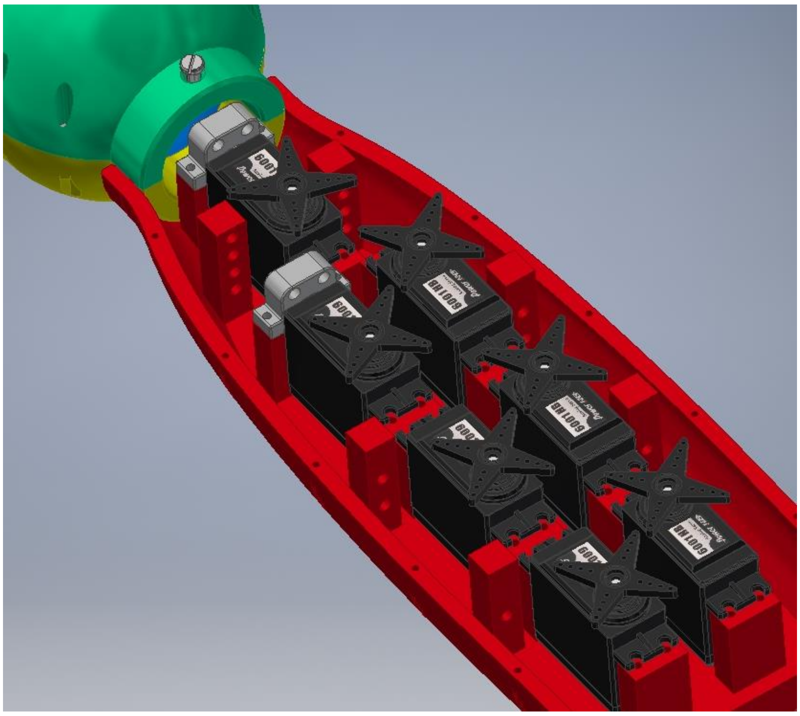


Figure 31 Model 5

Model 6

At the sixth stage of arm design I started to considered possibilities of elbow connection realization. One of the first ideas was mimic muscle motion of humanoid hand by introduction of wires. Those wire would replace muscles and by connecting them to motors, humanoid flexion and contraction could be simulated.

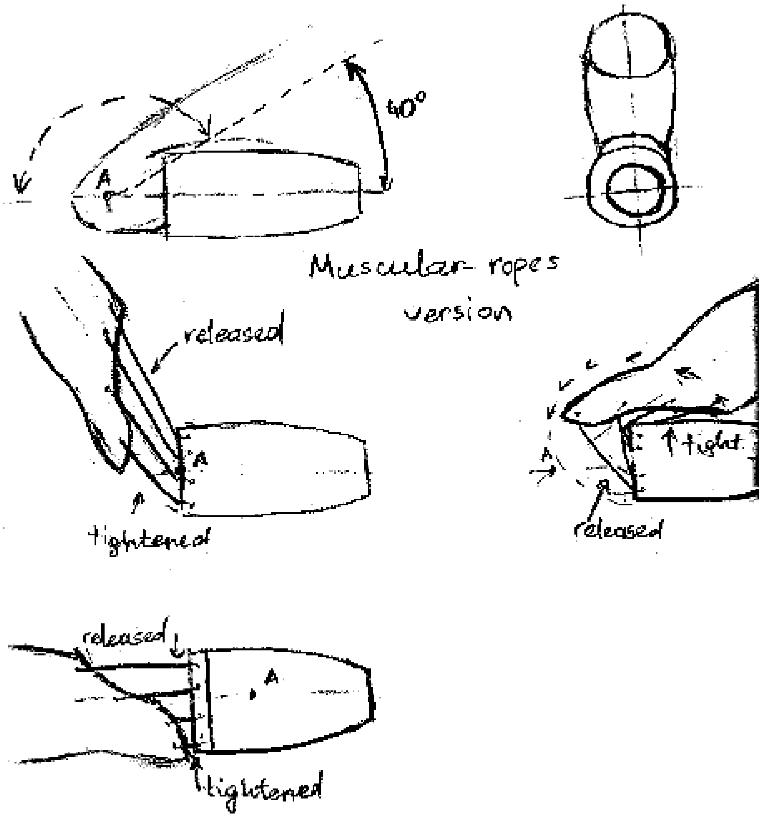


Figure 32 Sketch of muscle elbow joint

However, this approach was considered to be inefficient, since the load of the hand and forearm would be directly applied to the wires at elbow connection. To withstand the tensile load, wire should be either big in their cross-section, made of material with high hardness or there should be many of them. The first variant would not be possible due complication of the connection to the motor. The second version is possible however not economical, whereas the last one would lead to multiple of motors be installed somewhere, perhaps the chest of robot. Consequently, it was supposed to apply mechanical rather than natural approach towards realization of the elbow link.

The design of elbow is considered to be of 1 degree of freedom. This could be realized by introduction of two connecting parts with "U" shape of material added to their bases, which would be connected either to the forearm, for the respective part, or upper arm. The connecting agent between them could be a link shaft. This shaft would be connected by gearing to the forearm link, while having middle compartment for a V-belt. This V-belt could go from the motor installed in the upper arm.

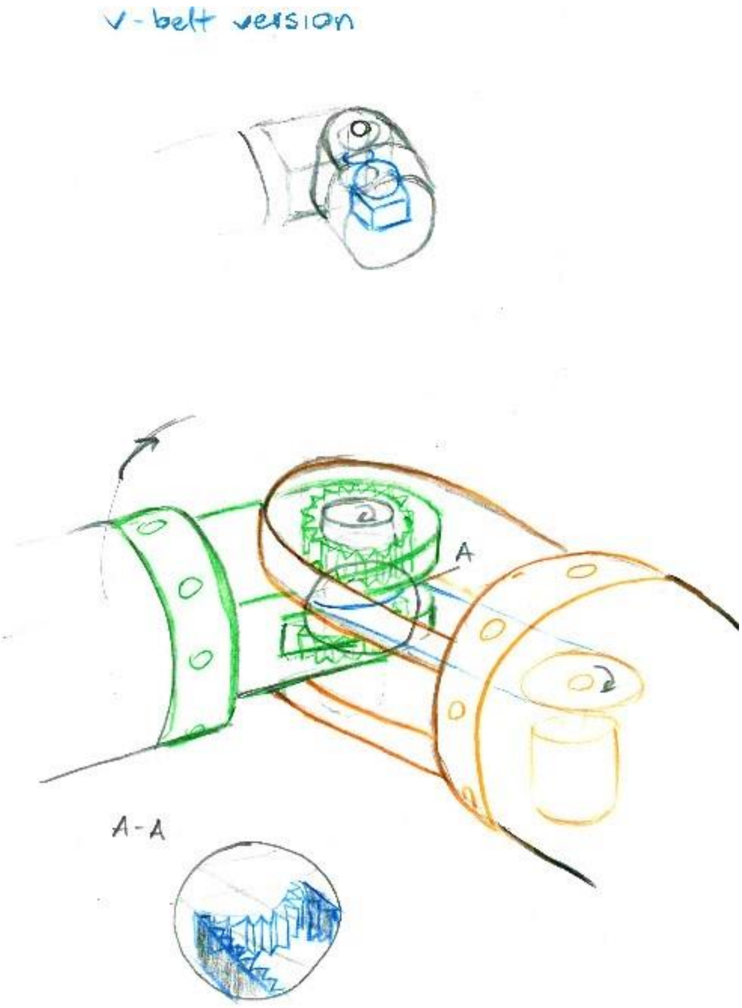


Figure 33 Sketch of V-belt version of elbow joint

However, due to complications of shaft design, V-belt configuration and load capacity of this type of elbow link, another approach was considered. Alternative method includes two connecting parts, but the link is realized by a straightforward application of gearing between them. The driving motor in this type of connection is supposed to be installed in one the two elbow link parts. The motor would be connected to a gear, which would transfer torque to another connecting part, thus to the forearm. The large gear should be connected by some means to the shaft between the parts, that was not yet designed. The shaft would be constrained by two sets of two bearings, which would later be found out to be an irrelevant number.

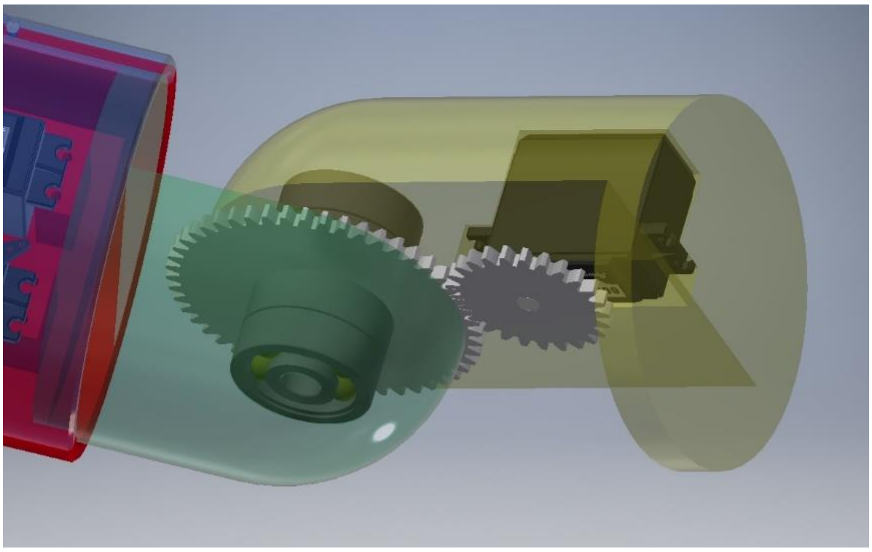


Figure 34 Elbow connection, model 6

Model 7

At the seventh stage of arm design, further considerations regarding improvement of elbow connection were taken. The challenge was to consider a way towards connection of the elbow parts to their respective links, forearm and upper arm. Moreover, the base of the connecting elbow parts should not remain filled since there is required routing of wires from motors to a controller board. To meet these requirements, the base was designed to contain some space for wires. The connection, similarly to the wrist joint, is beneficially chosen to be of bolt and nut type. The nuts and bolts should be installed alongside the external thick circumference of the connecting part. The main functional material is installed along a chorda of the circumference. The same procedure is applied towards the other connecting parts; however, a slight offset must be made from the longitudinal axis of the elbow joint, due to an appealing appearance and functional consistency of the connection. The part containing the driving motor should be elongated in comparison to the other one, for the motors compartment to be installed in the material. In contrast to the previous model, the motor base is not constrained to the material of connecting part. The compartment was made hollow for better appearance, while material on sides of the motor, for screws to be connected, remains the same.

The implementation of shaft was realized. It was supposed to install a couple of thread ends on the shaft, which would be connected to nuts. The shaft is supported by two roller bearings, each installed in the respective compartment of the elbow joint part. In order to fix the bearings in their positions, it was suggested to design a simple tube of material between them. The nuts, located at shaft ends would fix the connection and prevent parts from falling.

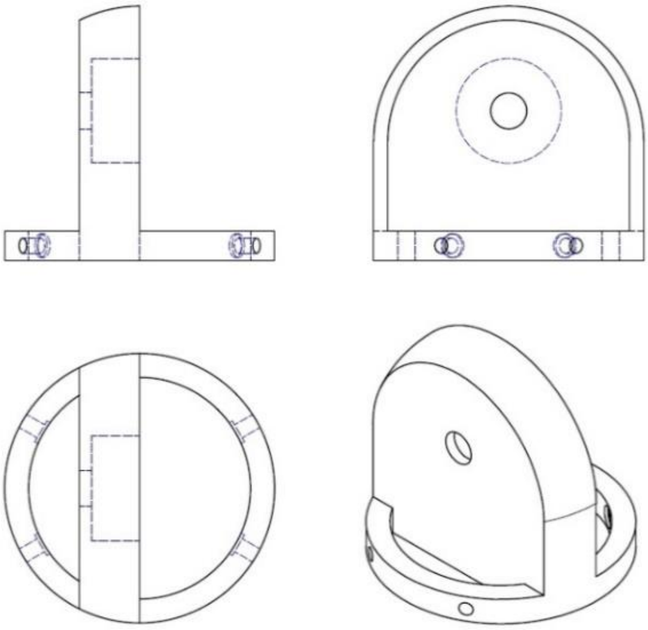


Figure 35 Elbow connecting part, Model 7

The important consideration of the model seven was to find a way of connecting large gear to the shaft and realize the transport of the motion. One way considered was to manufacture this gear with the shaft. However, due to the large diameter of the gear in comparison the shaft this would lead to inefficient material usage and a lot of waste, while the transfer would not be realized since there should be then considered some means of connection between the elbow part and shaft. Alternatively, the gear could be manufactured separately and connected to the shaft by means of a feather key, for example. However, it was finally decided to add the mating gear directly to the material of the elbow joint. This would lead to elimination of complications of design between shaft and the elbow part.

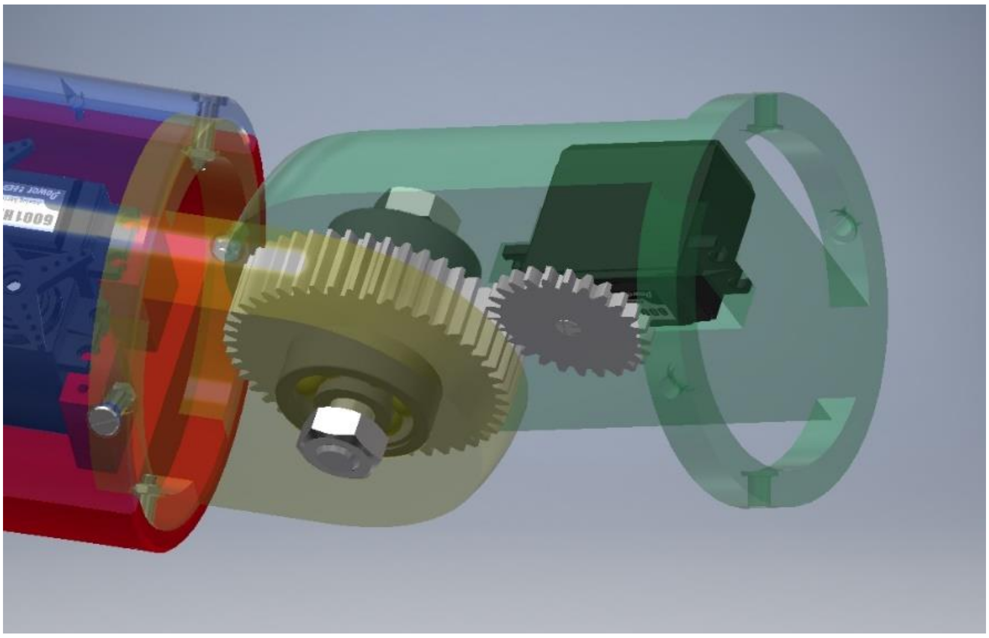


Figure 36 Elbow joint, model 7

Model 8

After having a certain concept of elbow joint, I decided to look further for possibility of upper arm and shoulder joint design. My implication was to create a part that is compact enough and at the same time would allow motion to be realized. Moreover, it was necessary to include some space inside the joint. To illustrate further, it was suggested to have some place for microcontroller installation inside the arm. Initially, the microcontroller was supposed to be a part of forearm, which would allow only power cables to go outside the part of arm. To check dimensions and possibility of compartment installation the 3D CAD model of Arduino Mega microcontroller was obtained from the Internet. Applying the model to the arm it turned out that there is insufficient space for the microcontroller inside the forearm and the installation would lead to intersection with cables and motors. Alternatively, it was suggested to have the microcontroller board installed inside the upper arm, where there is enough space for it. For good appearance and consistency upper arm was thought to be designed in the same manner as the forearm, but the length of the upper part was reduced since similar dimensions to the forearm would lead to extraordinary size of arm and inefficient use of space. The shape of the upper arm is curved cylinder.

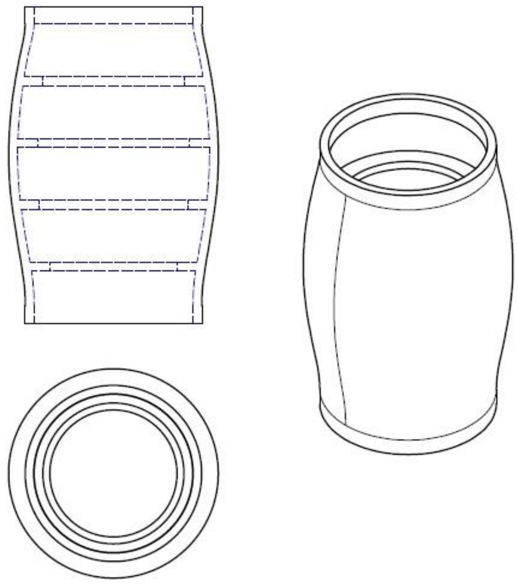


Figure 37 Upper arm concept, Model 8

The motion of the shoulder joint which is connected to the arm could be realized in a “mechanical” way by installation of servo motors inside a shoulder compartment. This solution would lead to a 3 DOF shoulder joint, however it would also require designing certain ways of transmission of torque to the respective axes of rotation of the shoulder. To avoid complications and maintain humanoid appearance of the hand, it was decided to implement a “natural way of joint”, by using ropes and motor. However, at this part the load is increasing in comparison to elbow and wrists joints. The joint should withstand weight of the entire arm plus motors and microcontroller. To increase strength of the shoulder joint it was decided to use four sets of three ropes, with each two sets connected to the respective motor. Consequently, the shoulder joint would have two degrees of freedom, which is supposed to be efficient for arm's maneuverability. This could be done by attaching this ropes to the upper arm. In order to facilitate cable routing, I decided to use circular compartments for the upper part of arm, along its length. Four of them is supposed to be enough with the last one having nut-bolt connection for cable fixing. The ropes would be connected to motors, installed in body or chest part of the robot, and go through a spherical joint directly to the upper arm bolts, which would hold them during the motions.

Additionally, the forearm was split into two halves to obtain sizes of parts that can be 3D printed in university.

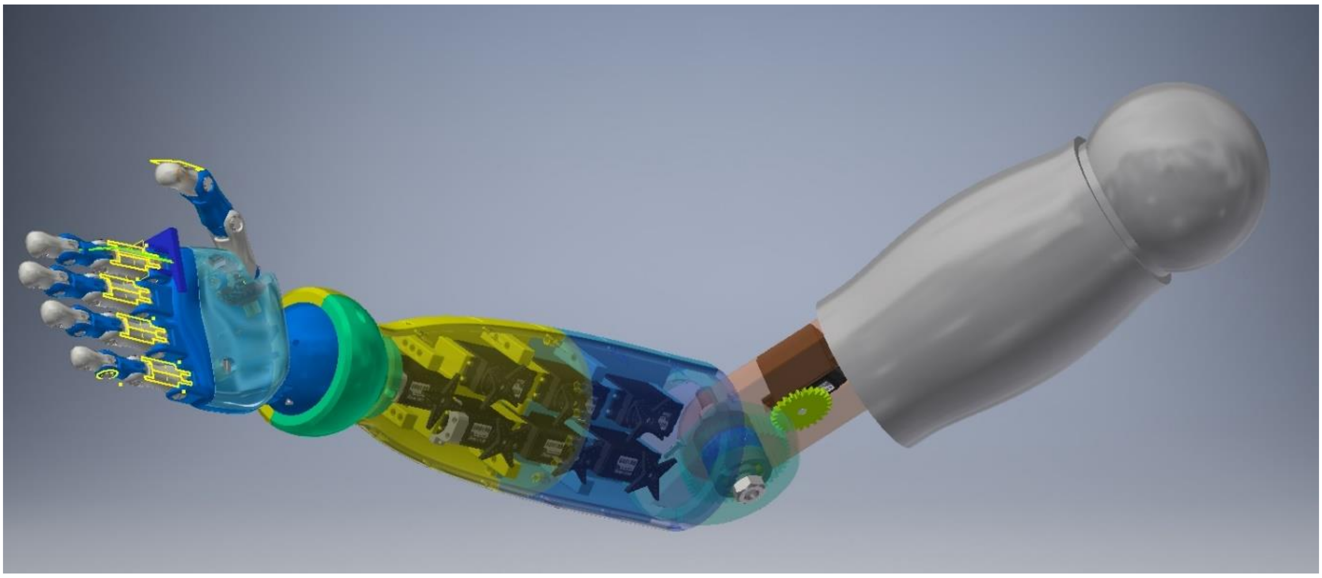


Figure 38 Model 8

Model 9

During the ninth stage of model no adjustments were implemented, but the overall design concept was rechecked and discussed. The main concern was regarding the elbow joint, how it could be realized, and it was necessary to find out mechanical mistakes in the design. The problem that appeared is the fixation of elbow shaft and the parts. It was considered that implementation of nuts as locking the mechanism would lead to block of rotation of the elbow joint parts. Therefore, some possible solution or alternative was to be found. The initial idea was to place a shaft bearing close to the end of shaft and have some means of fixing it. However, this approach would be later found out to lead to falling of the parts. It was also supposed to hold the bearing by using screws or attachments to the material, that was considered to be an irrelevant design concept for the case. To solve the rotational fixation of the elbow joint, I supposed to have hollow part of the arm and to fix bearing by shaft end nut. This would lead to bearing fixation and at the same time rotational freedom of the part. However, it is explicitly seen from model and could be easily visualized that the hollow elbow joint part would lead to falling of parts and unsuccessful mechanical design. The next discussion topic was design of the gears of the joint. It was agreed upon that the mating gear would be installed in one of the parts of the elbow joint. The pinions gear design, should be changed to match an available produced gear from shop and a certain way of connection to the motor should be designed.

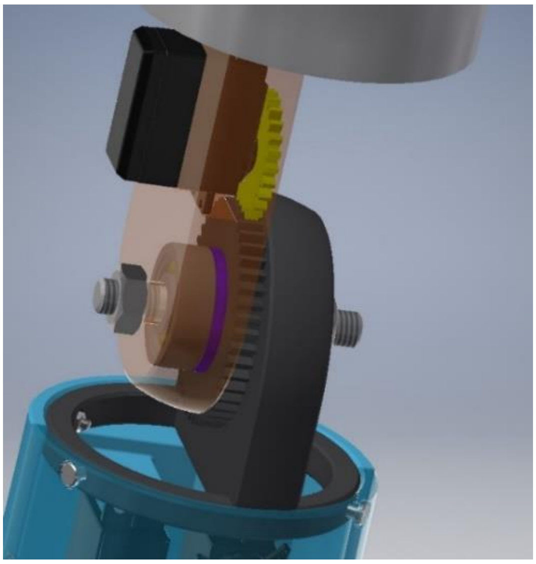


Figure 39 Model 9

Model 10

The tenth version of design concept of robotic hand represents changes, that have been done to the elbow joint, connection between upper arm and elbow, connection from upper arm to the spherical joint. At this stage, a possible solution for the problem of elbow constrained rotation was proposed. The idea of implementing hollow joint part was left behind and the alternative is to implement similar to initial variant of the elbow joint. In other words, use shaft and nuts to hold the parts. However, it was decided to decrease length of one thread on the end of shaft in such a way that nut would hold the parts, but not compress them to each other. This would allow parts to rotate, while not being restricted in motion.

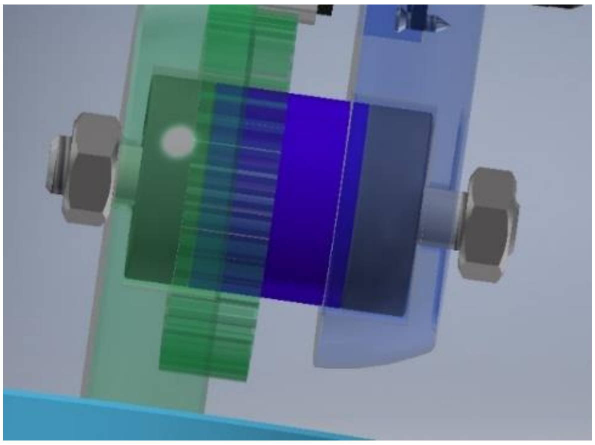


Figure 40 Solution for elbow joint, Model 10

The mating gear was changed in design slightly. Its width was increased in order to have more material for connecting to the "top" of the respective servo motor. This approach is an alternative to implementation from commercially available servo gears. Due to possibility of manufacturing the gear, it was suggested to implement this method. The gear is mounted on the servo motor top by using screws.

The overall composition of the gear and servo top is then attached to the motor by using a screw of a larger size.

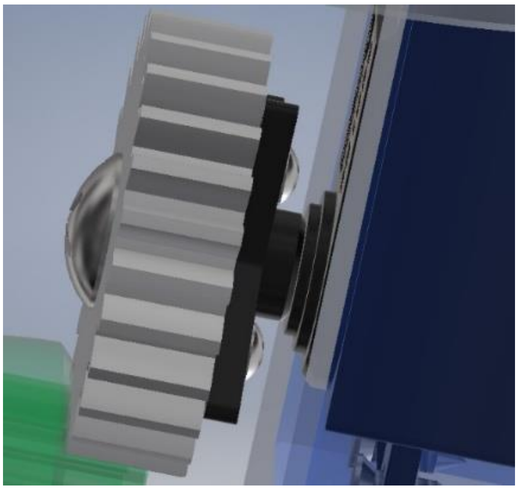


Figure 41 Servo motor, its top and the gear, Model 10

The connection between elbow joints and parts of the arm is done by implementation of bolt and nut approach. The bolts are placed along circumference of the part end. In the case of upper arm, it was decided to use more bolted connections on one side than on another. This decision was made due to availability of space in one compartment and scarcity of it on the other. Implementation of joint connection by using threads was not considered due to complications that arise with it, such as cable intertwining and difficulty of assembly.

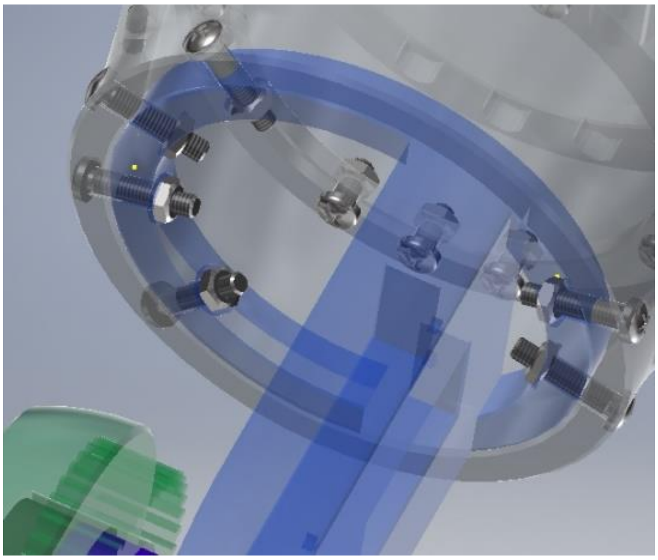


Figure 42 Elbow-upper-arm joint, Model 10

Furthermore, adjustments and improvements were applied towards the design of upper arm. Mainly, a certain way of Arduino Mega control board was designed. The possible configuration for microcontroller compartment could be to add material to the lower end of the arm to generate a planar surface. In this plane, there could be further installed material for board support, that is similar to the connection of servo motors inside the forearm. However, this approach would block circumferential wire routing of the upper arm. Hence, it was decided to use an alternative. The method was to attach columns of material towards lower part of the upper part. The height of columns was configured to match the best possibility of board placement in terms of its width. Moreover, the positions of columns were designed to match respective location of supporting holes of the Arduino Mega board. This was accomplished with the help of a 3D CAD model of the microcontroller. Finally, the diameter of columns was designed to be slightly bigger than that of the holes in order to insure the stability of the former.

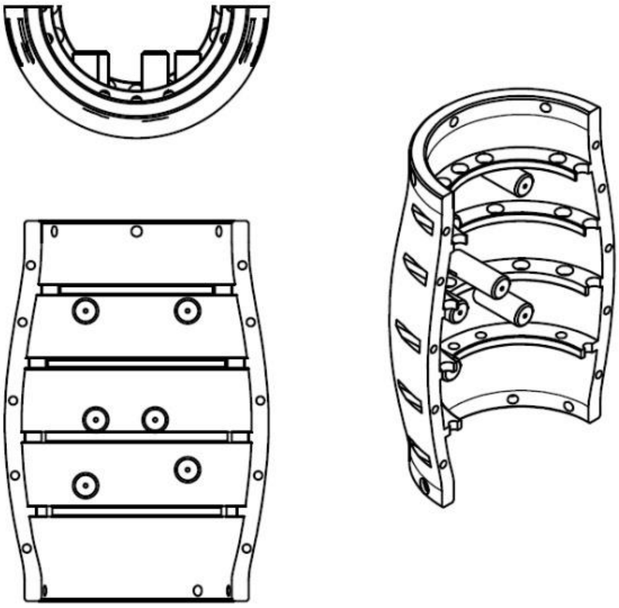


Figure 43 Base part of the upper arm, Model 10

The wire routing of motion sets of three cables were considered in this model. It was decided to place holes along side the circumferential internal compartments. The idea is to set three holes at top, three at bottom, and a pair of three holes at left and right of the upper arm, respectively. Despite implementation of column approach towards Arduino board configuration, bottom holes at two middle parts of circles were moved a little bit, which is different to the top, left and right. The configuration was implemented to resist wire intersection as far as possible.

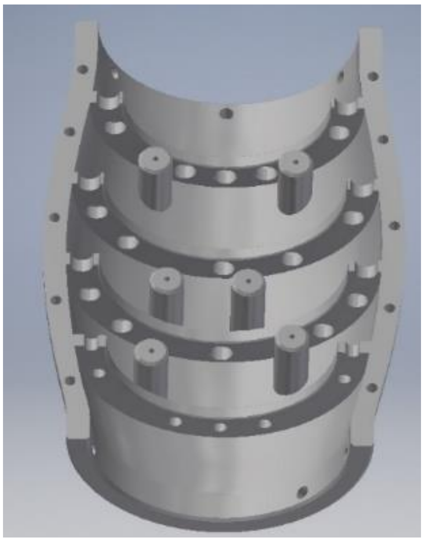


Figure 44 Wire routing of upper arm, Model 10

Finally, the upper arm was split into two parts. The connection between them is realized in a similar way that is used in design of the forearm. However, in this part mistakes obtained from assembly of the forearm were taken into account, such as size of connecting holes, placement of bolts and problems of nut compartments. The spherical joint of shoulder was designed to be maximally compact. It is a sphere located on connecting circular base. On the opposite to the base side of the joint there is a hole placed to enable routing of wire and cables. The base is connected to the upper arm in a similar way in other joints, by using bolts and nuts.

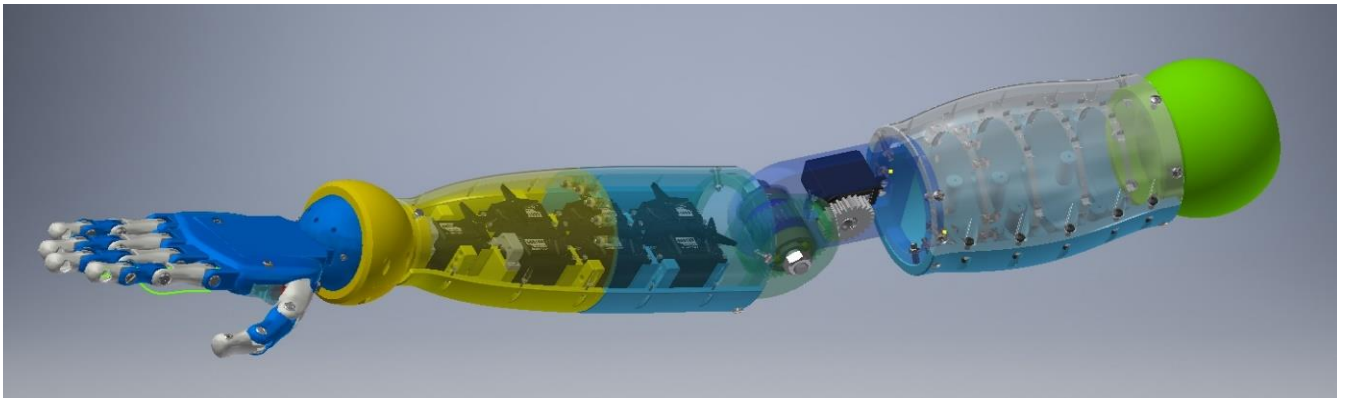


Figure 45 Model 10

Manufacturing and assembly

The parts of the hand are manufactured using additive technology. They are made from plastic and are 3D printed. The special machine was built in Czech Technical University by the supervisor of the thesis. The models of parts were converted to .STL files by a CAD software and further distributed to a 3D print controlling computer. The parts are almost precise, 1-2 mm error in dimensions, however some adjustments had to be taken during assembly of the parts. The compartments were firstly cleaned off and supporting structure was removed. After that, with grinding paper I smoothed sides, where supporting material was present. Finally, the bolts and nuts were attached to the parts. The size of the bolts for the forearm halves connection was too small and consequently it was increased to match the dimensions of bolts available at work shops. Furthermore, as the work proceeded improvements were applied and size of connecting bolts of the upper arm was increased before its manufacturing.

Figure 46 3D printed parts

The servo motors are arranged accordingly to the compartments that were designed for them and are connected to the material by small screws. The ropes are attached to the servo tops. A set of two ropes belongs to each motor thus enabling a 2 DOF motion for each part, towards which the ropes are attached. The cables for fingers are firstly connected to motors, then they are extended through the wrist connection and palm connecting end to the end point of plastic finger ends. The ropes for wrist pitch and yaw motions stretch from motors in forearm compartment to respective bolted connections of the sphere, where they are fixed by nuts.

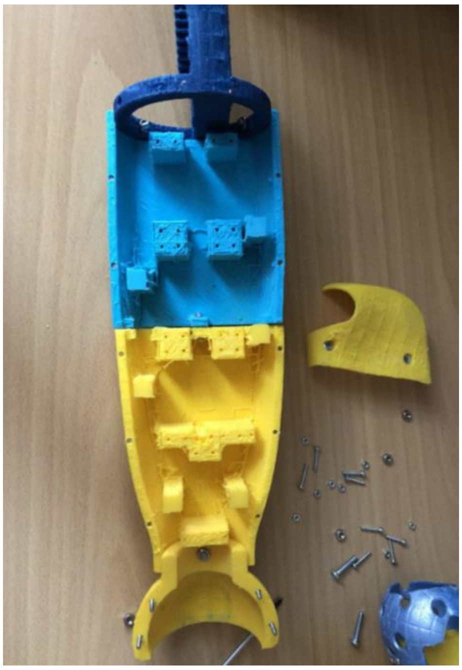


Figure 47 Forearm motor compartments

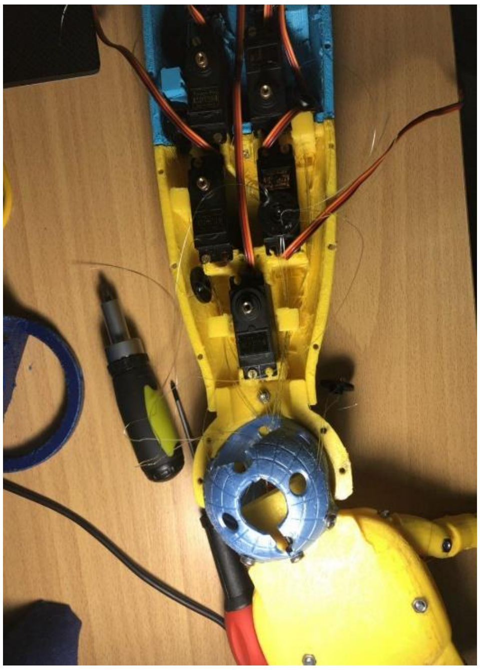


Figure 48 Wire connection to the motor, forearm

Figure 49 Floorball connected to ropes

In order to realize the elbow joint of the arm, some parts were 3D printed whereas the part of high load, shaft, was manufactured in the university technical laboratories. The supporting bearing are bought from stores available in the city. The pinion gear is attached to the elbow motor top by screws and is linked to the mating gear with the help of shaft. Two threaded ends must be manufactured on the shaft for nuts to be attached on the sides. The nuts will prevent parts from separation and consequent falling.

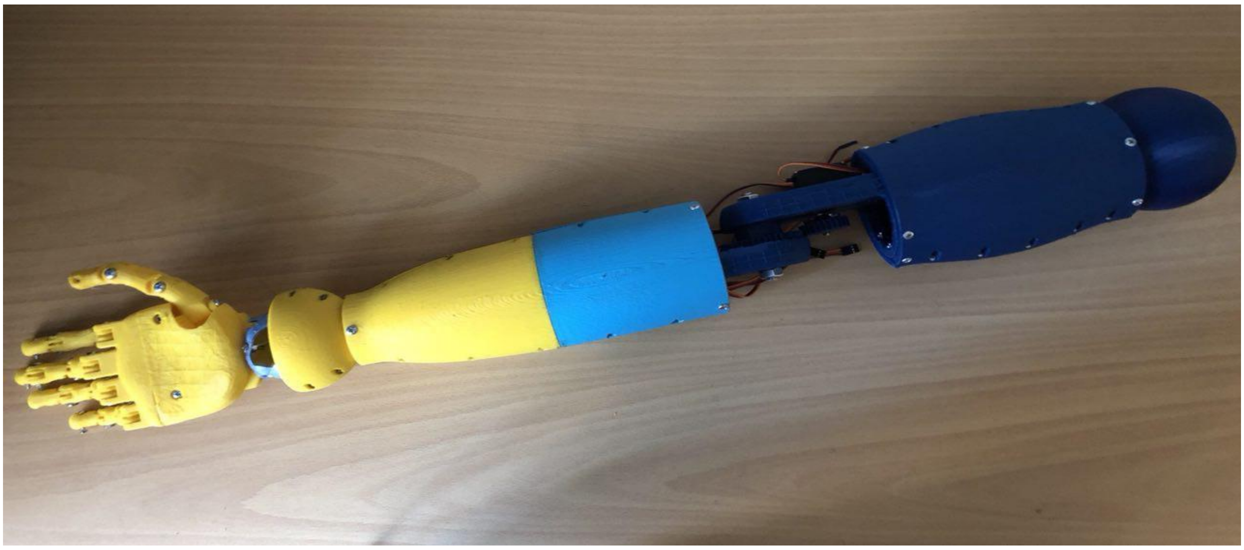


Figure 50 Arm assembly

The cables passing through the elbow link should be separated from the gears and prolonged through the hole, which does not lead to the gearing. Furthermore, the motor cables are connected to the control board installed in the upper arm compartment. The means of connection are small screws, which are linked to the columns that were designed to hold the board. The ropes for shoulder motion should begin from motors installed in the body compartment of the future robot and extend though the three sets of special holes designed in the upper arm towards the last and closest to elbow set of holes, where these cables are fixed.

Additional improvements

The progression of the design of robotic hand involves tackling problems that occurred during assembly. The first issue that I had to address is the lack of knowledge of the real motor configuration. To be more specific, cable routing from the motor towards the control board was not considered. Therefore, it was necessary to alter the design to include some space for cables, rather than try to press them inside the insufficiently large compartment in the forearm. Finally, this was accomplished by extrusion of additional space in the middle of motor fixing columns.

Secondly, the mechanism of the elbow joint turned out to be insufficiently stiff and another arrangement of bearings was suggested. The approach is to fix outer rings of the bearings inside one part of the elbow joint, while press the inner rings to bolt thus generating possibility for rotational motion.

Thirdly, it was necessary to alter directions of pulling forces for the wrist pitch and yaw motions, the ropes are installed externally, since this approach leads to better effectiveness of the joint. It important to note that shoulder joint could encounter similar problem, the motion could be improved in the same manner.

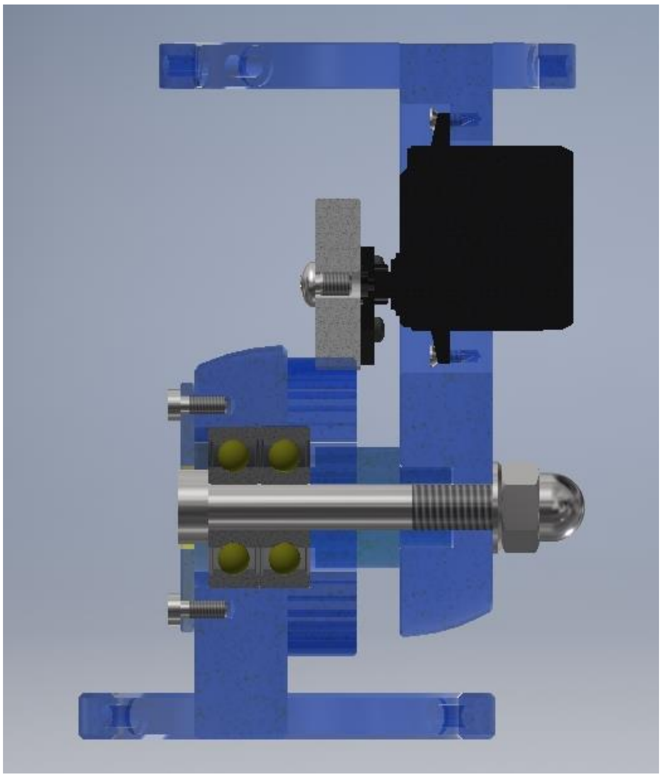


Figure 51 Modified elbow joint design

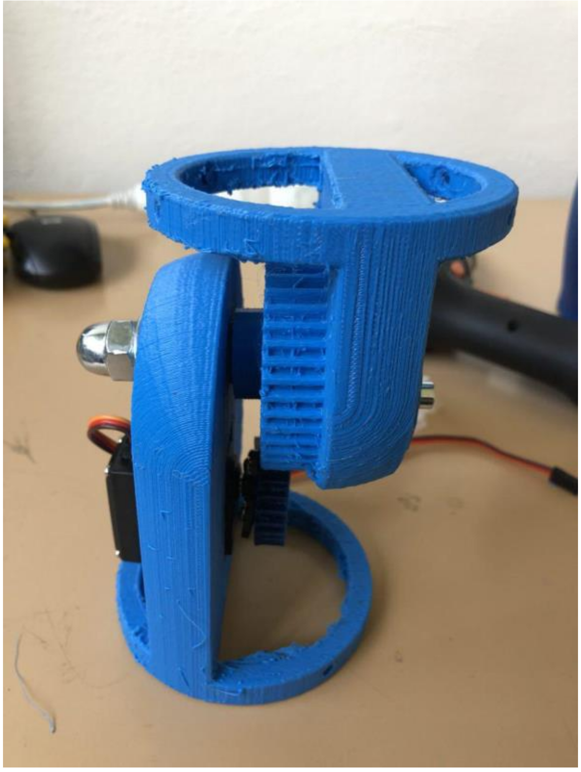


Figure 52 Assembled elbow joint

Moreover, it was decided to enlarge holes for the bolted connections of the forearm link between its upper and lower parts. The reason for that procedure was to be able to use bolts available on the market. Furthermore, material from sides of bolted connections was removed in order to have a better fitting of bolts and nuts.

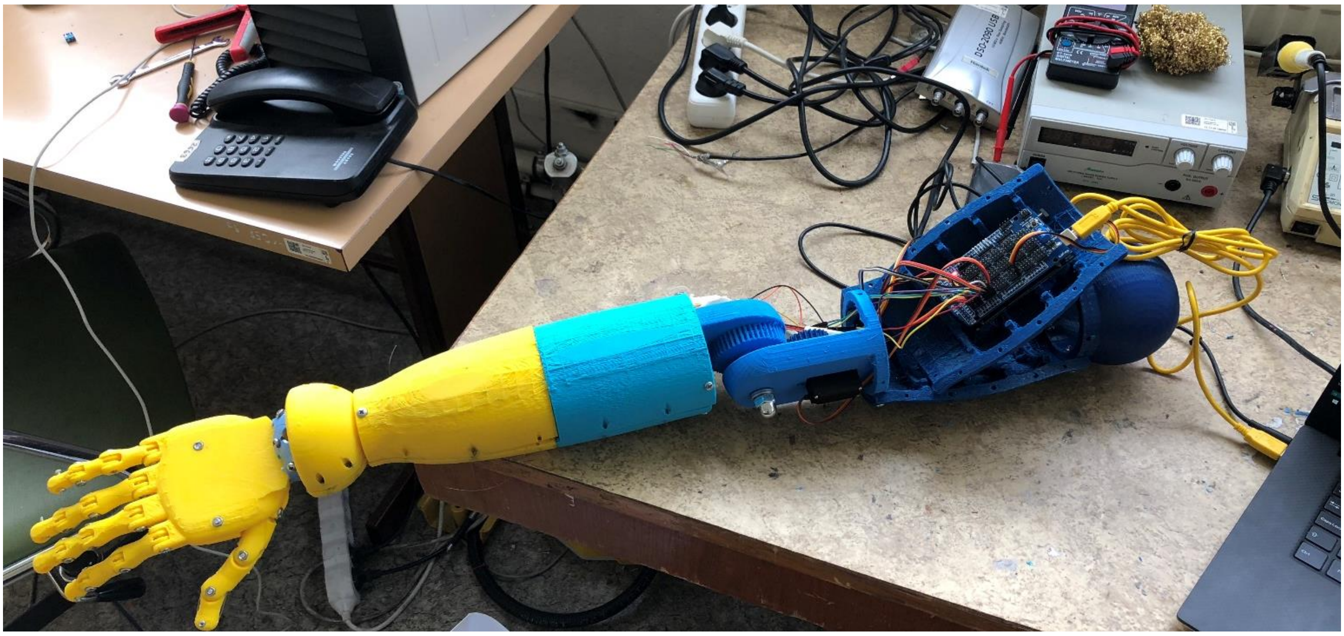


Figure 53 Assembled arm in laboratory

Testing and sequence algorithm

To test the realization of arm project, it was decided to have a short program written for the control of motors and to create a sequence of motions. The algorithm is written in the IDE, integrated development environment, provided by Arduino, manufacturer of the control board.

The code

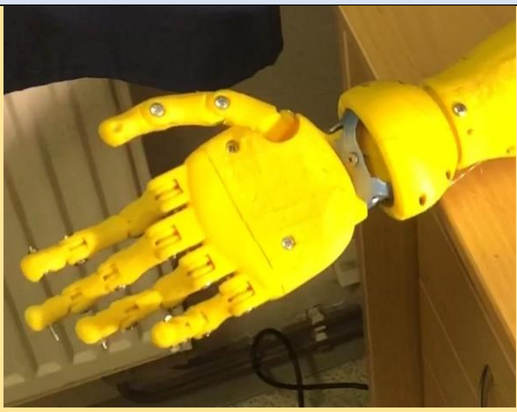
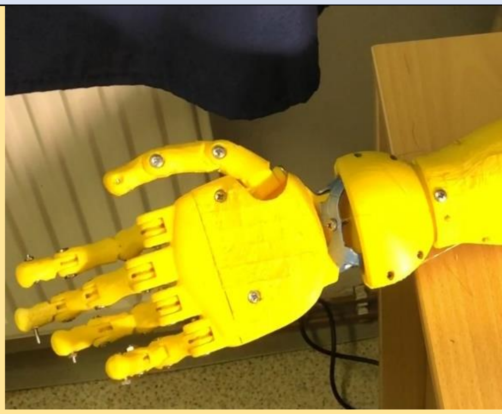
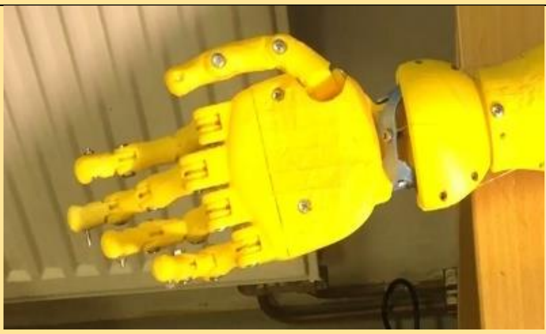
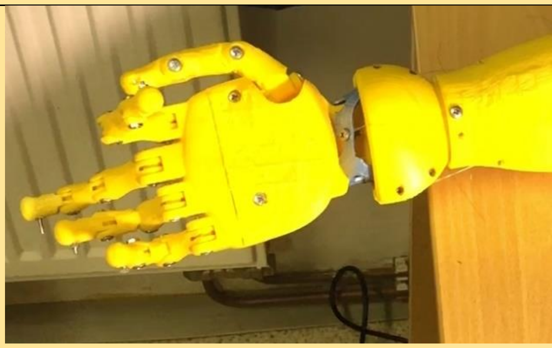
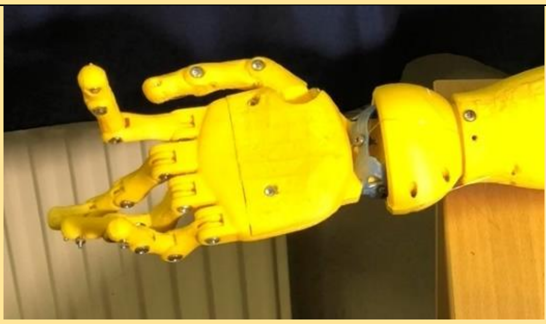
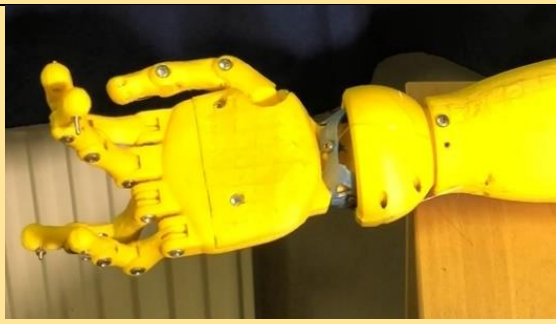
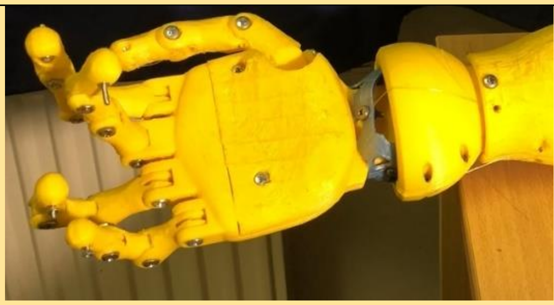
```
#include <Servo.h>
//creation of servo objects
Servo smallfinger;
Servo nonamefinger;
Servo middlefinger;
Servo indexfinger;
Servo thumb;
Servo pitch;
Servo yaw;
Servo elbow;
int pos = 0;
//functions are applied only once
void setup() {
```

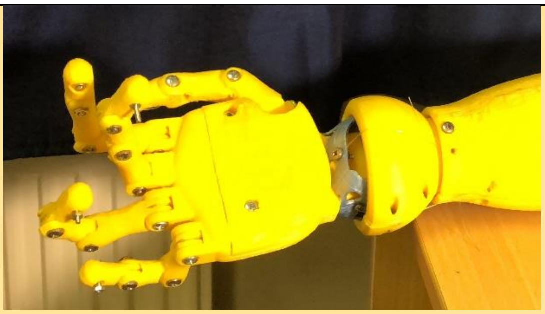
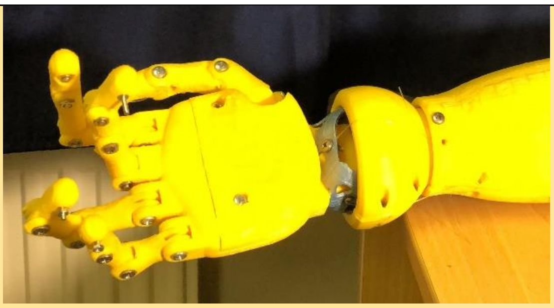
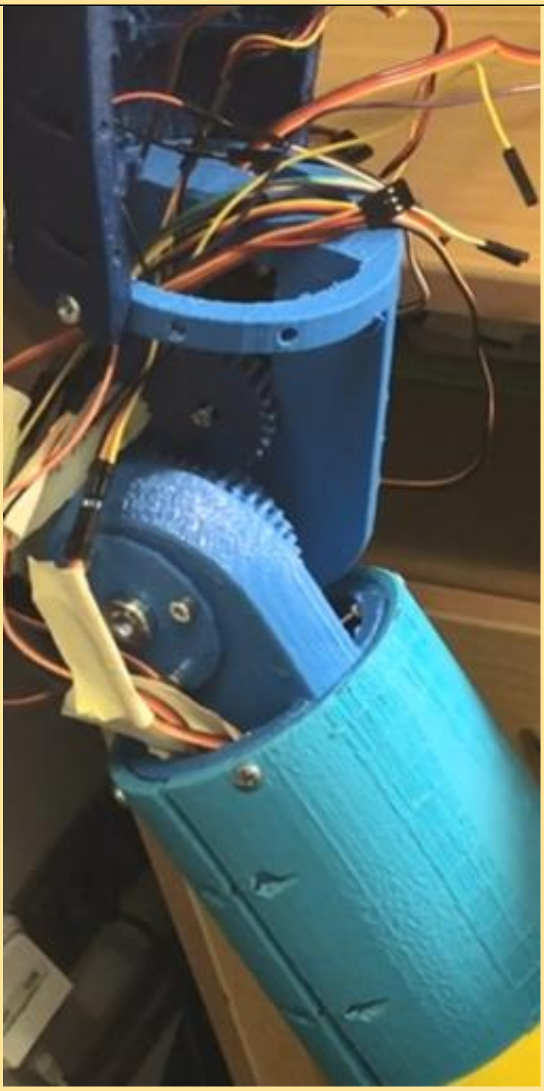
```
smallfinger.attach(6);
nonamefinger.attach(7);
middlefinger.attach(10);
indexfinger.attach(11);
thumb.attach(12);
pitch.attach(13);
yaw.attach(9);
elbow.attach(8);
}
//sequence is repeated
void loop() {
//each finger closes from open position
//small finger closing
  for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees    // in steps of 1 degree
  smallfinger.write(pos);              // tell servo to go to position in variable 'pos'
  delay(20);                       // waits 20ms for the servo to reach the position
 }
//noname finger closing
  for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees    // in steps of 1 degree
  nonamefinger.write(pos);              // tell servo to go to position in variable 'pos'
  delay(20);                       // waits 20ms for the servo to reach the position
  }
//middle finger closing
  for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees    // in steps of 1 degree
   middlefinger.write(pos);              // tell servo to go to position in variable 'pos'
   delay(20);                       // waits 20ms for the servo to reach the position
  }
//index finger close
  for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees    // in steps of 1 degree
  indexfinger.write(pos);              // tell servo to go to position in variable 'pos'
  delay(20);                       // waits 20ms for the servo to reach the position
 }
//thumb finger close
  for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees    // in steps of 1 degree
   thumb.write(pos);              // tell servo to go to position in variable 'pos'
```

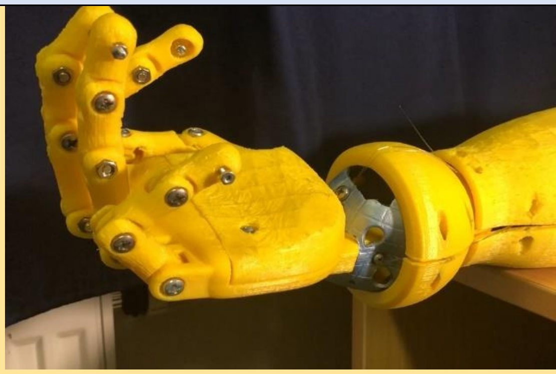
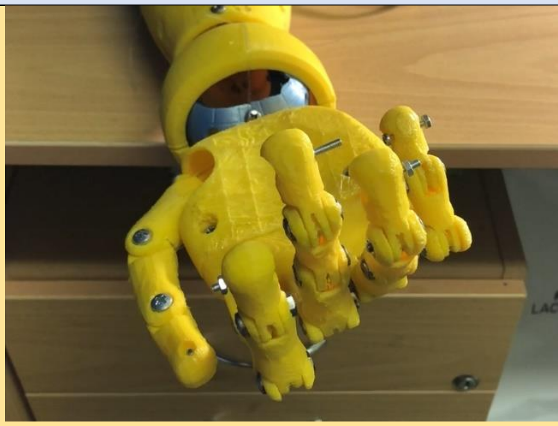
```
  delay(20);                       // waits 20ms for the servo to reach the position
 }
//pitch up/
for (pos = 90; pos <= 180; pos += 1) { // goes from 90 degrees to 180 degrees    // in steps of 1 degree
 pitch.write(pos);              // tell servo to go to position in variable 'pos'
 delay(20);                       // waits 20ms for the servo to reach the position
}
//pitch down
 for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees    // in steps of 1 degree
 pitch.write(pos);              // tell servo to go to position in variable 'pos'
 delay(20);                       // waits 20ms for the servo to reach the position
}
//pitch return
 for (pos = 0; pos <= 90; pos += 1) { // goes from 0 degrees to 90 degrees    // in steps of 1 degree
 pitch.write(pos);              // tell servo to go to position in variable 'pos'
 delay(20);                       // waits 20ms for the servo to reach the position
}
//yaw one direction
 for (pos = 90; pos <= 180; pos += 1) { // goes from 90 degrees to 180 degrees    // in steps of 1 degree
 yaw.write(pos);              // tell servo to go to position in variable 'pos'
 delay(20);                       // waits 20ms for the servo to reach the position
 }
// yaw another direction
 for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees    // in steps of 1 degree
 yaw.write(pos);              // tell servo to go to position in variable 'pos'
 delay(20);                       // waits 20ms for the servo to reach the position
 }
// yaw return
 for (pos = 0; pos <= 90; pos += 1) { // goes from 0 degrees to 90 degrees    // in steps of 1 degree
 yaw.write(pos);              // tell servo to go to position in variable 'pos'
 delay(20);                       // waits 20ms for the servo to reach the position
 }
//elbow up
 for (pos = 180; pos >= 45; pos -= 1) { // goes from 180 degrees to 45 degrees    // in steps of 1 degree
 elbow.write(pos);              // tell servo to go to position in variable 'pos'
```

```
  delay(20);                       // waits 20ms for the servo to reach the position
  }
//elbow down(return)
 for (pos = 45; pos <= 180; pos += 1) { // goes from 45 degrees to 180 degrees    // in steps of 1 degree
  elbow.write(pos);              // tell servo to go to position in variable 'pos'
  delay(20);                       // waits 20ms for the servo to reach the position
  }
//each finger opens from closed position
//small finger close
    for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees    // in steps of 1 degree
    smallfinger.write(pos);              // tell servo to go to position in variable 'pos'
    delay(20);                       // waits 20ms for the servo to reach the position
   }
//noname finger close
  for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees    // in steps of 1 degree
  nonamefinger.write(pos);              // tell servo to go to position in variable 'pos'
  delay(20);                       // waits 20ms for the servo to reach the position
   }
//middle finger close
   for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees    // in steps of 1 degree
   middlefinger.write(pos);              // tell servo to go to position in variable 'pos'
    delay(20);                       // waits 20ms for the servo to reach the position
  }
//index finger close
   for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees    // in steps of 1 degree
   indexfinger.write(pos);              // tell servo to go to position in variable 'pos'
   delay(20);                       // waits 20ms for the servo to reach the position
   }
//thumb finger close
   for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees    // in steps of 1 degree
    thumb.write(pos);              // tell servo to go to position in variable 'pos'
    delay(20);                       // waits 20ms for the servo to reach the position
    }
}
```

The control board Arduino Uno was used to test each motor. The wires were connected accordingly to the Figure 9, [15]. Parts of the code had to be commented and sequence was to make one motion for each motor and return it to the starting position. The following figures illustrate the procedure:

Name of part	Open position	Closed position
Thumb	 *Figure 54 Thumb, open*	 *Figure 55 Thumb, closed*
Index finger	 *Figure 56 Index finger, open*	 *Figure 57 Index finger, closed*
Middle finger	 *Figure 58 Middle finger, open*	 *Figure 59 Middle finger, closed*
No name finger	 *Figure 60 No name finger, open*	 *Figure 61 No name finger, closed*

<table>
<tr><td>Small finger</td><td>
Figure 62 Small finger, open</td><td>
Figure 63 Smalle finger, closed</td></tr>
<tr><td>Elbow</td><td>
Figure 64 Elbow, open</td><td>
Figure 65 Elbow, closed</td></tr>
</table>

	Down	Up
Pitch	 *Figure 66 Wrist, down position*	 *Figure 67 Wrist, upper position*
	Right	Left
Yaw	 *Figure 68 Wrist, right position*	 *Figure 69 Wrist, left position*

Conclusion and propositions for future work

The result of the project shows how a possible solution towards robotic hand design could be implemented. With the help of equipment available at university, manufacturing of the arm turned out to be reality from the paper drawn concept. Many design challenges were solved, and experience was gained from the work. These challenges were: design of wrist joint, elbow joint, compactness of overall design and others. One of the main goals of the bachelor thesis was to apply a creative approach towards realization of the task. Therefore, the joints of wrist and shoulder were not copied from other solutions, but rather a self-proposed approach of spherical joint was decided to be verified and implemented. Furthermore, elbow joint was designed to be as feasible as possible, while simplified enough to facilitate assembly and manufacturing. In future, it is necessary to use a motor with larger torque.

The rope concept was implemented to further enhance similarity of the mechanical arm to the natural human version. With the advancement of flexible robotic materials, controlled muscle tissue copies could be implemented, which would enable more maneuverability and beauty of the design. Finally, it is essential to consider installation of strain gauges, button load cells or other thin force sensors to fingers of the arm for the robot to obtain information and orient with reactions of bodies towards which the robot’s force is applied. This would be good for object grasping or playing instruments such as the piano.

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