TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Mechatronics, Informatics
and Interdisciplinary Studies

Control system of bionic hand

Master thesis

Study programme: N2612 – Electrical Engineering and Informatics
Study branch: 3906T001 – Mechatronics

Author: **Ekaterina Nyrobtseva**
Supervisor: Ing. Jan Koprnický, Ph.D.

Liberec 2018

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta mechatroniky, informatiky
a mezioborových studií

Control system of bionic hand

Diplomová práce

Studijní program: N2612 – Electrical Engineering and Informatics
Studijní obor: 3906T001 – Mechatronics

Autor práce: **Ekaterina Nyrobtseva**
Vedoucí práce: Ing. Jan Koprnický, Ph.D.

Liberec 2018

Technical University of Liberec
Faculty of Mechatronics, Informatics and Interdisciplinary Studies
Academic year: **2017/2018**

DIPLOMA THESIS ASSIGNMENT

(PROJECT, ART WORK, ART PERFORMANCE)

First name and surname:	**Ekaterina Nyrobtseva**
Study program:	**N2612 Electrical Engineering and Informatics**
Identification number:	**M17000006**
Specialization:	**Mechatronics**
Topic name:	**Control system of bionic hand**
Assigning department:	**Institute of Mechatronics and Computer Engineering**

Rules for elaboration:

1. Make an analysis of control systems of active prosthetic hands with respect to the used actuators and sensors.
2. Familiarize with bionic prosthetic hand of the HACKberry project.
3. Replace the control system of the hand by the Arduino Esplora microcontroller board.
4. Enlarge the hand system by other sensors to ensure feedback control.

Scope of graphic works: by appropriate documentation

Scope of work report (scope of dissertation): 40–50 pages

Form of dissertation elaboration: printed/electronical

Language of dissertation elaboration: English

List of specialized literature:

[1] KOPRNICKÝ, J., ŠAFKA, J. and NAJMAN, P. 3D Printed Bionic Prosthetic Hands. IEEE International Workshop of Electronics, Control, Measurement, Signals and their application to Mechatronics ECMSM 2017 1. ed. Donostia – San Sebastian: IEEE, 2017. ISBN 978-1-5090-5582-1

[2] HACKberry exiii [online]. [cit. 2017-10-20]. Available: http://exiii-hackberry.com/

[3] MUZUMDAR, Ashok. Powered Upper Limb Prostheses: Control, Implementation and Clinical Application. 1. Berlin Heidelberg: Springer-Verlag, 2004. ISBN 978-3-642-62302-8.

[4] PLÍVA, Z., KOPRNICKÝ, J., DRÁBKOVÁ, J. and PETRŽÍLKA, L. Guidelines for Writing Bachelor or Master Thesis. 1. ed. Liberec: Technical University of Liberec, 2014. ISBN 978-80-7494-104-7.

Tutor for dissertation: **Ing. Jan Koprnický, Ph.D.**

Institute of Mechatronics and Computer Engineering

Date of dissertation assignment: **10 October 2017**

Date of dissertation submission: **15 May 2018**

prof. Ing. Zdeněk Plíva, Ph.D.
Dean

L.S.

Technická univerzita v Liberci · 14 ·

Kolář

doc. Ing. Milan Kolář, CSc.
head of institute

Liberec, dated: 10 October 2017

Declaration

I hereby certify that I have been informed that Act 121/2000, the Copyright Act of the Czech Republic, namely Section 60, Schoolwork, applies to my master thesis in full scope. I acknowledge that the Technical University of Liberec (TUL) does not infringe my copyrights by using my master thesis for TUL's internal purposes.

I am aware of my obligation to inform TUL on having used or licensed to use my master thesis in which event TUL may require compensation of costs incurred in creating the work at up to their actual amount.

I have written my master thesis myself using literature listed therein and consulting it with my supervisor and my tutor.

I hereby also declare that the hard copy of my master thesis is identical with its electronic form as saved at the IS STAG portal.

Date: 14.05.2018

Signature:

Abstract

This work focuses on the development of feedback control system for inexpensive prosthetic hand HACKberry. This hand was originally designed in Japan and then printed with 3D printing technology and modernized in Technical university of Liberec. Before explaining the components and the feedback control design some information about previous works of this topic was collected and presented here. Arduino Esplora board is used here for establishing remote gestures and grips control due to its functional ability. The circuit of the hand powered by Arduino Micro board is not changed and thus, it is possible to control the hand both with muscles activity which and with Arduino Esplora. Communication between Arduino Esplora and Arduino Micro is performed via the wireless transmission. Since the prosthetic hand should be extended with feedback control it was decided to utilize force sensing resistors and flex sensors. Such types of sensors match to the project aims and at the same time allow the prosthetic hand remains at the same price category. Another advantage is in their affordability. Furthermore some hand-made sensors were created. All of the sensors were tested and estimated. The results of these tests are discussed herein.

Key words: bionic hand, 3D printing, feedback control, bend sensors, force sensors, Arduino Micro, Arduino Esplora, wireless communication, open-source, velostat material

Abstrakt

V této práci hlavní důraz je kladen na vývoj systému zpětné vazby pro řízení dostupných protéz horní končetiny HACKberry, který byl navržen japonskou společností Exiii a je otevřeným projektem. Tato protéza byla vytištěna na 3D tiskárně a modernizována na Technické univerzitě v Liberci. V této diplomové práci zkoumána možnost vytvoření zpětnovazebního systému založeného na hmatové zpětné vazbě. K dispozici jsou také další možnosti implementace tohoto úkolu, které byly vyvinuty nebo jsou vyvíjeny jinými společnostmi a institucemi, které řeší stejné úkoly. V našem projektu používá dálkové ovládání ruční protézy, které se provádí pomocí bezdrátového přenosu signálů z ovládacího zařízení, - desky Arduino Esplora - na samotnou protézu, kde ovládání patří do desky Arduino Micro. Kromě toho je k dispozici provedení různých gest pomocí myoelektrických signálů. Pro organizaci zpětnovazebního systému bylo rozhodnuto použít dva typy snímačů - snímač ohybu a snímač síly. Cenová dostupnost těchto snímačů umožňuje vývoj levného zpětnovazebního systému pro rozšíření funkčnosti protézy. Kromě použití komerčních senzorů v diplomové práci se také zvažuje možnost vytváření ručně vyrobených senzorů z inteligentních materiálů. Všechny typy senzorů - komerční a ručně vyrobené - byly testovány a vyhodnoceny z hlediska jejich technických vlastností a možnosti použití v našem projektu. Výsledky testů jsou také k dispozici.

Klíčová slova: bionické rameno, 3D tisk, ovládání se zpětnou kontrolou, senzor ohýbání, snímač síly, Arduino Micro, Arduino Esplora, bezdrátové ovládání, inteligentní materiály

Acknowledgements

I would like to thank my scientific adviser Ing. Jan Koprnický, Ph.D. for all his valuable advices, which helped me to overcome all difficulties with this diploma work and with typesetting system .

Contents

List of Abbreviations

ADC	Analog-to-Digital Converter
DIY	Do-It-Yourself
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMG	Electromyography
FSR	Force Sensing Resistor
IDE	Integrated Development Environment
IMES	Implantable Myoelectric Sensors
IR	Infrared sensor
LED	Light-Emitting Diode
PCB	Printed Circuit Board
SRAM	Static Random Access Memory
TD	Terminal Device
TTL	Transistor–transistor logic
UART	Universal Asynchronous Receiver-Transmitter
USB	Universal Serial Bus

List of Figures

List of Tables

1 Introduction

The loss of a limb can take a toll on the individual regardless of the cause. Prostheses were designed to alleviate this loss and could be found as early as ancient Egyptian era. The term prosthesis (plural: prostheses; from Ancient Greek *prosthesis*—addition, application, attachment) can be described as an artificial device that replaces a missing body part [1]. Today, there are a vast amount of prosthetic devices in the world, which help to replace not only exterior body part, but also viscera. Most often one can meet the prostheses of external body part.

The human hand is an exquisite, sensitive part of our bodies. Unlike low-limb prostheses, where one can easily reproduce the structure of a leg and its movements, upper-limb prostheses are more sophisticated mechanisms due to the bidirectional communication between hand and brain, complex sensory system and mechanical structure.

From science fiction movies such as “Star Wars”, “I, Robot” and etc. that introduced us with upper limp prosthesis, we got used to think that the modern upper-limb prostheses work in the same way – one just need to plug it to their stump and obtain the same functions as a normal hand has. In fact, there are a huge amount of hidden things which are not so evident. For example, one of the daily human activity, where the hand can be applied is a gesture of grasping an object. Although it seems quite simple, one needs to take into account the pressing force of the hand, estimate the weight and texture of the object, in order not to smash it occasionally.

It is always quite complicated for an amputees to know how well an object is grasped by their prostheses.Although there are a lot of commercial projects [2, 3, 4], that allow in a varying degree provide such information with the help sensory feedback or by sending impulses back to the head (direct neural feedback). However, due to their high price it is not possible for everyone to obtain them.

This work focuses on developing a control system of upper-limb prosthesis, that would provide the sensory feedback to more efficiently grasp and handle objects by upper limb amputees. Low cost of the project is another condition. And this condition can be reached by using widely used 3D printing technology.

In this work the preassembled upper-limb prosthesis based on the open-source HACKberry project [5] is used. Arduino Esplora board is chosen to control the prosthesis. This board was originally developed by manufacturer as a game-pad for creating video games. However, the presence of different ready-to-use sensors, mounted on this board, can give more possibilities apart from using it as a game board.

In the 2 section different types and parts of upper-limb prostheses will be discussed and classified.

Before starting considering the available solutions of feedback control we would like to observe the commercial prosthetic hands in chapter 3.

The next 4 chapter contains the information about recent developments in the field of prosthetic hand control and various sensor types used in these systems.

As the control system is developed for 3D printed prosthesis HACKberry, it is necessary to make an observation concerning this hand. That is why the aim of this chapter 5 is to provide some information regarding the sensors it uses and the hands itself.

Various types of sensors, constituting the feedback control system will be described in the section 6. Information about other parts of the system such as micro controllers and communication device can be found in this section as well.

In section 7 logical structure of the system will be explained and several algorithms, which are implemented in our project can be also found here.

Practical experiments and their results will be discussed in section 8.

2 Types of Prostheses and Their Classification

The upper-limb prostheses can be classified by:

- Level of amputation.
- Types.

Prostheses by amputation level can be grouped by the following types:

- Humeral head prosthesis.
- Forearm prosthesis.
- Arm prosthesis.
- Finger prosthesis.

Prostheses by types can be divided into two main groups:

- Passive or cosmetic prostheses.
- Active or functional prostheses.

Active prostheses give the ability of grasping an object and they are controlled by variety of mechanisms. Such prostheses may have modern robot-like design or can be supplied by cosmetic covers, that look like real arms.

Active prostheses for their turn may have the following classification:

- Body powered.
- Intended for work.
- Electrically powered (bionic or myoelectric).

2.1 Passive Prostheses

Passive or cosmetic prostheses are oriented to recreate the external appearance of the hand. Such type of hand consists of a stump socket, hand frame and cosmetic glove.

One of the main pluses is the weight of this prosthesis. Even if it is not so functional in a comparison with active prosthesis, it is still possible to perform some simple non-manipulated activity with it, such as press a button, push a door, etc [6].

2.2 Active Prostheses

2.2.1 Body-powered Prostheses

Body-powered prostheses work by using cables to link the movement of the body to the prosthesis and to control it. Moving the body in a certain way will pull on the cable and cause it to open, close, or bend.

Main components of body-powered prostheses are (see Figure 2.1):

- Socket or interface.
- Suspension system.
- Harness.
- Control cable.
- Wrist unit.
- Terminal Device.

The terminal device can be presented as a hook or a mechanical hand. Both of this terminal devices can be either in voluntary opening mode or in voluntary closing. In the first mode terminal device remains closed till the moment when the pulled cable opens it. In case of voluntary closing mode terminal device is opened until pulling on the cable closes it with a grip force proportional to the amount of force the person puts on this cable [7].

If it is an upper arm body-powered prosthesis, the opening of a hook or a hand is provided with the help of purposive movements of the stronger shoulder. In case of elbow prosthesis, there is a possibility to bend the arm and block the elbow with the belt of prosthetic hand. However, such kind of prosthesis is suffer from the lack of movements, which a patient needs in his or her daily live. Moreover, one can need large number of hours to learn how to use it. There are some variants of body-powered control—by the help of upper arm, elbow, wrist joint, proximal phalanges [8].

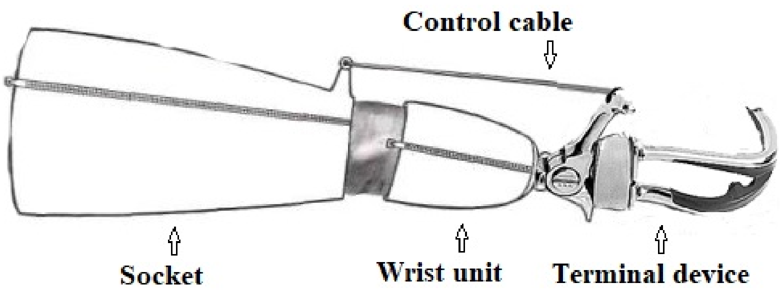

Figure 2.1: An example of body-powered prosthesis

2.2.2 Intended for Work Prostheses

This type of prostheses can be either externally-powered or body-powered. Holder of terminal device gives the possibility to use different terminal devices for various purposes. The terminal device is designed by such way, that the amputee can use this prosthesis to perform some working actions much easier. Distinction is made between passive or active terminal devices.

One of the example of this type of prosthesis was described in the article [9] and is depicted in Figure 2.2.

Figure 2.2: Myoelectric active prosthesis intended for work [9]

Another example of working prosthesis is a tattoo machine prosthesis [10], which is shown in Figure 2.3.

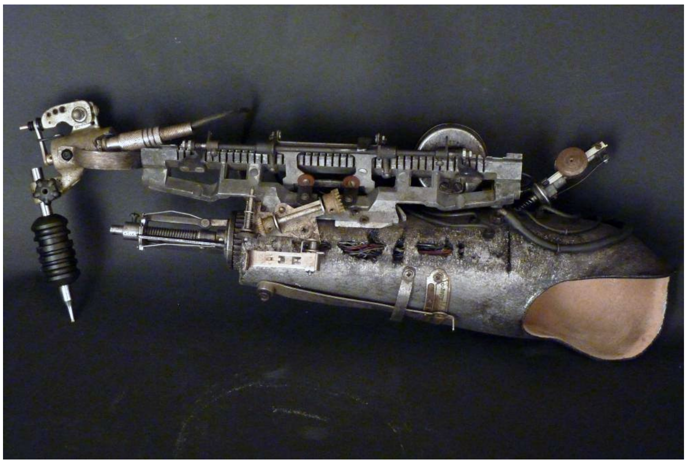

Figure 2.3: Tattoo machine prosthesis [10]

All of aforementioned prostheses have active terminal devices. However, passive terminal devices are more common among amputees. Examples of them are spanner, hammer, scissors, cutlery, pen and etc.

2.2.3 Externally-powered Prostheses

Externally-powered prostheses are also known as *myoelectric* or *bionic* prostheses. Such prostheses have components that are moved by motors and powered by batteries. The system is controlled by a microprocessor that uses signals from the body (in case of Myoelectric Control) or from the other devices (buttons, servo motors, harness) to tell the prosthesis what to do [11].

An externally-powered prosthesis may have the following components:

- Socket or interface.
- Electrodes or myoelectric sensors.
- Suspension system.
- Control unit or microprocessor.
- Battery.
- Terminal device or electric hand.

Such type of prosthesis may also possess additional components:

- Wrist Rotator.
- Elbow.
- Harness.

In usual situations brain tells muscles to move with electrical signals sent through nerves. However, in case of amputation muscles may not have a joint to move anymore, but signals from brain can still present. One of the solution is to use externally powered prosthesis.Myoelectric type utilizes muscle activity from the residual limb to control the movements of joint. The myoelectric hand prosthesis is an alternative to conventional hook prostheses. These prostheses have better grip, a stronger pinch force and are easier to use than conventional hooks. An example of such kind of prosthetic hand is demonstrated in Figure 2.4

In fact, the signal that is used to move an arm is utilized to move the prosthesis instead. For example, brain can still tell the biceps of the body to flex its elbow, and the muscle will still generate an electrical signal the same way it does normally. When the signal is strong enough and can be detected, then it is collected via electrodes embedded in the prosthetic socket, amplified and then processed by a controller to drive battery powered motors that move the prosthesis.

Sockets or Interfaces

Socket is the prosthesis foundation that in cases the residual limb. All other components of prosthetic hand are connected to it. Since the socket is the basis it must fit well to provide not only comfortable feeling, but also required functionality. The prosthesis should feel and acts like an extension of human body. It has not

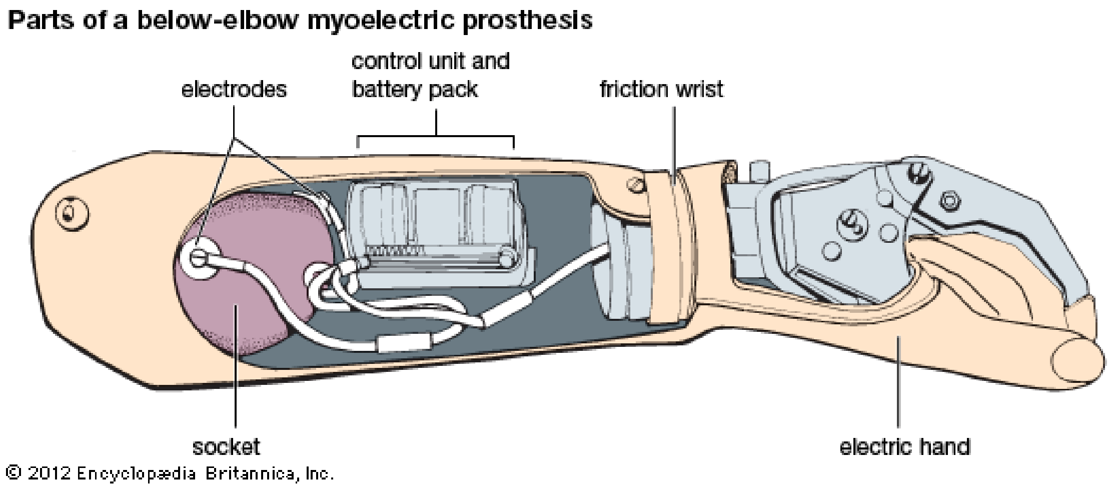

Figure 2.4: An example of externally-powered prosthesis [12]

to be too loose or otherwise, when the limb is moved, it will just move inside the prosthesis and not move the prosthesis itself. Furthermore, myoelectric sensors will not have a good contact with a skin and therefore will not work in the way it was supposed [13].

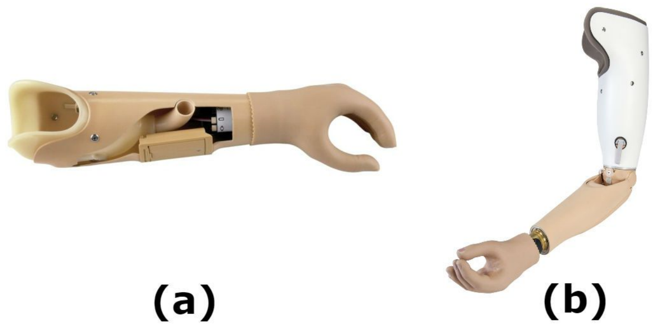

Figure 2.5: Sockets for different amputation level from Ottobock company [2], (a) socket for below-elbow amputation, (b) socket for above-elbow amputation

Sometimes the shape and the size of patient's residual limb can change during the time, especially if to speak about children. In such situation socket should be replaced by a new one. To overcome the problem of loose socket a residual limb is scanned with lasers.

Sockets an be done for both above-elbow and below-elbow amputation (see Figure 2.5).

Electrodes or Myoelectric Sensors

Electromyography (*mio* - muscles, *grapho* - write) or EMG measures muscle response or electrical activity in response to a nerve's stimulation of the muscle [14]. Muscle response is measured with electrodes. The electrodes employed are correspondingly called skin electrodes, percutaneous and implantable electrodes.

Skin electrodes or myoelectric sensors are placed on the skin surface close to the muscle whose activity they are supposed to detect. Placement is very precise, and being off, even just a few millimeters, can make a big difference in the quality and strength of the signal that the electrode observes [11]. This type of electrodes are optimal to register the total sum of muscles activity, but cannot give the precise data of any separately taken muscle's potential. The main disadvantage of such type of electrodes is a possible distortion of electromyogram appeared by so-called muscle cross-talk. This terminology means that the signal from nearest muscles influences the signal we want to measure by over-crossing it.

Advantages of skin electrodes:

- Hygienic.
- Non-invasive
- Simple everyday usage

Myoelectric sensors in a classical feedback theory represent the gain. The higher the gain the more it is sensitive. Unfortunately, we cannot increase the gain infinitely because we will amplify the ambient noise as well [11].

Skin electrodes can be classified to wet and dry electrodes. The dry ones consist of a metal plate fitted to the skin, whereas the wet ones are supplied with an electrolytic layer between the skin and the metal plate [15].

Implantable electrodes are almost free from the cross-talk problem. Compared to using surface EMG electrodes, IMES can provide multiple degrees of freedom of control. This allows an amputee to perform the functions of grasp and wrist rotation at the same time, thus providing significantly enhanced limb control [16].

However, advantages of skin electrodes are transformed to the disadvantages of implantable one. Moreover, not everyone after having a lot of operations will agree to have an additional one for implanting the sensors.

It can be quite sophisticated to control the prosthetic hand only with the usage of EMG signals, as not all muscles, that human has under normal conditions, can be presented in patient's residual limb. As a consequence such gesture like waving the thumb without bending it cannot be determined unambiguously and thus, some additional techniques should be added to the control system of prosthetic hand.

Control Unit or Microprocessor

The major component of prosthetic hand is a control unit. Speed of the response and hence the comfortable usage depends on this particular part. Commercial prosthetic hands are usually equipped with special dedicated micro-controllers or microprocessors. In most cases control unit is developed especially for the needs of exact prosthesis.

In some economical solution Arduino boards or other available micro-controllers are harnessed.

Regardless of what type of the control unit is used its main function is receiving and processing signals.This is usually done with a computer program that dictates which signal is responsible for what function and under what conditions.

Terminal Device or Electric Hand

Nowadays it is possible to find in literature three main types of terminal devices (TD) for upper limb prostheses: hooks, hands and specialized terminal devices.

Figure 2.6: Various terminal devices for prosthetic hand, (a) commercial hook of Ottobock company [2], (b) variants of specialized terminal devices

The only externally-powered hook available for clinical use at this time is a commercial external hook form Ottobock company.

Hand as a terminal device can be self-dependent or covered with a glove for human hand appearance.

Specialized TD such as cutlery or working tools can be connected to the prosthesis instead of hook or hand. Anything that we use in our daily live can be made as a terminal device.

3 Available Prosthetic Hands

In this chapter we would like to familiarize readers with available solutions of prosthetic hands. The well-known solutions came from such companies like Ottobock [2], which the first created flexible wrist joint; Touch Bionics [3], that introduced the possibility to control any gestures with mobile application; RLSteeper [17], which managed to develop a hand with rotation angle of 360 degree. However, they are not only these companies that are working on the upper-limb prostheses solution. Some less known companies such as Russian Motorica [8] and MaxBionic [4] also dedicate their efforts to this problem.

Three solutions of aforementioned leading companies can be found in Figure 3.1 below.

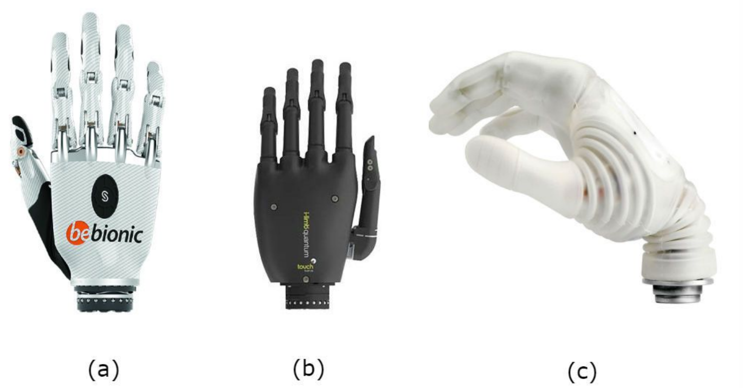

Figure 3.1: Leading Prosthetic hands, (a) BeBionic hand of Ottobock company [2], (b) i-limb quantum of Touch Bionics [3], (c) Michelangelo prosthetic hand of Ottobock [2]

Besides the commercial prosthetic hands there are also research projects from scientific institutions [18, 19], open source and Do-It-Yourself (DIY) projects [20].

3.1 Commercial Prosthetic Hands

Before going deeper in characterization of separate commercial prostheses we would like to present a comparative table (3.1) of the most known kinds of prostheses existed today.

Table 3.1: Characteristics of some kind of commercial prostheses [21]

Name of the hand	Weight	Number of Joints	Degree of Freedom	Number of Actuators	Actuation Type
i-limb Ultra	563	11	6	5	DC Brushed motors. Worm gear
Michelangelo	572	6	2	2	DC Brushed motors. Planetary gear head
BeBionic v2	682	11	6	5	DC Brushed motors. Lead screw
Vincent evolution 2	509	11	6	6	DC Brushed motors. Worm gear

3.1.1 Solutions of Ottobock Company

Ottobock company is a German company which was founded in 1919 by prosthetist Otto Bock. This company focuses both on upper-limb prostheses and lower-limb prostheses. Till 2017 the leading myoelectric upper-limb prosthesis was Michelangelo. Nowadays Ottobock is an owner of another cutting-age prosthesis—Bebionic. Besides the foremost prostheses there are also solutions focused on children such as Electrohand 2000 or on moving heavy things like AxonHook.

Michelangelo Prosthetic Hand

As it was mentioned before Michelangelo prosthetic hand possesses the advantage of wrist flexibility.Inward and outward rotation of the wrist is also supported. The hand can be fixed in rigid mode in any supported angle (see Figure 3.1 (c)). Thanks to the powered abduction/adduction it is possible to hold thin flat objects, such as credit card between fingers independently of thumb position. Responsibility for gripping movements and grip force lies on main drive. Only three fingers are actively driven in this prosthesis - thumb, index finger and middle finger. The ring and little fingers simply follow the others. Here thumb is positioned with myoelectric control regardless of other famous prosthesis such as Bebionic.

Specification of this hand can be found in table 3.2 below and on the official web page [2].

The center control unit of the system is self-produced AxonMaster microprocessor. It receives control signal from the myoelectric sensors mounted on the patient's residual limb and transforms to the respective prosthesis components. AxonMaster control unit has inner Bluetooth module. Adjustments to the prosthetic components

Table 3.2: Technical characteristics of Michelangelo prosthetic hand

Operating temperature	from –10º C to +60º C
Weight	420g
Operating voltage	11.1 V
Gripping force in Opposition Mode	70N
Gripping force in Neutral Mode	15N

can be uploaded to the system with Bluetooth data transfer using the AxonSoft software.

Bebionic Hand

This hand was initially the product of the British med-tech company RSLSteeper, but at the beginning of 2017 Ottobock company acquired the BeBionic prosthetic products and related business from it.

Today the last version of Bebionic hand provides 14 different grips which are monitored with build-in microprocessor. For customizing hand gesture the wireless technology is used to upload new program to microcontroller.

Each Bebionic hand finger is equipped with its own motor. Such feature allows moving fingers and making any grips in a similar way as a human hand does. On the fingertips there are soft finger pads that help to enhance grips. When a gripped object is slipping the Bebionic hand adjusts the grip by implementing more forces to secure it.

Usage of durable constriction makes bionic hand strong enough to take heavy objects up to 45 kg and push oneself up from a seated position.

Unfortunatelly, it was not possible to find the microcontroller characteristics as well as used control system in open source.

Some information found in [22] of prosthetic hand Bebionic is presented in table 3.3.

Table 3.3: Technical characteristics of Bebionic prosthesis

Tripod grip force	36.6 N
Time to open or close tripod grip	0.5 s
Hand carry load (static)	45 kg
Finger carry load (static)	25 kg
Vertical push down load (through knuckles)	90 kg

3.1.2 Solutions of Touch Bionics Company

The history of Touch Bionics company began with a program of work conducted at the Princess Margaret Rose Hospital in Edinburgh, Great Britain from 1963 [23].

In 2007 this company launched their first version of i-limb prosthetic hand. Now the representatives of this product line are i-limb ultra and its successors i-limb quantum and i-digits quantum.

As the information of these prosthetic devices are not in a public access sorely some of the most important material from official web pages of two aforementioned solutions is presented below.

I-digits Quantum Prosthetic Hand

This prosthesis is similar to the i-limb quantum, but in contrast to i-limb quantum, it was designed for patients with partial hand amputation. According to the Touch Bionics company [3] it is possible to replace from one to five digits and any loss of the palm with this prosthesis. That is why there is no sense to speak about the weight and other characteristics as they depend on the level of amputation.

There are 4 possible methods to control this hand:

- Gesture control.
- Muscle control.
- Application control.
- Proximity control.

Gesture control enables gestures to be accessed by simply moving the hand to one of the 4 available directions. Muscle control implies the hand control by means of myoelectric sensors.

Proximity control is an ability to perform predefined gesture by moving i-digits quantum close to any objects that have a special grip chip. Bluetooth technology is used for these purposes.

Another interesting feature is to control the hand grips and gestures with any mobile devices that have preinstalled application. In this application 20 preprogrammed gestures and grips can be extended by 12 custom ones [3] .

I-limb Ultra Prosthetic Hand

This hand was the precursor of the i-limb quantum and i-digit quantum hands.

Today the newest version of this solution has a powered thumb that possesses its own motor as well as all other 4 fingers. For saving battery live power management is used. It includes the liability to return the prosthetic hand to its original position after some period of inactivity.

As all other types of Touch Bionics hands, gestures and grips of i-limb ultra prosthesis can be controlled with smartphone application. Sleep prevention system is also provided here.

Technical specification of this hand is presented in table 3.4.

Table 3.4: Technical characteristics of i-limb Ultra hand from Touch Bionics company

Voltage	7.4 V (nominal)
Max. Current	5 A
Battery	Rechargeable lithium polymer; 7.4 V (nominal); 2000 mAh capacity;
Max. hand load limit (static limit)	40kg for extra small hand 90kg for small/medium/large hands
Time from open position to full power grip	0.8 seconds

3.1.3 Solutions of Motorica Company

A fairly new Russian company Motorica started its work with active body-powered prosthesis for children—Cybi. Currently the company is working on the external-powered type of prosthesis for adults, that was received the name Stradivary.

Body-Powered Prosthesis Cybi

This prosthetic hand can be made with any design by wishes of a patient. Cybi allows grasping by tension of cables, which are connected with prosthetic fingers and fixed at the forearm. Tension of a cable happens during the ankle's movements. With Cybi hand it is possibly to hold any objects up to 10 kg, where the maximum border depends on forearm muscles strength. This prosthesis has an extension for mounting some gadgets such as smart-watch, MP3-player, pen-holder and smartphone.

Figure 3.2: Different design of body-powered prosthetic hands Cybi [24]

Externally-Powered Prosthesis Stradivary

Bioelectrical prosthesis Stradivary shown in Figure 3.3 is currently allows providing close grip and open hand gesture. Such unsophisticated functionality can be enough to make daily affairs like grasping small objects, cook and dress without third person assistant. As this prosthesis belongs to externally-powered type its control system

Figure 3.3: Externally-powered prosthetic hand Stradivary [8]

is based on the myoelectric sensors reading the muscles signals and transmitting them to the microprocessor, where then they are transformed to the prosthetic hand movements.

Strength and pace of grip can be controlled by muscles tension that lets the person to take fragile objects without fear to break them.

One peculiarity is build-on payment system based on contactless PayPass technology that allows people to pay in shops and public transport by simply bringing Stradivary prosthesis to the vicinity of payment terminal. It is also planned to introduce speech control of hand gestures, LCD-display and GSM module for making calls.

Some prosthesis characteristics can be found in table 3.5.

Table 3.5: Technical characteristics of externally-powered prosthesis Stradivary

Operating temperature	form -10 to +40°C
Time to fully open the hand	1.5 s
Strength of hand	90 N
Battery life	48 hours
Full charge time	2 hours

3.1.4 Solutions of Vincent Systems Company

There is another German company that focuses its attention on developing upper-limp prosthetic hands. Nowadays this company has 2 branches of prostheses. There are VINCENTyoung for children and teenagers and VINCENTevolution for adults. We are going to consider one of the possible solutions provided by this company.

Vincent Evolution 3 Prosthetic Hand

This prosthetic hand is the latest development of Vincent Evolution company [25]. It has anatomic design and due to it can have almost natural movements. The weight of this hand is lower than 500 grams. Bow springs on the fingers help to adapt to any grasps. Thumb can be controlled separately from other fingers and that allows extending the number of possible gestures and grips. Today such arm provides 14 different types of grasps. Moreover, it is able to handle the prosthesis movements by the help of smartphone application.

Furthermore, the VINCENTevolution 3 is the first commercial hand prosthesis with a sense of touch giving the prosthesis wearer a force feedback. The sentient prosthesis should stimulate the sensory area of the cerebral cortex by selective stimulation of receptors on the arm stump and thus has a positive effect on phantom pain and also makes gripping of goods easier and safer [25].

3.2 DIY Project

This Belarusian MyoTriton project [20] represents the type of active electrically powered prosthesis and can be classified as a DIY (Do It Yourself) device, since one can easily assemble it from limited number of details.

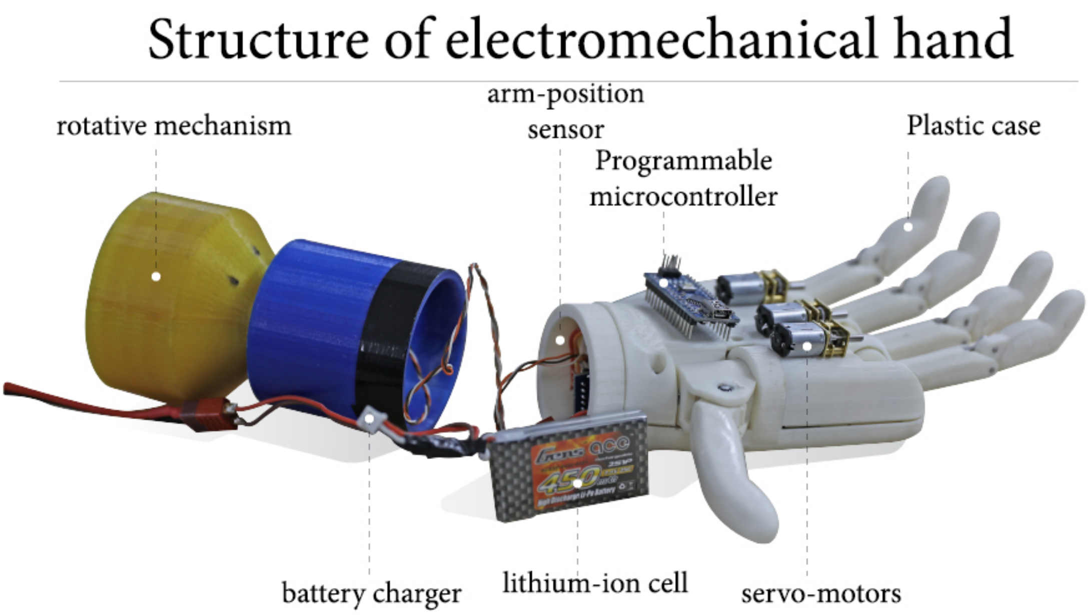

Figure 3.4: Main elements of MyoTriton prosthetic hand [20]

The main advantage of this project consists of allowing fingers to adapt to the shape of any items using no sensors on the fingertips. That is when someone takes a cone-shaped item, fingers must tightly grab the item all along the height of it. Unfortunately, a problem can appear when someone decides to grab an item: fingers can continue gripping an object trying to reach the last point. That can lead to motor overheating. Instead of implementing different types of sensors, such as bend or pressure sensors, on the tips of the fingers, the author solved this problem by the inner means of the motor.

The logic is following: the program running on the Arduino Nano board checks whether there is a change in the resistance of the potentiometer during the work of the motor. If there is no change two possible variants could occur:

- The finger met an obstacle.
- The potentiometer is in its extreme position.

Such approach allows using no additional sensors and thus makes this prosthesis free from laying different cables.

All main parts of this project are depicted in Figure 3.4. All parts of the prosthesis, which can be printed by 3D technology, are on open access. In spite of main parts the prosthesis can be also equipped with a cosmetic cover.

4 Present Control Systems of Active Prosthetic Hands

In order to prevent undesirable failures in grasping functions, such as slip in case of lack of applied force or over-gripping in contrary case, researchers have created a number of techniques [20, 26, 27].

Most of the existed feedback systems focus to the sensory feedback in order to avoid aforesaid difficulties.

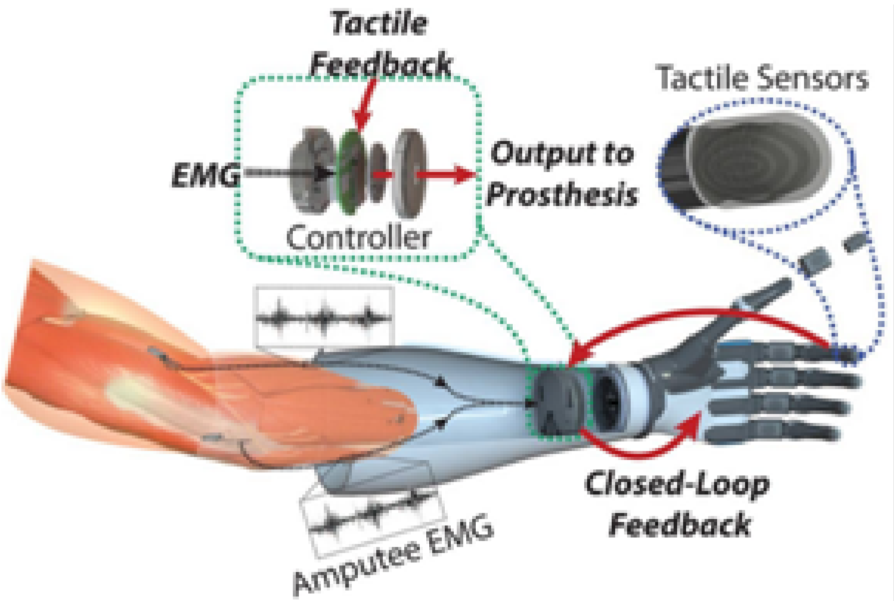

Figure 4.1: Closed-loop control of the tactile feedback system [26]

The image depicted in Figure 4.1 illustrates the sensory feedback system that adjust the gripping of prosthetic hand.Regardless of types of sensors used for feedback control, the scheme remains the same. The amputee EMG signals play the role of the gain that indicates the forces which the hand will apply to an object. Feedback control performs in the following way. Once the control unit receives the signal from myoelectric sensors it commands to execute a particular grip. In case an object is slipping the data from sensors is changed and microprocessor corrects it by introducing more forces, for instance.

Besides harnessing different sensors on the fingertips of the prosthetic hand, there are absolutely unique solutions to the problem of sensory feedback.For example, there is a work, where the pinch force of the prosthesis hand is estimated with the help of computer vision and machine learning [19].

As there is no available information about feedback control of commercial prostheses on the official web pages of vendors mentioned in chapter 3 we can only guess what sensors are utilized in their hands. However, there are some companies that provide the access to their previous solutions, such as MaxBionic [4].

If to speak about open source projects and DIY projects the possibility to gather information comes from the names. There are some more known projects that can be classified by their accessibility:

- Commercial solutions.
  - Ottobock [2].
  - Touch Bionics [3].
  - Motorica [8].
- Open source projects.
  - HACKberry project from Exiii company [5].
  - Open Bionics [28].
  - You Bionics [29].
- DIY projects.
  - MyoTriton Project [20].

In previous chapter we described some types of available prosthetic hand. A few of them initially used some kind of feedback (see section 3.2 and 3.1.4 of chapter 3). We do not present them again in this chapter.

Hereafter, we are going to presents some available feedback control solutions of upper-limp prosthetic hands from commercial companies and scientific institutions. Then some information of possible commercial sensors for organizing feedback control will be also introduced.

4.1 Other Types of Feedback Control

In this section we would like to summarize all works that look to the problem of feedback control from unconventional angle of view.

4.1.1 Solutions of Scientific Institutions

Feedback Control Based on Artificial Vision

This project is the work of Newcastle University, United Kingdom. The main idea of this project is to use artificial vision and pattern recognition. For these purposes the team from aforementioned university [19] used 2 image libraries of household goods.

For dividing human gestures according to the particular images (see Figure 4.2) convolutional neural network (CNN) was implemented.

Figure 4.2: Grasp recofnition according to the object type [19]

For catching image of an object a simple web camera (Logitech Quickcam® Chat) was utilized. All off-line and computer-based real-time tests were made in MATLAB in a personal computer with an Intel Core i5-47670 CPU (3.4 GHz), running a 64-bit Windows 7 operating system, with 32 GB RAM [19].

However, it is not affordable yet to use this control system in everyday life as it relies on Delsys Trigno lab wireless EMG electrodes [30] and needs to have very powerful computational unit.

For providing experiments the team used i-limb Ultra prosthesis from Touch Bionics [3]. The real-time test was implemented in MATLAB® on a Lenovo laptop with an Intel Core i7-4559U CPU (2.10 GHz), running a 64-bit Windows 7 operating system, with 8GB RAM. Once the system obtains the signal from EMG sensors it turns to the image recognition and the grasp performing.

Feedback Based on Implanted Electrodes

There is another solution of feedback control realization. The distinctiveness of this solution is an ability of an amputee to feel the shape and material of an object with bionic hand. This is done by means of sensors that detect information about whether an object is hard or soft. This message is then send to the computer in a rucksack that converts these signals into a language understandable for human brains.

The information is transported to patient's brain via tiny electrodes implanted in nerves in the residual limb [18].

4.1.2 Solutions of Commercial Prostheses and DIY

Most of the commercial prosthetic hands use some kind of feedback control. However, the information of it does not lie on the surface, as the companies which produce them try to keep it in a secret. For example, we cannot say what kinds of sensors are placed on the fingertips of the Bebionic prosthesis, but from the official information we can assume that it uses some kind of force sensors.

Here we focus our attention only on the free and open information of the feedback systems of commercial and DIY projects.

Feedback of Vincent Systems prostheses

One of the company focuses on developing upper-limb prostheses is Vincent Systems (see subsection 3.1.4). This is only one commercial company which states that their hands have feedback control.

The feedback control is organized by vibrations, which are appeared during grasps. These vibrations are provided by the strain gauges that lengthen when the fingers are bending and thus change the voltage. An amputee can feel these vibrations with the help of vibromotors located on the residual limb [31].

Feedback of MyoTriton Prosthesis

All the information about this hand is available in section 3.2. The feedback of this system is based on the servomotors feedback that provides the position of fingers and protect the fingers go further after they find an obstacle.

4.2 Sensory Feedback Control

In this section three different solutions of sensory feedback control are examined. The sensors are used in these works are aimed to measure either the applied forces or the degree of fingers' bending.

According to the information that is taken from official web pages [2, 3] of commercial prosthetic devises almost all of them provide some kind of feedback control to prevent objects from slipping. Nevertheless, the first work that is described under this section claims the opposite [26] and provide its own solution of tactile feedback control.

4.2.1 Tactile Feedback System Based on Force Sensing Resistors (FSR)

Regardless of the aforementioned project, the work of Luke E. Osborn [26] uses self-made textile force sensing resistors on the fingertips of the prosthetic hand.

The textile force sensors are designed using several crossing traces of conductive fabric, which are separated by a piezoresistive textile layer. The conductive traces are used to sandwich a piezoresistive fabric layer, while an outer stretchy covering acts as a protective barrier between the conductive traces and the environment. A small rubber patch is cured directly over the conductive trace crossing areas.

The rubber layer acts as a compliant gripper to help increase the tackiness of the sensor cuff. The nature of the textile force sensing resistors allows them to easily be fit on different regions of a prosthetic hand. The stretchable material that makes up each sensor cuff allows it to fit snugly against the surface of the prosthesis. Additional benefit of this design is that it enables the sensors to be placed on different models of prosthetic devices.

Figure 4.3 gives the information about sensor's components and visualizes the structure of textile force sensor.

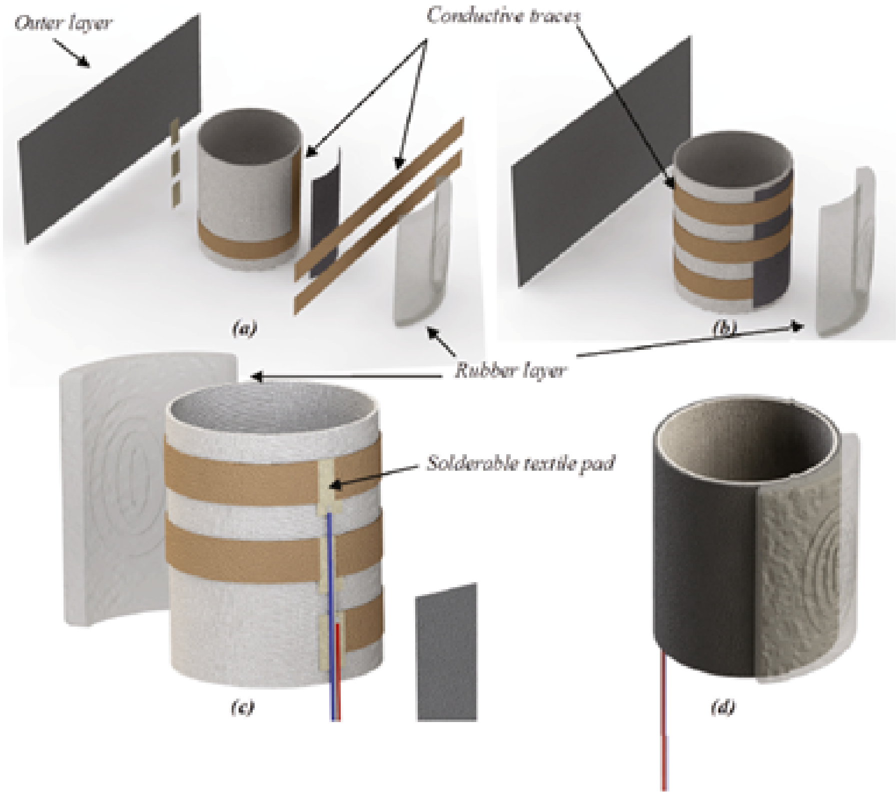

Figure 4.3: (a) shows an exploded view of all the components and (b) shows how the conductive traces are wrapped around the inner cuff. (c) shows the textile solderable pads used to create the hard-to-soft connection between the textile cuff and wires, and (d) shows a completed sensor with the outermost rubber fingertip-like layer [26]

The fingertip tactile sensor is covered with 1 mm silicone layer (Dragon Skin 10) and placed on the thumb, index, and middle fingers of a bebionic3 prosthetic hand. The prosthesis was controlled using a customized development board, which also measured and recorded the tactile signals [26, 32].

The tactile feedback, which is sent to the prosthesis controller directly, influences the behavior of the limb in order to better complete the current task (for example, adequate grasping or slip prevention).The sensory information comes from the fingertips plays a key role in the decisions made by the controller.

4.2.2 Feedback Control System Based on Soft Stretchable Bending Sensor

There is also another approach [27] how to design sensory feedback in prosthetic hand—using bend (flex) sensors (Figure 4.4). Despite the target of the project, which is going to be described here, is a little bit different from the aim of this thesis, the main idea can be still applicable.

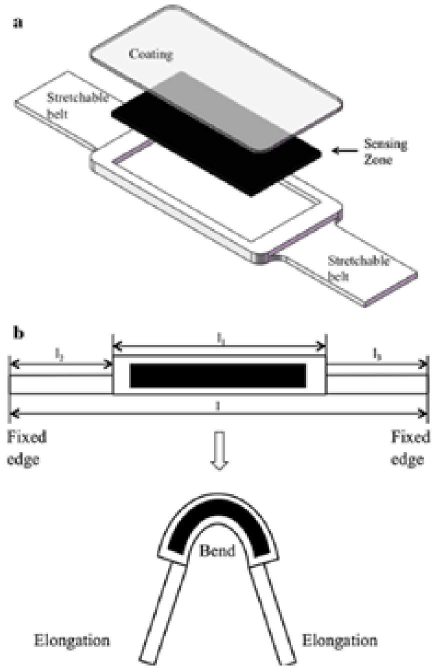

Figure 4.4: (a) Sensor structure. The middle part is designed to be thicker and wider than the two belts, offering better stiffness to avoid stretching. (b) Profile chart of the sensor. The middle part, which contains the sensing material, is bend with permitted stretch. Elongation caused by finger bend will be offset by the stretch of the two belts [27]

The possibility of using flex or bend sensor for designing sensor feedback system in upper-limb prosthetic hand is abundant. Such sensor works in the following way: once it is bended, the resistance across the sensor increases. Thus, one can simply estimate the level of grasping and utilize obtained data to develop a sensory feedback system.

However, all commercial bend sensor solutions are non-stretchable, and they can slip when fingers bend. Moreover, due to the stiff structure of the sensors, a gap between the glove and hand may appear and, it is obvious that such gap will cause some significant error.

As a solution to this problem, authors introduce another structure of such kind of sensor, which represent the soft stretchable element.

According to the article [27], this sensor provides good sensitivity and is stretchable. The size of the sensors is also varied and can be fitted to the specific project.

The middle part of this sensor is thicker than the belts, which gives better stiffness to avoid stretching. This part also contains the sensing material, and will be bent with permitted stretch. The elongation caused by finger bend is offset by the stretch of the two straddling belts.

The control system that is able to create with the help of these sensors is based on the knowledge of resistance. As soon as it changes during bending of fingers, the signal from the sensor is sent to the microcontroller, which further decides about next movements.

Although, this type of bend sensor was created for data gloves, such as Nintendo Power Glove [33], it is possible to implement it in a prosthetic hand, having in mind that analogous goal is used in both cases.

4.2.3 Sensory Feedback Add-on for Upper-limb Prostheses

This work [34] shows another approach of using force sensing resistor in sensory feedback of the upper-limb prosthesis. However, in opposite from the previously considered work in chapter 4.2.1, here a commercial solution of force sensing resistor is used.

The level of grasping is evaluated with the force sensing resistor, placed on the fingertip of the index finger and then converted into a position (angle) reference signal via the process unit. Power from the battery and control signals are sent to the actuator mechanism which is secured on arm by a stretchy cuff.

Mounting the single sensor on the index finger is described by the fact, that maximum pick of pressure during grasping objects is fell on this finger.

One of the advantages of this work is possibility to assembly this system on any prosthetic hand, which has already been utilized.

4.3 Commercial Sensors for Feedback Control

The physical object which is able to detect events and changes in various parameters such as environment, temperature, humidity, and so on are termed as sensors [35]. Based on the detected events or changes the sensor is able to generate appropriate output.Different types of sensors are classified based on different laws such as electrical, level, sound and etc. The most widely used sensors are proximity, force, temperature, position and so on.

4.3.1 Force Sensing Resistor

Force sensing resistor (FSR) can be defined as a special purpose resistor. Such sensors are made of conductive polymer which has a property of changing its resistance based on the force applied to its surface.

The force sensing resistor is generally supplied as a polymer sheet or ink which is applied as screen printing. Both the electrically conducting and non-conducting particles are present on this sensing film.These particles are generally

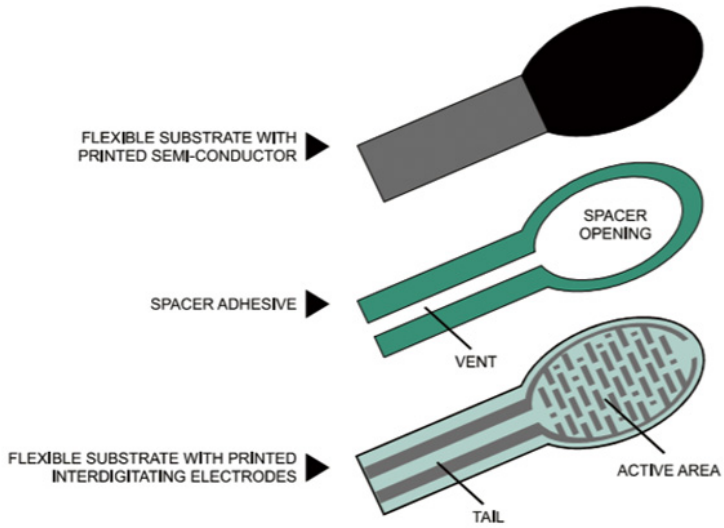

Figure 4.5: Structure and layers of Force Sensing Resistor [36]

sub-micrometer sizes which are formulated for reducing the temperature dependence and also for improving mechanical properties, increasing surface durability [35].

Table 4.1: Force sensor specification

Shape	Circular
Sensing area	12.7 mm in diameter
Min Pressure	100 g
Max Pressure	10 kg
Stand-Off Resistance	$> 1\text{M}\Omega$
Break Force (Activation Force)	0.2N min
Life Cycle	> 10 million actuations

A good example of one of these sensors is Interlink Electronics' Force Sensing Resistor [37]. This thin form factor device provides an inverse change in resistance in response to an increase or decrease in applied force, targeting human-machine interface applications. The force sensing resistor consists of a polymer substrate, with the first functional layer taking the form of a conductive-carbon-based patterned circuit that serves as the sensor. On the underside of the next functional layer, one will find a printed electronics network, which also serves as the encapsulant of the stack. The structure of this sensor is depicted in Figure 4.5 These sensors are available in a range of sizes, shapes and lengths [36].

In our application we use force sensing resistor with sensing area of 12.7 mm in diameter [38]. This FSR changes its resistance in compliance with the applied pressure to the sensing area. According to table 4.1 the maximum pressure cannot be more than 10 kg. If the pressure exceeds this range, for example 12 kg, the sensors will not be able to tell the difference between 10 kg and 12 kg.

Figure 4.6: Utilized Force Sensing Resistor [38]

The sensitivity of this sensor can be specified with the static resistor. This resistor is used to maximize the desired force sensitivity range and to limit current. The current through the FSR is determined to be less than 1 mA/cm^2 of applied force [39]. For our sensor there is a graph of the force-to-voltage conversion, which is depicted in Figure 4.7 and shows how the sensitivity of the sensor varies with different nominal resistors.

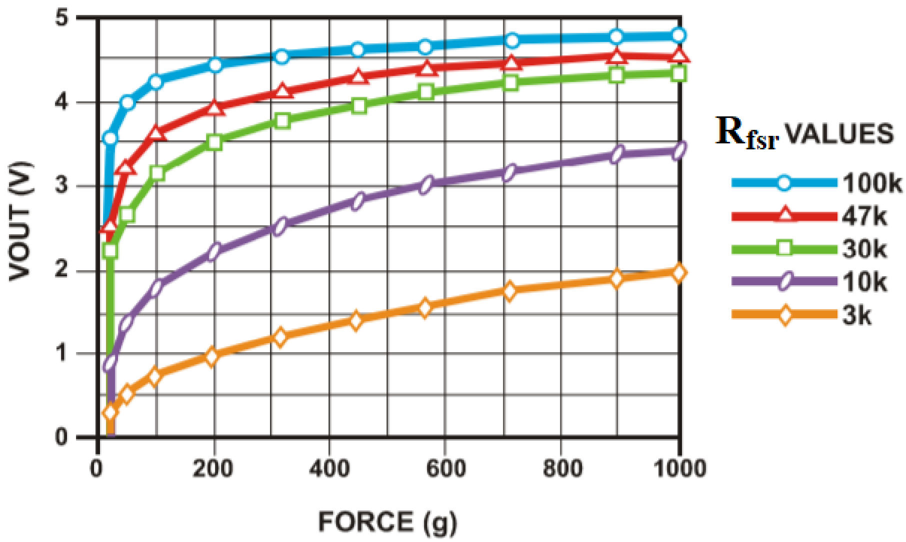

Figure 4.7: FSR Voltage Divider [39]

For calculating the resistance value of the sensor we need to use voltage divider configuration. In this configuration, the output voltage increases with increasing force. The formula can be found below:

$$\frac{V_{out}}{V_{cc}} = \frac{R_{fsr}}{R_1 + R_{fsr}} \tag{4.1}$$

It was decided to take the resistor of 10 kΩ because this sensitivity is sufficient enough. Taking less resistance can add unnecessary susceptibility to the system and, thus, wrong results.

4.3.2 Bend Sensor

Bend sensor or as it can also be called *flex sensor* is used to measure angle displacement, which occurs with bending. Usually, the sensor is stuck to the surface, and resistance of sensor element is varied by bending the surface. Since the resistance is directly proportional to the amount of bend it is used as goniometer [40], and often called flexible potentiometer [41].

Such sensor is also a resistive one, because it changes the resistance once it is bent.

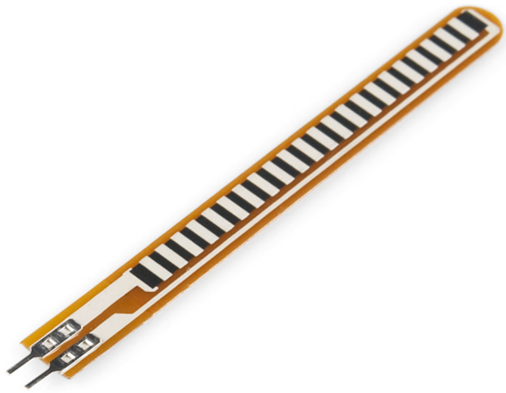

Figure 4.8: Bend sensor [42]

Flex sensors can be of different types:

- Conductive ink based flex sensor
- Fibre optic flex sensor
- Capacitive flex sensor
- Velostat flex sensor

Sensor that is used in our application is depicted in Figure 4.8. Our bend sensor

Table 4.2: Bend sensor specification

Life Cycle	>1 million
Temperature Range	-35°C to +80°C
Flat Resistance	10K Ohms ±30%

consists of small conductive particles. When the sensor is straight these particles are closed together and provide 30 kΩ, nominal resistance value. Once the sensor is bent, the conductive particles go further apart and value of the resistance is increased. This particular flex sensor does not provide bidirectional bending. That is why it can be bending only to one side. Moreover, the bending cannot exceed the angle of 90°.

5 Bionic Prosthetic Hand of HACKberry Project

HACKberry prosthetic hand belongs to the Japanese company Exiii. It is an open-source project. The developers of this project declare that their goal is to develop an artificial arm that would become the platform upon which developers and artificial arm users from all over the world are able to build as they wish [5].

Figure 5.1: The exterior view of HACKberry prosthetic hand [5]

At the beginning of HACKberry project a number of amputees who used prosthetic devices were investigated. It turned out that more than 90 percent of amputees were just using cosmetic, not functional, prosthetics, as generally people wanted to hide the fact of hand or arm amputation. Having this knowledge in mind, designers from exiii [5] decided to integrate the warm feeling of a natural hand with a robotic look [43].

Nowadays this project has 5 versions, Hackberry (see Figure 5.1) is the latest - the 5th - version of the Exiii work. Previously the hands were under Handii and then Coyote Handii names. Hackberry is lighter and more compact than the previous version - Coyote. It is roughly the size of an actual human hand, and thus more appealing to female users who may have felt that previous versions were too imposing. The primordial and official version of HACKberry uses an Arduino Micro,

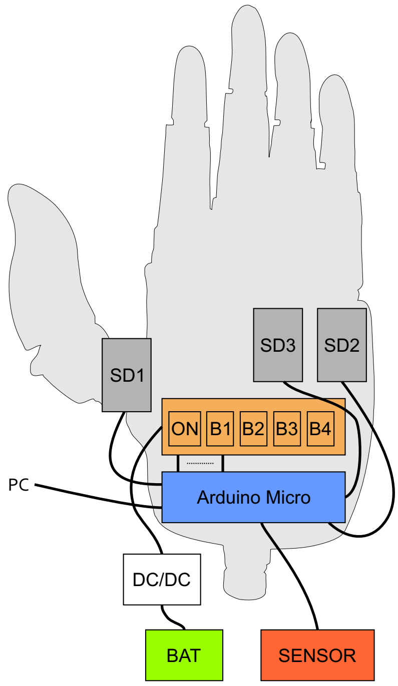

Figure 5.2: Block-scheme of HACKberry prosthetic hand [44]

has only three motors one for the thumb, one for the index finger and one for the other three fingers, to keep it light, and features a passive wrist joint – important when a user wants to hold a drink without spilling it.The weight of the prosthesis was reduced in this new version and now it is 650 grams. The number of motors was reduced as well, thus providing longer battery life.

For acquiring data signal from the muscles for initial prosthetic hand an infrared sensor (IR) is used. The sensor measures the distance to the skin, so when a muscle contracts, it detects changes and send a signal to the Arduino Micro. One cannot say that this sensor is very precise. Moreover, it can be difficult sometimes for it to distinguish what finger should be moved. However, HACKberry team tries to implement the cheapest sensors in their product, which at the same time can give sufficient results. And IR sensor fits exactly to these criteria, as it is not so expensive as dry EMG sensor or wet one.

IR sensor can be attached to different places of the human hand. If to attach it to the upper arm, for instance, biceps shrinking will activate the hand.

HACKberry can be printed with a consumer 3D printer, like MakerBot [45]. The entire prosthesis can be assembled at home using roughly US$300 worth of parts [43].

As it is shown in Figure 5.2 the original hand components are Arduino Micro board, 3 servo motors, DC-DC converter, a battery and a myoelectric sensor, that is connected to Arduino Board. Information about microcontroller and other parts is given below.

5.1 Arduino Micro Board

The peculiarity of this board is in the conjunction of its size and number of analog inputs that are of the high demand due to the different sensors implementation.

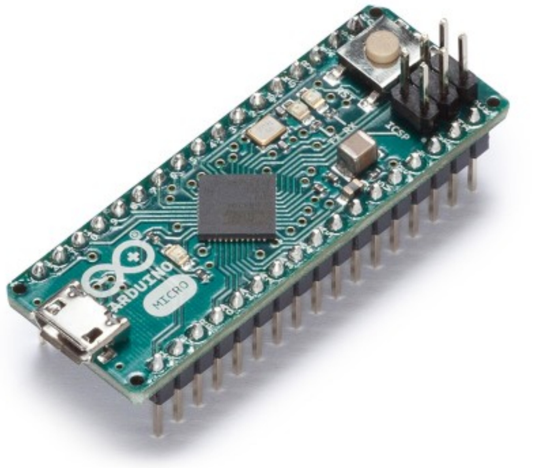

Figure 5.3: Arduino Micro board [46]

This board contains 34 pins, where 20 of them are digital input/output pins. Each of these pins can be used as an input or output, using *pinMode()*, *digitalWrite()*, and *digitalRead()* functions. The Micro has a total of 12 analog inputs, pins from A0 to A5 are labeled directly on the pins and the other ones can be accessed in code using the constants from A6 trough A11. Those pins can be found on digital pins 4, 6, 8, 9, 10, and 12 respectively.

The Micro can be powered via the micro USB connection or with an external power supply. External power can come either from a DC power supply or battery. Leads from a battery or DC power supply can be connected to the Gnd and Vin pins. The board can operate on an external supply of 6 to 20 volts. However, the recommended range is 7 to 12 volts [46].

Arduino Micro board provides various possibilities for communication between different devices. For our purposes UART interface is used. There are 2 pins on the board 0 (RX) and 1 (TX) for receiving and transmitting information via this interface.

5.2 Servo Motors

As it was said previously the final version of the hand contains 3 servo motors. One of them is used to control the movement of index finger - HS-311 Servo [47]. Two others are identical - EMAX ES08MA II [48] - and are aimed to move the thumb and three connected fingers. Such type of motors are pretty cheap and can be found without any problems on the Internet.

5.3 Sensors for Detecting Muscles Contraction

In this section we are going to consider 2 types of sensors (see Figure 5.4) that are able to detect the signals of muscle activity.

(a) (b)

Figure 5.4: Sensors for detecting muscles constriction, (a) myoelectric sensor, (b) infrared sensor [49]

5.3.1 Infrared Sensors

Original solution of HACKberry project was equipped with infrared sensor (IR) TPR105 [50] which was then changed to QRE1113 [49]. The IR reflectance sensor QRE1113 (see Figure 5.4) is comprised of two parts—an IR emitting LED and an IR sensitive phototransistor. When power is applied to the VCC and GND pins the IR LED inside the sensor will illuminate. For current limitation there is a 100 Ω resistor on-board that is placed in series with the LED. A 10 kΩ resistor pulls the output pin high, but when the light from the LED is reflected back onto the phototransistor the output will begin to go lower. The more infrared light is sensed by the phototransistor, the lower the output voltage of the breakout board [49].

5.3.2 Myoelectric Sensors

This type of sensor replaced the IR sensor in the modifications that were made in TUL. The sensor used is MyoWare™ Muscle Sensor (AT-04-001) [51]. It has 2 modes EMG Envelop and Raw EMG, single supply from 2.9 to 5.7 V with polarity reversal protection. As this sensor designed to be used directly with microcontroller its primary output is not raw EMG, but envelope EMG that will work well with the microcontroller's analog-to-digital converter (ADC). For correctly placing the sensor one need to read the datasheet of it [51] since only the correct placement guarantee the good quality of signal.

5.4 Software Support

All programs for this project were written in Arduino Integrated Development Environment (IDE) that connects to the Arduino boards to communicate with them and upload programs. The language of this environment is C++. Programs written in Arduino IDE are called sketches. All Arduino sketches have two void functions –*setup()* and *loop()*. First function initializes and sets the initial values, while the second one loops consecutively, allows a program to change and respond [52].

As Arduino sketches are written in C/C++ language, the syntax remains the same as it is in C/C++ language.

Before uploading the code it is better first compile it and only if no errors return upload it to the specific board on the chosen interface.

6 Enhancement of HACKberry Prosthetic Hand

The HACKberry prosthetic hand that was described in chapter 5 was taken as a basis for this work. It was printed in the Institute for Nanomaterials, Advanced Technology and Innovation in TUL. All the used materials, 3D printing techniques and parts of the hand were described in details in [53].

Instead of taking all original parts from HACKberry project some modifications were made. For example, IR sensor was changed with MyoWave muscle sensor, some modifications with power supply was made as well. And now there will be described some new changes in control system of the prosthetic hand.

According to the tasks of this diploma work HACKberry hand should be extended with feedback control and Arduino Esplora board should play the role of command device.

To follow the tasks new components were added to HACKberry hand. These components are:

- Arduino Esplora board.
- Communication module APC220.
- Force sensing resistor.
- Bend sensor.

Adding Arduino Esplora board to the project modified the system in a way, that it can be now described as a master-slave system (see Figure 6.1), where the master device (Arduino Esplora board) sends the commands through the wireless module to the slave device (represented by Arduino Micro board that characterized in section 5.1) and the slave device then executes a proper function.

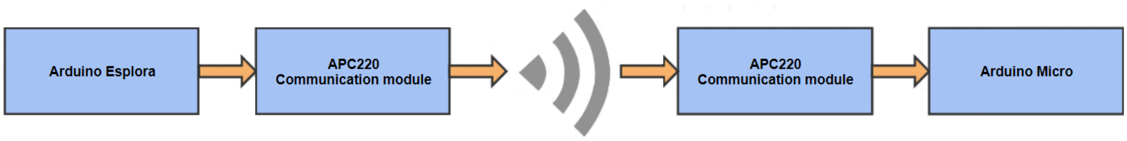

Figure 6.1: Master-Slave communication module

Taking everything into account it is possible to calculate all main parts of the project. Thus, the whole system is currently equipped with HACKberry hand prototype, 3 servo-motors for moving thumb, index and all the 3 left fingers, sensors 4.3 for feedback control, 2 transceivers, 2 control units—Arduino Esplora and Arduino Micro, external power supply that provides 6V.

6.1 Arduino Esplora Board

The Arduino Esplora (see Figure 6.2) is an Arduino Leonardo based board. It differs from all preceding Arduino boards in that it provides a number of built-in, ready-to-use set of on-board sensors for interaction. These sensors are joystick, a slider, a temperature sensor, an accelerometer, a microphone, and a light sensor.

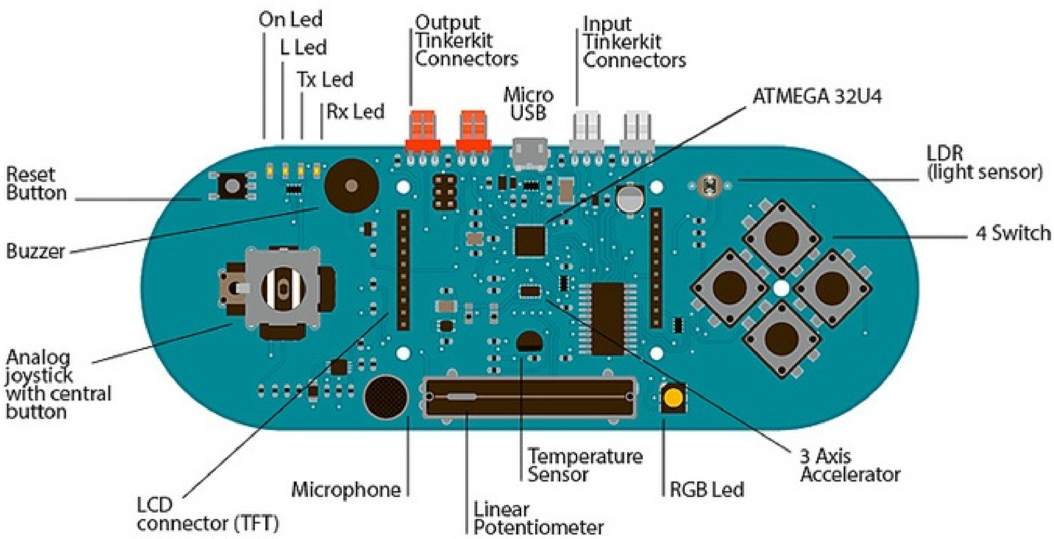

Figure 6.2: Main components of Arduino Esplora board [54]

Like the Leonardo board, the Esplora uses an Atmega32U4 AVR microcontroller (see the specification in table 6.1) with 16 MHz crystal oscillator and a micro USB connection capable of acting as a USB client device, like a mouse or a keyboard [55].

One of the obvious benefits of Arduino Esplora board is an embedded bootloader, that enables users to utilize no additional programmer for loading a new code to this board.

6.2 Wireless Data Communication Module

In order to broaden HACKberry hand functionality it was decided to add another Arduino board, which has sufficiently enough on-board sensors for this purpose. However, it means that we need to think about communication between these two boards. As prosthetic hand can be considered as a portable device, organizing

Table 6.1: Technical specification of ATmega32u4 microcontroller

Microcontroller	ATmega32u4
Operating Voltage	5V
Flash Memory	32 KB of which 4 KB used by bootloader
SRAM	2,5 KB
EEPROM	1 KB
Clock Speed	16 MHz
Length	164.04 mm
Width	60 mm
Weight	53 gr

communication by means of wires is not very logical approach. That is why the wireless communication was chosen.

The wireless data communication module, which is used in this application is APC220 [56].

6.2.1 APC220 Communication Module

APC220 communication model can be used for wireless communication not only between different Arduino devices, but also for PC-PC communication, or for PC-Arduino communication. TTL/USB converter comes with this module to provide the last two aforementioned connections.

Figure 6.3: APC220 Wireless Communication Module [57]

APC220 has the following characteristics:

To ensure the proper communication the RF-magic software is used. The main window of the software is shown in Figure 6.4. Such parameters of APC220

Table 6.2: Specification of APC220 wireless transceiver

Working frequency	431 MHz to 478 MHz
Power	3.3–5.5V
Current	<25–35mA
Working temperature	-20°C +70°C
Range	1200m line of sight (1200 bps)
Interface	UART/TTL
Baud rate	1200-19200 bps
Receive Buffer	256 bytes

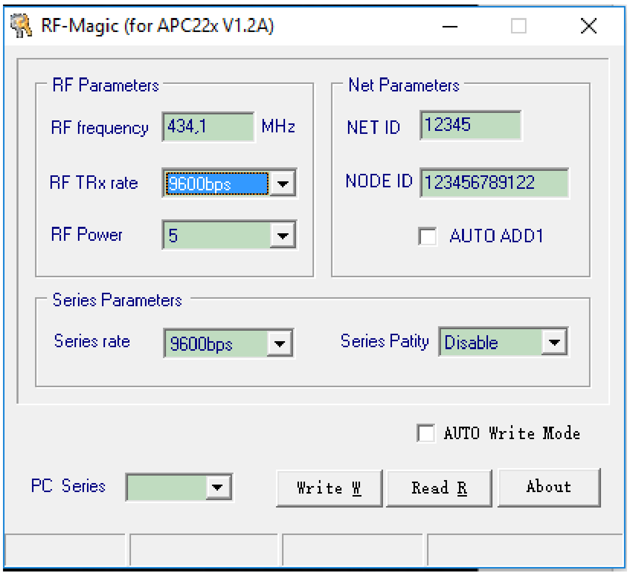

Figure 6.4: Configuration of RF-magic software [58]

transceiver as RF frequency, RF TRx rate, RF power, Series rate and Series parity should be the same for all transceivers, which are used in an application. Otherwise, the communication between two or more transceivers is not guaranteed.

Net ID and Node ID are arbitrary. Net ID is the identity of the network and must be the same for all modules in the network. Node ID is the device identical number and that is why different value should be set for each individual device.

The maximum distance that these transceivers can cover is 1000 meters. In case one needs to shorten the working range, the value of RF power in RF-magic software should be decreased.

As indicated in table 6.1 connection is organized with the help of UART interface. In contrast to other protocols such as SPI and I2C, no external clock signal is required. Both receiver and transmitter have internal clock signals, which are not transmitted from one communicating device to the other [59]. Instead of a clock signal, the transmitting UART adds start and stop bits to the data packet being transferred. These bits define the beginning and end of the data packet so the receiving UART knows when to start reading the bits.

Table 6.3: Pins marking of communication module APS220

Pin	Definition	Detail
1	GND	0V Ground
2	VCC	3.3V-5.5V Power
3	EN	Enable the device when leave it disconnected or apply >1.6V Disable the device when apply <0.5V
4	RXD	UART RX
5	TXD	UART TX
6	AUX	UART Signal- Receive (low) Transmit (high)
7	SET	Set parameters (low)

When the receiving UART detects a start bit, it begins to read the incoming bits at a specific frequency known as the baud rate. Baud rate is a measure of the speed of data transfer, expressed in bits per second (bps). For a normal communication both UARTs must operate at about the same baud rate [60].

Thanks to such parameters as Net ID and Note ID we can send our data to the exact earlier specified device and receive information only from the devices of our network.

7 Software and Programs

This chapter begins with short description of Arduino programming environment and then expands to the explanation of master-slave relation model. Algorithms of some couple of gestures and grips written for our project are finally described here.

7.1 Master-Slave Communication Model

In computer networking, master-slave is a model for a communication protocol in which one device or process (known as the master) controls one or more other devices or processes (known as slaves). Once the master/slave relationship is established, the direction of control is always from the master to the slave(s) [61].

Such model is used in this project, where the Arduino Esplora acts as a Master part and Arduino Micro as a slave part. Thus, the Esplora board controls the gestures and grips by sending an appropriate command to the Arduino Micro. Thanks to the sufficient amount of buttons and various on-board sensors it is possible not only to set a gesture, but also the grasping force of it.

Communication of both microcontrollers is performed by means of APC220 wireless modules (see Figure 6.1), which use UART interface. As both of the boards use Leonardo based controllers, they have 2 serial ports (*SerialMonitor*, *SerialMonitor1*). Such feature allows sending data via wireless connection through UART interface with the *SerialMonitor1* and simultaneously observing additional information with the help of *SerialMonitor*.

Arduino Esplora board can be powered from computer through the USB connection or with the help of Power Bank. As it contains a wide range of possibilities due to its design, only transceiver was added additionally to this part.

The slave part consumes the energy through the external power of 6V.

7.2 Project Working Algorithm

As it was told previously we have two separated parts master and slave. The working algorithm is depicted in Figures 7.1. The left region of the picture (a) gives us information about working algorithm of the master part whereas the right one (b) describes slave part of the system.

The software part of this project utilizes the same IDE, that was presented in section 5.4.

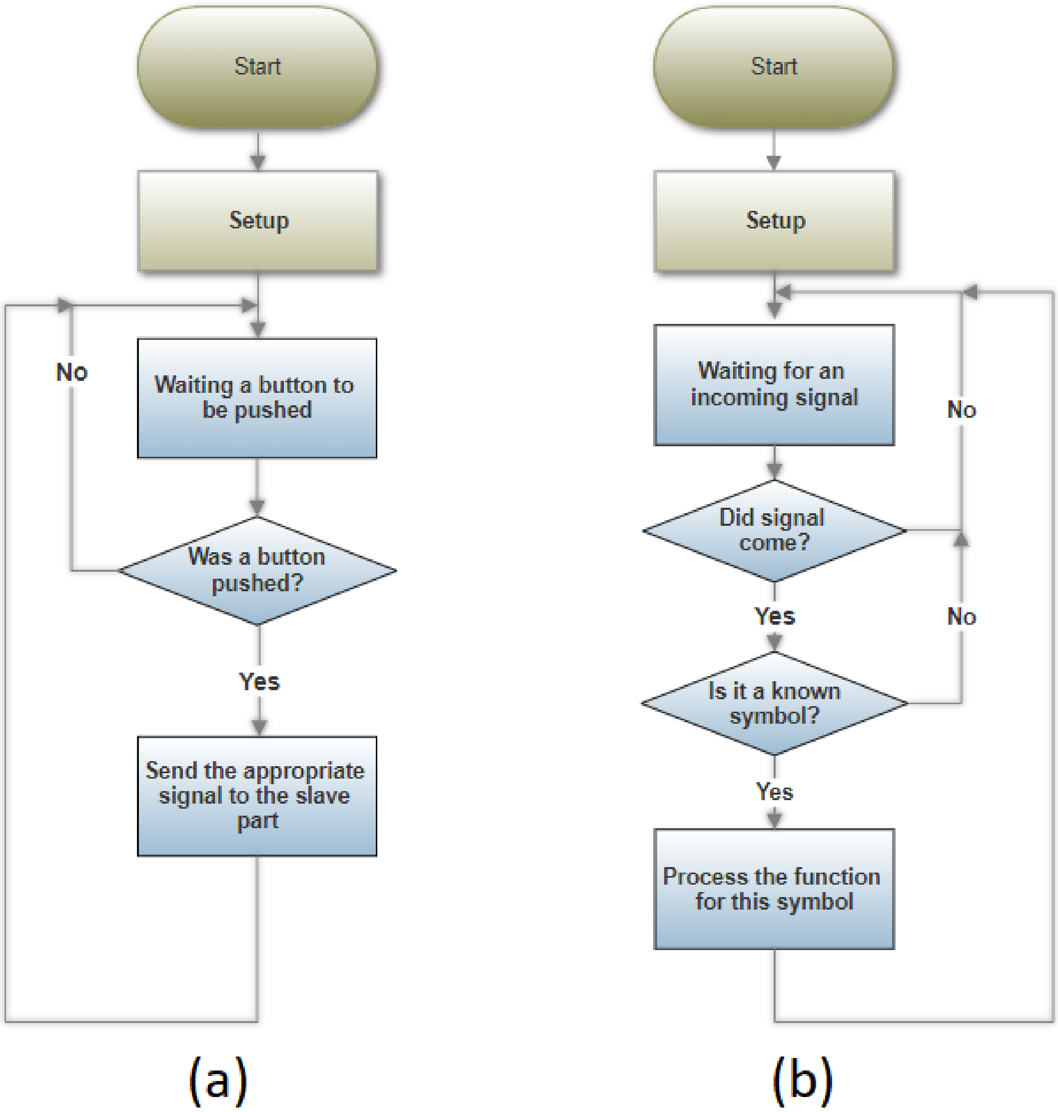

Figure 7.1: (a) Working algorithm of master part represented by Arduino Esplora, (b) Working algorithm of slave part represented by Arduino Micro

7.2.1 Master Part

Master part can work as i-limb mobile application from Touch Bionics company [62], since it has some buttons to regulate and set gestures as well as it is done in the aforementioned application. One main distinction is that the i-limb application utilizes touch screen, whereas this project use the potentiality of Esplora board.

For simplifying the usage of the board it was decided to put some stickers on the buttons or near with joystick, which can indicate the name of the particular gesture. As this board can be used as a keyboard, every button is provided with specific symbol, and once the button is pressed the signal according to this symbol is sent to the slave part with the help of wireless communication module that is described in Section 6.2. Besides utilizing buttons and joystick, we get the data from potentiometer to set the maximum force that may be applied by index finger on the opposite part of the device. This information is sent simultaneously with the command symbol and then can be parsed to extract the integer value of the maximum force to be applied to the object when the pinch grip is performed.

The block diagram of master part connection is presented in appendix B in Figure B.1.

7.2.2 Slave Part

Block diagram of the elements which is contained in slave part of the project can be found in the appendix B in Figure B.2.

Slave part of the device working on the external power of electrical network, which is transformed to the appropriate for Arduino boars power of 6V.

As it is shown in Figure 7.1 part (b) the main loop firstly waits for an incoming data and after receiving a symbol checks whether this symbol is in our switch-case structure or not. Since we use more than 5 different incoming symbols it was decided to utilize this structure instead of if-else, because in contrast to if-else, switch-case uses a lookup table or a hash list. This means that all items get the same access time, whereas to reach the last item of if-else structure requires much more time as it has to evaluate every previous condition first.

Once the incoming symbol matches one condition from the switch-case structure the action according to this condition starts to execute. There are a numbers of function that control grips and gestures of our prosthetics. One of the function represents presentation mode, that contains the sequence of gestures and grips of that the hand provides.

7.3 Functions of Gestures and Grips

Before listing the gestures it would be rational to provide some terminologies about the grasping and griping. So, a grasp can be considered as any static hand posture with which an object can be held securely with one hand, irrespective of the hand orientation [63].

According to different articles, the number and the name of human gestures can vary significantly. However, there are some common types of gestures that can be found in almost all scientific works. On the current stage of this project the following common gestures and grips are available:

- Gestures
  - Full open
  - Full close
  - Index finger point
  - Thumbs up
- Grips
  - Pinch grip
  - Hook

For naturally interaction it would be better to have a model for human's grasp forces, which can illustrate the main forces according to specific gestures or grips. Such model was introduced in this article [64].

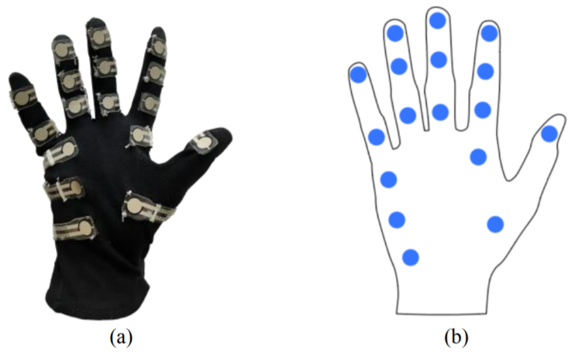

Figure 7.2: (a) Developed sensory data glove at Robotics Lab. At the University of Illinois at Chicago, (b) the location of the force sensors [64]

The authors of this work firstly used the existing grasp taxonomies from [63] and then created data glove with which the force data was later collected and the force distribution pattern over different regions of the hand were observed.

The data glove was realized as a cotton glove with 17 mounted pressure sensors (force sensing resistors).The image of the hand is presented in Figure 7.2. All the 17 sensors were connected to an Arduino microcontroller board. The sensory information was collected at a sampling rate of 70Hz. To separate the observation K-means clustering method was chosen. This method can be used when the number of clusters is known in advance, because it uses shard separation instead of fuzzy techniques.

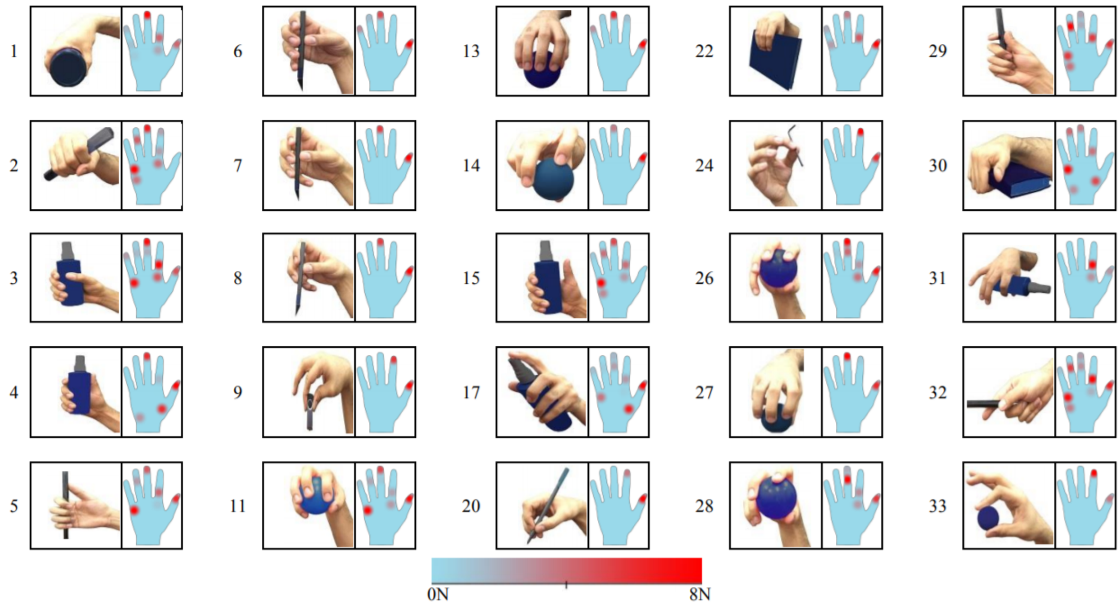

Figure 7.3: Different grasps types and force distribution in each grasp type [64]

At the end of the experiment the authors of this approach counted 544 valid data points 25 grasp types and 7 subjects (Figure 7.3). The final numbers of grasping groups are 10.

The knowledge of the force position during grasping was used in our project. Having in mind the position of applied forces it is possible to place the force sensing resistors at appropriate position and process the data only from the necessary sensors for the exact grasp.

The first of the group (contains the gestures 9, 20, 24, 33 from Figure 7.3) was named as two-finger gripping type grasps since the main force is detected between index finger and thumb. For such kind of grasping it is achievable to obtain the data of applied forces from only one sensor, located on the thumb. The algorithm for this grasp is presented below.

7.3.1 Pinch Grip Algorithm

One of the sophisticated grips is a pinch grip. A pinch is a grasp in which the tip of the thumb is pressed against any or each of the tips of the other fingers [65]. The closest the other finger to the thumb, the stronger the pinch. That is why the pinch grip in any prosthetic hands is usually performed between index and thumb fingers.

In our project pinch grip is realized between index and thumb fingers as well. Since the pinch grip belongs to the first group [64] the force sensing resistor is placed on the tip of thumb.

The algorithm is following. Once we enter the function of the grip, the angle of the servomotor starts to be incremented and thus, provides the movements of index finger. Once the implemented force that is measured with the force sensing resistor exceeds the constant force (different for different types of objects to be taken) incrementation of the angle is finished.

```
while(analogRead(fsrAnalogPin) <= fsrConst ) {
   delay(25);
   if(analogRead(fsrAnalogPin) <= slightTouch){
       position += 3;
   }
   else{
       position += 1;
   }
   //Check the maximum angle range
   if (position < positionMin){
               position = positionMin;
   }
   if (position > positionMax){
       position = positionMax;
    }
       Serial.print("Analog data = ");
       Serial.println(analogRead(fsrAnalogPin));
       fsrVoltage = map(AnalogData, 0, 1023, 0, 5000);
               Serial.print("Voltage reading in mV = ");
               Serial.println(fsrVoltage);

   if (fsrVoltage == 0) {
     Serial.println("No pressure");
   } else {
     fsrR = 5000 - fsrVoltage;      // fsrVoltage 5000mV=5V
     fsrR *= 10000;                 // 10K resistor
     fsrR /= fsrVoltage;
     Serial.print("FSR resistance in ohms = ");
     Serial.println(fsrR);

     fsrC = 1000000;            // Conductance in μΩ
     fsrC /= fsrR;

     // Use the two FSR guide graphs to approximate the force
     if (fsrConductance <= 1000) {
       fsrForce = fsrC / 80;
       Serial.print("Force in Newtons: ");
       Serial.println(fsrForce);
     } else {
       fsrForce = fsrC - 1000;
       fsrForce /= 30;
       Serial.print("Force in Newtons: ");
       Serial.println(fsrForce);
     }
   }
     Serial.println("--------------------");

   //Index position
   indexPos = map(position, positionMin, positionMax, IndexExtend,
      IndexFlex);
```

```
    myservo0.write(indexPos);
    //Trio proceeding
    if (fingerPinState == HIGH) {
      middlePos = map(position, positionMin, positionMax,
          middleExtend, middleFlex);
      myservo1.write(middlePos);
    }
    //Thumb position
    myservo2.write(thumbPinch);
  }
```

The initial constant force when the programming code starts to execute equals to the common value of human grasping force that was found in practice. There is also a possibility to choose the force with potentiometer which is presented on the master part of the device.

In this case the decision of choosing constant force is based on the empirical knowledge. To provide prosthetic hand the same haptic force as a human has, it was indispensable to check the force sensing resistor on the number of people in order to make a decision how the force varies for the different objects (different mass and shape).

Slip prevention algorithm launches after the constant force from the main part of grip algorithm exceeds. Once it was happened, programmable timer starts to work for a period of 5 seconds. If the force reduces then, probably a slip occurred. In such case the angle of the servo motor is changed to prevent this slip.

```
  time = millis();
  while(millis()-time <= 5000){
     if(analogRead(fsrAnalogPin) < fsrConst){
       position+=2;
       if (position < positionMin) position = positionMin;
       if (position > positionMax) position = positionMax;
       Serial.print("Force = ");
       AnalogData = analogRead(fsrAnalogPin);
       Serial.println(AnalogData);
       Serial.print("indexPos= ");
       Serial.println(indexPos);
       indexPos = map(position, positionMin, positionMax,
           IndexExtend, IndexFlex);
       myservo0.write(indexPos);
     }
  }
```

Another possibility is to check *Serial1* buffer. If it is not empty then we have a new command for execution and thus can stop slip prevention algorithm. This approach is better in case the mass of the object between index finger and thumb can be changed. For instance, when we pour some liquid like tea or beer into the empty glass.

7.3.2 Algorithm for Cylindrical Grip

For realizing this grip bend sensor was implemented. During the bending the resistivity of this sensor changes. Knowing the information of this change we can set the final position of the index finger.

```
 while(analogRead(bentAnalogPin) >= bendConst ) {
  position += 2;
    if (position < positionMin) position = positionMin;
    if (position > positionMax) position = positionMax;
    Serial.print("Bending= ");
    Serial.println(analogRead(bentAnalogPin));
    indexPos = map(position, positionMin, positionMax,
       IndexExtend, IndexFlex);
    myservo0.write(indexPos); //Index
    myservo1.write(55);       //trio servo
    myservo2.write(100);      //thumb
    delay(500);
}
```

7.3.3 Receiving Data from Esplora Potentiometer

This particular algorithm provides the settings of constant force value. We need to change it as different objects need to be held with different force in order to prevent damages.

As it was told previously, we use *Serial1* to receive data from master part and *Serial* to display any information on computer screen.

```
int PotentiometrRead(){
  int force;
  bool flag = 0;
      while(flag == 0){
         if (Serial1.available() || Serial.available() ){
          force =  Serial1.parseInt(); //extraction of the first
               integer value - our new constant force
          fsrConst = force;
          Serial.print("Number is ");
          Serial.println(force);
          flag = 1;
         }
      }
  return (0);
}
```

7.3.4 Gestures Algorithms

Algorithms for gestures like thumb-up, hello-gesture and others, which are available to produce with our hand, are very unsophisticated and need only the angle to be determined. Thumb-up algorithm and algorithm for hello-gesture or simply for opening the hand are shown below.

```
void Open_the_hand(){
  myservo0.write(IndexExtend); //index servo
  myservo1.write(TrioOpen);    //trio servo
  myservo2.write(thumbExtend); //thumb servo
  delay(500);
}
```

```
void Thumb_Up(){
  myservo0.write(IndexFlex);   //index servo
  myservo1.write(middleFlex);  //trio servo
  myservo2.write(thumbExtend); //thumb servo
  delay(500);
}
```

Of course it is also possible to introduce some speed for all gestures. Having in mind the time when the program was started with the help of *millis()* function we can make some delays. However, it will not be delays which will bring the whole program to a stop as the *delay()* function does. Instead of that, some if structure will be utilized to check whether the time for making some action is coming or not.

8 Practical experiments

In this section implementation of different sensors and the results obtained with each of them are analyzed and discussed. Information about possible solutions which were not made is provided here as well as the explanation about the reasons for it.

In Figure 8.1 two types of used sensors are presented. In this picture 2 FSR sensors are mounted to the middle finger and thumb. The flex sensor is mounted to the index finger.

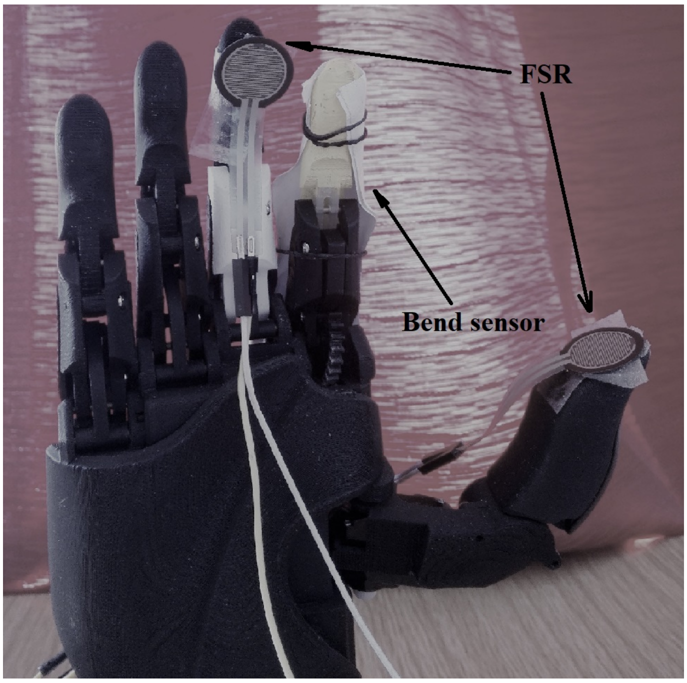

Figure 8.1: Sensors for feedback control

8.1 Bend Sensors

In this section we are going to show the obtained results with commercial and self-made flex sensor. Their structure and the subsequent results as well as their benefits and drawbacks are also discussed below.

8.1.1 Commercial Bend Sensor

This sensor was firstly presented in the subsection 4.3.2.

Due to the specific form of prosthetic fingers it is possible to mount such sensor only on the index fingers and/or on one out of the 3 connected fingers. Mounting it on the thumb is not reasonable as bend sensor is used to measure the bending angle and in our prosthetic hand the thumb can move only around one direction. For experiments it was decided to set this sensor firstly only on the index finger and add another one to each other 3 fingers in case the results would be sufficient.

Bend sensor, that represents in Figure 4.8 has very tough structure. So, to locate it on the index finger one can use double side tape or elastic band. However, we cannot bend the part of flex sensor that has no ink particles. This can be done only by placing flex sensor on the external side of the finger.

However, another problem may occur. Again due to the prosthetic hand design it is not possible to set the sensor on the index fingers with the help of tape. During the experiments elastic bands were used to place bend sensor tightly along the finger, but these bands restrained the index movements.

8.1.2 Self-made Bend Sensor

Aforesaid reasons constrain us to use the bend sensor from subsection 8.1.1 in our application. Analyzing all obtained results, it was decided to develop our own bend sensor for measuring angle position of the finger.

The main advantages of hand-made bend sensor are soft structure and lightness that is suitable for our aims.

Our flex sensor is velostat-based sensor, which has sandwich structure. The structure of layers is depicted in Figure 8.2.

Velostat is a piezoresistive material (type of semi-conductive polymer composites), what actually means that its electrical resistance decreases during pressure or banding. However, utilizing it as a force sensor has no sense and the reason for it will be explained in the next section.

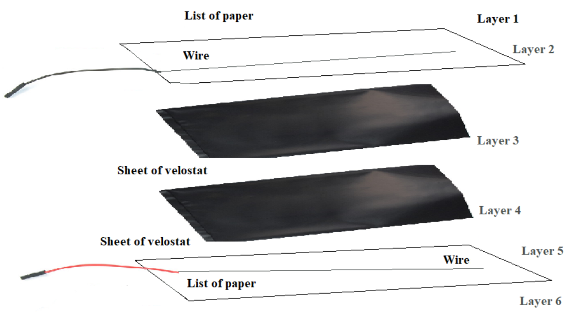

Figure 8.2: Sandwich structure of self-made bend sensor

Final self-made bend sensor was placed to the external part of the index finger with the help of elastic bands. In opposite to the previous commercial variant of bend sensor, this one does not restrain the index finger movement. One of 2 wires should be connected to the Gnd pin of the Arduino Micro and another to the analog input. Analysis of obtained data gave the possibility to speak about sensor's characteristics.

However, this sensor is very sensitive to the movement. During the static hand position, without transporting it, for example, the sensor data is sufficiently precise and can be used for obtaining position of angle. However, once the hand is moved to another place, the range that is provided by the sensor changes. It happens since the wire slides between paper and velostat sheet. One of the potential to change it is to use tape instead of paper and reduce the sensitive area.

8.2 Force Sensing Resistor

Another type of sensor for establishing sensory feedback control is a force sensing resistor. Herein we are focusing our attention mainly on the commercial FSR and the results obtained with it.

8.2.1 Commercial FSR

In our application we use the force sensor depicted in Figure 4.6. Thanks to its diameter this sensor fits ideally for placing it on the tip of thumb. The data of the applied forces was read from the analog input of Ardino Micro in the range from 0 to 1023, where 1023 is related to 5V.

Force Estimating

For obtaining the information about sensor resistivity and then about applied forces one can use the equation 4.1:

$$V_{out} = V_{cc} * \frac{R_{fsr}}{R_{fsr} + R_1} \tag{8.1}$$

Modification of the aforementioned equation with will lead to another equation:

$$R_{fsr} = \frac{(V_{cc} - V_{out}) * R_1}{V_{out}} \tag{8.2}$$

This exact formula was used in our application to transform dimensionless quantity into resistivity and the into Newton forces with the help of guide graphs that are shown in Figure 8.3

For calculating Newton forces we need firstly find conductance:

$$G = \frac{1}{R_{fsr}} \tag{8.3}$$

And then being guided by the graphs in Figure 8.3 we can find an applied force. This algorithm is presented in listing in subsection 7.3.1.

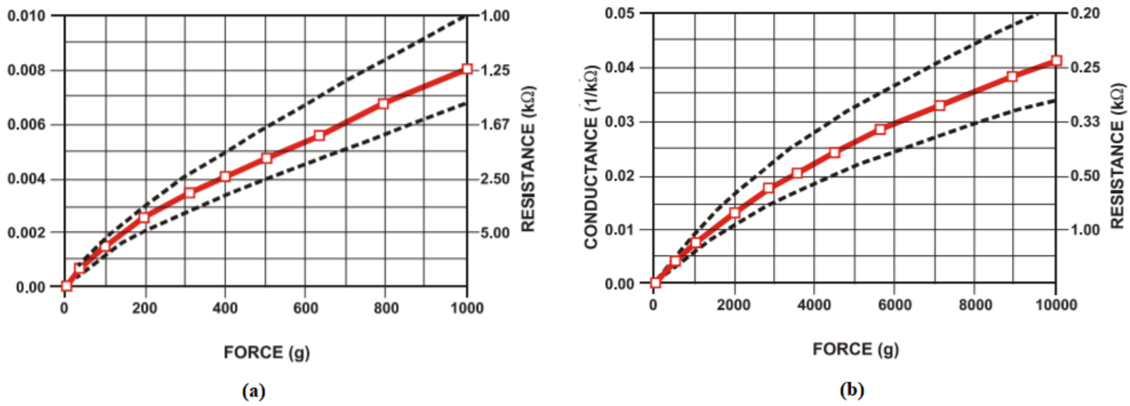

Figure 8.3: Graph of conductance-force dependence. (a) conductance is lower than 1000 mΩ, (b) conductance is higher than 1000 mΩ [66]

Table 8.1: Information of applied forces and changes in resistivity of FSR

Applied force, N	Resistivity, Ω
0.00	124900000 (125MΩ)
0.30	44465 (44.5KΩ)
1.58	7921
2.00	6265

There are usually 2 approaches that are used to organize feedback system. One of them is providing so-called compliant grasping [26] and another one is a slip prevention algorithm.

The first approach includes the necessity of taking objects without breaking them. Software-programmable way was chosen for realization of this approach. Moreover, the applied forces can be chosen by users according to his conception and knowledge.

The average human force for taking some objects like phone, pen, tape and so on was found in practice. Firstly the force sensor was attached to human hand and then different forces applied to the aforementioned objects were analyzed. However, it was found that the maximum human force and maximum prosthetic hand force do not equal [67]. Moreover, forces vary between different prosthetic types due to the construction, material and servo motors used for exact prosthetic hand.

Maximum forces for index finger and thumb are almost the same with that presented in work [67]. Maximum force of index finger is 2.1 N. Having in mind the maximum border it is realizable to change the range of 0-1023 that is read from analog input.

Results of two different applied forces is shown in Figures 8.4 and 8.5. Both of these results were provided with changing value of on-board potentiometer of Arduino Esplora.

The dependency between angle of servo motor rotation and corresponding force is presented in Figure 8.6. In this figure one can see that the dependency tend to

Figure 8.4: Applied force of 0.30 N

Figure 8.5: Applied force of 1.58 N

have the linear character.

Changing of FSR resistivity accordingly to the applied forces is shown in Figure 8.7. One can immediately notice the inverse relationship between Figure 8.6 and Figure 8.7.

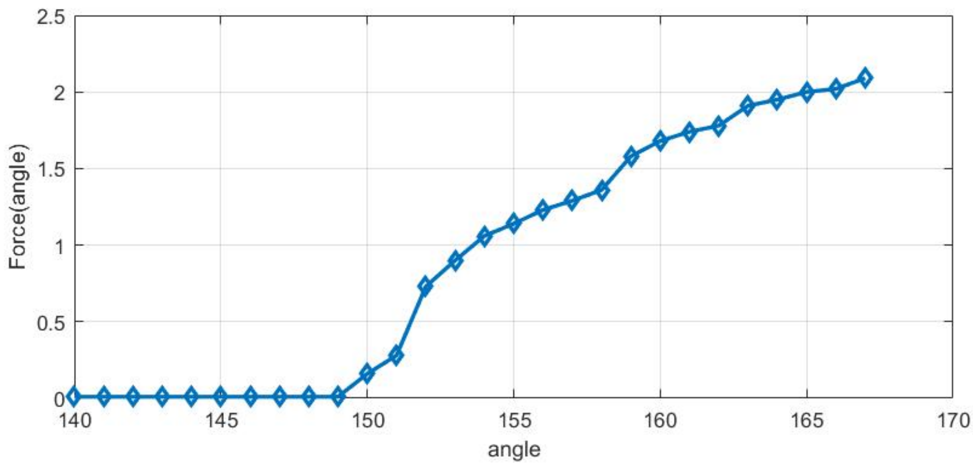

Figure 8.6: Graph of relationship between force and angle

The upper limit of FSR resistivity is higher than 5MΩ (when no forces are applied). By increasing the force the FSR resistivity declines significantly. That is why the logarithmic scale is used here.

The data was obtained with Arduino *Serial Monitor* and then graphical dependencies were plotted in MATLAB. The angle range starts from the vicinity of the motor's angle when the force firstly applies and ends in the maximum possible value of servo motor's angle.

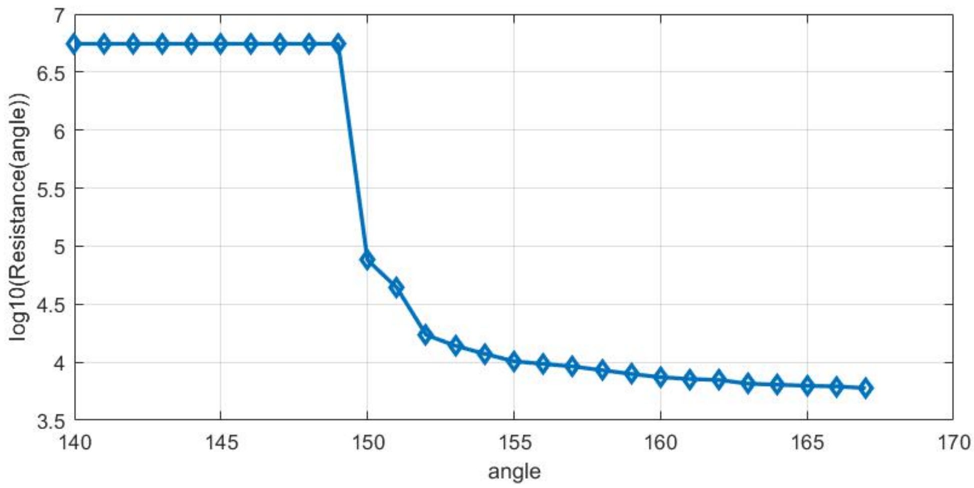

Figure 8.7: Graph of relationship between resistivity and angle in logarithmic scale

After testing the feedback control on pinch grip it was decided to conduct another experiment with cylindrical grip. For this purpose utilizing only one force sensing resistor is not enough, as we need to estimate the forces on the tips of middle, ring and little fingers. Since all of these fingers are connected and moved only by one servo motor, we can place the sensor to any of these three fingers. According to the research of grasp taxonomy [64] the grip force of the middle finger is higher that the grip force of ring and little fingers. Remembering this information we finally placed the second FSR on the fingertip of the middle finger.

Using the same approach that was used for testing pinch grip, we were trying to obtain the similar results for cylindrical grip. However, due to the hand structure the surface of the FSR just slightly touches any objects and only with the utmost region. This can be seen from the Figure 8.8. This leads to the inability of providing stable feedback control.

To overcome this difficulties it is possible to get the FSR of the smallest sensing area or with ability to estimate tangential forces as it was done in [26]. The second variant can also be done with the FSR of the small sensing area covered with the rubber layer that will provide this tangential force.

Figure 8.8: Test of the cylindrical grip

Slip Prevention

The slip prevention algorithm is available in subsection 7.3.1. In case a slip was detected the force is increased by bending the index finger. Two examples are presented in Figure 8.9.

Initial constant force for the left image was set very low (approximately 0.1 N) in order to check the algorithm. As this force was not enough for holding pen tightly slip occurred and the algorithm prevented it by providing higher force from

(a) **(b)**

Figure 8.9: Results of slip prevention algorithm, (a) grip with shifted center of gravity, (b) hold the relief-structured object

index finger. If to speak about the right picture of image 8.9 the initial force was sufficiently enough for holding almost any types of objects tightly. To launch the slip prevention algorithm the tape was slightly moved by hand on some angle.

8.2.2 Force Sensing Resistor from Conductive Materials

There is another approach how to obtain the applied force on any objects. A number of piezoresistive materials is used for these purposes. According to the purpose of usage and manufacturing of materials it is possible to separate them into 2 categories:

- Films
- Fabrics

Films, such as velostat material (information can be found in section 8.1, can be used as a material with a transversal working resistance. Fabrics, like EEONTEX

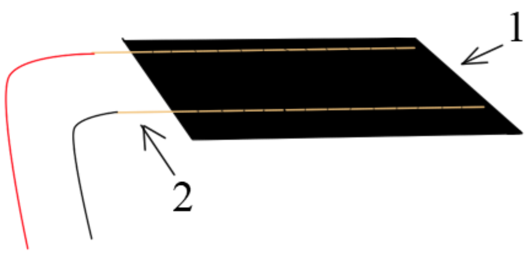

Figure 8.10: Force sensing resistor based on fabric. 1 - EEONTEX NW170-SLPA fabric material, 2 - conductive wires

NW170-SLPA [68], can be used as a material with both transversal and longitudinal working resistance.

The main structure of the sensor made from velostat material represents a sandwich structure of 3 layers. Two of the layers are conductive and the velostat material is supposed to be between these two layers. Classical materials such as blank PCB or any conductive materials which do not possess the piezoresistive property. All of the layers can be glued together with conductive glue or sewed. Such kind of material is not a very good example for determination of forces to be applied. Velostat-based force sensor is only able to provide the information about the force in a qualitative, not quantitative value.

For creating the sensor from the fabrics, one just need to sew the material with 2 or more copper wires (Figure 8.10).

Previously it was supposed to check this type of force sensor that could be created at home. However, due to some delivering issues it was not possible to make any test it and discuss the probability of its behavior.

8.3 Controlling the Force

As we have only one core microcontroller on the Arduino Micro board it is not possible to implement PID controller. The gist of the problem is that in our *loop()* function we call the functions of grips and gestures, which require some time for execution and cannot be stopped. Even if we can use protothreading for mitigate the problem of one core, it is still not enough, since protothreading in Arduino boards is only available for short period of time. Otherwise, we need to wait too long and thus, can miss start of other functions. For utilizing PID controller we need to have more powerful computational unit.

Instead of PID controller we use here something similar to fuzzy controlling. We check the range of applied forces and according to the result increasing the speed and the force of the hand by incrementing the angle of servo motors.

9 Conclusion

In this diploma work various types of upper-limb prosthetic hands were considered and classified according to different criteria. Researches of the last years, which concern the control systems of prosthetic hands were analyzed. HACKberry prosthesis of the Exiii company that had been taken as a basis in TUL was examined in details. And then the possibility of utilizing diverse sensors for organizing feedback control is considered for this particular prosthetic hand.

Moreover, the control system of the prosthesis was changes. Instead of using muscles signals with the help of myoelectric sensors, another approach similar to that used in Touch Bionic company is introduced. Here wireless signals are come from the master part of the system to the slave part, which controls the hand. Such approach with the usage of radio transceivers allows us to keep the schematics of the prosthesis without any modifications and thus, gives the opportunity to control the hand either with muscle signals or with the signals come from the master part. Here Arduino Esplora board is presented as master part of the device that allows intuitive control of prosthesis due to the sufficient numbers of buttons and on-board sensors.

The feedback system is based on force sensing resistors and programmable algorithms, which allow determining the gripping force and prevent an object from slipping. Working capability of sensors and algorithms was checked in practice with the number of everyday objects and show quite acceptable results.

Rigid structure of bend sensors and shape of prosthetic hand prevent us to use them on the outside of the prosthesis in our application. However, mounting these bend sensors inside the fingers of prosthetic hand can bring better results. Otherwise, servo motors with feedback are supposed to utilize instead of bend sensors for the future. Since they provide exacter information of servo motor angle, they can be used to control middle, ring and little fingers. To control these three fingers bending the force sensing resistor of smaller area covered with rubber layer can also be used.

References

[1] CONTRIBUTORS, Wikipedia. *Prostesis — Wikipedia, The Free Encyclopedia*. 2004. Available also from: https://en.wikipedia.org/wiki/Prosthesis. [Online; accessed 24-02-2018].

[2] COMPANY, Ottobock. *Ottobock Prosthetic hands*. Ed. by HTTP://MOTORICA.ORG. 2017. Available also from: https://www.ottobock.com/en/.

[3] BIONICS, Touch. *Products*. Ed. by HTTPS://WWW.TOUCHBIONICS.COM/. 2018. Available also from: https://www.touchbionics.com/.

[4] MAXBIONIC. *MaxBionic. Prostheses Lab. (Russian)*. Ed. by HTTP://WWW.MAXBIONIC.COM/. 2018. Available also from: http://www.maxbionic.com/.

[5] COMMUNITY., HACKberry Open Source. *Japan company offered as open source its model of prosthetic bionic hand. The body of the hand is 3D printed.* 2017. Available also from: http://exiii-hackberry.com/. [Online; accessed 24-02-2018].

[6] FRASER, C. M. An evaluation of the use made of cosmetic and functional prostheses by unilateral upper limb amputees. *Prosthetics and Orthotics International*. 1998, vol. 22, no. 3, pp. 216–223. Available from DOI: 10.3109/03093649809164486.

[7] HESS, Andrea. *Body-Powered Prostheses*. 2015. Available also from: http://upperlimbprosthetics.info/index.php?p=1_9_Body-Powered. [Online; accessed 24-02-2018].

[8] DEBLIKOV, Konstantin. *Types of upper-limp prostheses. (Russian)*. Ed. by HTTP://MOTORICA.ORG. 2016. Available also from: http://motorica.org/vidy-protezov-ruk/.

[9] MADERER, Jason. *Robotic Prosthesis Turns Drummer into a Three-Armed Cyborg*. 2014. Available also from: http://www.news.gatech.edu/2014/03/05/robotic-prosthesis-turns-drummer-three-armed-cyborg. [Online; accessed 24-02-2018].

[10] RIDDEN, Paul. *Amputee's prosthetic arm transformed into awesome inking machine*. 2016. Available also from: https://newatlas.com/sheitan-tenet-gonzal-prosthesis-tattoo-machine/43812/. [Online; accessed 24-02-2018].

[11] HESS, Andrea. *Externally Powered Prostheses*. 2015. Available also from: http://upperlimbprosthetics.info/index.php?p=1_10_Externally-Powered. [Online; accessed 24-02-2018].

[12] STUDENT, Britannica. *Below-elbow prosthesis*. 2018. Available also from: https://kids.britannica.com/students/assembly/view/167510. [Online; accessed 07-05-2018].

[13] HESS, Andrea. *Sockets and Interfaces*. 2015. Available also from: http://www.upperlimbprosthetics.info/index.php?p=1_25_Sockets-Interfaces. [Online; accessed 07-05-2018].

[14] MEDICINE, Johns Hopkins. *Electromyography (EMG)*. 2018. Available also from: https://www.hopkinsmedicine.org/healthlibrary/test_procedures/neurological/electromyography_92,P07656. [Online; accessed 08-05-2018].

[15] HERBERTS, Peter. *MYOELECTRIC SIGNALS IN CONTROL OF PROSTHESES: Studies on arm amputees and normal individuals*. 1st ed. Copenhagen: Acta Orthopaedica Scandinavic, 1969. Available from DOI: 10.3109/ort.1969.40.suppl-124.01.

[16] NEURAL PROSTHETIC RESEARCH, Laboratory of. *Implantable Myoelectric Sensors*. 2018. Available also from: http://neural.iit.edu/research/imes/. [Online; accessed 08-05-2018].

[17] GROUP, Steeper. *Steeper company*. Ed. by HTTP://RSLSTEEPER.COM. 2018. Available also from: http://rslsteeper.com.

[18] FERGUS WALSH, Medical correspondent. *Woman receives bionic hand with sense of touch*. 2018. Available also from: http://www.bbc.com/news/health-42430895. [Online; accessed 10-05-2018].

[19] GHAZAEI, Ghazal; ALAMEER, Ali; DEGENAAR, Patrick; MORGAN, Graham; NAZARPOUR, Kianoush. Deep learning-based artificial vision for grasp classification in myoelectric hands. *Journal of Neural Engineering*. 2017, vol. 14, no. 3, pp. 036025. Available also from: http://stacks.iop.org/1741-2552/14/i=3/a=036025.

[20] GALTSEV, Oleg. *MioTriton project. (Russian)*. 2015. Available also from: http://myotriton.com/. [Online; accessed 24-02-2018].

[21] CONTROZZI, Marco; CLEMENTE, Francesco; BARONE, Diego; GHIONZOLI, Alessio; CIPRIANI, Christian. The SSSA-MyHand: A Dexterous Lightweight Myoelectric Hand Prosthesis. *IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING*. 2017, vol. 25, no. 5, pp. 459–468. Available from DOI: 10.1109/TNSRE.2016.2578980.

[22] OTTOBOCK. *bebionic. The world's most lifelike bionic hand*. 2018. Available also from: https://www.ottobockus.com/media/local-media/prosthetics/upper-limb/files/14112_bebionic_user_guide_lo.pdf. [Online; accessed 08-05-2018].

[23] BIONICS, Touch. *History*. Ed. by HTTPS://WWW.TOUCHBIONICS.COM/. 2018. Available also from: https://www.touchbionics.com/about/history.

[24] MOTORICA. *3D printing: making prosthetic hands and cyborgs. (Russian)*. 2017. Available also from: https://pikabu.ru/story/3dpechat_za_dobro_delaem_protezyi_ruk_i_kiborgov_5482777. [Online; accessed 08-05-2018].

[25] SYSTEMS, Vincent. *Vincent systems.VINCENT EVOLUTION 2*. Ed. by SYSTEMS, Vincent. 2018. Available also from: https://vincentsystems.de/en/prosthetics/vincent-evolution-2/.

[26] OSBORN, Luke Emmett. *Reflex: A Closed-Loop Tactile Feedback System for Use in Upper Limb Prosthesis Grip Control*. Baltimore, Maryland, 2014. Available from DOI: http://jhir.library.jhu.edu/handle/1774.2/38045. Master's thesis. Johns Hopkins University.

[27] SHEN, Zhong; YI, Juan; LI, Xiaodong; LO, Mark Hin Pei; CHEN, Michael Z. Q.; HU, Yong; WANG, Zheng. A soft stretchable bending sensor and data glove applications. *Robotics and Biomimetics*. 2016, vol. 3, no. 1, pp. 22. ISSN 2197-3768. Available from DOI: 10.1186/s40638-016-0051-1.

[28] BIONICS, Open. *Open Bionics company*. Ed. by BIONICS, Open. 2018. Available also from: https://openbionics.com/hero-arm/.

[29] BIONIC, You. *You Bionic company*. Ed. by BIONIC, You. 2018. Available also from: https://www.youbionic.com/.

[30] TRIGNO. *Trigno Wireless System*. 2018. Available also from: https://www.delsys.com/products/wireless-emg/trigno-lab/. [Online; accessed 11-05-2018].

[31] SYSTEMS, Vincent. *Vincent Systems - Deutscher Zukunftspreis 2017 (in German)*. 2017. Available also from: https://vimeo.com/252880699. [Online; accessed 12-05-2018].

[32] OSBORN, L.; KALIKI, R. R.; SOARES, A. B.; THAKOR, N. V. Neuromimetic Event-Based Detection for Closed-Loop Tactile Feedback Control of Upper Limb Prostheses. *IEEE Transactions on Haptics*. 2016, vol. 9, no. 2, pp. 196–206. ISSN 1939-1412. Available from DOI: 10.1109/TOH.2016.2564965.

[33] CHANDLER, Nathan. *How the Nintendo Power Glove Worked*. Ed. by HOWSTUFFWORKS.COM. 2015. Available also from: https://electronics.howstuffworks.com/nintendo-power-glove.htm.

[34] FALLAHIAN, Nader; SAEEDI, Hassan; MOKHTARINIA, Hamidreza; GHOMSHE, Farhad Tabatabai. Sensory feedback add-on for upper limb prosthesis. *Prosthetics and Orthotics International*. 2017, vol. 41, no. 3, pp. 314–317. Available from DOI: 10.1177/0309364616677653.

[35] AGARWAL, Tarun. *Know all about Force Sensing Resistor Technology*. 2015. Available also from: https://www.elprocus.com/force-sensing-resistor-technology/. [Online; accessed 06-03-2018].

[36] KEVAN, Tom. *Sensors Transform*. 2016. Available also from: http://www.digitaleng.news/de/sensors-transform/. [Online; accessed 06-03-2018].

[37] INC., Interlink Electronics. *FSR 402*. 2015. Available also from: https://www.interlinkelectronics.com/fsr-402. [Online; accessed 06-03-2018].

[38] SPARKFUN. *Force Sensitive Resistor 0.5*. 2018. Available also from: https://www.sparkfun.com/products/9375. [Online; accessed 29-04-2018].

[39] ELECTRONICS, Interlinc. *FSR Integration Guide and Evaluation Parts Catalog*. 2018. Available also from: https://www.generationrobots.com/media/FSR400-Series-Integration-Guide.pdf. [Online; accessed 29-04-2018].

[40] WIKIPEDIA. *Goniometer*. 2018. Available also from: https://en.wikipedia.org/wiki/Goniometer. [Online; accessed 25-04-2018].

[41] WIKIPEDIA. *Flex sensor*. 2018. Available also from: https://en.wikipedia.org/wiki/Flex_sensor. [Online; accessed 25-04-2018].

[42] SPARKFUN. *Flex Sensor 2.2*. 2018. Available also from: https://www.sparkfun.com/products/10264. [Online; accessed 25-04-2018].

[43] QUIGLEY, J.T. *This gorgeous, 3D-printed robotic arm from Japan is changing how prosthetics are perceived*. 2015. Available also from: https://www.techinasia.com/exiii-hackberry-robotic-prosthetic-arm-startup. [Online; accessed 25-02-2018].

[44] KOPRNICKÝ, Jan; NAJMAN, Petr; ŠAFKA, Jiří. 3D printed bionic prosthetic hands. In: *2017 IEEE International Workshop of Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM)*. Donostia – San Sebastian: IEEE, 2017, pp. 1–6. Available from DOI: 10.1109/ECMSM.2017.7945898.

[45] MAKERBOT. *The All-New MakerBot Print*. 2018. Available also from: https://www.makerbot.com/print/. [Online; accessed 03-03-2018].

[46] ARDUINO.CC. *Arduino Micro*. 2018. Available also from: https://store.arduino.cc/arduino-micro. [Online; accessed 24-04-2018].

[47] SERVOCITY. *HS-311 Servo*. 2018. Available also from: https://www.servocity.com/hs-311-servo. [Online; accessed 01-05-2018].

[48] EMAX. *EMax 12g ES08MD high Sensitive servo*. 2018. Available also from: https://media.digikey.com/pdf/Data%20Sheets/Seeed%20Technology/108090001_Web.pdf. [Online; accessed 01-05-2018].

[49] SPARKFUN. *SparkFun Line Sensor Breakout—QRE1113 (Analog)*. 2018. Available also from: https://www.sparkfun.com/products/9453. [Online; accessed 11-05-2018].

[50] CORP., Genixtek. *Photo interrupters—mini reflective type*. 2018. Available also from: http://www.gtctw.com/file/LED/INVISIBLE%20LED%20SERIES/pho.int.tpr,min.ref.%201.pdf. [Online; accessed 12-05-2018].

[51] ADVANCER TECHNOLOGIES, LCC. *MyoWare*. 2010-2016. Available also from: http://www.advancertechnologies.com/. [Online; accessed 03-03-2018].

[52] ARDUINO. *Loop function*. 2018. Available also from: https://www.arduino.cc/en/Reference/Loop/. [Online; accessed 24-04-2018].

[53] NAJMAN, Petr. *Bionic Hand*. Liberec, Czech Republic, 2017. Available from DOI: http://pub.mti.tul.cz/~jan.koprnicky/BioRuka/diplomova_prace_2017_Petr_Najman.pdf. Master's thesis. Technical University of Liberec.

[54] ARDUINO.UA. *Arduino Esplora. (Russian)*. 2012. Available also from: https://doc.arduino.ua/ru/hardware/Esplora. [Online; accessed 03-03-2018].

[55] ARDUINO.CC. *Arduino Esplora*. 2018. Available also from: https://store.arduino.cc/arduino-esplora. [Online; accessed 25-02-2018].

[56] DFROBOT.COM. *APC220 Radio Data Module*. 2010. Available also from: http://image.dfrobot.com/image/data/TEL0005/APC220_Manual_en.pdf. [Online; accessed 14-04-2018].

[57] ROBOTICS, Micro. *APC220 Radio Comms Module*. 2018. Available also from: https://www.robotics.org.za/APC220. [Online; accessed 14-04-2018].

[58] NAROM. *Transceiver*. 2018. Available also from: https://www.narom.no/undervisningsressurser/sarepta/the-cansat-book/the-primary-mission/using-the-radio/transceiver/. [Online; accessed 14-04-2018].

[59] KEIM, Robert. *Back to Basics: The Universal Asynchronous Receiver/Transmitter (UART)*. 2016. Available also from: https://www.allaboutcircuits.com/technical-articles/back-to-basics-the-universal-asynchronous-receiver-transmitter-uart/. [Online; accessed 14-04-2018].

[60] ELECTRONICS, Circuit Basics | DIY. *BASICS OF UART COMMUNICATION*. 2018. Available also from: http://www.circuitbasics.com/basics-uart-communication/. [Online; accessed 24-04-2018].

[61] ROUSE, Margaret. *Master/Slave*. 2018. Available also from: https://searchnetworking.techtarget.com/definition/master-slave. [Online; accessed 24-04-2018].

[62] BIONICS, Touch. *i-limb mobile apps*. 2018. Available also from: http://www.touchbionics.com/products/i-limb-mobile-apps. [Online; accessed 27-04-2018].

[63] FEIX, Thomas; ROMERO, Javier; SCHMIEDMAYER, Heinz-Bodo; DOLLAR, Aaron M.; KRAGIC, Danica. The GRASP Taxonomy of Human Grasp Types. *IEEE Transactions on Human-Machine Systems*. 2015, vol. 46, no. 1, pp. 66–77. ISSN 2168-2305. Available from DOI: 10.1109/THMS.2015.2470657.

[64] ABBASI, B.; NOOHI, E.; PARASTEGARI, S.; ŽEFRAN, M. Grasp taxonomy based on force distribution. *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. 2016, pp. 1098–1103. ISSN 1944-9437. Available from DOI: 10.1109/ROMAN.2016.7745245.

[65] FARLEX, The free dictionary by. *tip pinch*. 2018. Available also from: https://medical-dictionary.thefreedictionary.com/tip+pinch. [Online; accessed 25-04-2018].

[66] ELECTRONICS, Interlinc. *Force Sensing Resistor Integration Guide and Evaluation Part Catalog*. 2018. Available also from: https://www.sparkfun.com/datasheets/Sensors/Pressure/fsrguide.pdf?_ga=2.91805466.1899382584.1524998867-1205937786.1523787514. [Online; accessed 07-05-2018].

[67] KARGOV; PYLATIUK; J, Martin; S, Schulz; L., Doederlein. A comparison of the grip force distribution in natural hands and in prosthetic hands. *Disability and Rehabilitation*. 2004, pp. 705–711. Available from DOI: 10.1080/09638280410001704278.

[68] SPARKFUN. *EeonTex Conductive Fabric*. 2018. Available also from: https://www.sparkfun.com/products/14110. [Online; accessed 02-05-2018].

A Content of enclosed CD

- Text of diploma work
  - Full text of diploma work
  - Tasks
- Measured data
- Images
  - Parts of the system
  - Photos of the working algorithms
- Technical documentation
  - APC220-Datasheet.pdf
  - FSR400-Series-Integration-Guide.pdf
  - FSR-guide.pdf

B Device schematics

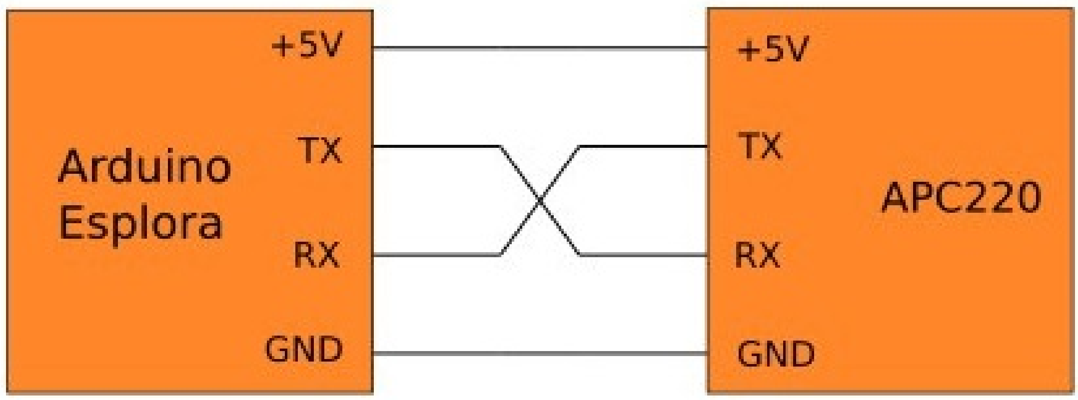

Figure B.1: Scheme of Master part

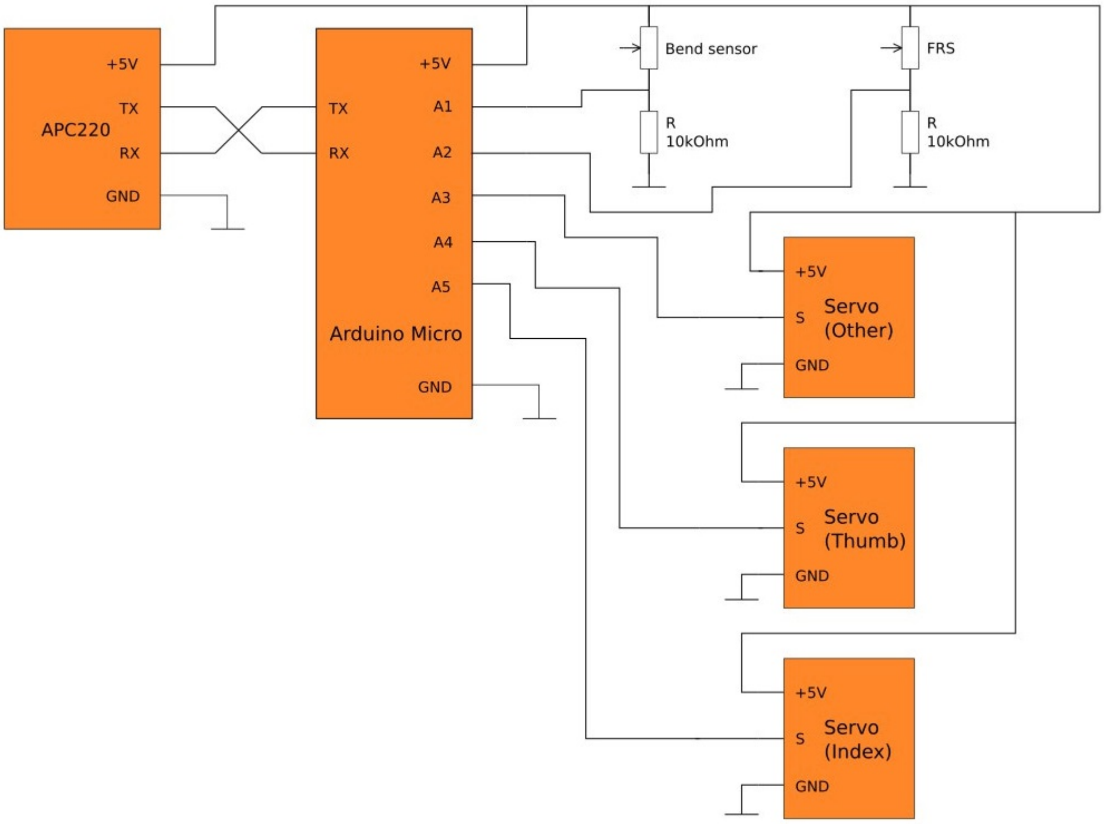

Figure B.2: Scheme of Slave part

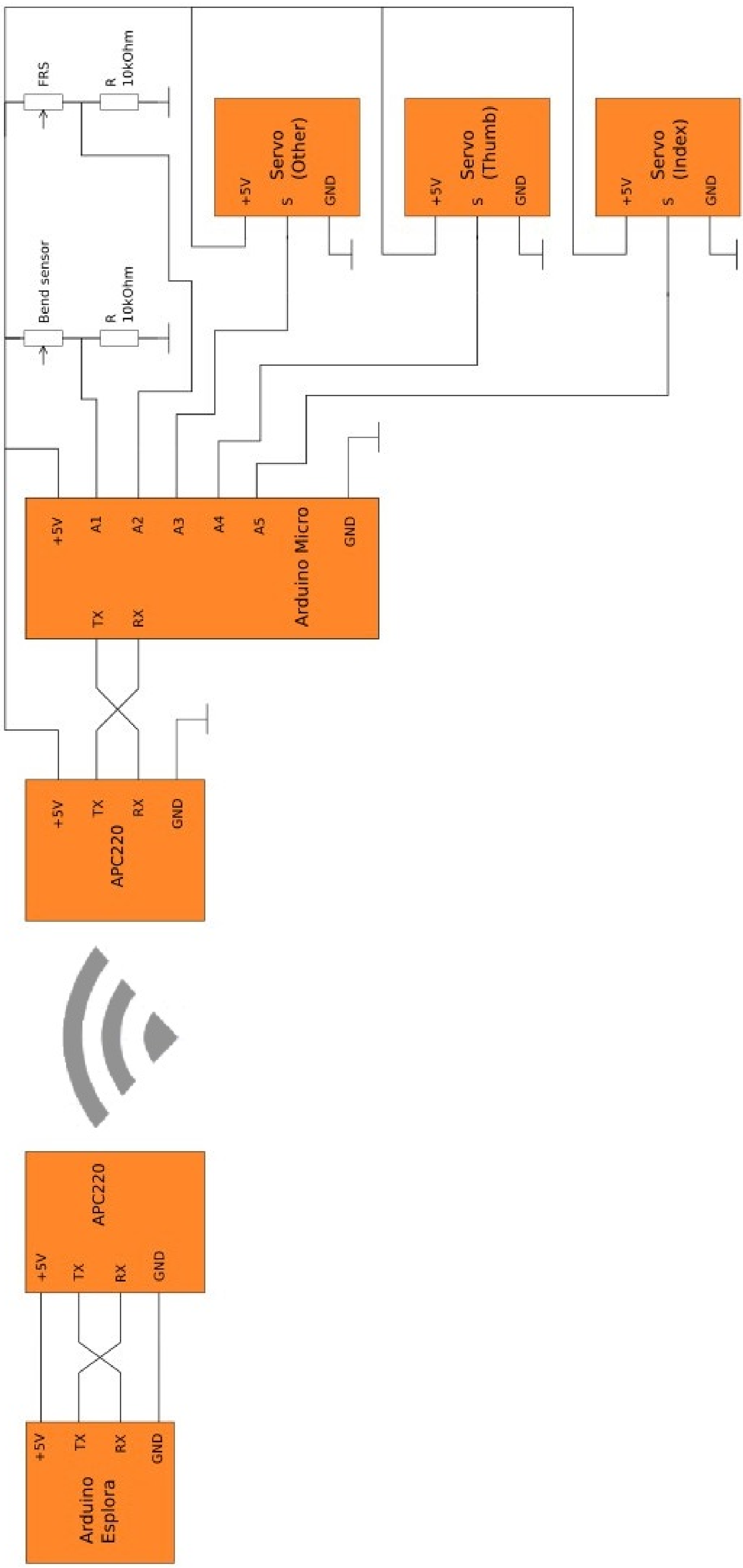

Figure B.3: Scheme of the whole system