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DEVELOPMENT OF A CONTROL PLATFORM FOR A ROBOTIC GRIPPER UTILIZING EMG SIGNALS OF HUMAN'S MUSCLES

Examiner(s): Prof. Heikki Handroos
D. Sc. (Tech.) Hamid Roozbahani

ABSTRACT

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Development of a Control Platform for a Robotic Gripper Utilizing EMG Signals of Human's Muscles

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For industrial robots at a factory, repetitive actions are satisfactory. However, in a dangerous situation, such as a building collapse, difficult climatic conditions, or any other life-threatening conditions, it is safer to send a robot instead of a human to perform tasks. In this case, the robot must react according to circumstances. There are several ways to control a robot. This study concentrates on the control based on the repetition of human movement. This type of control was chosen because of its intuitive approach. The research was performed in the laboratory of intelligent machines at LUT University. The control object of this study was three-finger gripper by Robotiq, for obtaining EMG signals from muscles that used to control the gripper the Trigno wireless biofeedback system by Delsys was chosen. During this research, the control platform was developed based on the LabVIEW environment which allows to perform three main gripper movements: open, close, and change in scissor position. The evaluation showed a good reaction on open-close movement, the reaction on change in the angle between the index and the middle fingers has to be improved. Possible methods to increase accuracy are presented in the research. Also, the concept of future development of the system is described in this study.

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Aleksandra Loskutova
Aleksandra Loskutova
Lappeenranta 10.06.2020

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LIST OF SYMBOLS AND ABBREVIATIONS

DAQ	Data Acquisition
EMG	ElectroMyoGram
FLC	Fuzzy Logic Controller
HRI	Human-Robot Interface
IP	Industrial Protocol
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
MAV	Mean Absolute Value
NI	National Instruments
RMS	Root Mean Square
TCP	Transmission Control Protocol
SVM	Support Vector Machine
VI	Virtual Instrument
VR	Virtual Reality

1 INTRODUCTION

Robots conquer the world as they are replacing humans in different areas of life. Nowadays fully robotic manufactures are gaining popularity. The main advantage that divides robots from a human is that it can perform very precise actions. However, the world is not perfect and there are applications where a robot needs to react according to a situation. Control can be implemented programmatically or by repeating a human movement. The control from the human body is more intuitive. This research is dedicated to a 3-finger gripper control platform development. In this research Human-Robot Interface (HRI) is provided as control by signals from arm muscles.

When the human moves the upper body, as well as other body parts, the brain sends down electrical signals through the nerves which causes muscle contraction. Electromyography (EMG) is a method to detect potential in the muscles while they contract. The signals exist at a range of ±5 mv. During data acquisition, many factors introduce random fluctuations that obscure the real signal. Signals have to be processed before interpretation, because of noise within them. In figure 1 the raw signal is presented.

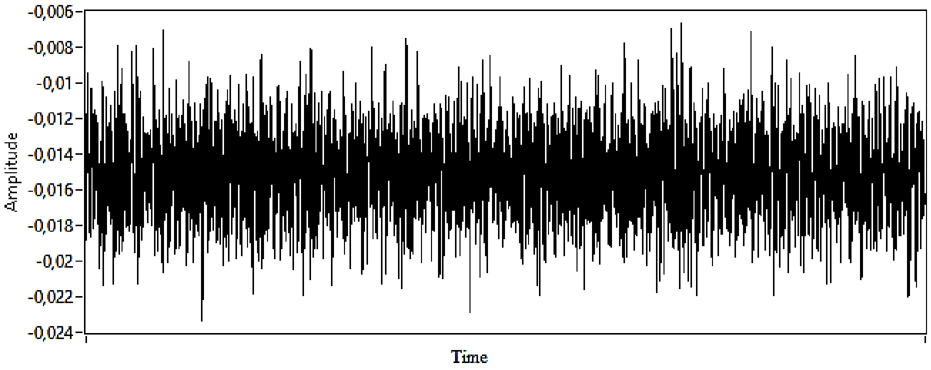


Figure 1. Raw EMG signal.

In the future, the developed platform of EMG sensors and the gripper can be combined with different bases, cameras, and/or Virtual Reality (VR) to complete a system. The whole system supposed to replace a human being in dangerous situations.

Possible hazardous situations are the main areas where a robot can be used instead of a human that can perform dangerous tasks. There are various hazardous applications where such a robotic system can be utilized:

- Manufacture;
- Healthcare;
- Space industry;
- Research;
- Military
- Public hazardous applications such as firefighting

For instance, to avoid spacewalk to repair a shuttle, this system can be used and controlled from inside the space station with visualization from a camera or real-time simulation. Another example can be in healthcare when during a pandemic, it is important to avoid contact between people. This system cannot be used to treat infected people, but it can be used to transport infected items and materials.

1.1 Research goals and objectives

The platform under investigation would transfer and re-generate the human hand and fingers movements. To achieve this goal, it is necessary to create a network where the gripper can understand the signals from EMG sensors. As the base programming software of this network, LabVIEW from National Instruments was chosen. To choose a suitable point on the arm, the anatomy of a human hand will be studied. The easiest way to read the signal is to locate the sensors on the skin. These signals at the range of 0 – 10 mV and frequency of 0 to 500Hz. Once these signals processed then they can be used for robotic-arm control.

The project was divided to the following tasks:

1. Creating access to signal acquisition data from LabVIEW;
2. Create a driver to control the gripper from LabVIEW;
3. Study the anatomy of the hand to find locations for sensors;
4. Conduct signals analyze;
5. Interpret results to control the gripper;
6. Carry out experiments to check the gripper performance.

1.2 Structure of the thesis

The research is divided on chapters and sections. The first chapter is the introduction of the research where the topic, examples of possible applications for the system are given. The goals and objectives are included in this section as well.

The second chapter consists of a background and literature review. A brief history of EMG signals discovery is described and previous researches about EMG sensors usage and methods of analysis are presented in the literature review.

The next chapter, chapter 3, is dedicated to the developed platform components description. The detailed technical data is presented for the 3-finger gripper and the Trigon Wireless Biofeedback System. Finally, in this section, the whole developed platform is introduced in detail.

Chapter 4 of this report is dedicated to the development of the control platform which is divided into 4 sections: the creation of the connection between Trigon System and LabVIEW, creation of control of the gripper from LabVIEW, a study of hand anatomy and finding a suitable location on it, signal analysis and its interpretation. After development, the evaluation is carried out.

Chapter 5 consists of experiments with the system. During the experiments, a number of issues are raised. They are described in Chapter 6. The possible methods of signal analysis are listed. These methods can improve the gripper performance.

To conclude, Chapter 7 presents the discussion and conclusions of the project.

2 BACKGROUND AND LITERATURE REVIEW

The first documented discovery of a connection between muscle tissue and electricity was made by Francesco Redi in 1666 while he observed an electrical eel (Kazamel M., Province P., Alsharabati M., Oh S., 2013). Only in 1773, the eel fish's muscle ability to generate electricity was demonstrated by John Walsh (Piccolino M., Bresadola M., 2002). The study of electromyography started in the 18th century when the publication "De Viribus Electricitatis in Motu Musculari Commentarius", written by Luigi Galvani, showed that electrical stimulation can cause muscle contraction in disembodied frog legs (Heilbron J.L, 1979). Attempts to record the electrical transmission of nerve signals were made since 1849 when Emil du Bois-Reymond discovered this possibility. By 1890, the first recording of muscle activity and term electromyography was introduced by Marey (Raez M.B.I., Hussain M.S., Mohd-Yasin F., 2006). Although, modern recording method was created in 1942 by Harbert Jasper at McGill University, Montreal, Canada (Herbert H. Jasper fonds, 2006-2007). Nowadays EMG signal analysis is wildly used in medicine, biomechanics, motor control, et cetera.

The processing of the EMG signals is a difficult and challenging task. There are different methods to analyze EMG signals. Nishikawa K., Kuribayashi K. (1991) created a neural network to recognize hand movement based on EMG signals. This work was carried out to control prostheses. The neural network had 3 layers and showed the best probability result of 0,61 from experiments with more than 100 cells and a significant number of teaching data.

To improve EMG pattern recognition as one of the methods a fuzzy logic is used to classify EMG patterns (Chan F.H.Y, Yang YS, Lam F.K., Zhang Y.T., Parker P.A. 2000) This approach showed better results than classification based on a neural network. An advantage for this approach is insensitive to over-training and the ability to take over an expert experience.

The Fuzzy Logic Controller (FLC) is a broadly used approach to analyze EMG signals for different applications. For example, it was implemented to develop a hand exoskeleton (for shoulder and elbow) by Kiguchi K., Tanaka T, Watanabe K, Fukuda T. in 2003, the fuzzy controller was used to control multifunctional prosthetic arm (Weir R.F., Ajiboye A.B., 2003). Also, the fuzzy logic controller was used to control the prosthetic in real-time with an updated rate of 45,7 ms (Ajiboye A.B., Weir R.F. 2005).

Kiguchis K., Tanaka T., and Fukuda T. (2004) applied a neuro-fuzzy controller that interpreted EMG signals to an upper-limb exoskeleton which combined fuzzy logic and neuro network. Although the system requires time due to the controller adaptation, it showed good efficiency in the EMG signals recognition from the experiments.

A different approach was used by Krysztoforski K., Wolczowski A., Bedzinski R., and Helt K. (2004). In the paper, signals were analyzed to control prosthesis based on the wavelet transformation which requires training and formulation of recognition rules. Information about finger position was recorded from data glove and corresponded with forearm EMG signals to provide training for the algorithm. Only two classes were reviewed in the research.

In the study conducted by Shalu G.K., Sivanandan K.S., Mohandas K.P. (2012) the comparison of the efficiency of both fuzzy logic and probabilistic neural network were conducted. During the research of the interstation of the EMG signals from biceps based on elbow movements speed the FLC showed better accuracy than the neural network. However, only two subjects were used in the experiments.

In research by Alkan A.and Gunay M. in 2012 authors showed that support vector machine (SVM) has better results in EMG signals classification than a classification based on discriminant analysis. SVM is one of the methods used in machine learning. This method also was used to detect neuromuscular disorder based on EMG analysis (Subasi A., 2013.). Due to computational complexity, this approach is difficult to use in practice in real-time. However, the research by Meattini R., Benatti S., Scarcia U., De Gregorio D., Benini L., Melchiorri C. (2018) consists of a development of a similar system where gripper controlled by sEMG (surface EMG) signals from the arm that were recognized by open-source libSVM for MATLAB. and showed a mean success ratio of recognition of 96,3% among the four subjects.

The system developed by Rahman M.M. and Rosly M.H.M. (2016) has a similar goal to the current project with a different control object and other control tools. EMG signals were used to control a 5-fingers artificial hand with sensors located on the forearm that a created mobile system for everyday use. The best results for the threshold approach showed by Mean Absolute Value (MAV) and sample entropy.

One of the issues when using EMG signals analysis is the location of the sensors on the hand. In a study by Baranski R., Kozupa A.in 2014 authors use this approach as a replacement for a tool handle. In this paper, the question of the position of the location of the sensors was answered. Authors picked three muscles on the forearm(fig.2) to read signals:

- Brachioradialis (flexes the forearm at the elbow),
- Flexor Carpi Ulnaris (flexes and adducts the hand),
- Flexor Carpi Radialis (flexes the hand and fingers, also the elbow, but not so strong as the hand and fingers).

The results show that the most sensitive location was over Brachioradialis muscle even though Flexor Carpi Ulnaris and Flexor Carpi Radialis directly connected with the grip function.

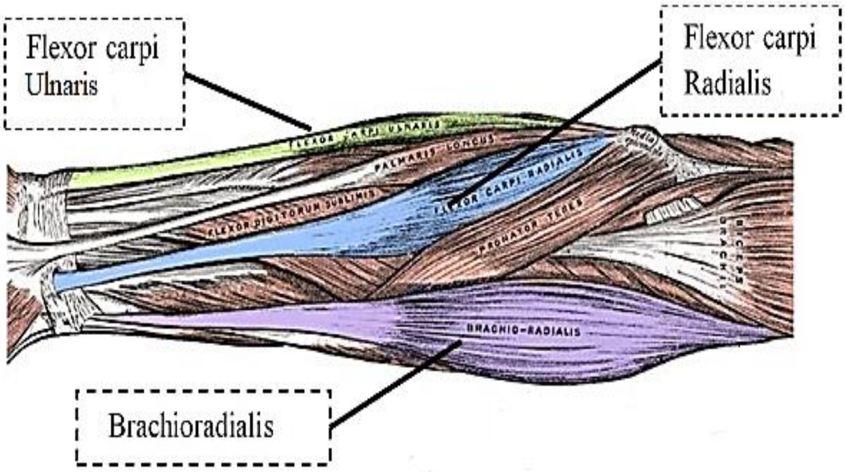


Figure 2. Muscles used to compare effective signals acquisition (Baranski R., Kozupa A., 2014).

There are different areas where EMG signals approach is employed. One of the reasons to research EMG signals is an accurate way to control artificial hands with a human body in order to help people with a disability such as a limb loss (Herrera A., Bernal A., Isaza D., Adjouadi M., 2010). In this paper authors design and construct a prosthesis that can offer precise force control which is challenging to create. For convenience, two types of control were designed: mechanical by a pseudo-clutch on the linear actuator, and electrical by detection of EMG signals for initial movement. Another work on the same topic is presented by Nhu N. (2018). In this paper, the researcher created a low-cost 3D printed prosthetic arm and used EMG signals from the forearm to control it to perform simple daily tasks. The system does not copy the human hand movement but reacts to a specific combination of the hand and the arm position to control fingers position.

Another reason is a weakness of hands after a stroke. This kind of projects are not aimed at replacing the human hand completely as the previous ones, but only at helping restore the hand movement. Delph M., Fischer S., Gauthier P., Martinez Luna C. (2012) designed the rehabilitative glove. The glove has three different control modes: switch, programmed position, and EMG. As a part of the current research, the EMG mode is most interesting. To obtain control signals two bipolar electrode-amplifiers were used: one of the sensors read signals from Extensor Digitorum Communis, and the other was placed on the ventral side of the forearm atop the Flexor Digitorum Profundus. Also, a reference electrode was secured above the bony part of the elbow. These muscles are shown in figure 3. This glove performs only grip movement by reacting to the peaks in the EMG signals from muscles liable for fingers flexion-extension movements.

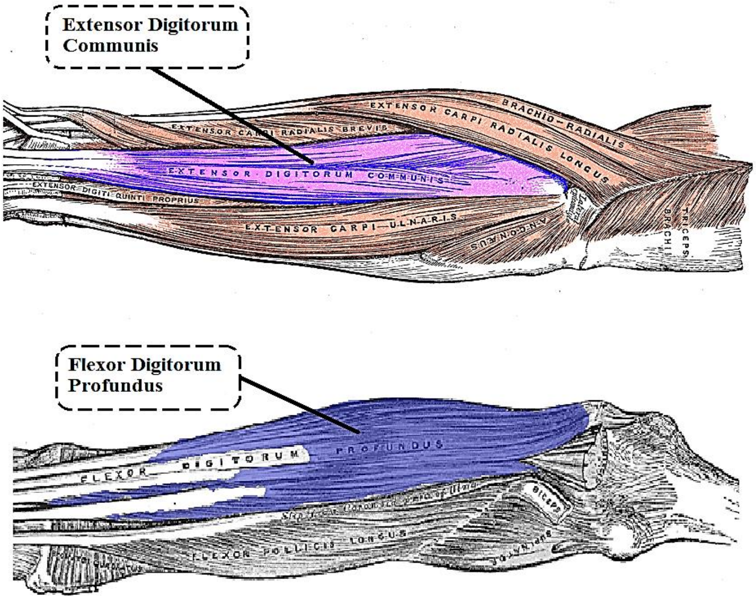


Figure 3. Muscles used in (Delph M., Fischer S., Gauthier P., Martinez Luna C, 2012).

The same goal was chased by Lu Z., Tong K., Shin H., Li S., and Zhou P. (2017) created the algorithm which uses EMG sensors for the hand training of the woman after stroke. Although the control of the right hand was compromised after stroke, EMG sensors could recognize contractions of the muscles of the forearm, that triggered the exoskeleton hand to move. This exoskeleton is placed on the damaged hand and helps to move.

3 COMPONENTS OF THE PLATFORM

The system consists of different parts from different corporations. A three-finger gripper is an object of control in this project, Delsys EMG sensors is a tool to read signals from a human hand to control the gripper, and LabVIEW is a mediator for these two components. A computer with a program in LabVIEW will be referred to as a server in this thesis.

The basic structure of the network is represented in the figure 4.

Figure 4. Scheme of the system.

Trigno EMG sensors detect signals in muscles and transmit it to LabVIEW in real-time. The program filters the signal, analyzes them, and sends a corresponding command to the gripper. Communication between the gripper and the VI is two way. This means that the gripper constantly sends its status to the program. In the next sections, detailed information will be presented for each component of the developing platform.

3.1 Robotiq three-finger gripper

A gripper is a robotic hand, designed to interact with the environment. Grippers are used in different fields of industry for pick-and-place tasks mostly. In this work, the main object is a three-finger gripper by Robotiq (fig.5). This model consists of three articulated fingers which each have three joins as a human finger. That allows the gripper to have ten contact points on the object: three on each of the phalanges and one on the palm.

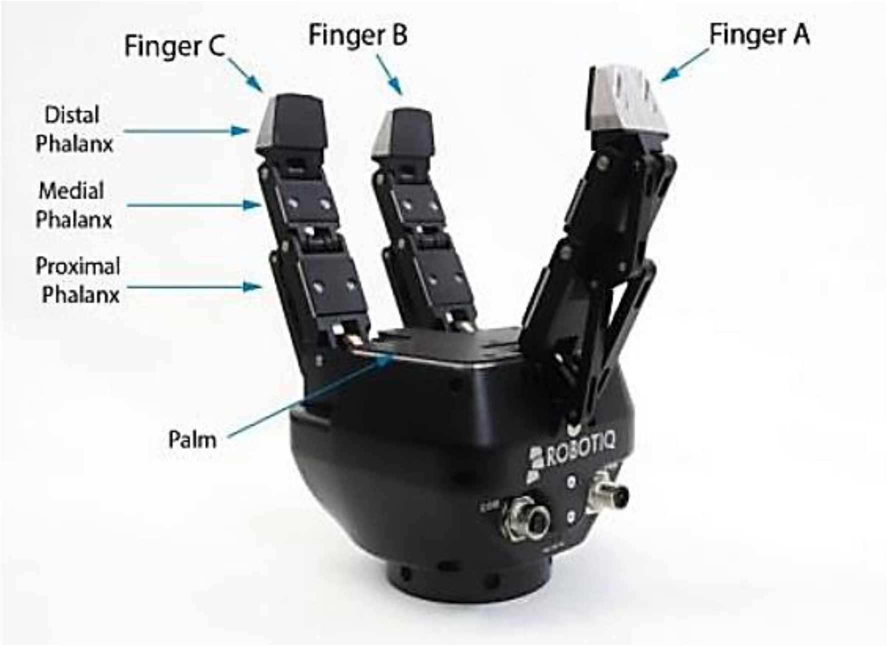


Figure 5. Three-finger gripper by Robotiq (Robotiq Three-Finger Gripper Manual).

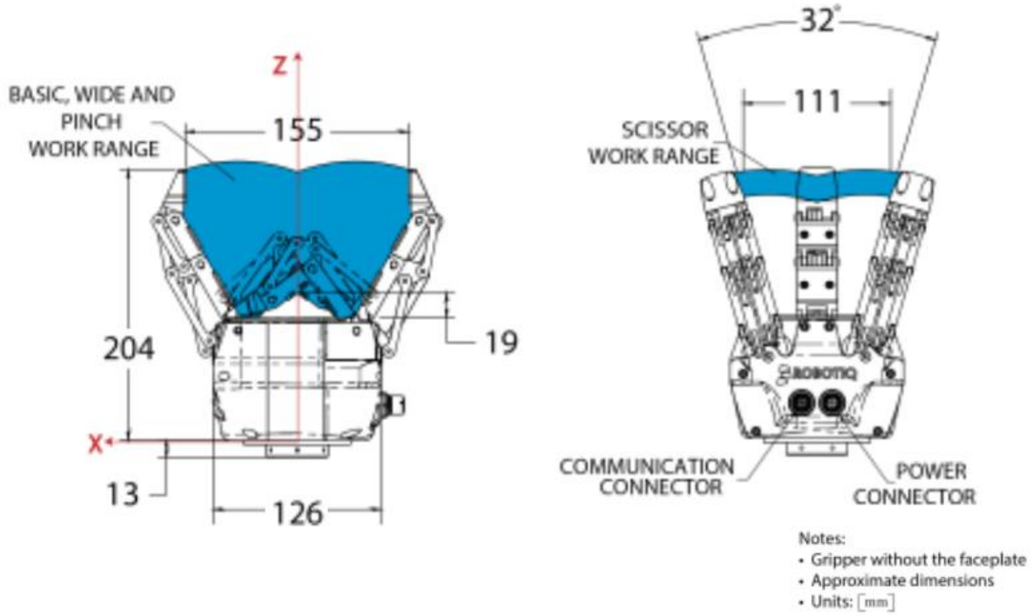
The absence of the motors on each of the phalanx makes the gripper to easily adapt to any shape of the object. One of the features of this gripper is the reaction to obstacles when the fingers feel resistance, they stop. It makes impossible to apply significant force to an object or a surface. The grip force is in the range of 30 - 70 N.

The gripper has four operation modes of grip:

1. basic mode, where fingers B and C are in the fixed distance from each other
2. wide mode, where fingers B and C are in the maximum distance from each other
3. pinch mode, where fingers B and C are in touch with each other
4. scissor mode, where finger A is still, fingers B and C move relatively each other

As can be seen, the difference between modes is in the angle between fingers B and C.

The technical dimensions are presented in figure 6. Since the study of the gripper mechanical realization is not part of this thesis for more information about mechanical specification can be found in section 6. Specifications (Robotiq Three-Finger Gripper Manual).



Notes:
- Gripper without the faceplate
- Approximate dimensions
- Units: [mm]

Figure 6. Technical dimensions (Robotiq Three-Finger Gripper Manual).

The weight of the gripper is 2,3 kg. The maximum actual load in the basic or the wide modes is 10 kg, for the pinch mode this number decrease to 2.5 kg.

The operating supply voltage for the gripper is 24 V which is provided from a power supply. The gripper communication with the computer can be established through EtherNet/IP (Industrial Protocol), TCP/IP ((Transmission Control Protocol)), Modbus RTU, and others.

To control the gripper is possible from the official application. For the goals of this thesis, the official application is not suitable because it does not support a third party. The development of the software will be based on the official program and will be discussed later (Section 4.2 LabVIEW and 3-finger gripper integration).

The gripper can be attached to an articulated robot arm through a coupling. It can be used in future developments to place the gripper nearby an object that needs to be picked up. The concept for future development is presented in figure 7.

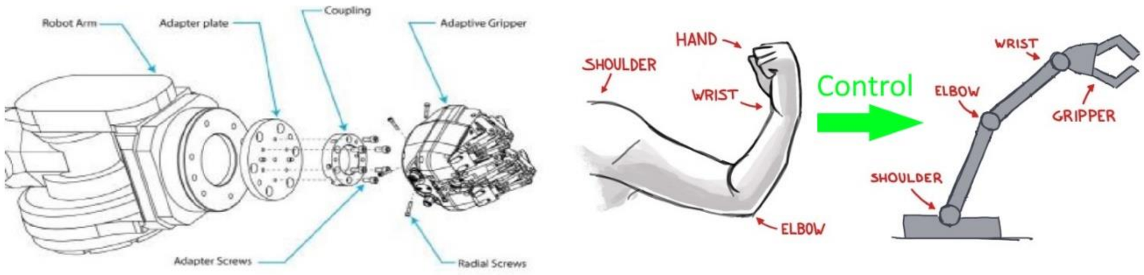


Figure 7. The gripper attachment to a robot arm (Robotiq Three-Finger Gripper Manual) and concept of the future development of the system.

In the next section, the Trigno System for EMG signals reading is presented. The principle of sensors and software from Delsys usage is described.

3.2 Trigno Wireless Biofeedback System

Trigno Wireless Biofeedback System by Delsys is a device to simplify the collection of electromyographic and biofeedback signal. The main components are Trigno Avanti™ Wireless Sensors and Trigno Base Station. As it can be understood from the name, the sensor and the base have a time-synchronized wireless connection which minimizes data latency across the sensors. The base is powered with a power supply cable and connected to a personal computer with USB Cable.

The measurement unit contains 16 Trigno Avanti™ Sensors which can measure relay acceleration, rotation, and earth magnetic field information with a built-in 9 degree of freedom inertial unit.

Every sensor has a number that corresponds to a dock number, an example presented in figure 8. When sensors are extracted from the charging dock they turn on and searching to base connection. To connect sensors to the base the sensor should be placed on a marked specific place on the base (magnet plate). After the sensor connects with the base the indicator will change its color to green/black. Also, the status can be checked in Delsys Trigno Control Utility 3.5.6 from Delsys.

Figure 8. Trigno Sensor 1.

Sensor contacts made of pure silver. Some sensor technical specification represented in the table below based on Delsys Trigno Wireless Biofeedback System User's Guide (2018):

Table 1. Sensor specification

Mass	14 g
Battery Life	Up to 8 h
EMG Maximum Sampling Rate	4370 samples/sec
EMG Bandwidths	20-450 Hz or 10-850 Hz
EMG Range	11 mV or 22 mV
Transmission Range	Up to 20 m
Temperature Range	5-45 degree Celsius

The base for the Trigno Wireless Biofeedback System is presented in figure 9. It communicates with the computer via a USB connection and analog output, the antenna provides communication with sensors via a Wi-Fi connection, and a magnet plate is necessary for sensor's initial contact with the base.

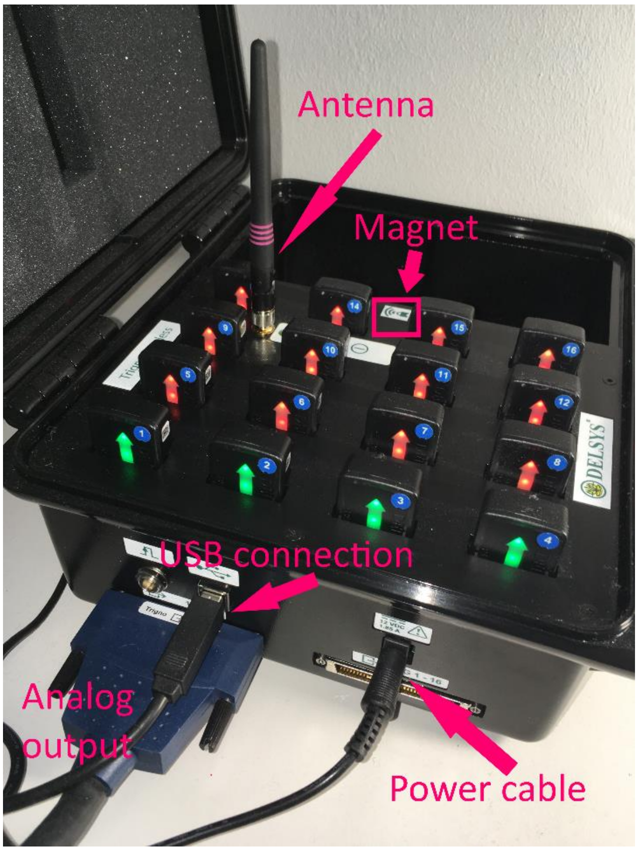
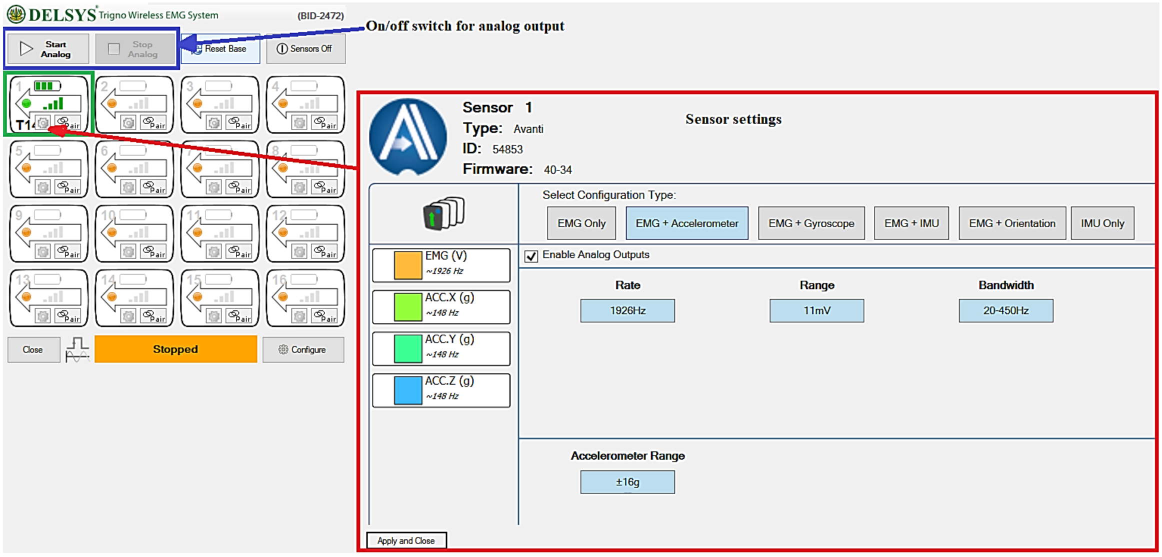


Figure 9. Base, sensors, and cables.

In this project, the official software to obtain and analyze data is not suitable because signals should be used in gripper control and the official application does not support the third party. To solve this issue the analog output is used which contains 68 pins to pass 64 signals (EMG signal, X, Y, and Z acceleration of each sensor, three GND and NC).

To switch into Analog output mode a Delsys Trigno Control Utility 3.5.6 (Status console) for Trigno Sensors (fig.10) is used. Sensors condition such as battery charge, pairing condition, and other information. can be observed and changed in the Status console. Access to sensor settings can be provided through the Status console as well. Sensor parameters affect data acquisition and signal analysis.



On/off switch for analog output

Sensor settings

Sensor 1
Type: Avanti
ID: 54853
Firmware: 40-34

Select Configuration Type: EMG + Accelerometer

☑ Enable Analog Outputs

Rate: 1926Hz
Range: 11mV
Bandwidth: 20-450Hz

Accelerometer Range: ±16g

Figure 10. Status console for Trigno Sensors.

In the next section, the used devices by National Instruments are presented.

3.3 National Instruments devices and LabVIEW

National Instruments (NI), Austin, Texas, USA is an American company with international operations in 41 countries. It was founded in 1970 as part of research on the acquisition and analysis of data for the U.S. Navy. Nowadays the company produces both software and hardware.

In order to acquire information from the Trigno sensors the National Instruments CompactDAQ 9174 (fig.11, a) chasse was used (NI cDAQ-9174 Specifications. 2013). This chasse has USB 2.0 Hi-Speed communication and does not require additional steps to connect to the computer. The device can hold up to four terminals for acquiring analog input. In this project two C series voltage input modules NI 9206 (fig.11, b) were used (NI 9206 Getting Started Guide. 2017.). Each of them has 32 channels that provide access for all signals from all 16 sensors. The prosses of system integration will be described in Chapter 4. Platform Development.

a) NI cDAQ-9174 b) NI-9206

Figure 11. National Instrument devices used in the project (NI cDAQ-9174 Specifications, 2013, NI 9206 Getting Started Guide, 2017).

LabVIEW is a platform graphical development environment, which is based on a visual programming language ‘G’ developed by NI in 1986. LabVIEW is widely used in industry for data acquisition, instrument control, et cetera.

Program in LabVIEW is called Virtual Instrument (format is .VI) and consist of two parts:

- *block diagram* describes the logic of the instrument;
- *the front panel* shows an interface of the instrument.

To create a connection between the server and the 3-finger gripper the TCP/IP connection and Modbus library were used from LabVIEW 2017 SP1.

4 PLATFORM DEVELOPMENT

In this chapter, the physical and programming development of the platform will be described. The platform development was divided into 5 steps:

1. Create a connection between Trigno sensors and LabVIEW,
2. Create a connection between the three-finger gripper and LabVIEW,
3. Study anatomy of the hand,
4. Analyze signals from hand muscles and interpret them into the gripper command,
5. Test the system.

Evaluation of the platform will be carried out in the next chapter. The following flow diagram reflects the simplified control platform process:

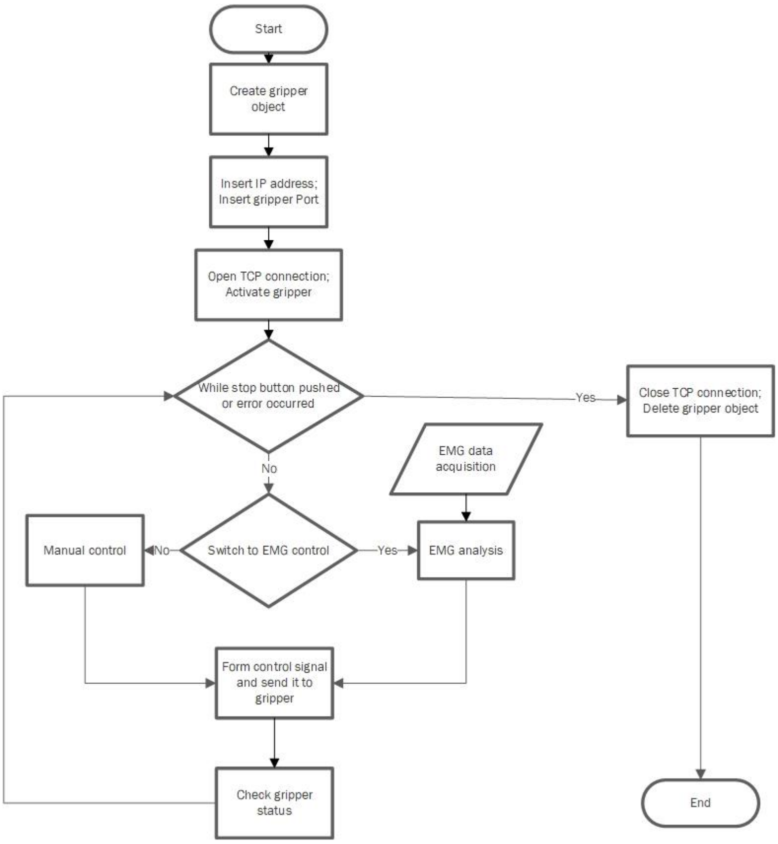


Figure 12. Flow diagram for gripper control by EMG signals.

4.1 LabVIEW and and Delsys Trigno System integration

Trigno Wireless Biofeedback System has two ways to communicate with the computer:

- the USB connection,
- the Analog output and the USB connection.

The USB connection allows obtaining information from sensors in official software. Even though it is a powerful tool, it cannot be used in this project. For this platform, it is necessary to obtain information in LabVIEW for further processing and interpretation. Thus, the decision of the analog output usage was made.

The DC-A22 supplied by Delsys provides a connection by breaking out the individual channels into single wires. There are 68 wires for this system: 64 – signals from sensors, 3 – ground, and 1 – no connected. Each conductor has unique two-color code to identify signal which assigned by a color scheme from the table in Appendix I There is an example for two schemes are shown in figure 13:

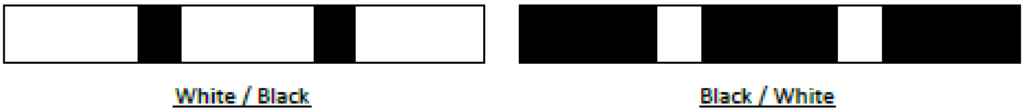
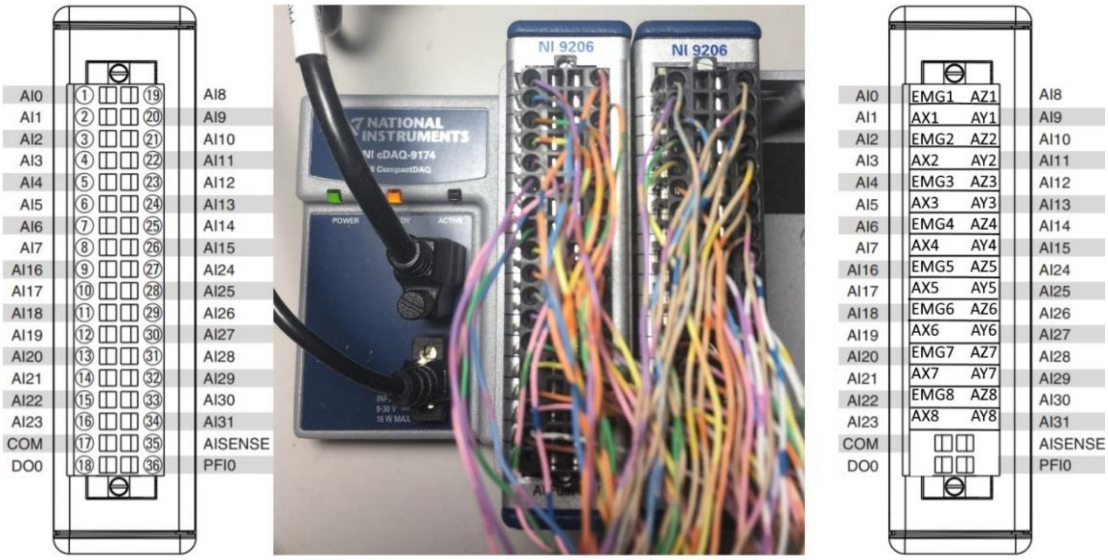


Figure 13. Scheme example for the DC-A22 cable (Delsys Trigno Wireless Biofeedback System User's Guide, 2018).

Delsys provide pinouts scheme of the analog output for a terminal that can hold 68 channels. However, NI does not have an appropriate model. The next best device is module NI-9206, which can hold up to 32 channels. To accommodate all signals from 16 sensors two modules NI-9206 are required. According to NI-9206 pinout (fig.14, a) and colors indicator for DC-A22, the wiring was complete (fig.14, b).



a) pinouts for NI-9206 b) result of wiring c) scheme of connections

Figure 14. Trigno System connection to use in LabVIEW.

There is a scheme of connection for the first 8 sensors placed on the MOD1 (fig.14c), a similar circuit for sensors from 9 to 16 is located on the MOD2. Pins COM are reserved for ground connections.

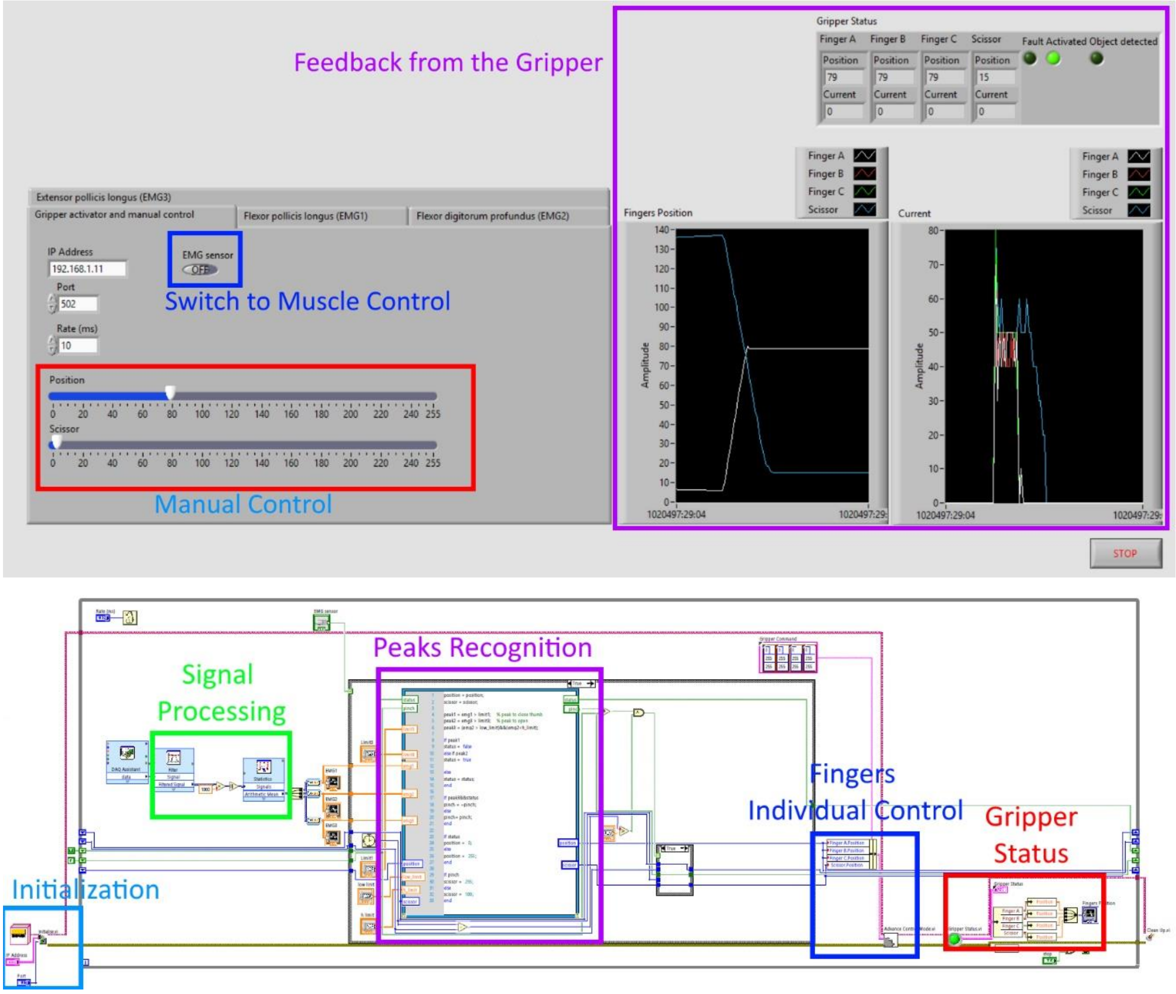
To read data from sensors in LabVIEW DAQ Assistant block is used. The physical channel (ai0-ai31) must be specified according to the scheme and the physical channels that are created in the block diagram cannot be changed manually from the platform interface.

After receiving, the signal can be analyzed and interpreted into a command to the gripper. This process will be described in section 4.4 Signal analysis and interpretation.

4.2 LabVIEW and 3-finger gripper integration

Robotiq does not have an official driver to control the gripper form the LabVIEW environment. To create communication between server and gripper the dissuasion pages at Robotiq and NI websites were studied. The usage of TCP/IP connection in LabVIEW was suggested and showed on examples for other devices from Robotiq. TCP connection considered a reliable protocol due to ordered and error-checked delivery feature. The Modbus library from NI was used to send command and read gripper status.

To be able to control gripper from LabVIEW user should run VI where the gripper IP address is entered. The interface and block diagram of the platform are presented in figure 17 below. It consists of several parts: gripper activation, manual control, switch between types of control, graphs for each sensor and calibrations for signals, grippe status, plots of the fingers position and current, and spot button.



IP Address 192.168.1.11
Port 502
Rate (ms) 10
EMG sensor OFF

Gripper Status

	Finger A	Finger B	Finger C	Scissor
Position	79	79	79	15
Current	0	0	0	0

Figure 17. Interface and block diagram of the platform to control the gripper from the LabVIEW.

The structure of the block diagram will be described in detail below: the feedback from the gripper and individual fingers control presented in this section, the signal process, and peak recognition are described in 4.4 Signal analysis and interpretation.

After this, the initialization of the gripper the TCP connection will be created. The VI reads gripper status and if there are no errors it would be ready to operate. Status (activation status, object detection, position, and current for each finger and scissor movement) is read by the program according to table 3 which is based on information provided in Robotiq Three-Finger Gripper Manual, 4. Control. The corresponding scheme in the LabVIEW envierment is presented in the figure 18.

Table 3. Bytes for the gripper status

	Finger A	Finger B	Finger C	Scissor
Position	Byte 4	Byte 7	Byte 10	Byte 13
Current	Byte 5	Byte 8	Byte 11	Byte 14

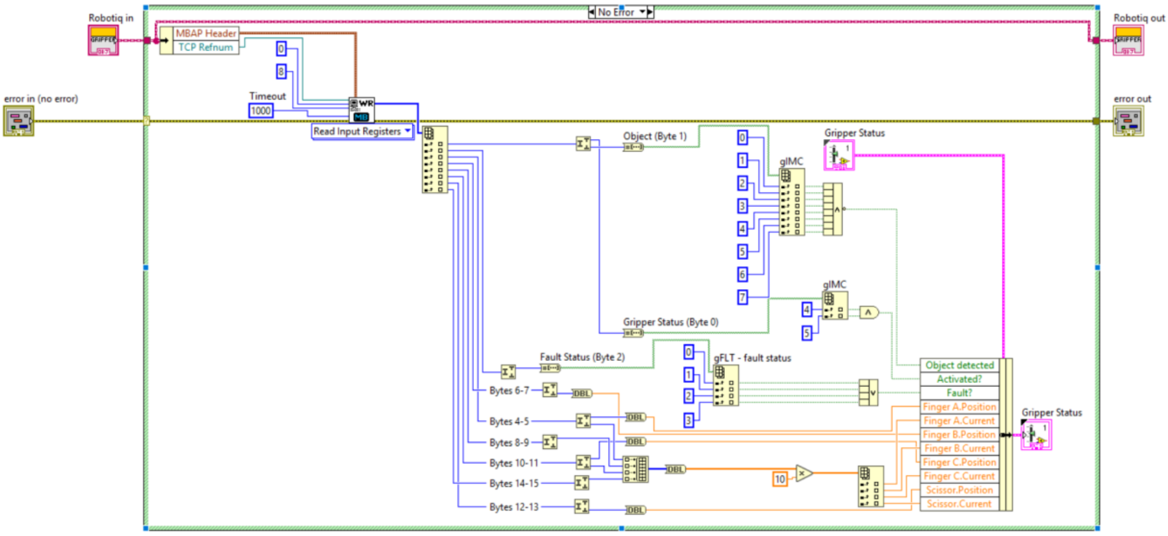


Figure 18. The gripper status extraction.

Although the official software has two types of gripper control (simple and advance), it can be seen that advance control can be transformed into simple control by sending the same position to each finger. The implementation of advance control will be beneficial in the future development of the platform. Thus, in this project, advance control was realized according to section 4. Control (Robotiq Three-Finger Gripper Manual) from which the following table was created. The Advance control created in LabVIEW is shown in the figure 19.

Table 4. Bytes for the gripper

	Finger A	Finger B	Finger C	Scissor
Position	Byte 3	Byte 6	Byte 9	Byte 12
Speed	Byte 4	Byte 7	Byte 10	Byte 13
Force	Byte 5	Byte 8	Byte 11	Byte 14

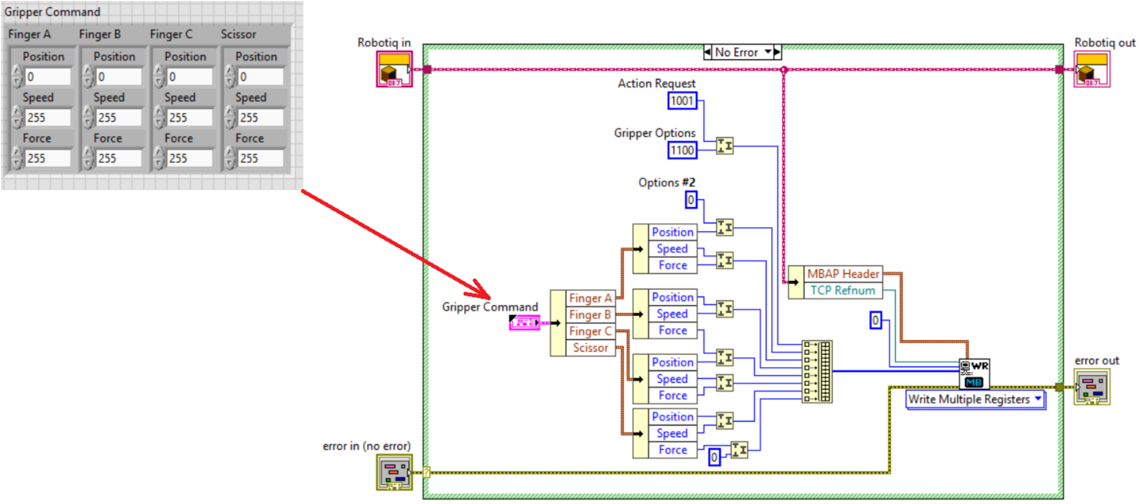


Figure 19. Advanced control of the gripper from the LabVIEW.

The program allows switching between manual control provided by horizontal bars for position and scissor, and muscle control which is collaborated from observing signals graphs from separated pages. After the program is finished the TCP connection will be closed.

The gripper control via LabVIEW was tested and the reaction was stable. The task to create communication between gripper and LabVIEW completed successfully. The next section describes human hand anatomy and the choice of a location on the arm for placing the sensors.

4.3 Muscle choice

This section describes the correspondence relationship between the human hand and the 3-finger gripper. The question of sensors placement on a forearm will be answered.

The human body is a unique system. Thus, even though there is a theoretical part of the choice of muscles, the calibration of the platform should be carried out individually. For example, as a controlling object in this project, the left hand was chosen because the researcher who has conducted this project is right-handed and required another hand to control the program. The main goal from muscles choice is to be able to obtain information from the hand and interpret it in two parameters for the gripper: fingers position and scissor position (fig.20).

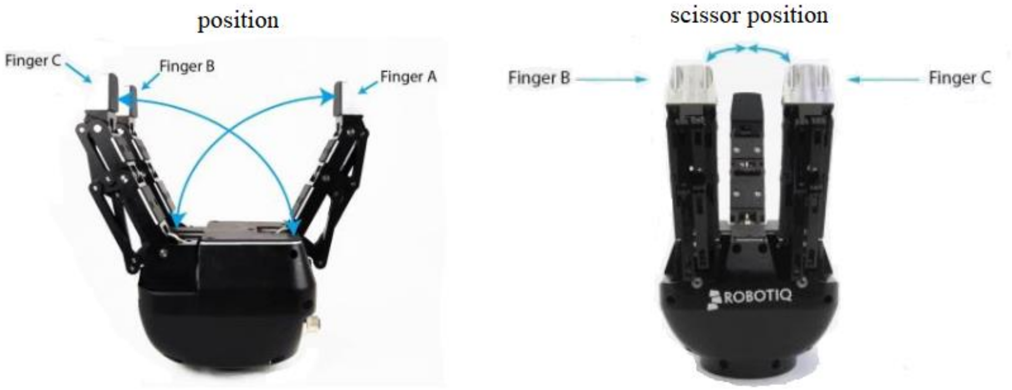


Figure 20. Parameters to obtain (Robotiq Three-Finger Gripper Manual).

Despite the ability of each gripper finger to change position, the position value will be the same for all three to simplify the task. In this project, the focus was on a hand and forearm muscles since every muscle in the human body responsible for certain movements and other parts of the body does not significantly affect hand movement performance.

The human hand is a very complex system. After studying a muscle structure of the wrist and forearm (Forearm, wrist, and hand. AMBOSS, Jones O. Muscles of the Hand, TeachMeAnatomy, Muscles. Handcare the upper extremity expert by American Society for Surgery of the Hand, ASSH.), it was concluded that the thumb is mostly controlled from the muscles located as showed in figure 21 and the index and the middle fingers are controlled by the muscles located on the forearm(fig. 22, fig.23)

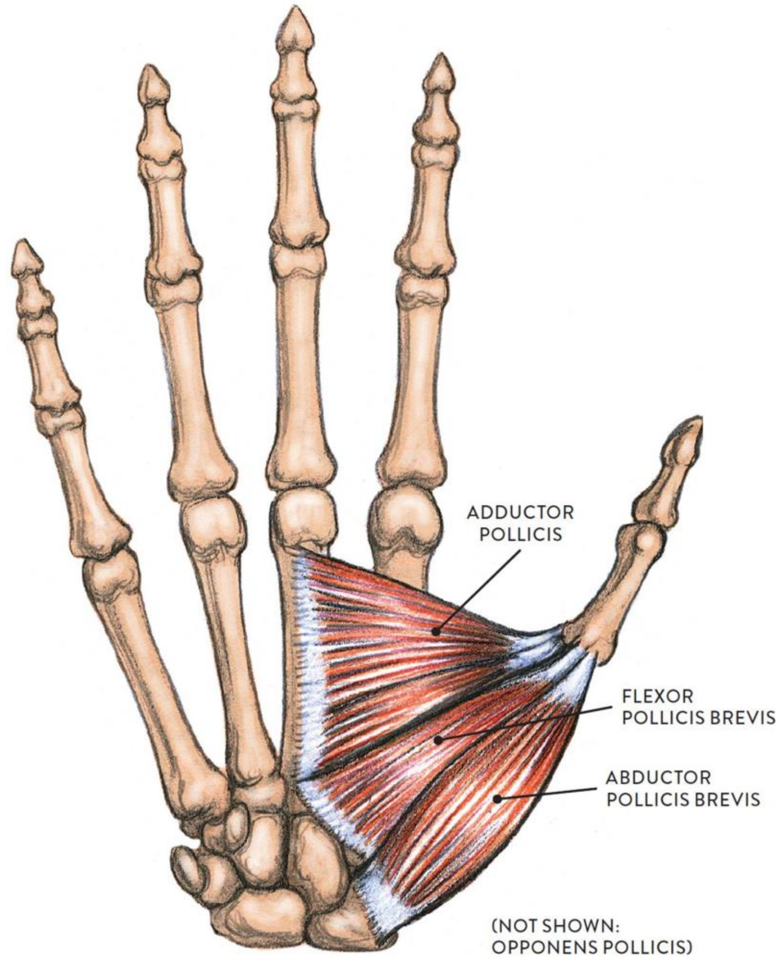


Figure 21. Thumb muscles (Winslow V.L., 2015).

After several attempts to use the muscles of the thumb, it became obvious that the size of the sensor does not allow to correctly obtain the information. While the finger moves, the sensor comes off and loses contact with the skin, which is crucial for proper data collection. Thus, it leaves only forearm muscles to obtain control.

There are two types of finger movements: flexion and extension. The left hand presented in figures 22, 23. Flexor muscles are located on the inner side of the forearm (anterior). and can be divided into 3 layers. In the figure 22 presented the superficial layer, the intermediate layer, and the deep layer respectfully. The muscles that overlapped with other muscles called deep muscles.

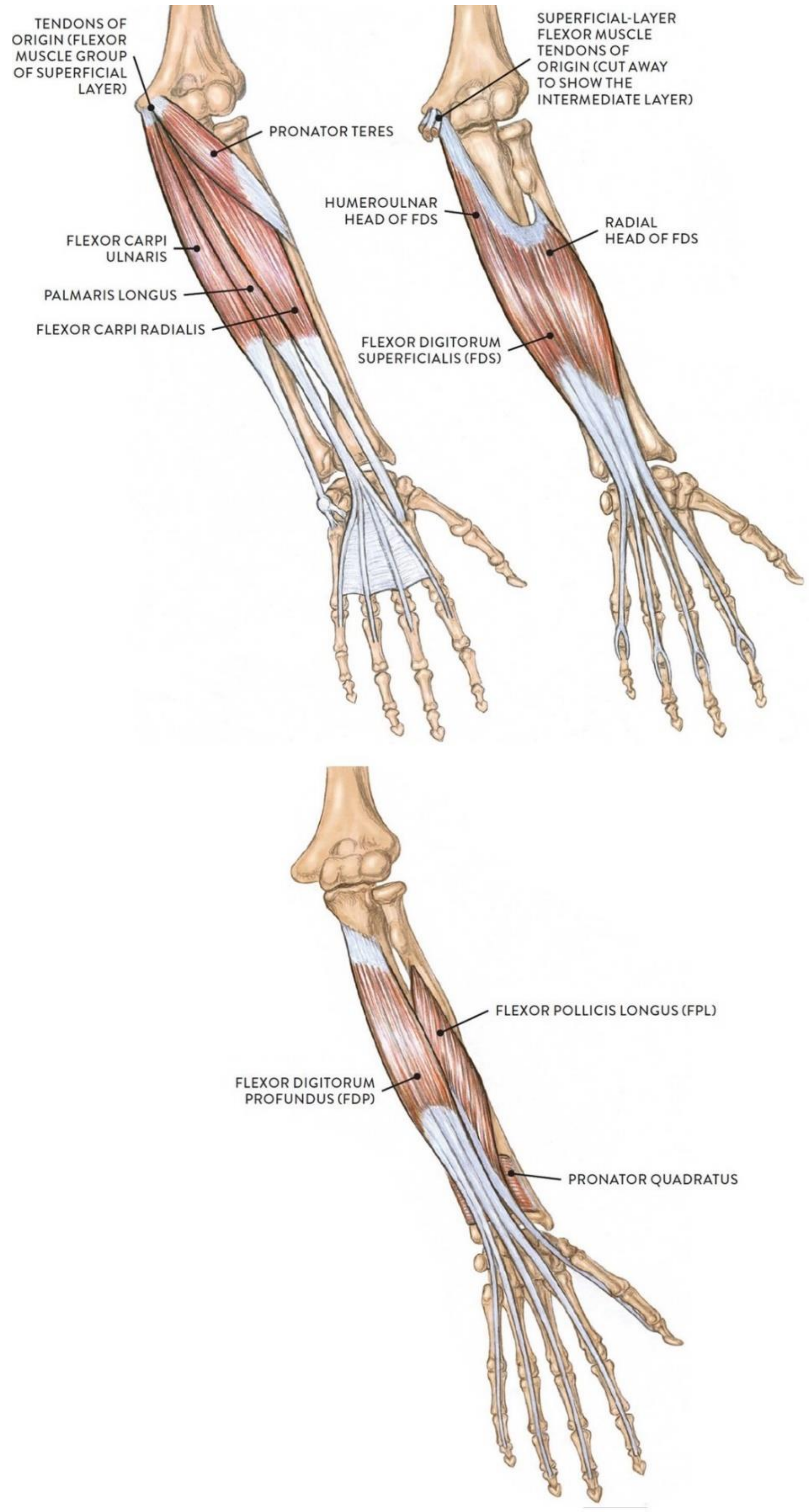


Figure 22. Anterior forearm (Winslow V.L., 2015).

Extensor muscles are located on the outer side (posterior) which can be divided into two layers. The layers are called the superficial and deep layers respectfully.

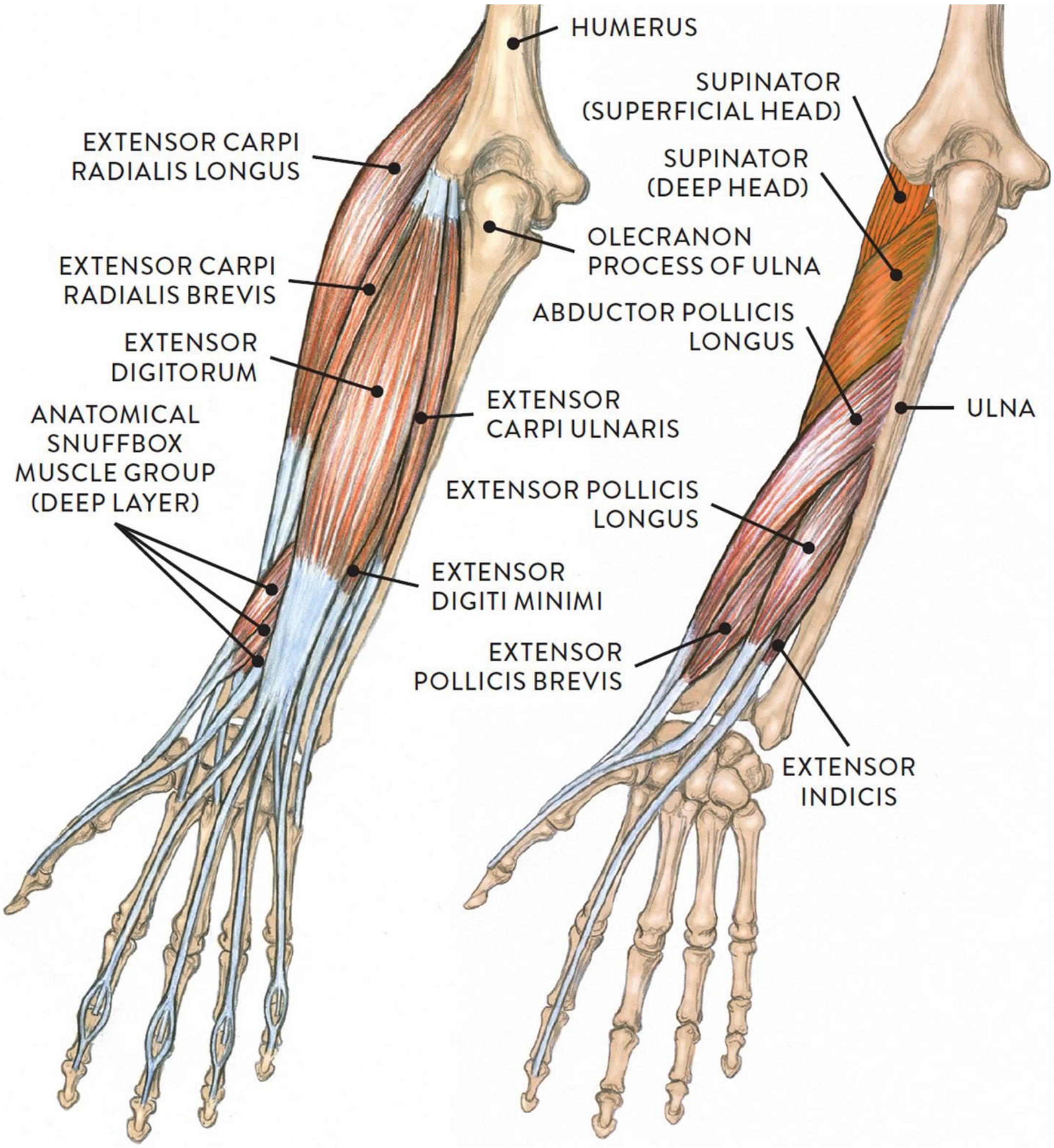


Figure 23. Posterior forearm (Winslow V.L., 2015).

The study of the forearm of the human hand was conducted from the functional purpose of the muscle. The table 5 reflects the muscles from both sides of the forearm that affect fingers control and their functions.

After establishing muscles responsible for the change of the fingers position the tests were carried out. The results of muscle evaluation during hand movements are shown in figure 28 with the final sensor position.

Table 5. Muscles on the forearm to control fingers

Muscle	Functions
Flexor Pollicis Longus	Bend the tip of the thumb (layer 3).
Flexor Digitorum Profundus	Bend index, middle, ring, and small fingers (layer 3).
Extensor Digitorum	Straighten index, middle, ring, and small finger (layer 1).
Extensor Pollicis Longus	Straighten the tip of the thumb (layer 2).
Extensor Pollicis Brevis	Straighten the thumb at the middle joint (layer 2).

The next step was to identify the muscles that responsible for the scissor movement which will be used for change pinch mode. From the theoretical study of human hand anatomy, it was established that they are located on the palm and can not be used in this project for the same reason as thumb muscles. Despite this, a series of experiments was carried out to find a location on the forearm where signals of a change of scissor position will be detectable. As a result, the following location of the sensor (fig.24) shows the best response to a change in fingers position for scissor movement during the signal observation.

Figure 24 Sensor position on the forearm.

As can be seen, this location corresponds to the Flexor Digitorum Profundus. On the graphs below (fig.25, fig.25) the signals are represented with and without a physical interpretation.

However, not only scissor movement causes peaks in the signal, but the open-closed hand movement also affects the signal.

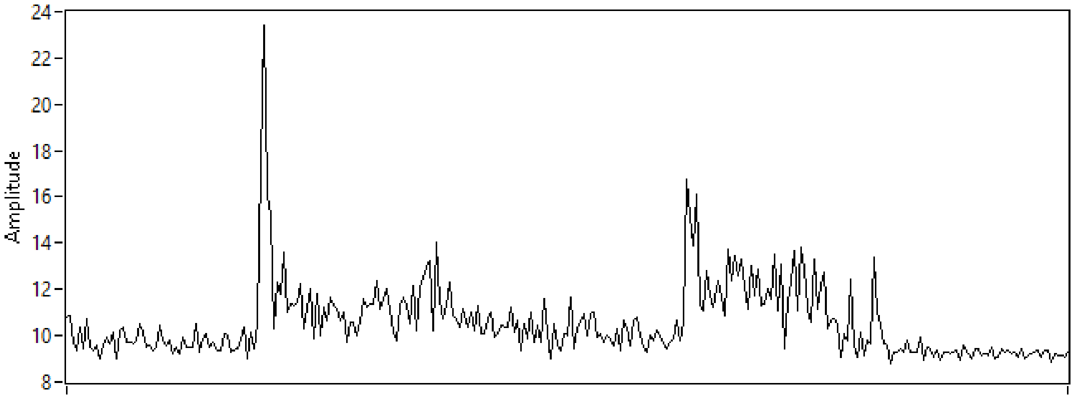


Figure 25. Processed signal from the sensor without interpretation.

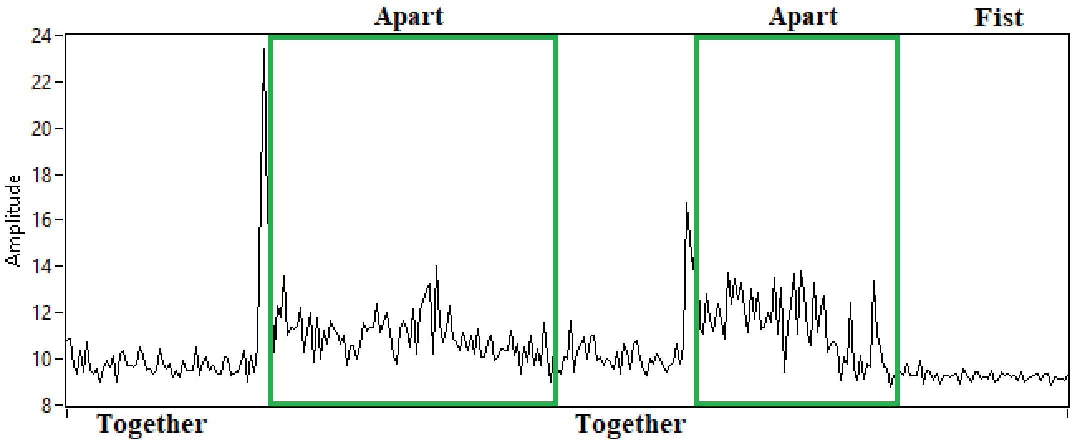


Figure 26. Signal with interpretation.

As can be seen, the physical interpretation can be extracted from the signal which gives a possibility to detect only two positions of fingers: are they apart or together, but the open-close movement as well. It will provide uncertainty in the change of the pinch mode.

The final sensor's positions were chosen mostly from signal observation and are presented in figure 27 with the purpose of the signal acquisition.

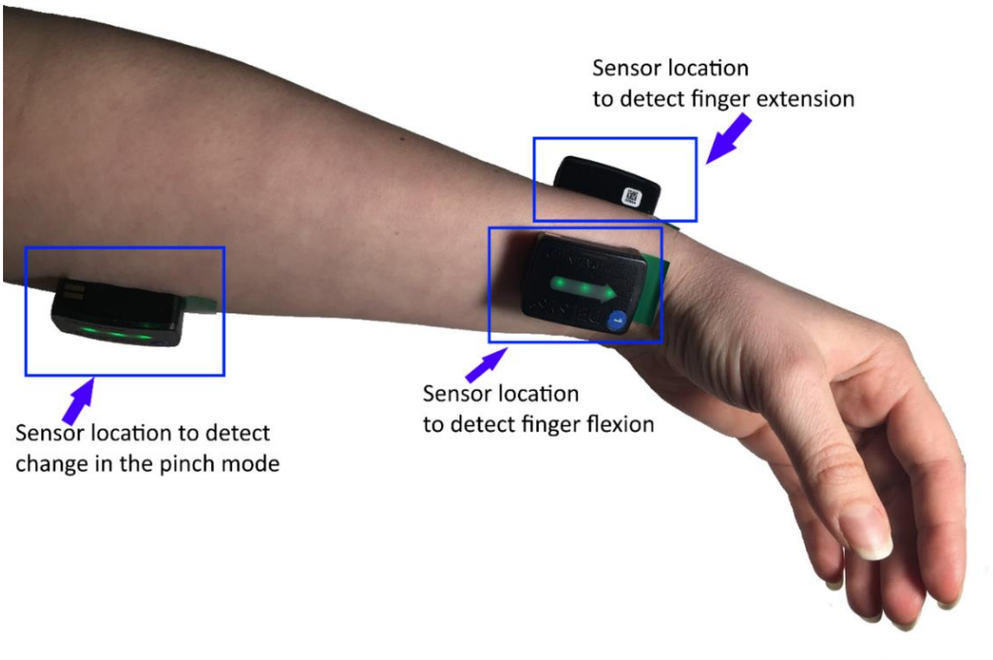


Figure 27. Sensors location on the left forearm.

In the figure below signals of movement open hand-fist from Flexor Pollicis Longus, Extensor Pollicis Longus, and Flexor Digitorum Profundus are shown (fig.28). The explanation for the obtained results will be made in the next section.

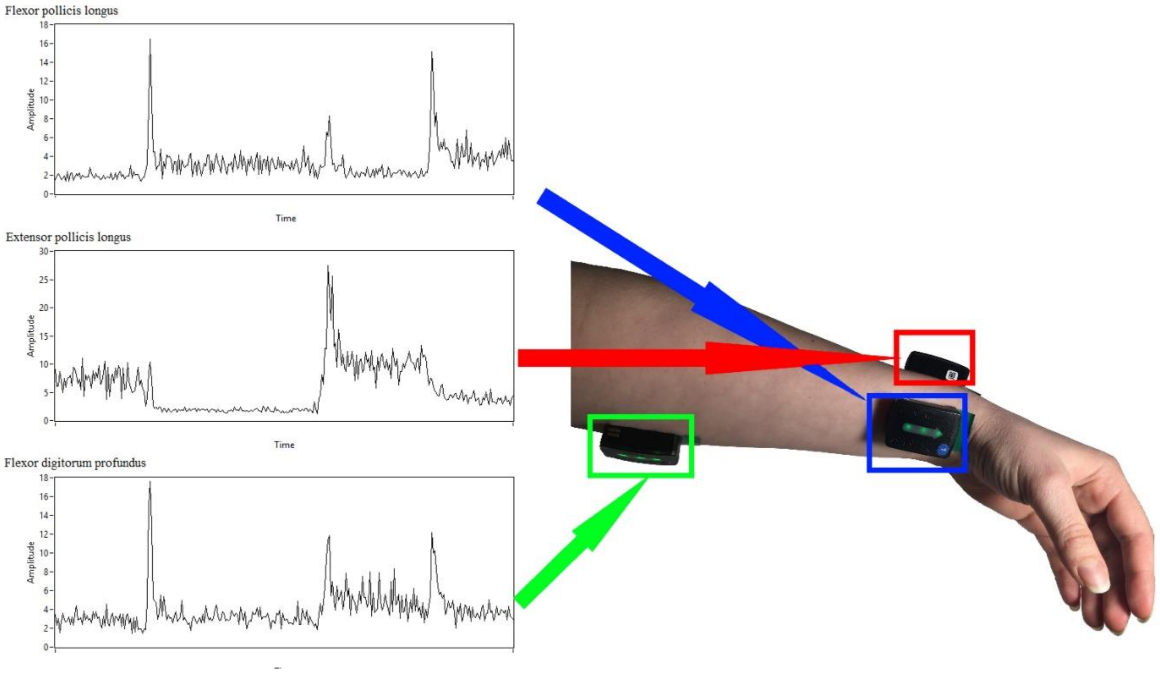


Figure 28. Signal without physical interpretation.

In the next section, the signal analysis and their physical interpretation are described.

4.4 Signals analyze and interpretation

The object of this section is the validation of EMG signals received from muscles described in section 4.3. Muscle choice.

There are 4 operation motions that gripper can perform which difference is in the angle between gripper fingers B and C. The physical restriction from the human hand affects gripper performance in a way that only basic and pinch modes are realized in this project. The possible hand postures that gripper can interpret are represented by figures 29, 30, 31.

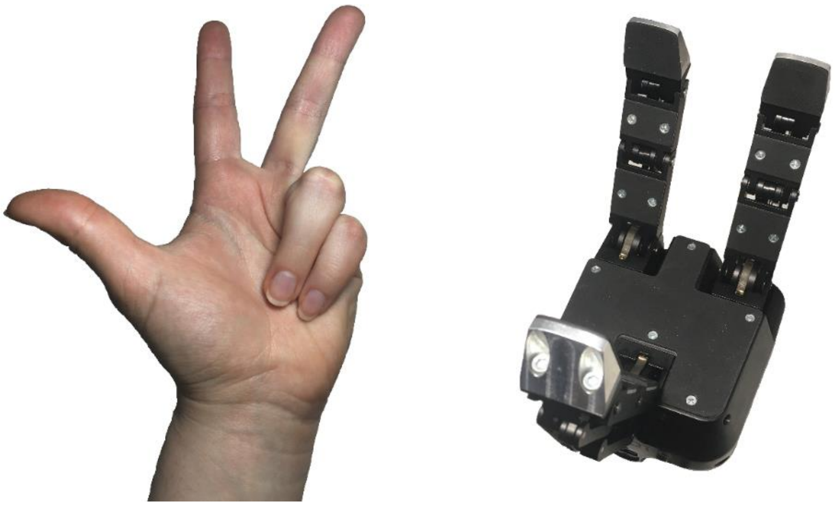


Figure 29. Open hand.

Figure 30. Fist.

Figure 31. Pinch.

From the posture it can be seen that human fingers are closed in both: fist and pinch modes, but for the gripper the positions are different that makes it one of the challenges of this project. Table 6 reflects the gripper command (position) and meaning to each finger and scissor.

Table 6. Meaning of the fingers position

Value/Mode	Fingers	Scissor
0	open	apart
100	initial position	initial position
255	closed	together

The most challenging task in this project was the analysis of the signals. The study of EMG signals was carried out (De Luca C.J, 2002, De Luca G, 2003). The EMG signal range is 10 mV prior to amplification. The signal fidelity affected by two main phenomimes: noise and distortion.

The noise can be caused by many factors: electronic equipment, electromagnetic radiation from the body, signals from a different tissue, condition of the subject. To remove unwanted noise or “crosstalk” (Chowdhury R.H., Reaz M.B.I., Ali M.A.B.M., Bakar A.A.A., Chellappan K., Chang T.G, 2013), filtering and signal amplification were used. There are several commonly used filter types for EMG signals analysis:

- The Butterworth Filter,
- The Chebyshev Filter,
- The Elliptic Filter,
- The Thompson or Bessel Filter.

All these filters are realized in LabVIEW and can be accessed from Filter express VI or Signal Process library. The comparison of these filters presented below:

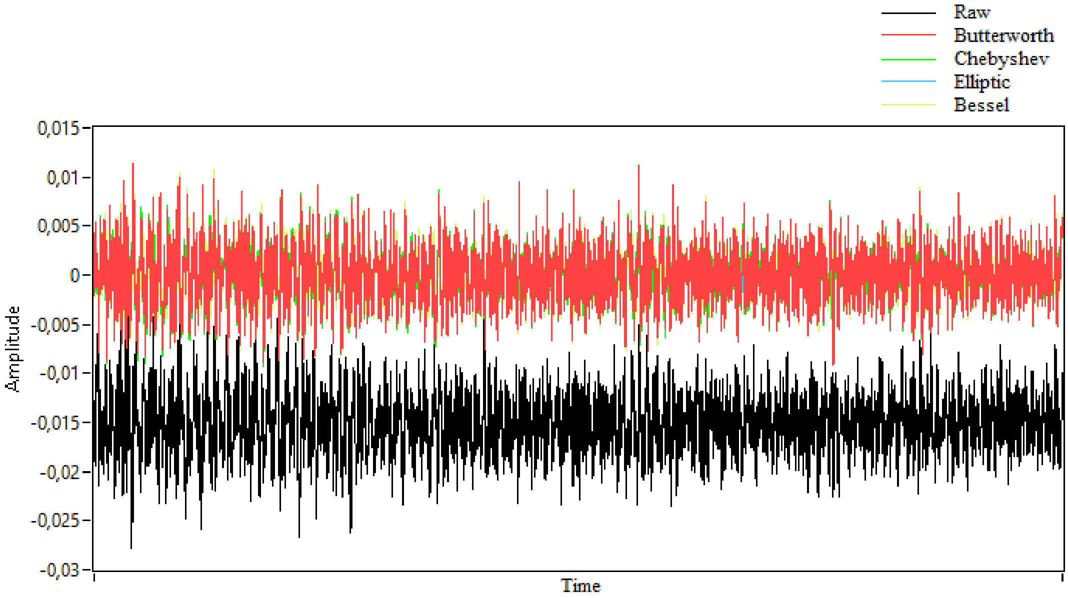


Figure 32. Compare different types of filters and raw signal.

In figure 32 it is hard to notice a difference in filter types; therefor in appendix II separate graphs for each filter are presented.

As recommended by Delsys the sampling is collecting at frequency 2000 Hz. After a frequency analysis of the amplified signal, the parameters for signal filtering were chosen: the first-order bandpass filtered with a cutoff frequency of 20 and 450 Hz and the Butterworth topology which maximally flats magnitude. These parameters are corresponding with sensor settings. Also, the test with the second-order filtering was carried out. However, this did not significantly affect the resulting signal.

Magnitude response for the digital Bandpass Butterworth Filter is:

$$M(\omega) = \frac{1}{\sqrt{1 + \left(\frac{\omega - \omega_0}{\omega_c}\right)^{2n}}},$$

where n is filter order, $\omega_0 = \frac{\omega_h - \omega_l}{2}$– a center frequency,$\omega_l$ is a low cutoff frequency, ω_h is a high cutoff frequency, and ω_c is a cutoff frequency.

In figure 33 the raw and filtered signal is presented while muscle contraction to show difference.

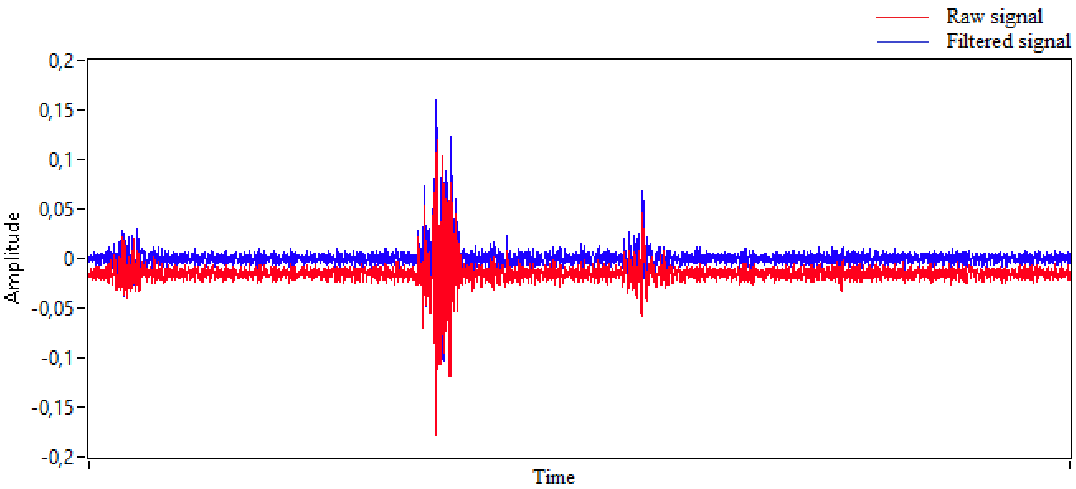


Figure 33. Comparison of a raw and a filtered signal.

The resulting signal is still difficult to interpret to the gripper command. Thus, future processing is required. To increase scale, the following applied:

$$x = Af(t),$$

where *f(t)* is the filtered signal, *A* is an amplification value.

Instead of a complex signal process, three methods were executed in this research that allow using threshold activation. This approach reduces the computation resources and time for system training. The methods to process signals are Mean Absolute Value (MAV), root mean square (RMS), and median.

$$MAV = \frac{1}{n}\sum_0^N |x|,$$

where MAV is the mean absolute value of pre-processed signal collected for *t* ms.

$$RMS = \sqrt{\frac{1}{n}\sum_{0}^{N} x^2},$$

where RMS is the root mean square of pre-processed signal collected for *t* ms.

And median from each sample group was extracted. A comparison of the results of all three process is shown in the graph below (fig.34).

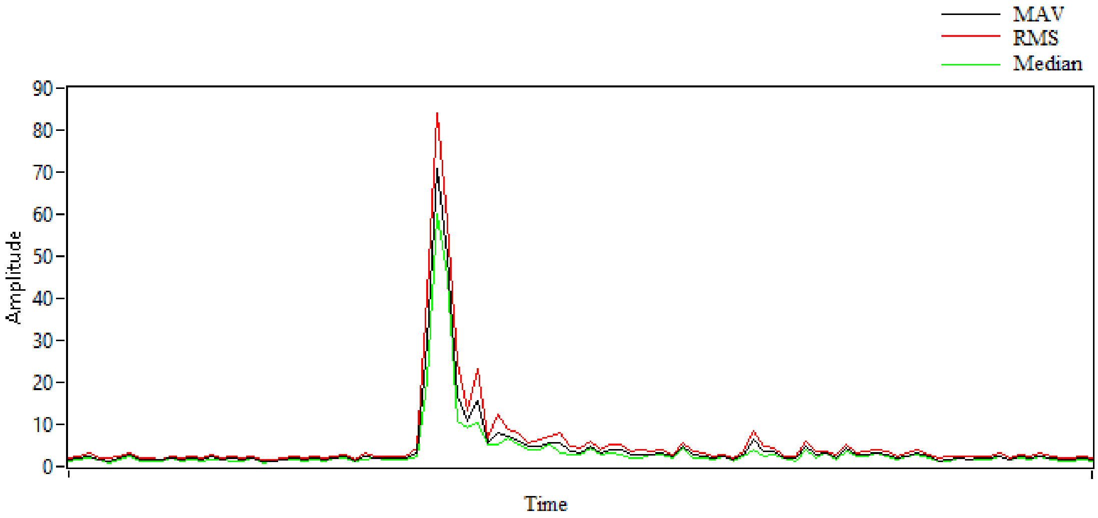


Figure 34. Comparison of the signal with different processing methods.

There is no significant difference in the graph. The MAV has better results than other processing methods according to Rahman M.M, Rosly M.H.M. (2016). This is the reason why MAV was also used as an EMG signal processing method in this research.

In figure 35 two signals from the same muscle at the same time are represented. To show both, processed and raw signals, in the same chart, the raw signal was amplified by the same value as the processed one.

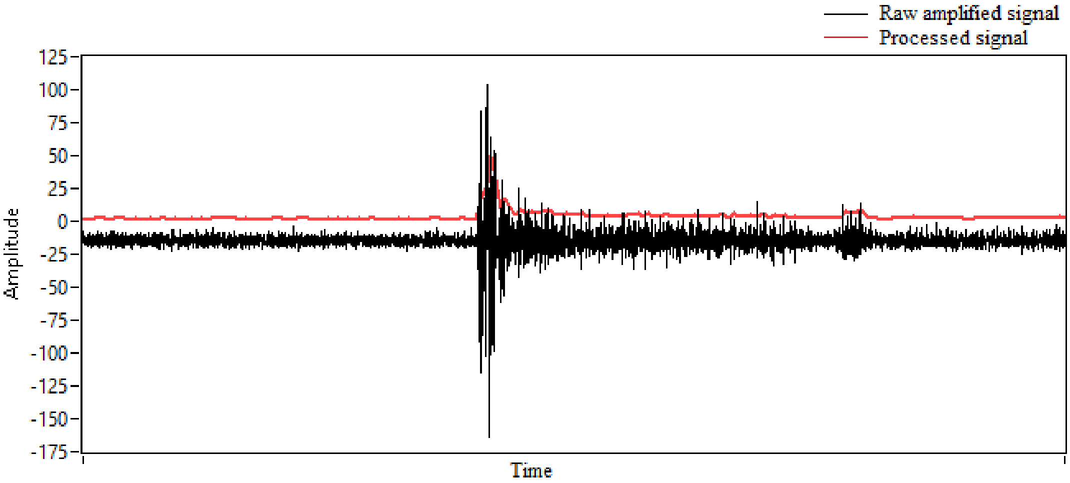


Figure 35. Comparison of raw and processed signals.

In the previous section, the signals from the Flexor Pollicis Longus, the Extensor Pollicis Longus, and the Flexor Digitorum Profundus were shown (fig.28). In the following figure, the example of obtained data and its interpretation are presented.

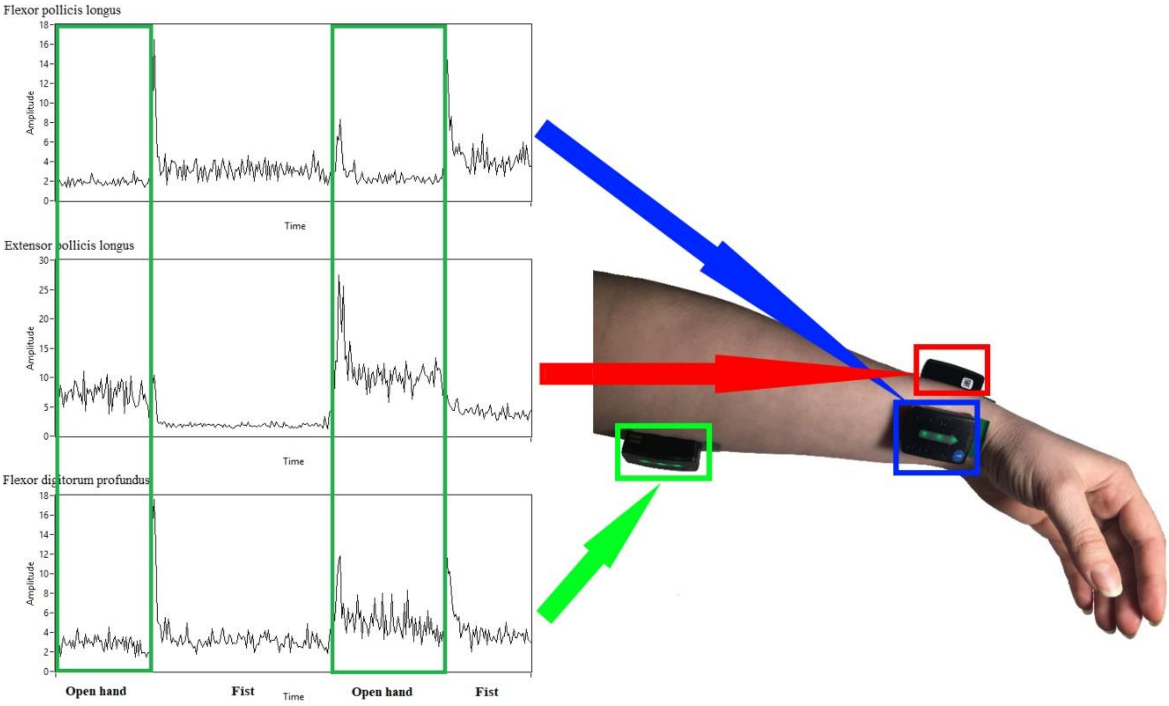


Figure 36. Signal with a physical interpretation.

As can be seen, the peaks occur during the change of hand posture. These peaks indicate muscle contractions. The signal from Flexor Pollicis Longus showed a significant response to fist posture. The Extensor Pollicis Longus well reflect the moment of change position from fist to open hand. In the previous section, it was established that the Flexor Digitorum Profundus react not only to movement open-close but also to scissor movement. There is no possible movement of the index and the middle fingers during the closed hand. Thus, there is a possibility to use this muscle to control the scissor position for the gripper during the open hand.

Firstly, the algorithm that reacts to the open-closed hand movement was created. When the contraction occurs in the Flexor Pollicis Longus, the gripper goes to the fist. When peak detected from the Extensor Pollicis Longus, the gripper changes position to the open mode.

After checking the efficiency of this algorithm, the detection of the scissor position was added. Change is detected from the Flexor Digitorum Profundus. The flow diagram in figure 37 reflects a simplified analysis of EMG signals.

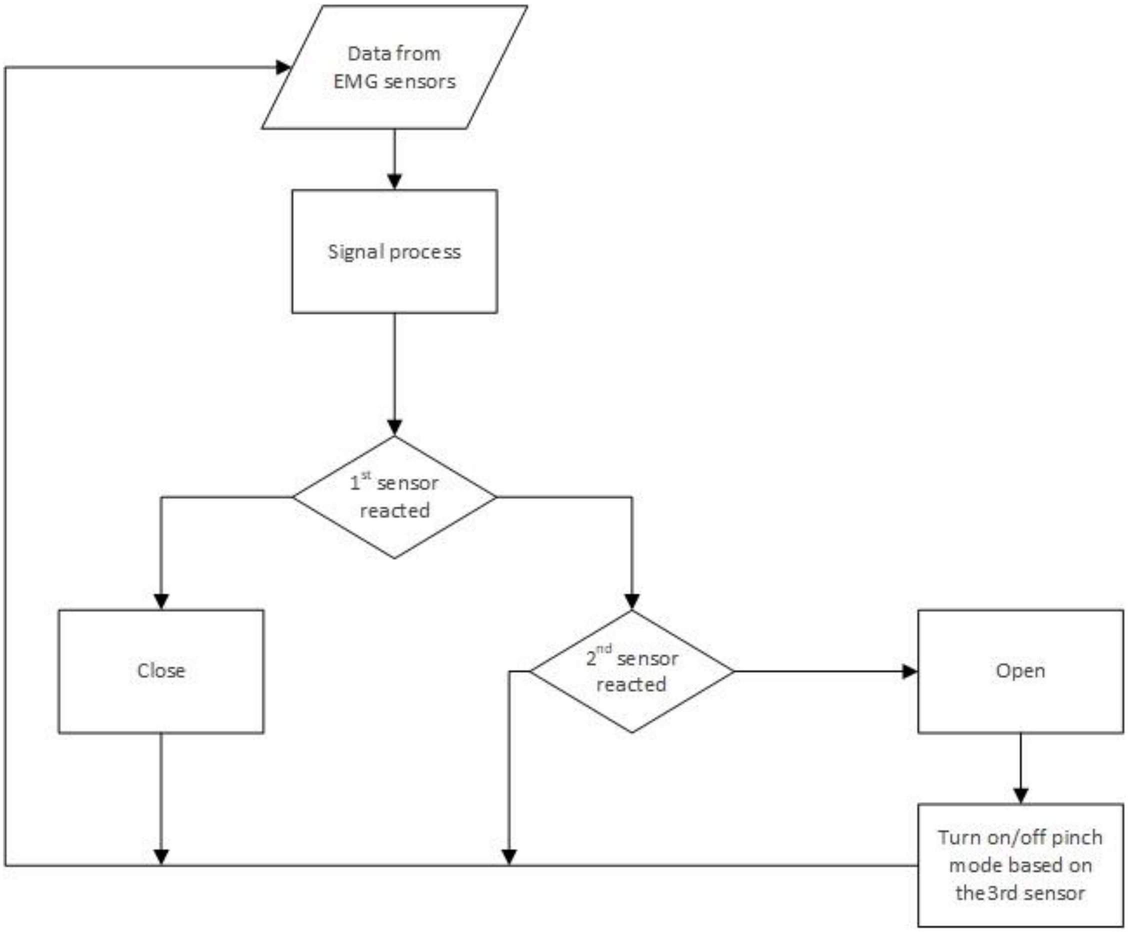


Figure 37. Flow diagram for EMG signals process.

If there are no significant peaks, the position remains the same. The importance of the peaks is regulated by threshold that set by calibration values which can be changed during the gripper performance by user.

In the first testing of the scissor mode, there was a problem with uncertainty in the interpretation from the Flexor Digitorum Profundus that react to the open-close movements as well. It was solved by adding values into the calibration process to determine the range of which the peak for pinch mode occurs. Also, there are several peaks in a short time can be detected which caused the false change of pinch mode. To solve this problem, a timer for a reaction was set (fig.39).

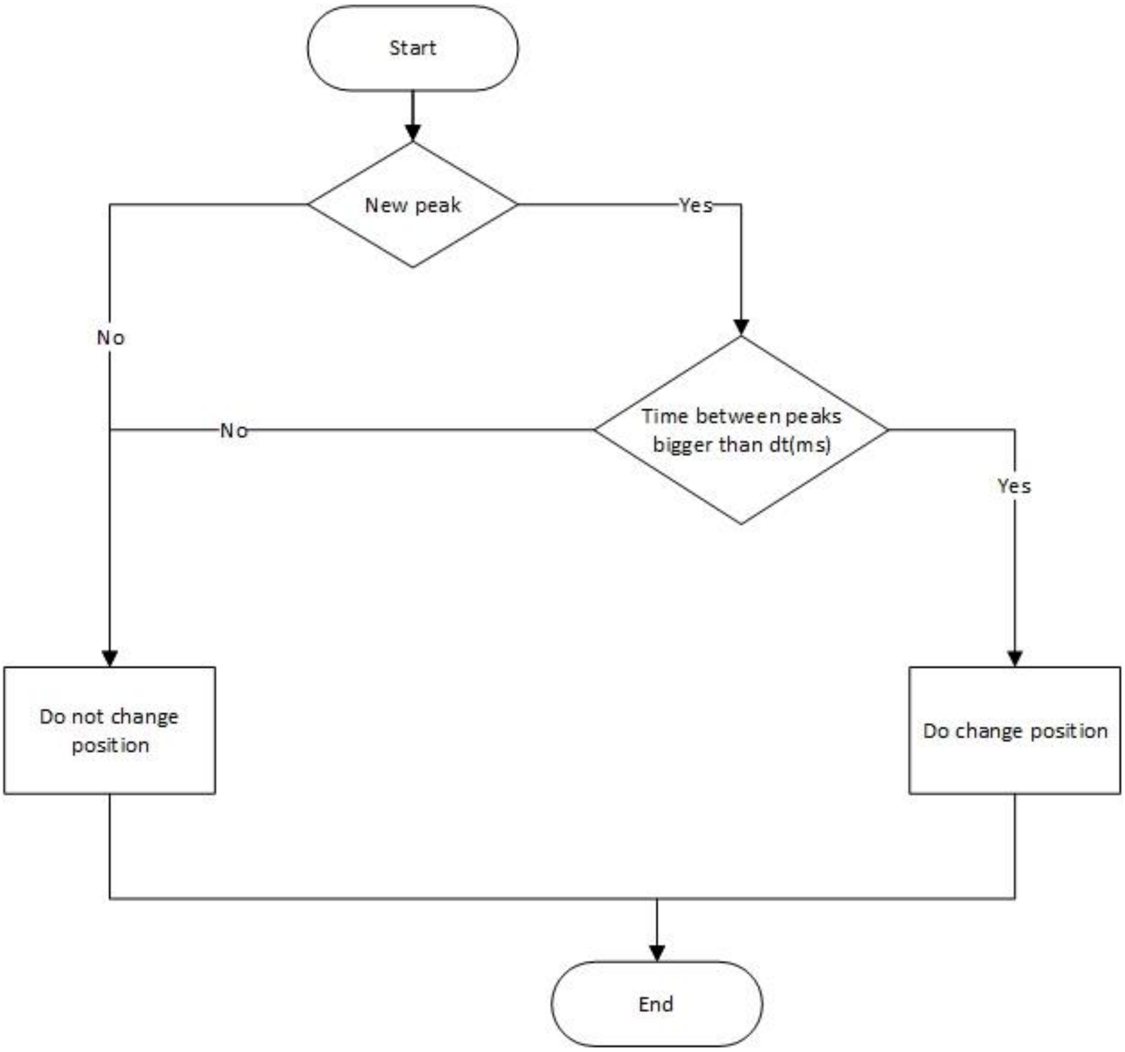


Figure 39. Flow diagram for EMG signals.

The full LabVIEW scheme for the gripper control from EMG signals is presented in Appendix III. In the next chapter, the evaluation of this system is shown.

5 EXPERIMENTS

This chapter is dedicated to platform testing and evaluating. The system presented in figure 40. As can be seen, the platform is mobile which is an advantage. The gripper range is limited by the length of the cables and the sensors range (up to 20 meters from the base).

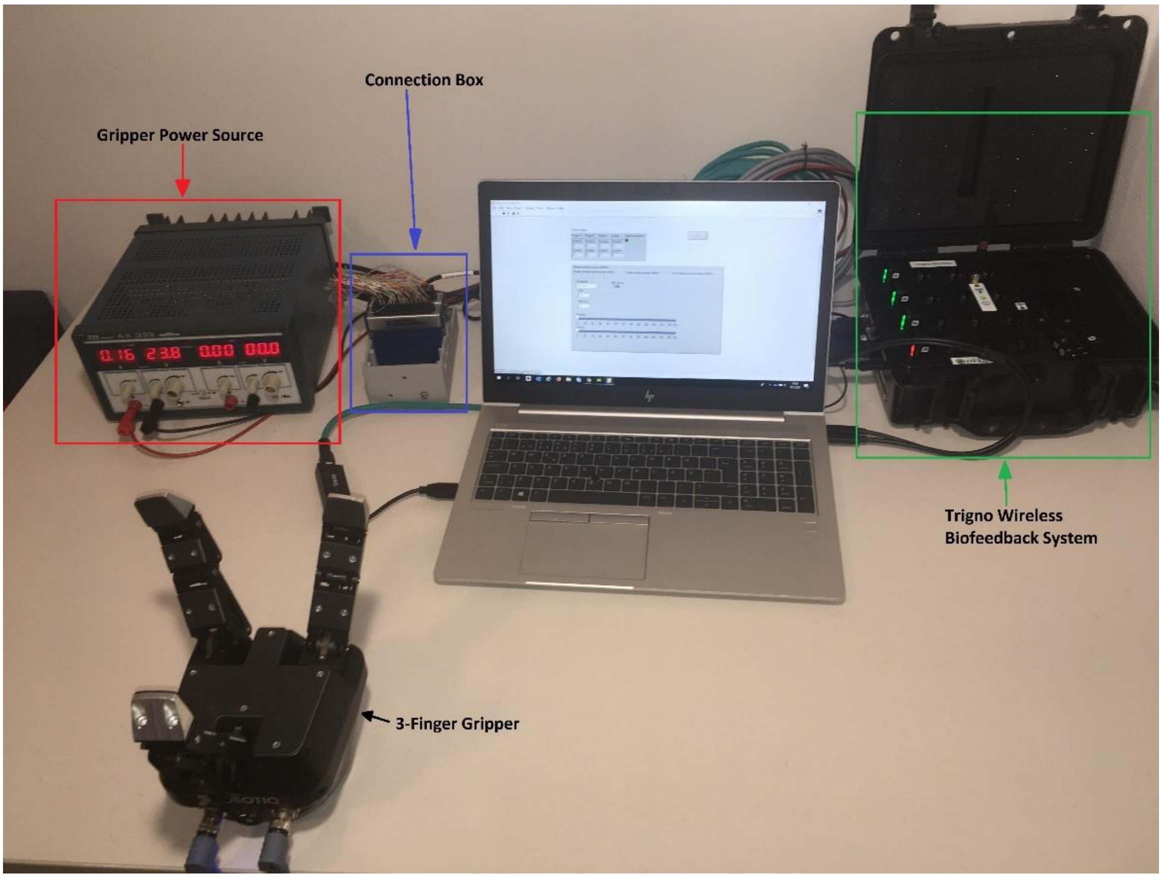


Figure 40. The developed platform.

To evaluate the efficiency of the developed platform tests were carried out. There are several cases held to check the gripper ability and accuracy of movement in different modes with and without objects to simulate real conditions.

Initially, the gripper was supposed to be held above the table while picking up objects from it. Unfortunately, laboratory access was not available at the time. This is the reason why the three-finger gripper was installed on the table and tested in this orientation. The necessary objects were handed to the gripper in the area of its fingers reach.

Experiments were carried out with three healthy 24 years old subjects (two females and one male) with different muscle development without an allergic reaction to silver. To conduct experiments the hands should be shaved and processed with an alcoholic pre-injection swab (70% of isopropyl alcohol) to clean skin.

Sensor contacts should be cleaned before use. They are placed in the center of the muscle, tight to the skin with special stickers by Delsys are used.

5.1 Case 1: Open hand-Fist without a change in scissor position

In the first case, the gripper performance was tested with an algorithm that does not react to the scissor position. The case was carried out to check the reaction for different forces from the human hand. Results are shown in Success/ Fail format.

Table 7. Results for case 1

Subject	Open with maximum force	Rate, %	Close with maximum force	Rate, %	Open with medium force	Rate, %	Close with medium force	Rate, %
1	20/0	100	20/0	100	10/0	100	10/1	91
2	20/0	100	20/0	100	20/5	80	20/0	100
3	20/1	95	20/0	100	20/1	95	20/2	91

The full gripper movement from open hand to close position or back takes about 3 seconds. This restricts a user’s performance and makes a person to adapt to the gripper ability. The test showed good results for sensing open-close movements with different force applied with the average rate of success is 96%.

5.2 Case 2: Open hand-Fist with a change in scissor position

To carry out the second case, the algorithm was updated. The detection of the 3rd peak to activate pinch mode and timer were implemented in the program. Only movements to open gripper and close were tested.

Table 8. Results for case 2

Subject	Open (Success/Fail)	Rate, %	Close (Success/Fail)	Rate, %
1	41/1	91	41/0	100
2	39/9	81	40/0	100
3	35/0	100	35/1	97

During open hand movement, the algorithm sends a command to the gripper to go to pinch mode sometimes. Despite this, the average success rate for the open-close movement is 95%.

5.3 Case 3: Scissor mode

In this case, only the reaction to change scissor position tested. The position should be registered from the open palm and putting the index and the middle fingers apart.

Table 9. Results for case 3

Subject	Scissor position change (Success/Fail)	Rate, %
1	35/25	58
2	50/47	51,5
3	-	-

As can be seen, the attempt to control scissor position by signals from the forearm showed poor results. The 3rd subject could not perform separate scissor movement. Because of this, results for 3rd subject did not count in the overall result. Accordingly obtained results the average success rate is 55% for this separate movement.

On the following graphs (fig.41, fig.42) the successful change of positions for fingers and scissor are shown during different hand movements. Due to peaks from the Flexor Digitorum Profundus during the open movement in first graph oscillation in scissor position can be observed.

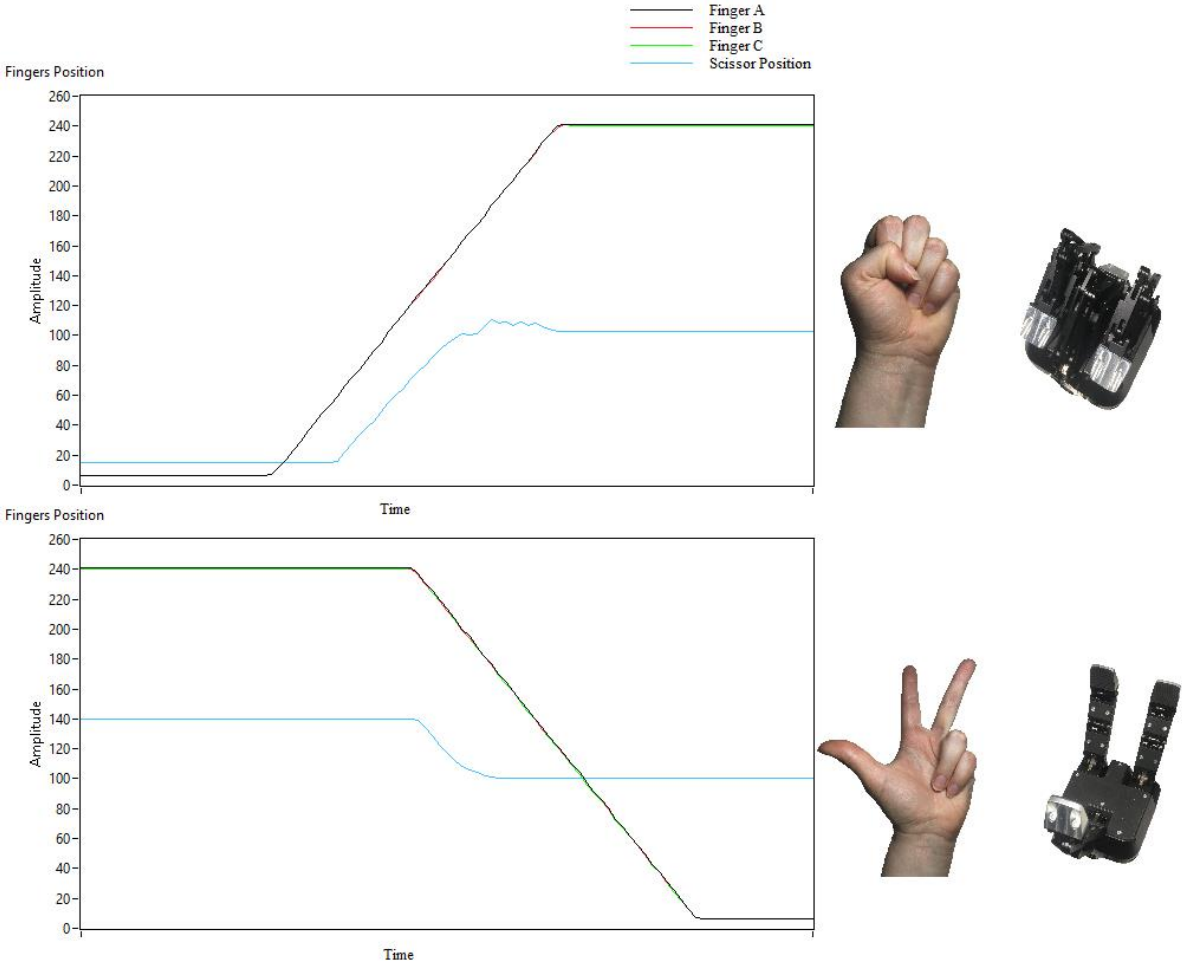


Figure 41. The gripper fingers and scissor positions during open-close movement.

In the next figure, the change of scissor position during without the grip movement is presented with an elucidation.

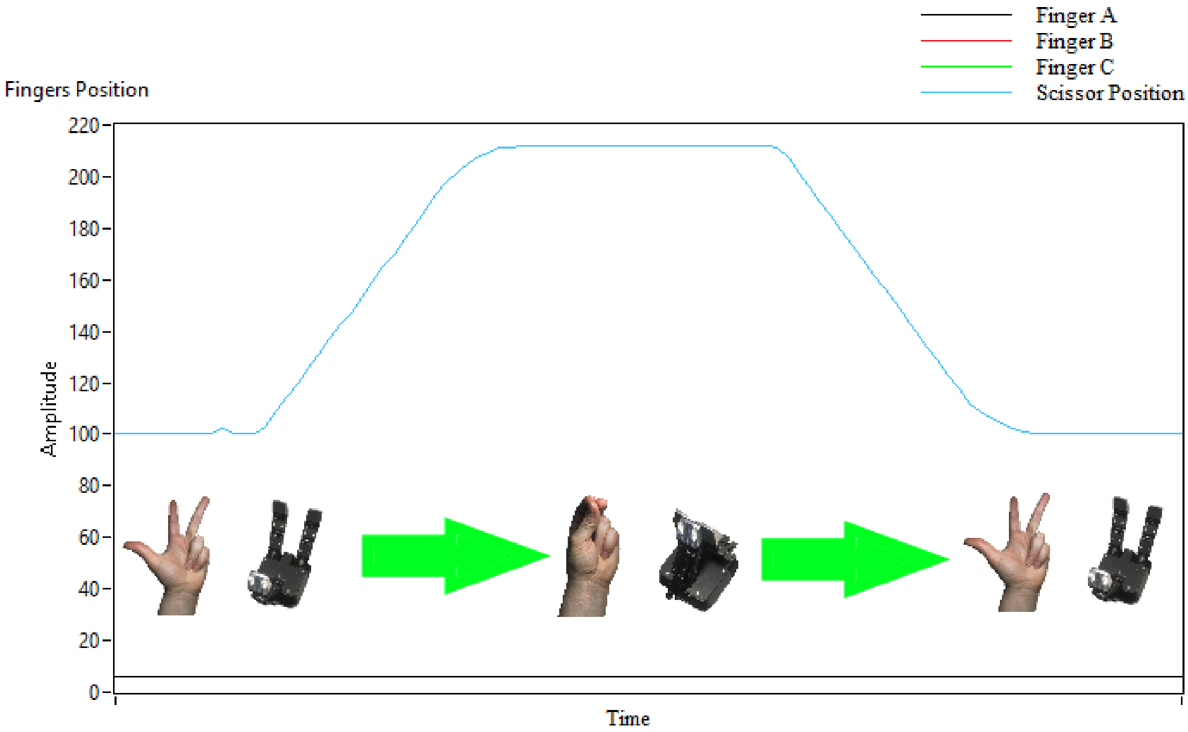


Figure 42. The gripper fingers and scissor positions during scissor position change.

5.4 Case 4: With objects

Since the gripper will not be used just for opening and closing without objects, the interaction with objects has to be tested. Initially, the gripper was supposed to be tested in a laboratory condition. However, it was not possible. Improvised objects were used to check gripper efficiency which can be found in daily life.

Improvised objects were used in this experiment:

- Plastic cylindrical container (height 16 cm, diameter 8 cm), as a big object
- Pencil, as a small object
- Small plastic container
- Pencil sharpener
- Glass object
- Book

The task was to grab different objects, hold them at least for 5 seconds, and realize. Examples of the gripper in use are shown below (fig. 43): the pinch mode with a small plastic container and basic mode with a book are presented.

Figure 43. The gripper holding different objects.

The gripper showed an ability to grip an object with different shapes in different modes with all subjects. Every participant could perform pick and realize tasks. However, it took a while to adjust to the gripper control. Also, the repetition of similar movements for a long time exhausted subjects and decrease the accuracy of the gripper performant.

The best-combined results were shown by subject 1. It can be explained by several reasons. Firstly, subject 1 was more familiar with the system. Secondly, the muscles to control gripper were selected on this subject's hand. And finally, the calibration values were more accurate due to experiences with the system.

Both female subjects had similar hand anatomy. Finding the location on the male hand was difficult due to the development of upper-level muscles (layer 1 and layer 2). Experiments were also conducted on the right hand and showed the ability to control gripper from both left and right hands.

6 CHALLENGES AND ALTERNATIVE APPROACHES

As in every project, some obstacles that were not overcome during the research. In this chapter, the main faced problems and raised issues are discussed, and possible solutions are presented as well.

6.1 Accuracy improvement

The main challenge in 3-finger control is the interpretation of the scissor position to activate pinch mode. Alternative methods to improve recognition and increase the gripper performance accuracy of the scissor position are listed:

- Create a neural network to analyze EMG signals,
- Create a fuzzy controller to analyze EMG signals,
- Use the support vector machine method, for example from open sources by Chang C.C. and Lin C.J. or other open sources (Github. OYSSTU, 2017) which provide code for SVM in LabVIEW
- Control gripper from both hands. For instance, control the close-open movement controlled from the right hand and the scissor movement from the left hand. This approach is easy but was not used in this project because the task was to copy human movement.

These approaches require computational resources.

6.2 Additional noise

In this research, the change in muscle activity due to different changes in arm position was not counted. The control was provided from the fixed state of the arm, during arm movement an undesired EMG signals appears. In figure 44 the change in signal from the Flexor Pollicis Longus is shown during hand and fingers movements. As was described previously, this muscle mainly responsible for thumb flexion. The position of the thumb and the wrist did not change while raising the hand, flexion and extension of the elbow, and flexion and extension of fingers except the thumb.

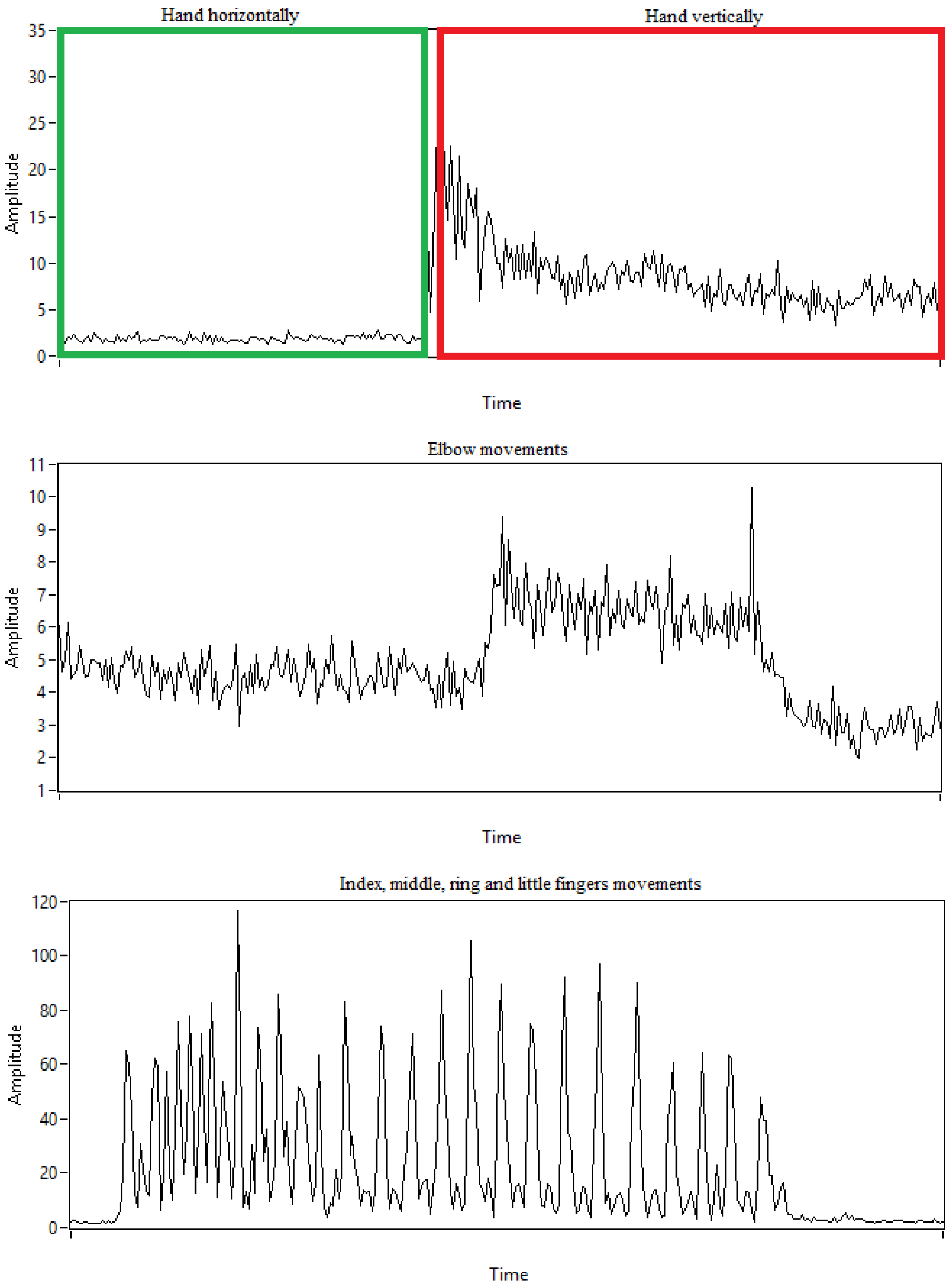


Figure 44. An arm activity effect on the signal.

It is obvious how substantially arm state and movements of fingers affect the electrical potential in the muscles that do not responsible for these movements. In this project, the position for open-close mode was read from the thumb and all the gripper fingers set this position. But for more flexible individual control the issue should be solved. Additional sensors can provide information to isolate certain movements for reducing uncertainty in the interpretation of EMG signals. At this point, only three sensors were used to detect three states of the gripper.

6.3 Other faced obstacles

Although people have similar systems, the unique muscular structure of the hand can have a significant effect on the system. It was shown during the experiments. This problem has only one solution: careful individual set up before system use focusing on the signal graphs.

Wearing sensors for a long time causes a rash and dry skin. It can be associated with reaction to silver in the sensor's contacts or glue that is used to connect sensors to the skin.

7 DISCUSSION

Even though a robot’s surrounding people in everyday life is increasing, their independent thinking and decision making are far from human abilities. Thus, a human brain and reaction behind the robot's algorithm are extremely important. This project was aimed to keep direct human influence on robot behavior.

In this research, the control of the 3-finger gripper by processing EMG signals from the human forearm muscles was developed. The network between the gripper and the Trigno Wireless Biofeedback System was created in LabVIEW that allows collecting, processing, and interpreting EMG signals and send commands to the gripper in one environment and do not use third-party software. The gripper able to perform three main actions: open, close hand, and change angle between fingers B and C. Gripper reactions triggered when processed signals reach a threshold set by the user during system calibration.

The main advantage of the developed platform is a feature that leaves the decision making to the person who controls the system. Such behavior has been selected in order to substitute a human in life-threatening situations where a robot response can not be pre-calculated, and the environment can not be measured.

As a future development, due to developed advance control in the LabVIEW driver for the 3-finger gripper by Robotiq, the current control can be replaced with individual finger control which will lead to an increase in the number of used sensors. Besides, the force control can be implemented in account the slowdown in the gripper performance. At the moment it works at full speed and takes about 3 seconds to finish the action.

The next step in the project is adding a robotic arm to the gripper that also controlled from the human arm. That will allow copy full arm movement, not only hand movement. The basic concept presented in figure 45.

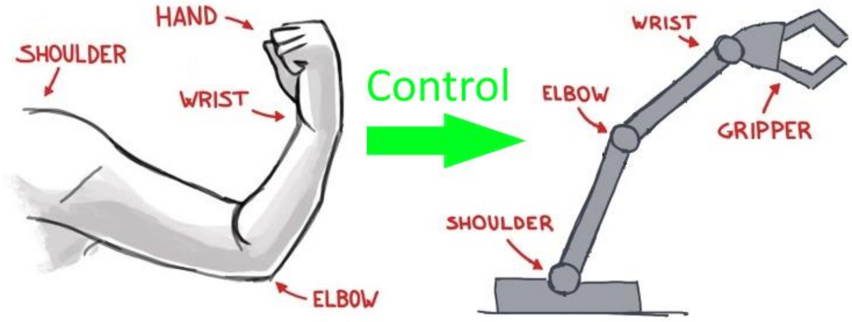


Figure 45. The concept for future development.

The system can be combined with different bases, cameras, and VR. Also, based on a similar principle the other human body parts can be replicated in robotic devices. This system aimed to replace humans in potentially life-threatening situations in different areas of human life.

Similar projects with different controlled devices and tools for EMG reading were developed in the last 20 years. Most of them are carried out in healthcare: to replace the hand on the human body or restore hand movement. This project was developed in order to create an intuitive control for the robot that can replace a human in potentially hazardous situations.

8 SUMMERY

In this research, the platform to control the 3-finger gripper using EMG signals from the left human forearm muscles, as well as from the right forearm muscles due to symmetrical body anatomy, was developed. As the base programming software of this system is LabVIEW the driver to control the gripper was created. Also, the Trigno System was connected to the LabVIEW environment. These steps made collaboration between devices from different corporations possible. The EMG signals analyze was conducted to recognize hand movements to interpret them into the gripper commands. The results of the developed system performance are presented. The system showed satisfying results for griping movement and poor results for pinch mode change with the average rate of success of 95% and 55% respectfully. To improve the accuracy of the system the alternative approaches are described and can be applied. All tasks were completed.

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Trigno Output	**Trigno Pin**	**Conductor Color Primary/Secondary**	**Trigno Output**	**Trigno Pin**	**Conductor Color Primary/Secondary**
EMG 1	68	Violet / Orange	AY 9	16	Tan / Violet
AX 1	67	Blue / Orange	AZ 9	17	Tan / Gray
AY 1	33	Orange / Blue	EMG 10	49	Blue / Tan
AZ 1	34	Orange / Violet	AX 10	48	Green / Tan
EMG 2	66	Green / Orange	AY 10	14	Tan / Green
AX 2	65	Yellow / Orange	AZ 10	15	Tan / Blue
AY 2	31	Orange / Yellow	EMG 11	47	Yellow / Tan
AZ 2	32	Orange / Green	AX 11	46	Orange / Tan
EMG 3	64	Gray / Pink	AY 11	12	Tan / Orange
AX 3	63	Violet / Pink	AZ 11	13	Tan / Yellow
AY 3	29	Pink / Violet	EMG 12	45	Pink / Tan
AZ 3	30	Pink / Gray	AX 12	44	Brown / Tan
EMG 4	62	Blue / Pink	AY 12	10	Tan / Brown
AX 4	61	Green / Pink	AZ 12	11	Tan / Pink
AY 4	27	Pink / Green	EMG 13	42	Violet / White
AZ 4	28	Pink / Blue	AX 13	41	Blue / White
EMG 5	60	Yellow / Pink	AY 13	7	White / Blue
AX 5	59	Orange / Pink	AZ 13	8	White / Violet
AY 5	25	Pink / Orange	EMG 14	40	Green / White
AZ 5	26	Pink / Yellow	AX 14	39	Yellow / White
EMG 6	58	Gray / Brown	AY 14	5	White / Yellow
AX 6	57	Violet / Brown	AZ 14	6	White / Green
AY 6	23	Brown / Violet	EMG 15	38	Orange / White
AZ 6	24	Brown / Gray	AX 15	37	Pink / White
EMG 7	55	Green / Brown	AY 15	3	White / Pink
AX 7	54	Yellow / Brown	AZ 15	4	White / Orange
AY 7	20	Brown / Yellow	EMG 16	36	Brown / White

Trigno Output	**Trigno Pin**	**Conductor Color Primary/Secondary**	**Trigno Output**	**Trigno Pin**	**Conductor Color Primary/Secondary**
AZ 7	21	Brown / Green	AX 16	35	Tan / White
EMG 8	53	Orange / Brown	AY 16	1	White / Tan
AX 8	52	Pink / Brown	AZ 16	2	White / Brown
AY 8	18	Brown / Pink	GND	9	White / Gray
AZ 8	19	Brown / Orange	GND	22	Brown / Blue
EMG 9	51	Gray / Tan	GND	43	Gray / White
AX 9	50	Violet / Tan	NC	56	Blue / Brown

APPENDIX II

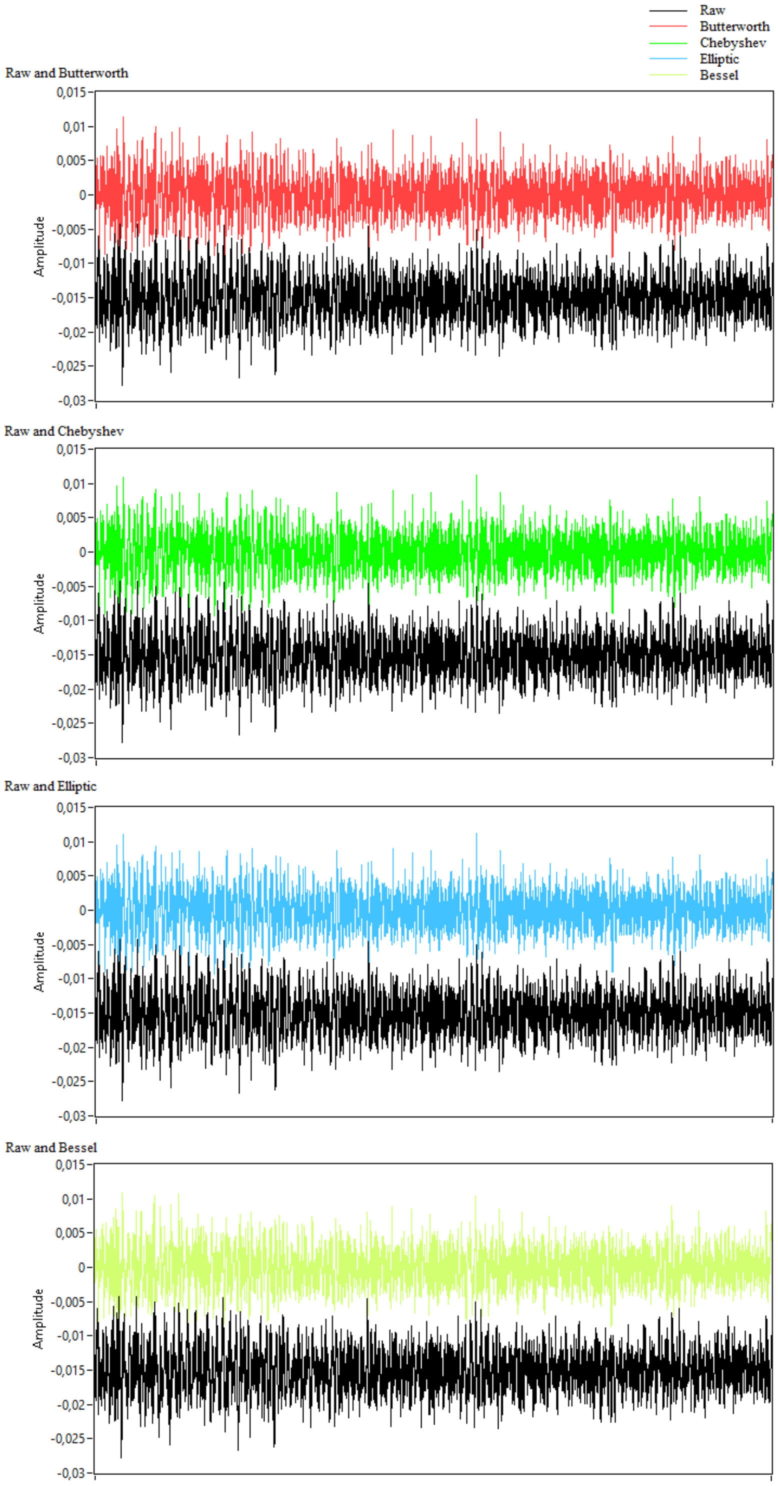
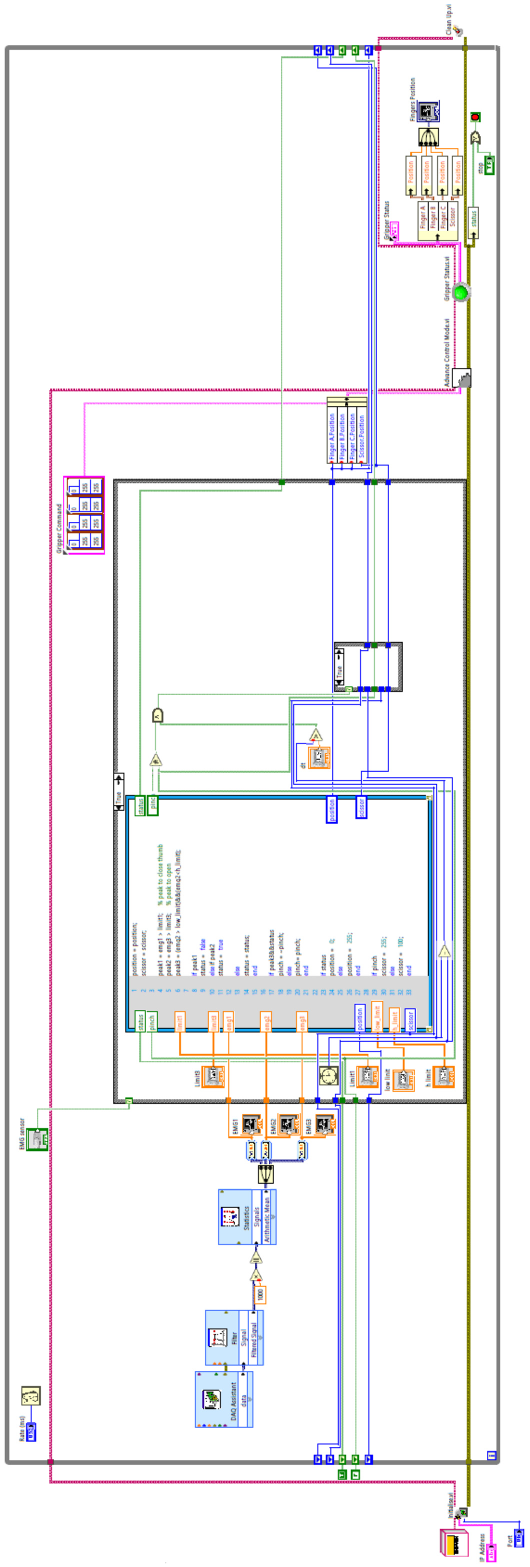


Figure 46. Results for separated filter types.



```
position = position;
scissor = scissor;

peak1 = emg1 > limit1;    % peak to close thumb
peak2 = emg3 > limit3;    % peak to open
peak3 = (emg2 > low_limit)&&(emg2<h_limit);

if peak1
status = false
elseif peak2
status = true

else
status = status;
end

if peak3&&status
pinch = ~pinch;
else
pinch= pinch;
end

if status
position = 0;
else
position = 255;
end

if pinch
scissor = 255;
else
scissor = 100;
end
```

Figure 47. Full LabVIEW program.