TEL AVIV UNIVERSITY

The Iby and Aladar Fleischman Faculty of Engineering
The Zandman-Slaner School of Graduate Studies

Wearable, Muscle Activity Sensing and Arm Positioning System

A project submitted toward the degree of
Master of Science in Mechanical Engineering

by

Assaf Harel Alshochat

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This research was carried out in the School of Mechanical Engineering
The Department of Mechanical Engineering
Under the supervision of Dr. Avishai Sintov

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1. Abstract

As a part of research in the robotics lab at Tel-Aviv University, there is a need for a system that will allow a human operator to work in coordination with manipulator robots. There is a need for the robots to "understand" the operator's action or intention and assist him with a specific task without the operator doing anything else than the task. The results of this project can, essentially using a neural network and machine learning, assist with developing a "third hand" helping robot for professional work in multiple-person tasks, or to assist a person with a disability or an old adult in day-to-day tasks such as pouring water from a bottle while the person is holding a drinking glass or home chores[1, 2].

The wearable system is designed for the task of performing various actions while cooperating robot is taking part in the action, together with the operator. The system was constructed of 9 sensors that were placed against muscles and measured the force each muscle produced during the action. 5 more sensors are used to measure the curving of the hand finger during the tests and an IMU unit is measuring the linear acceleration, angular velocity, and the relative change of the magnetic. This system is also equipped with labels, two on each finger, to detect the finger ID and position in space using a set of cameras in the robotics lab.

The system requires to be wearable by multiple users and transmit the recorded data to a PC that will record the measurements. Another important feature is the independent and robust sensor casing, to ensure minimum events of breaking of the contacts during the test, and ease of maintenance when required.

A series of tests will be performed using the system, each test will produce data for every measurement and the data will be plotted. As will be presented later it is shown that the system is working reliably with a measurement for every sensor and all the IMU measurements.

2. Literary Review

2.1. Machine learning – creating a dataset

Machine Learning[3] (ML) is a field of research concerned with the question of how to construct computer programs that automatically improve with experience and learn from existing data and improve performance.

Working with an ML program is constructed out of two main parts: learning and testing. During the learning phase, the program gets a known input while the operator "tells" the program what the data is. For example, a program that will be able to identify handwritten numbers[4]. At first, the program will get an image of the number in handwriting while, for that matter, it knows that the image is one of the number 3.

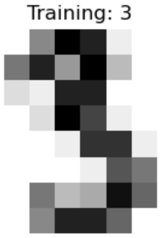

Figure 1 - handwritten number for ML

At the testing part, the program will receive an input of a handwritten number without knowing what the number is written, and it will be required to identify it by itself. The output of that part is usually the program's success rate in a confusion matrix, a visual representation of how accurate the program was.

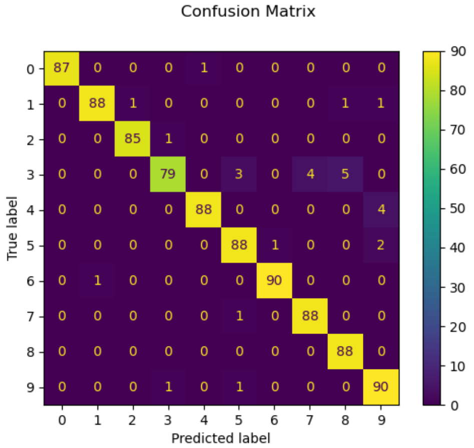

Figure 2 - ML confusion matrix

In this work, a wearable system was designed to read and record the orientation and muscle activity of the arm, as a part of research in the robotics lab at Tel-Aviv University. The system will allow a human operator to work in coordination with manipulator robots in the robotics lab, while the robots "understand" human intentions using the principles of machine learning.

2.2. Anatomy of an arm

The arm is a part of the human anatomy and normally refers to the entire arm from the shoulder hand (entire arm)[5].

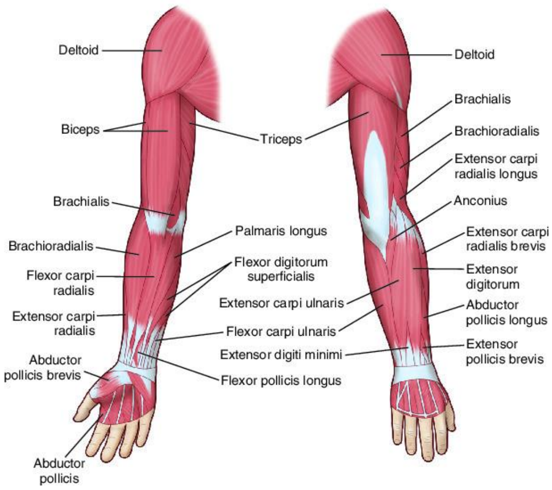

Figure 3 - Human arm anatomy

The anatomy of the arm will be divided into three main groups in this project, hand (palm in this project), forearm, and upper arm (biceps and shoulder in this project).

2.2.1. Hand

The hand is structured of a palm (Metacarpal and Carpal bones), and five fingers, Phalanges (the bones of the fingers), each finger has three phalanges, except for the thumb, which has two[6].

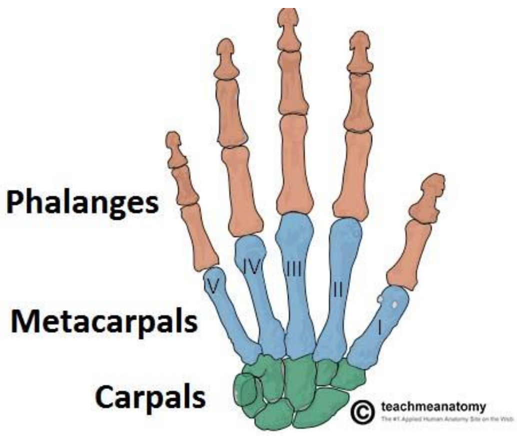

Figure 4 - Human hand anatomy

2.2.2. Forearm

The forearm is a part of the entire arm and is located between the elbow and carpus (carpals)[7]. The forearm is structured of two bones the radius and the ulna, and several muscles cover the radius and ulna and act to move the hand and fingers in various ways.

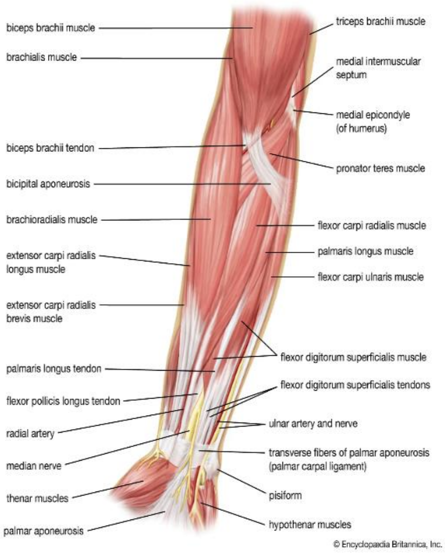

Figure 5 - Human forearm anatomy

2.2.3. Upper Arm

The upper arm, from shoulder to elbow (the proximal part of the arm) and has one bone called the Humerus[7]. The muscle that extends, or straightens, the arm is the triceps, which arises on the humerus and attaches to the ulna at the elbow; the brachialis and biceps muscles act to bend the arm at the elbow.

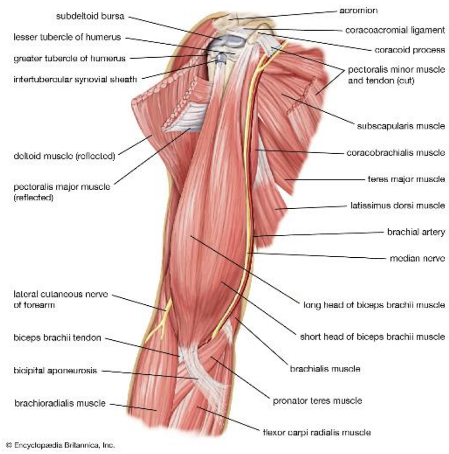

Figure 6 - Upper arm anatomy

2.3. Microcontroller

A microcontroller (also known as an embedded controller) is an electronic component that contains a complete computational system that includes a processing unit (CPU), memory, programable inputs and outputs, timing components, and a serial communication port[8]. The microcontroller is a compressed microcomputer manufactured to control the functions of embedded systems.

2.3.1. Serial communication

Serial communication is a way of sending data from one component to another. UART, (universal asynchronous receiver-transmitter) is a common serial communication protocol[9]. The two UART devices are connected as the transmitter (TX) of the first is connected to the receiver (RX) of the second and the receiver of the first is connected to the transmitter of the second as shown in Figure 7.

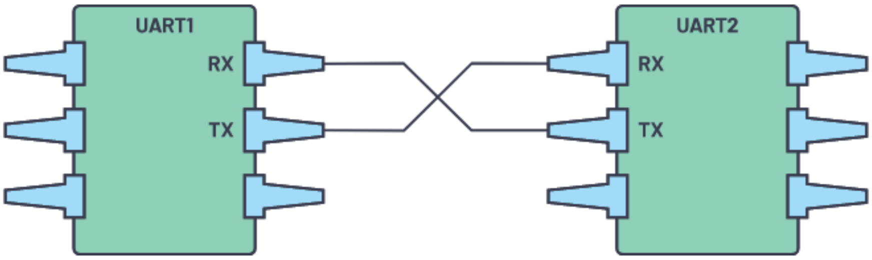

Figure 7 - two UARTs in direct communication

The UART has no clock to synchronize the data from the transmitter to the receiver, so the data transmits in the form of a packet. A packet is constructed of a start bit, a data frame, a parity bit, and a stop bit.

Start Bit (1 bit)	Data Frame (5 to 9 Data Bits)	Parity Bits (0 to 1 bit)	Stop Bits (1 to 2 bits)

Figure 8 - UART packet

- Start bit – signals the beginning of a transmission
- Data frame – actual transmitted data, 5-9 bits
- Parity bit – validating the transmitted data integrity (checks if odd or even number of bits received)
- Stop bit – signals the end of a transmission

2.4. FSR (force sensitive resistor) and Flex sensors

FSR sensor, as can be understood from its name is a resistor that is sensitive to force, and as force is applied to the resistor the resistance changes in coordination with the force size[10].

It is made of two layers with a spacer between them, and as force is applied to the top layer the space between the two layers is getting smaller causing a decrease in the resistance.

Figure 9 - FSR400 short, exploded view. from top to bottom: adhesive, top substrate, spacer adhesive, bottom substrate

A flex sensor (sometimes called flexible potentiometer) is an electronic device that changes its conductivity due to deflection or bending of the substrate[11]. The flex sensor is constructed of a flexible substrate with conductive ink deposited on it with a segmented conductor positioned on top causing a change in resistance as a reaction to deflection or bending.

2.5. IMU – Inertial Measurement Unit

IMU is an electronic device that is made of a three-axis gyroscope, three-axis accelerometer, and three-axis magnetometer[12]. The IMU measures linear acceleration with the accelerometer, the angular velocity with the gyroscope, and the relative change of the magnetic field with the magnetometer.

2.6. Related Work and Motivation

There has been an increasing interest in the measurement of muscle activity over the past years. Most of the recorded muscle activity has been demonstrated by surface electromyography, however, there have been several attempts to measure muscle contraction with a non-invasive technique using an FSR sensor[13]. An FSR sensor, 3D printed cuff system which was able to measure the muscle contraction for the lower limb has been demonstrated[14]. The system, meant to answer the basic functional demands required from prosthetics for limb-amputees, was placed only above the knee area on non-amputee test subjects and demonstrated the muscle active location along with the inactive positions. Furthermore, the cuff system size needed to be taken into account in order to avoid tightening problems during use[14]. In another research a robust, low-cost, easy-to-use FSR-based system showed quantitative reliable evaluation of muscle contraction compared to previous EMG-based systems[13]. The system, constructed by EMG electrodes placed on the wrist and FSR sensors placed near the lower elbow, monitored the muscle performance only of the forearm. Another example successfully demonstrates the measurement of forces of only the human hand by an FSR-sensors system placed on the subject's finger tips[15].

This work follows a former work done by the group of TAU robotics lab led by Sintov[16,17]. The work suggested a wearable device, using FSR sensors to read the muscle activity and IMU measurements, however, the measurements were only concentrated on the forearm area. The novelty of this work is the ability to sense the muscle activity of the entire arm, shoulder to hand, and the finger's bending. This system is also equipped with labels, two on each finger, to detect the finger ID and position in space using a set of cameras in the robotics lab. Those changes could possibly give added value to the learning process of the neural network since it will be possible to differ between two similar tasks using the additional data.

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3. Methodology

3.1. System Design

The system is constructed of an array of 14 sensors, 5 Flex Sensors[18] on the palm (1 for each finger) and 9 FSR-400 short[19] sensors as seen in distributed on the entire arm: 4 on the forearm, 3 on the bicep, and 2 on the shoulder. Both the FSR and Flex sensors are changing their voltage (as a reaction to the change is resistance), the FSR when force is applied to the sensor and the Flex while being bent, so those sensors act as a resistor with changing resistance and the method of reading their values will be presented later.

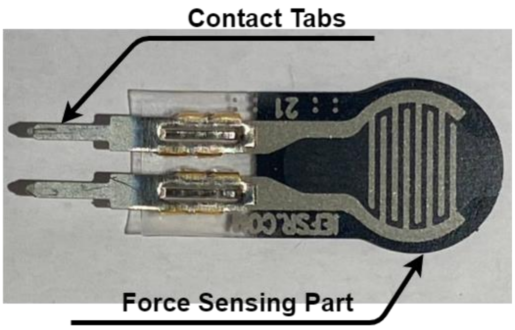

Figure 10 - FSR-400 Short sensor

Another component is the IMU: PMOD-NAV[20] which measures the g-linear-acceleration, angular acceleration, and gauss magnetic, each in 3 axes, with a total of 9 values.

Figure 11 - PMOD-NAV IMU

All the components are connected to a PCB, which is the same as in the first-generation system. The controller of the entire system, which reads all the sensors and transmits the data is the Teensy 4.1 [21]

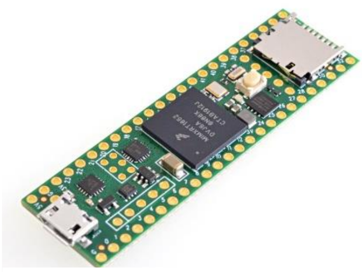

Figure 12 - Teensy 4.1

the sensors are connected to S1 and S2 analog inputs, and the IMU is connected to a designated input as shown in Figure 13.

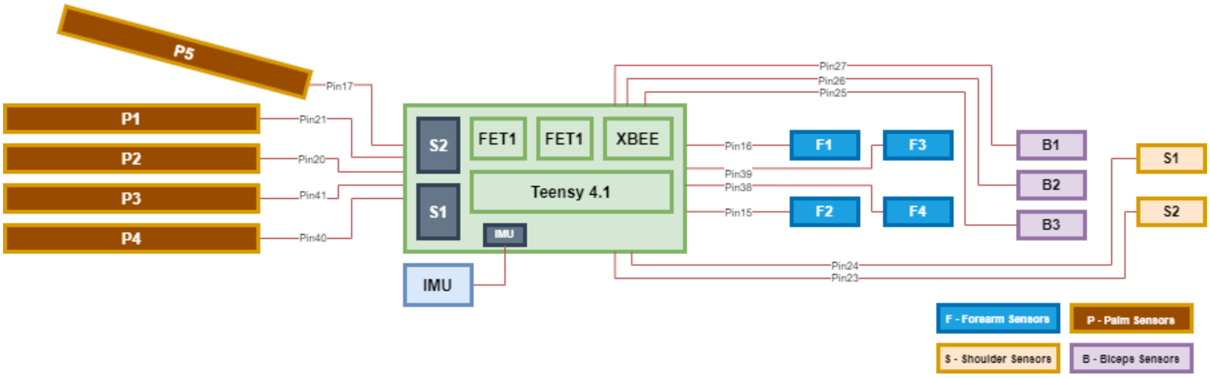

Figure 13 - System Layout Configuration

Each sensor is connected to an analog input via a voltage divider as shown in Figure 14. The voltage supply goes to the sensor’s input . The read value is the voltage on the 47kΩ resistor connected to the system’s ground, as presented in a detailed wiring diagram in Figure 15.

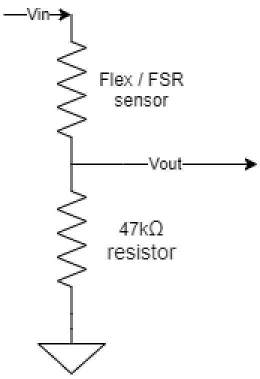

Figure 14 - Voltage Divider

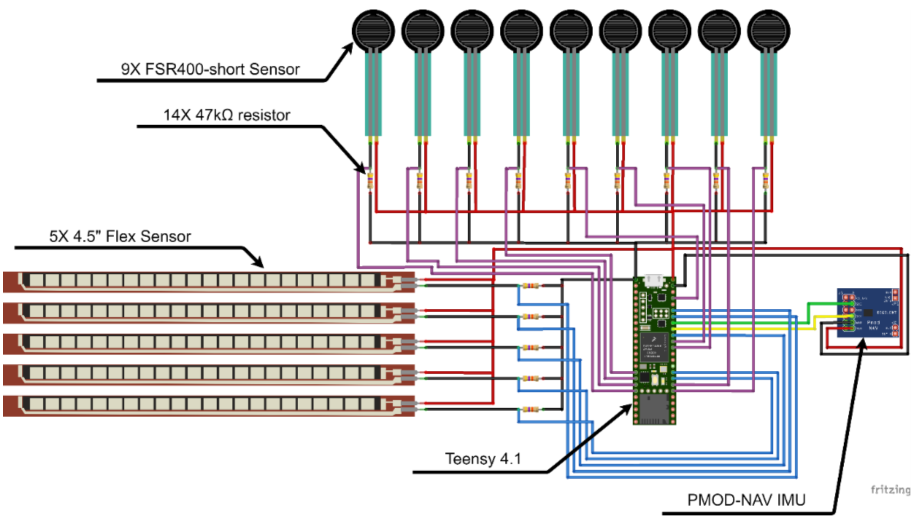

Figure 15 - System Wiring Diagram

3.1.1. Mechanical Design

The mechanical design's main objectives are to have the ability to attach an array of sensors to an arm – fingers to shoulder and use it to perform measurements of various activities while being the robustness of the sensor structure, wiring-wise is maintained, and the ease of maintenance will be achieved by enclosing the sensors individually.

All the models were designed using Solidworks[22], both in 3D files and drawings.

- Sensor's housing – each FSR-400 sensor is enclosed in an individual case, locked with M3 bolts and nuts. The sensor is connected to the system via its contact tabs, male jumper wires are soldered to contact tabs and insulated with a heat-shrink-insulation.

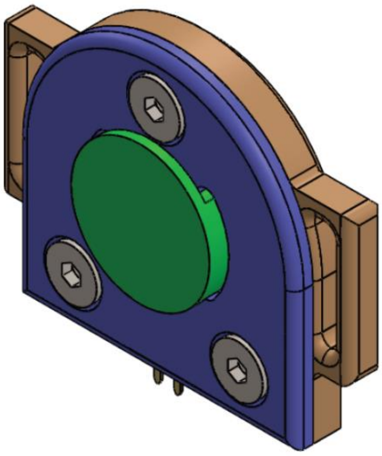

Figure 16 - FSR-400 Short Casing

- PCB case – the PCB case contains several components: PCB, Teensy 4.1 controller board, and IMU.

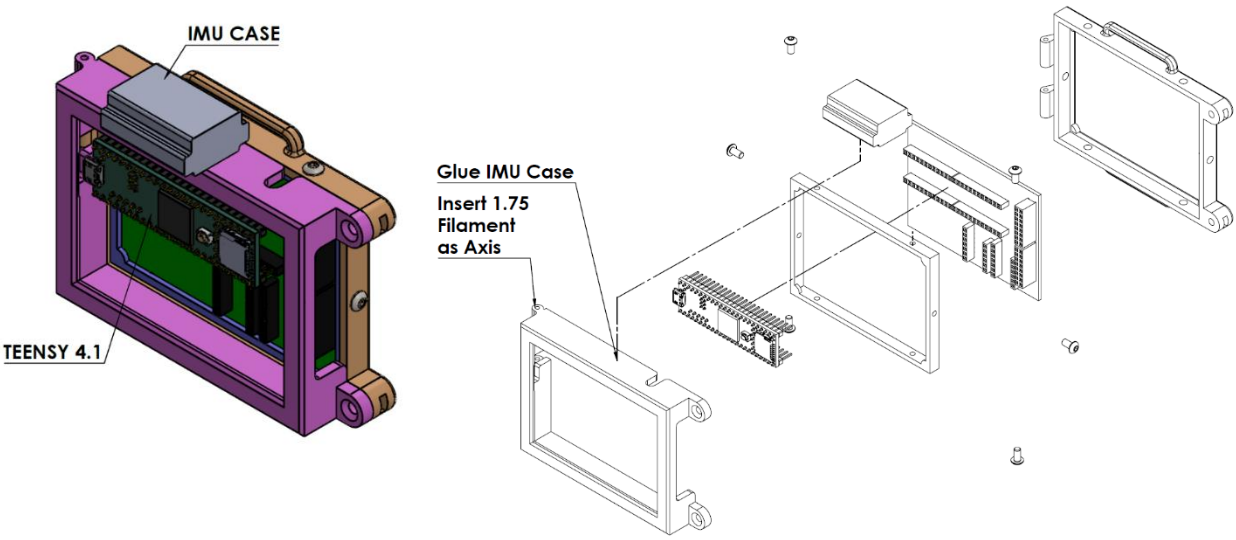

Figure 17 - PCB Casing and Interface

- Palm Flex Sensors Interface – as a part of the system design there is a need to add sensors that can read the finger's activity. The flex sensor has been chosen as it can be fitted as a wearable device in glove form. As a wearable part, it requires to be easy to wear, take it off, and be able to perform the testing activities as naturally as possible.

  This structure is constructed of 5 independent flexible straps, each strap will be installed with a single flex sensor, and jumper wires are soldered to the contact tabs and insulated with a heat-shrink-insulation.

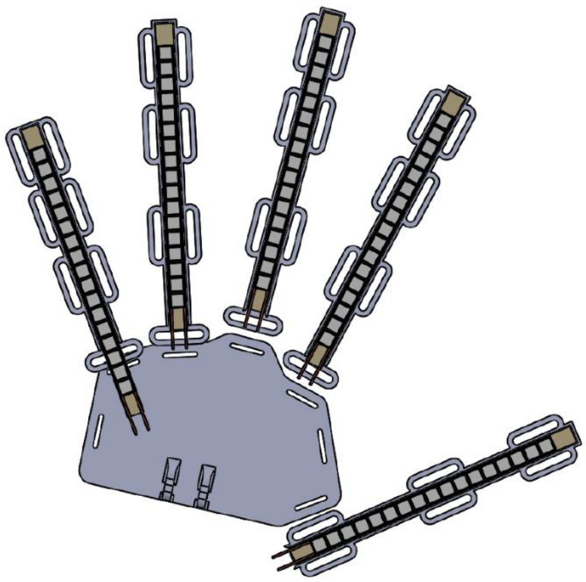

Figure 18 - Flex Sensors Interface

- FSR-400 Sensors Straps – the FSR sensors are enclosed, each sensor in a single case, and those assemblies need to be attached to different areas of the arm. Each set of sensors will be fitted on a flexible strap that will allow to tighten of the sensor case against the arm so that muscle activity could be read.

  The straps are all the same length and can be extended by gluing multiple straps thus creating a longer one, and for closing each strap a piece of Velcro will be glued.

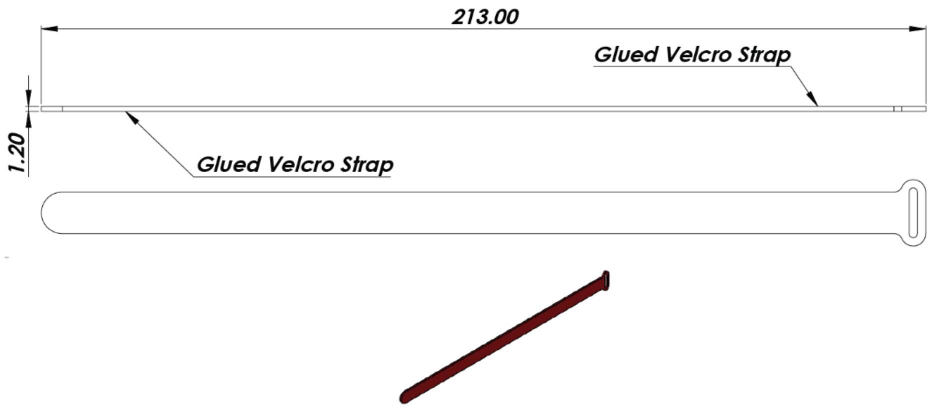

Figure 19 - Flexible TPU Straps

3.2. System Manufacturing

- Sensor's Housing - The case is printed out of PETG, as PETG doesn't require special printing conditions (such as a heated printing chamber for ABS) and it is user-friendly and easy to print, furthermore, PETG is less sensitive to humidity in comparison to PLA that becomes brittle over time.
- PCB Case – the case is also printed out of PETG. The case is attached to the arm close to the wrist with an elastic band.
- Palm Flex Sensors Interface – a quick and simple way to manufacture the interface is to 3D print it out of a flexible material, TPU (thermoplastic polyurethane).
- FSR-400 Sensors Straps – the same considerations were taken for the FSR-400 straps, which will be 3D printed out of TPU.

All the above were manufactured with a Prusa MK3s+[23] 3D printer and will be elaborated further later.

3.2.1. Wiring

Each sensor (FSR-400 or Flex) got two jumper wires soldered to its contact tabs, and heat-shrink-insulation is used to cover the soldered area. The other end of the wire is the male connector that will be connected to the PCB (or with a jumper wire extender).

3.2.2. Assembling

- Flex and FSR-400 short sensors – to prepare the sensors for assembling the system, it was soldered with a male jumper wire and a heat-shrink-insulation is added to cover the soldered area.

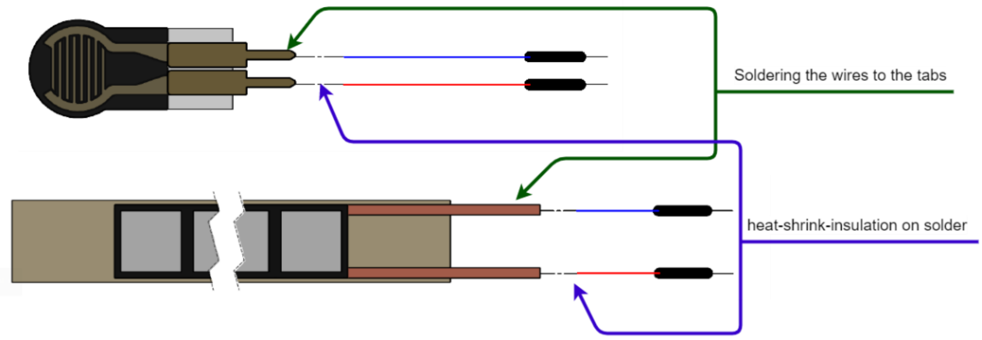

Figure 20 – Sensors Soldering Diagram

- FSR-400 short housing – after soldering the wires to the sensors, each sensor is glued onto the housing base with double-sided tape. The button is inserted into the lid and that assembled part is placed onto the base while 3 M3 bolts and nuts are locking everything in place.

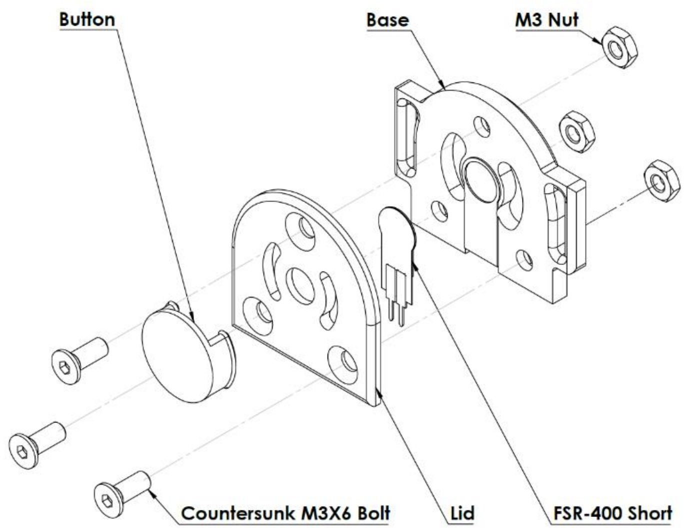

Figure 21 - FSR-400 Short Housing Assembly

- Flex Sensors Interface – each flex sensor is glued to the interface finger using a double-sided tape. To wear the entire part on the palm, a flat elastic band was added to the TPU parts and sewed to a closed loop thus used as a glove.

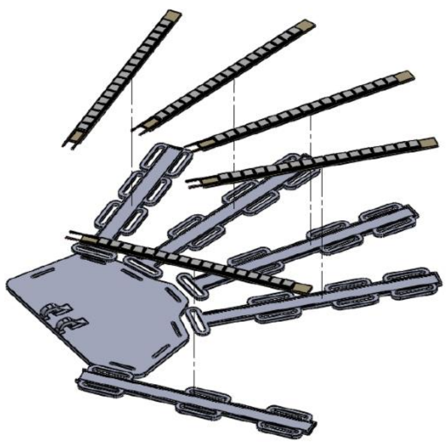

Figure 22 - Flex Sensors Interface Assembly

3.2.3. programming

- Data Creation - The data recording process required a programmed controller (Arduino-based Teensy 4.1 in this case). The program was written in Arduino[24] environment and collected a list of values structured as time, IMU (g angular acceleration, Angular rate, gauss magnetic), palm sensors, forearm sensors, bicep sensors, shoulder sensors, and the actual structure is: *"t,Gx,Gy,Gz,Ax,Ay,Az,Mx,My,Mz,P1,P2,P3,P4,P5,F1,F2,F3,F4,B1,B2,B3,S1,S2"* and it got sent over a serial communication port (COM port) a single line at a time.
- Data collection – to collect the above list of values a python[25] script is used. the program connects to the same COM port as the Arduino and initiates a serial communication collecting every line and writing it to a CSV (comma-separated-values) file. Every measurement session got written to an individual CSV file.
- Data processing – using the Pandas library on a python script to open each CSV file and created a chart for the values, the x-axis is the time in seconds while all the measurements are plotted on the y-axis.

3.3. Software and Manufacturing Tools

3.3.1. Arduino IDE

Arduino is an open-source electronics platform based on easy-to-use hardware and software, Arduino boards can read inputs and send outputs such as text and actuate components such as LEDs or switches[24]. The used controller, Teensy 4.1, can be programmed via the Arduino integrated development environment (IDE).

In this project, the Arduino IDE is used for the entire system programming, sensor reading, creating the data strings, and sending it via the COM port.

3.3.2. Python 3.9 + Pandas

Python is an interpreted, high-level programming language[25]. Python is used for scripting or glue language to connect existing components. Python's simple, easy-to-learn syntax emphasizes readability and therefore reduces the cost of program maintenance. Python supports modules and packages, which encourages program modularity and code reuse.

Pandas is an open-source package for data analysis tasks[26]. Pandas support working with 1 and 2-dimensional arrays of data, processing them, and using the result for any desired use such as plotting the data on a chart.

In this project, Python scripts are used to collect the data that has been sent by the Teensy board through the COM port and write to file and use the Pandas tool for processing the data from that file to create charts with the sensors.

Draw.IO[27]Draw.IO is an open-source platform for creating diagrams and charts, and many of the figures in this project were created with Draw.IO.

3.3.3. Fritzing

Fritzing is an open-source software tool, that allows users to design their project in a user-friendly environment and include their components in the design in the planning stage [28]. This platform also allows designing components for manufacturing (designs for a PCB). the user can also download and add parts to the software's library and use the actual part diagram in the design instead of just the scheme of the component.

In this project, Fritzing was used to create the wiring diagram in Figure 15.

3.3.4. 3D printer – Prusa MK3s+

The manufacturing technology for this project is additive manufacturing, an available, user-friendly, cheap, and fast way to make a small number of units (additive manufacturing is also called 3D printing) [23].

For this project, a Prusa i3 MK3S+ printer was used. This is an FDM 3D printer using thermoplastic polymers for rapid prototyping.

Figure 23 - Prusa MK3S+ 3D printer

3.4. Assembled System

The assembled system as can be seen in Figure 24, is constructed of four TPU straps mounted by FSR400 sensors, two straps with four sensors for the forearm, one strap with three sensors for the biceps, and one strap with two sensors for the shoulder. The Teensy 4.1 microcontroller is based on the forearm close to the wrist together with the IMU, and a TPU glove with five flex sensors for finger readings. In Figure 24a the assembled system is presented and in Figure 24b the system can be seen as it is worn on a left arm of a person. On the hand fingers, there are also labels. Labels are the spherical objects attached to the fingers, with two labels on each finger, and their purpose is to mark each finger's position on the test area space. The robotics lab is equipped with a set of cameras that identify the labels and by using labels it is possible to cooperate with the robotic arms, so the robots "know" where the operator's arm is positioned.

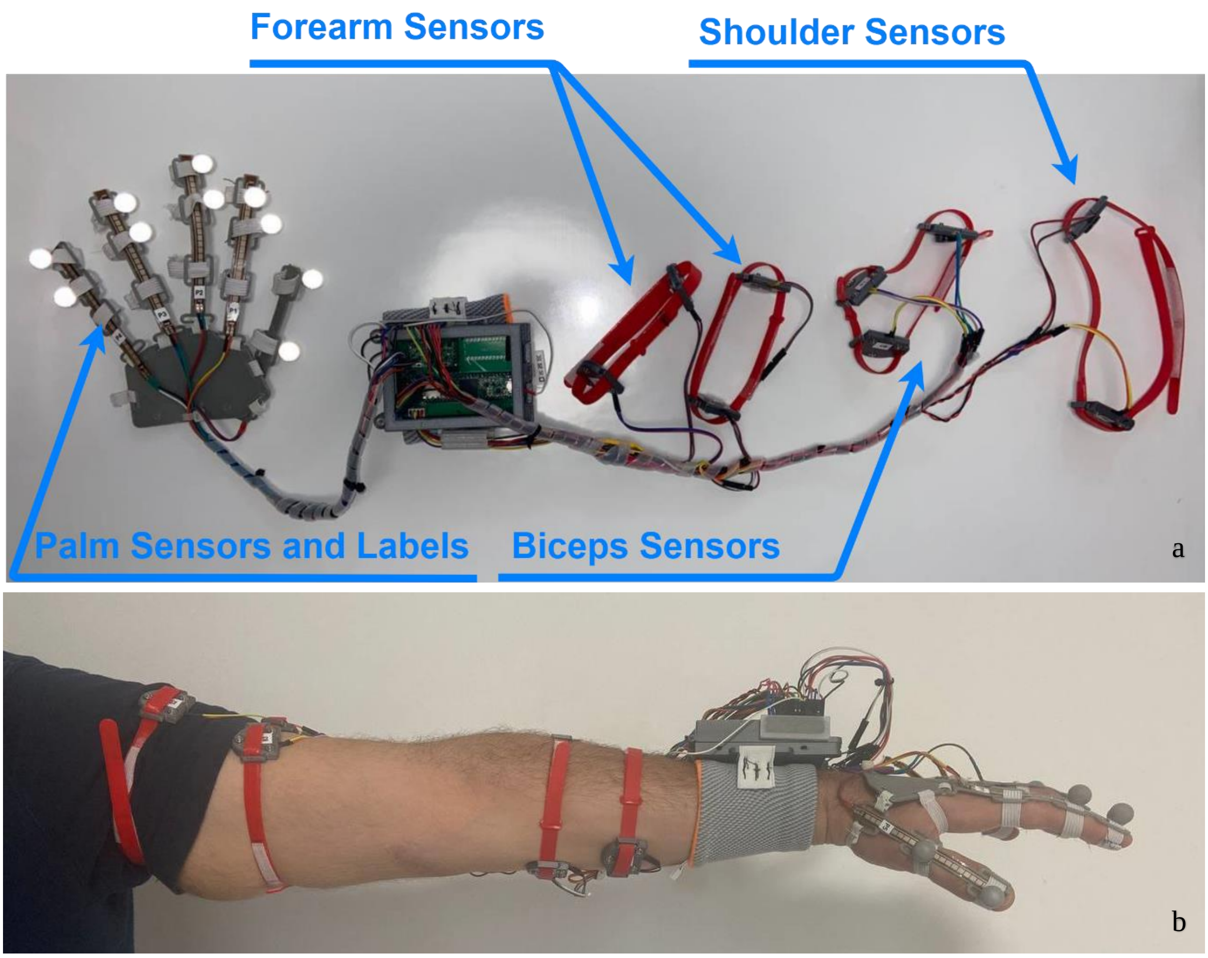

Figure 24 - Assembled system

4. Results and Discussion

4.1. Mapping the sensors by arm parts

The first stage of working with the system is validating the readings of each arm part. Start by measuring each part individually: palm, forearm, biceps, shoulder for ~30 seconds according to each part description.

4.1.1. Palm

Opening and closing the palm repeatedly, thus flexing and extending all five fingers as shown in Figure 25

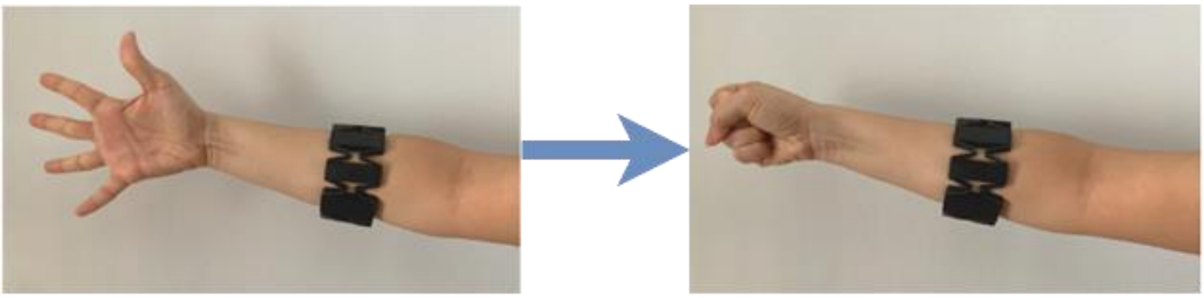

Figure 25 - Palm flexion and extension[29]

It is behavior is appearing in the graph Figure 26, as it shows the periodic values while the palm is flexing and extending while the five sensors are changing their values. P1-P5 indicates the reading for each finger as shown in Figure 15. All the readings are shows the change in the fingers bending as shown in Figure 25. The read values are drops as the sensor curves, bigger bend will result in a lower value.

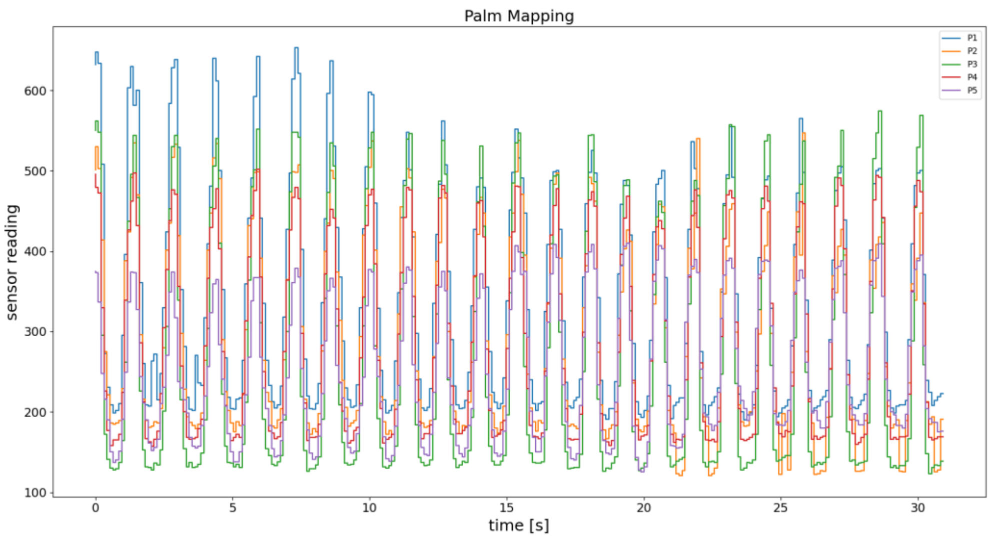

Figure 26 - Palm Mapping

4.1.2. Forearm

Moving the palm up and down repeatedly to flex and extend the forearm muscles as shown in Figure 27.

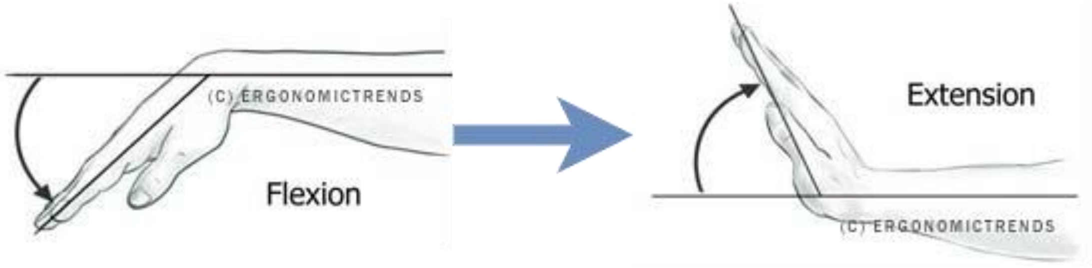

Figure 27 - Forearm flexing and extending[30]

Four sensors are attached to the forearm, and it appears that the 3rd sensor (F3) never reaches the value of 0 (no force is applied to the sensor), the explanation for that is that the sensor is attached to the arm with the elastic straps and by that some force is applied to the sensor even when no activity is performed.

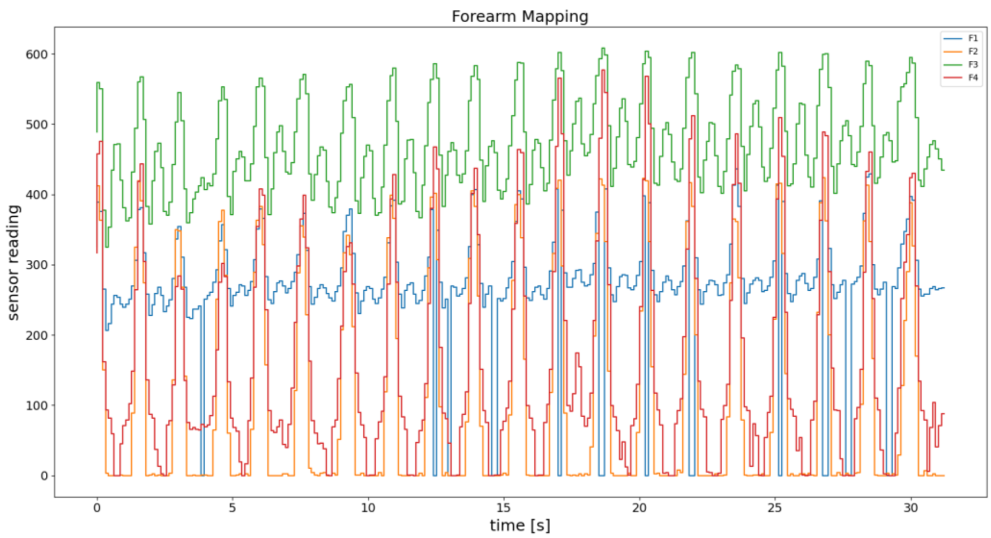

Figure 28 - Forearm flexing and extending

4.1.3. Biceps

Moving the forearm up and down repeatedly to flex and extend the biceps is shown in Figure 29.

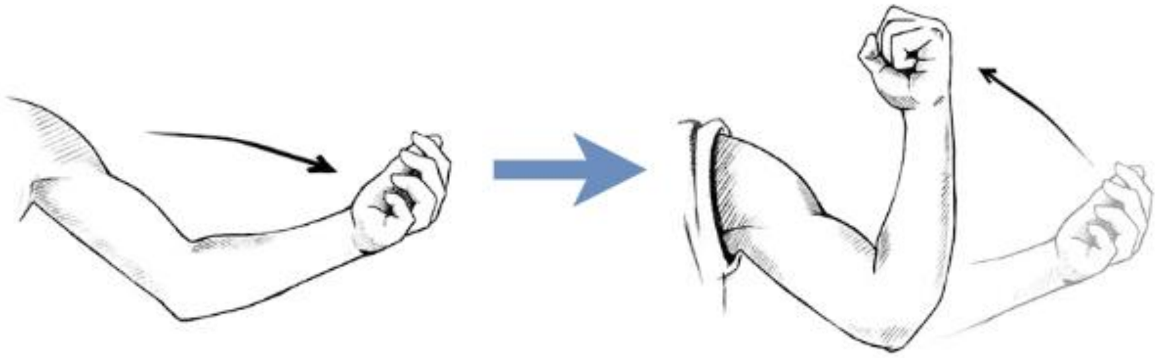

Figure 29 - Bicep flexing and extending[31]

The bicep is attached with three sensors around the middle of that arm part. Two sensors are tightened against the biceps and one against the triceps at the side of the arm.

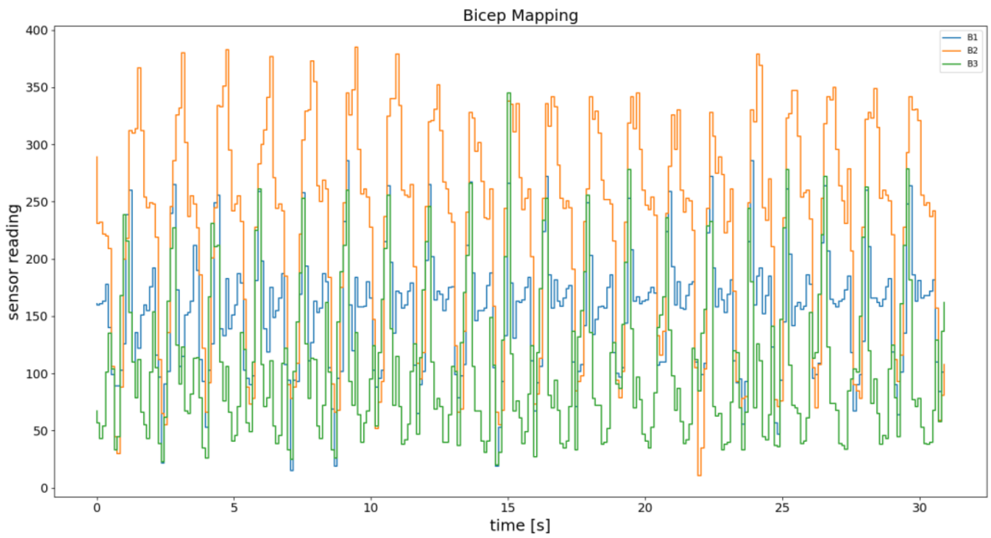

Figure 30 - Biceps mapping sensors readings

It is shown in Figure 30 that all three sensors are changing their values across the range while non are reaching 0. Again, as in 4.1.2 Forearm, the sensors are tightened so that even when the arm is idle, some force is still applied to the sensor.

4.1.4. Shoulder

Moving the entire arm up and down to flex and relax the shoulder muscles is shown in Figure 31.

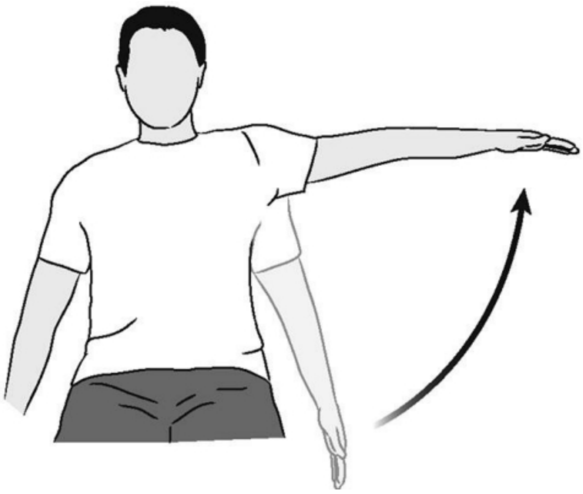

Figure 31 - Shoulder flexing and extending[32]

This is the most challenging body part for measurement with this kind of system, a system that should fit many types of arms and can be fitted on and taken off easily. the same mechanism is used to attach the sensors to the shoulder, FSR-400 is cased and tightened against the arm with an elastic strap. The problem occurs while moving the arm many times, and the strap can slip down. So, there is a need to fit the shoulder strap properly and perform the test, while rearranging the strap between tests is common.

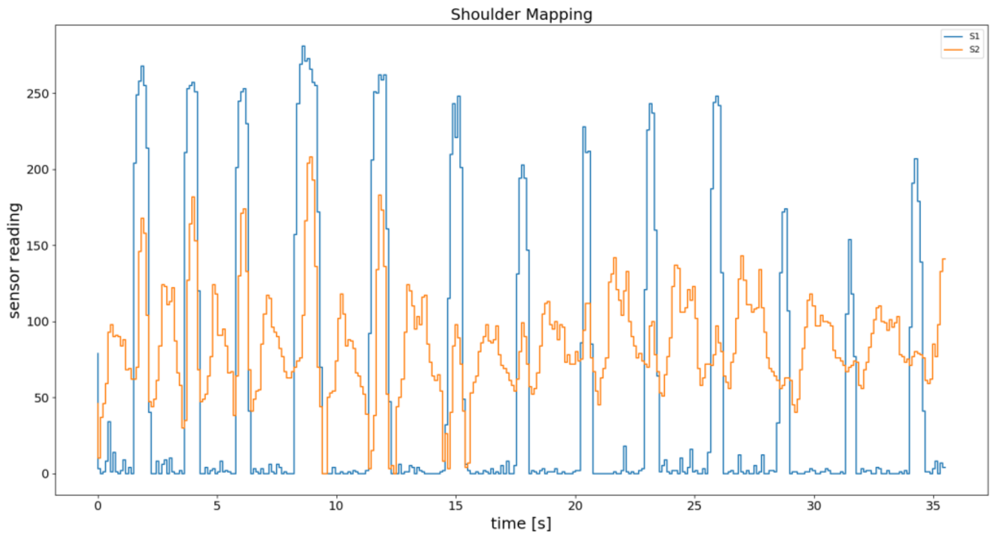

Figure 32 - Shoulder mapping sensors readings

here we can see that the sensors are reaching 0 because of the tightening issues that were discussed before. But the sensors are still moving across a range of measurable values that are sufficient for the testing.

4.2. Testing the complete system

The second testing stage is to install the complete system on the left arm and compare the measurements to various actions, object operations, gestures, and pointing.

4.2.1. No action

In this test, the arm stays with no movement for ~100 seconds while the sensor readings are being recorded.

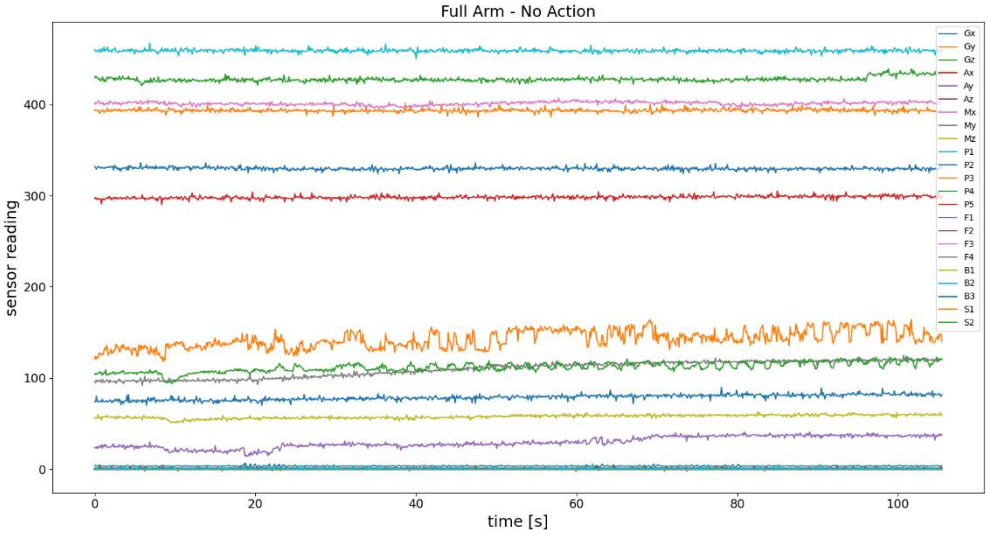

Figure 33 - Full arm, no action

In the first phase, the system is installed on the left arm while the arm is positioned at the side of the body with no action performed for ~100 seconds, as shown in Figure 33.

It seems that mostly the values are constant, as expected, since no action is performed, and the sensor's values should not be changed during this test.

4.2.2. Fist

After mapping the entire system, by sections and in an idle state for reference, the next phase is to start recording the entire system measurements while making a simple action, a fist for that matter.

Action: Start with an open palm then close the palm, holding for ~5 seconds, and reopen the palm.

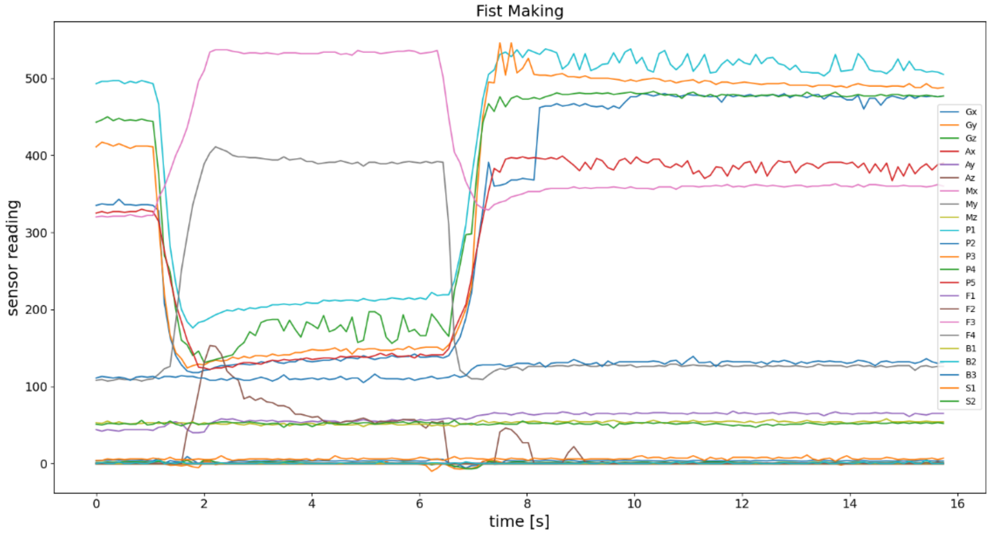

Figure 34 - Fist

It can be seen in the chart, Figure 34, that between seconds 1 to 6 all five Palm sensors changed their values, as expected from the fist action, it is also seen that the forearm muscles also gave a non-idle measurement for the fist action. In general, it is shown that the main muscle activity for the fist action is the forearm and the palm. The rest of the values maintain their value during the test since there is no activity in those muscles, the shoulder for example.

4.2.3. Actions with objects

In this section different actions with different objects will be performed, each object with a specific set of actions.

Each session will be started with a rested arm for ~2 seconds and lifting the session's object, then the set of actions will be performed according to the following descriptions.

- Mobile phone

Starting with lifting the phone of a table sweeping through the phone, and then moving the mobile phone against the ear (after ~50 seconds) for phone call simulation, then moving back to sweeping through screens.

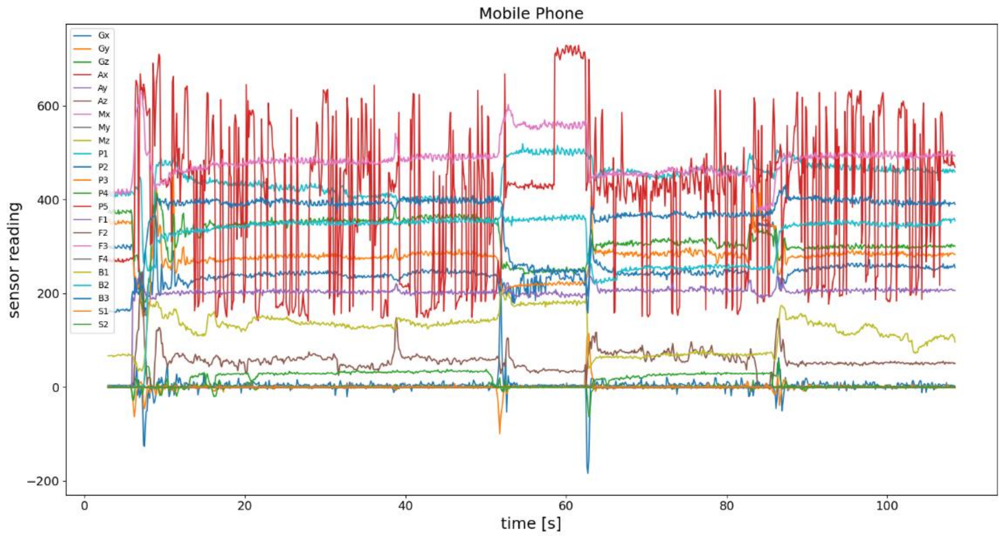

Figure 35 - Mobile Phone

In Figure 35 it is shown that while sweeping through the phone screens most of the muscle activities are relatively constant, the most significant activity visible is the thumb (P5), which does most of the activity. There is a very "active" area around 10 seconds into the testing, this is how picking up the phone appears in the muscle activities. Low or constant values during the test are both for inactive muscles such as the shoulder muscles or the IMU readings since there is no velocity or angular acceleration to the entire arm.

Around 50 seconds there is an area where many readings are changed to a different and constant value, this area simulates a phone call, so the mobile phone is moved and positioned against the left ear. What we see in the chart is the change in the biceps (B1-3) reading and the thumb has stopped sweeping, this phase lasts for about 12 seconds, and around 62 seconds the phone has been taken off the ear and resumes the sweeping activity for more ~40 seconds.

- Screwdriver

This test will present an actual tightening and loosening screws repeatedly. The Bolt is positioned in vice on a table, and the bolt is screwed to a nut as shown in Figure 36.

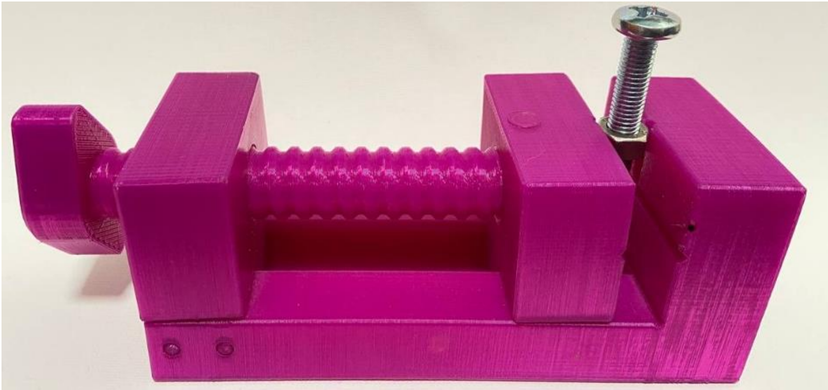

Figure 36 - Screwdriver test setup

Starting in idle, then picking up the screwdriver and moving it to the screw to start the activity. The first part shows the tightening activity, and the second part shows the loosening activity, while there is some pause between those parts. The testing also ends with putting the tool down and returning to an idle state.

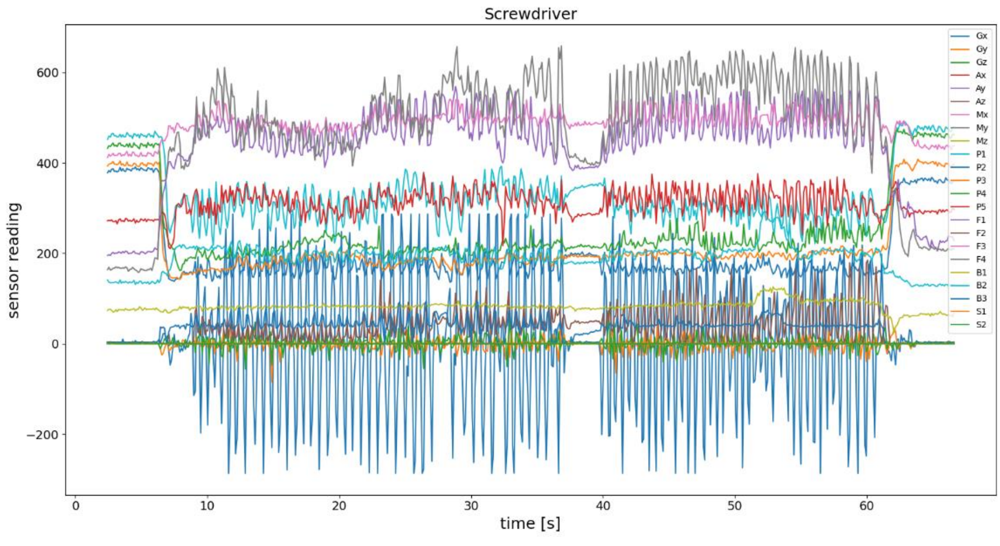

Figure 37 - Screwdriver

It is visible in the results in Figure 37 that most of the arm is active during this testing, all five fingers are changing as opening and closing the palm is required, and the forearm and the biceps are doing the twisting action.

The difference in the values is caused by the initial (idle state) while installing the system onto the arm. While fastening the straps, some sensors get slightly “pressed” so the initial value is not 0.

- Hammer

In the following test, the action is hammering down three nails on a wooden board as presented in Figure 39.

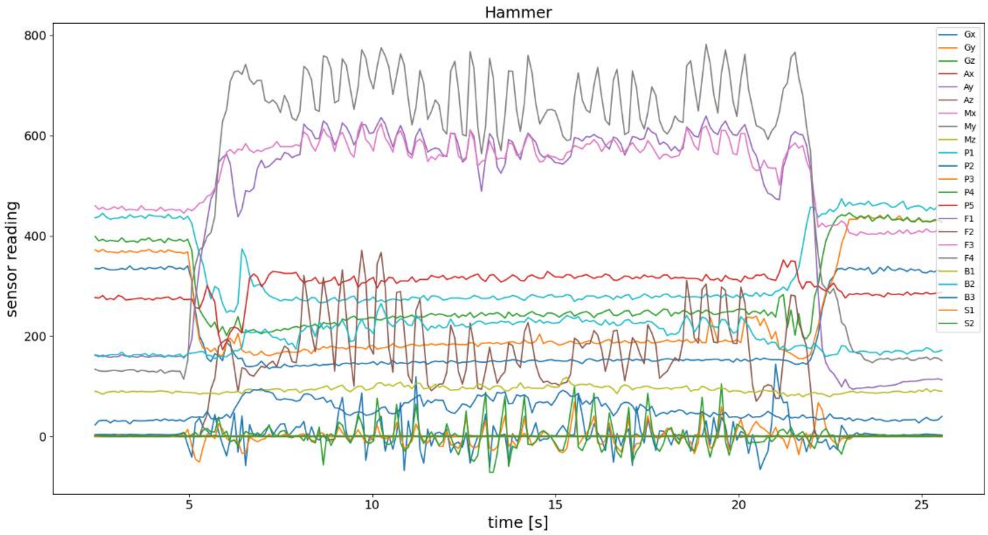

Figure 38 - Hammer

Figure 39 - Wooden Board with Nails

This test started at an idle state as well, as can be seen in the graph, Figure 38, the hammer got picked up at 5 seconds and the nail hammering started around 8 seconds. The periodic behavior is nicely presented as a group when hitting the nails one nail at a time, and the fourth group is because at the end I returned to the first nail.

- Coffee cup

in this test, the activity is as Lifting a cup and holding the cup, then moving it towards the mouth for drinking the content of the cup, and finally putting the cup down.

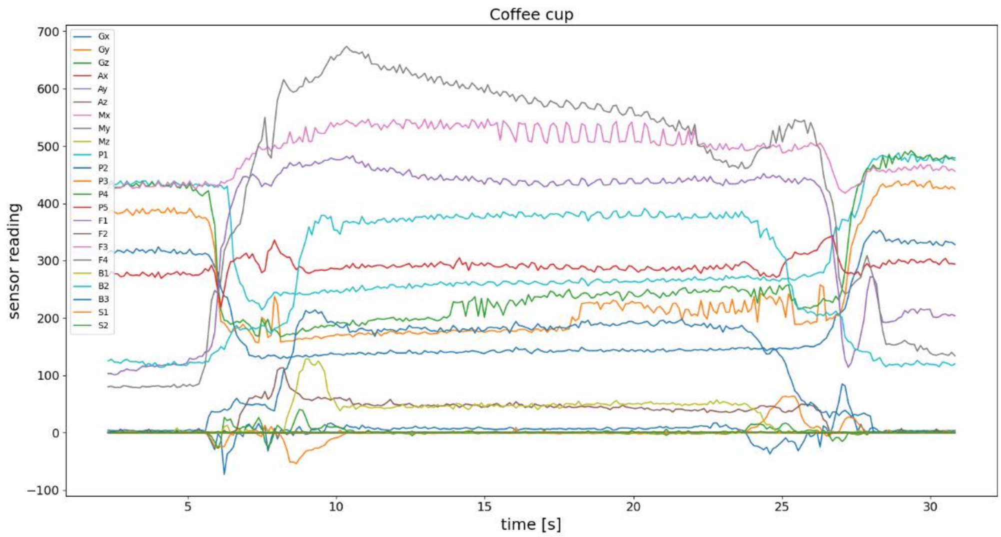

Figure 40 - Coffee Cup

As can be seen in Figure 40, starting with idle again, for 5 seconds, then picking up the cup then drinking the content of the cup. It is nicely shown that as the cup gets lighter since it contains less coffee the muscle reading of forearm sensor F4 is getting applied with less and less force.

- Bottle of water

for this test the action that will be performed is opening the lid and pouring water into a glass, putting the bottle back on the table, and closing the lid.

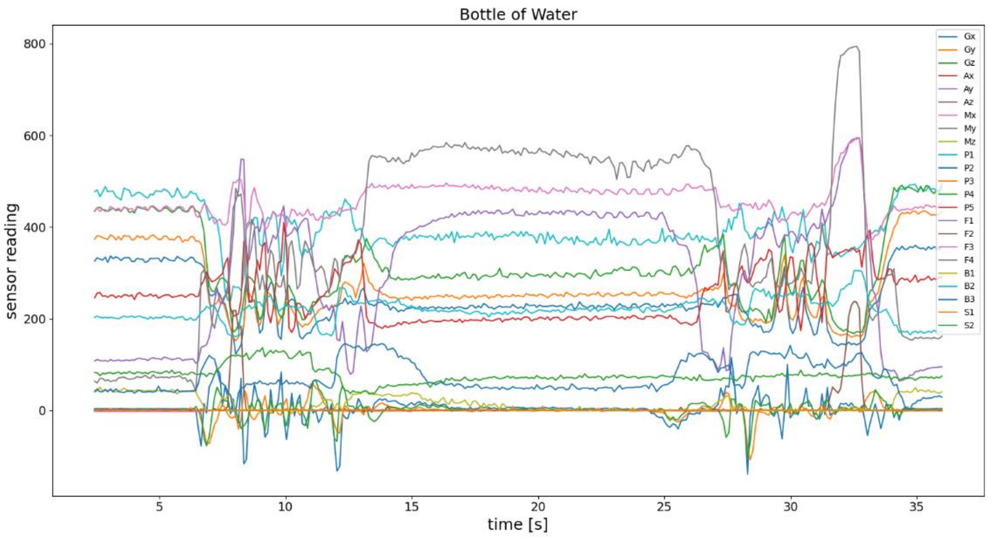

Figure 41 - Bottle of Water

As can be seen in Figure 41, from around seconds 7 to 13 the action is the lid opening, and up to seconds 27 the water pouring is performed. The final part, from 27 to 35 seconds, is putting the bottle down and closing the lid of the bottle.

- TV remote

The next action is pointing the remote towards the TV and pressing random buttons.

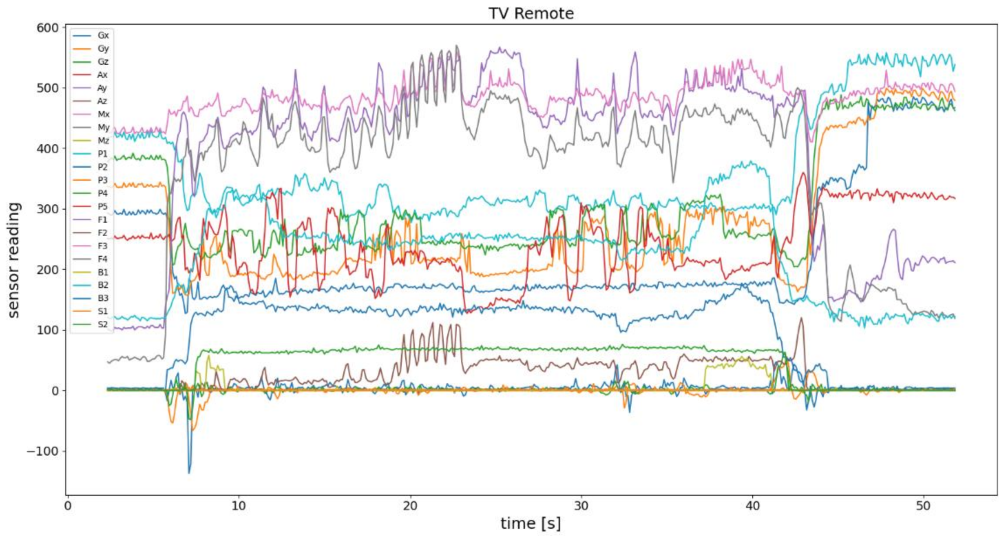

Figure 42 - TV remote

As can be seen in Figure 42 the fingers are doing most of the activity, the thumb (F5) pressing the buttons, and the other fingers counter this action from the other side. There is also some forearm and biceps activity for pointing the remote toward the TV.

- Electric guitar

Playing 3 chords: C, G, and F repeatedly, each chord for ~5 seconds. The finger positioning for those chords can be seen in Figure 43.

Figure 43 - Chords finger positioning. from left to right G, C, F [33].

The results in Figure 44 are showing a periodic activity as expected. It is also shown that it is possible to classify the activities into three types, each activity type for each chord, and there is a repeated behavior respectively to the chords that are being played.

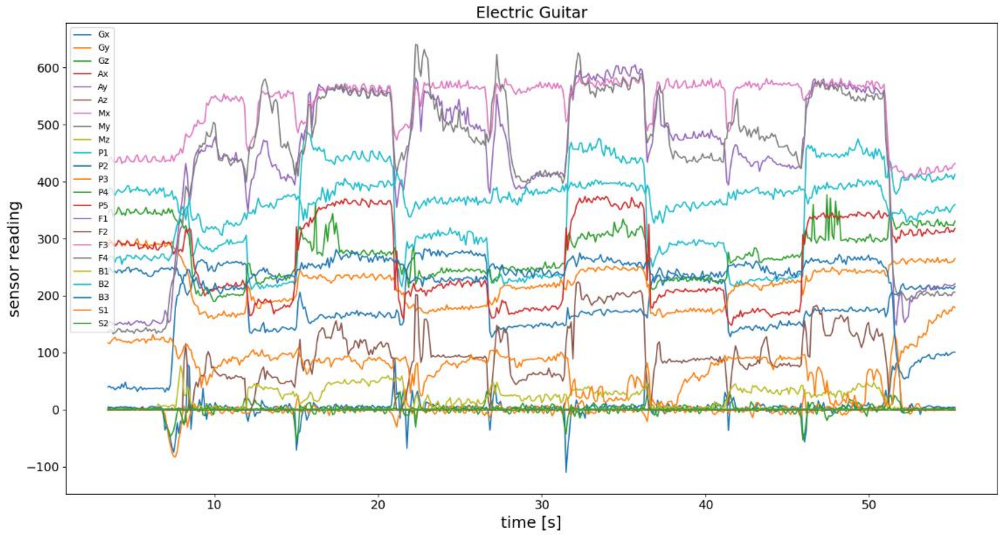

Figure 44 - Electric guitar

- PC keyboard typing

In the following test, the activity is typing with one hand the following sentence: “the quick brown fox jumped over the lazy dog”. That sentence was chosen for having all the letters in the English alphabet.

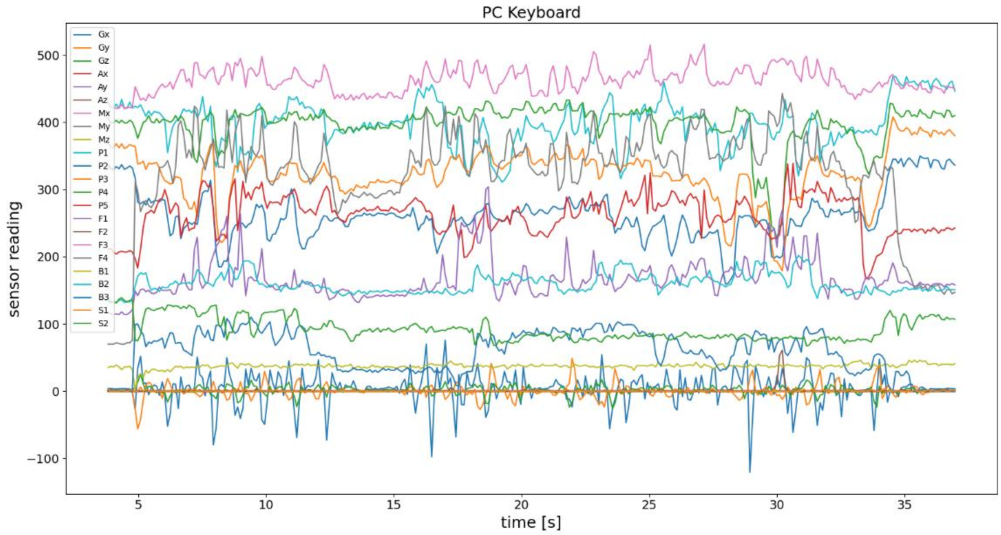

Figure 45 - PC keyboard

The results in Figure 45 show mostly finger activity and some forearm activity. fingers activity is obviously expected to be the most significant in a typing activity.

- Xbox 360 controller

The following test will be simulating playing a video game with the controller, pressing random keys with the left hand, relevant buttons are shown in Figure 46.

Figure 46 - XBOX 360 controller, Tested buttons

Most of the activity for this test was by the thumb (P5) for the arrow buttons and the analog stick (marked with a red arrow in Figure 46), with some activity by fingers 1 and 2 (P1 & P2) for the L-buttons (marked with the blue arrow in Figure 46), as can be seen in the results graph.

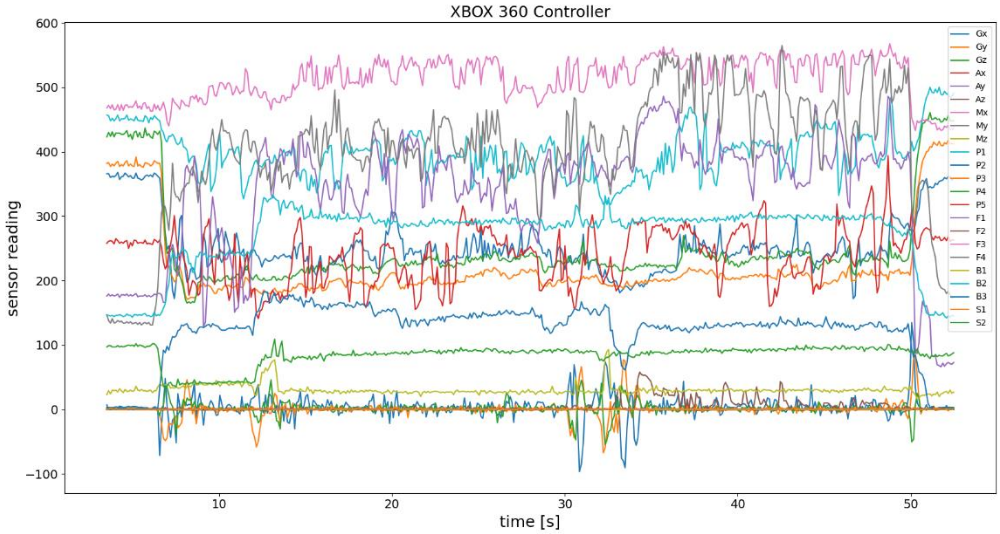

Figure 47 - XBOX 360 controller

- Electric drill

In this test, the action is tightening and loosening a screw in the wall at ~1.5 meter high using an electric drill. The buttons that were pressed during the testing are (10) and (6) as can be seen in Figure 48. Button 10, activating the drill, was pressed with finger 1 (F1) and button 6, switch rotation direction, was pressed both with fingers F1 and F5.

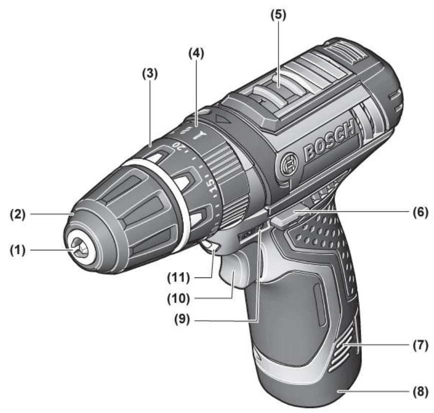

Figure 48 - Electric Drill, used model [34]

The results presented in Figure 49 show the activity of the muscles. We can see the activity of F5, for example as, peaks that represent the direction switching, while between presses there was no action performed. Additional muscles are the biceps, both for tightening and loosening the screw there is a need to press the drill against the screw to grip it. The forearm muscle activity is mainly for holding the drill, as shown there are no significant peaks.

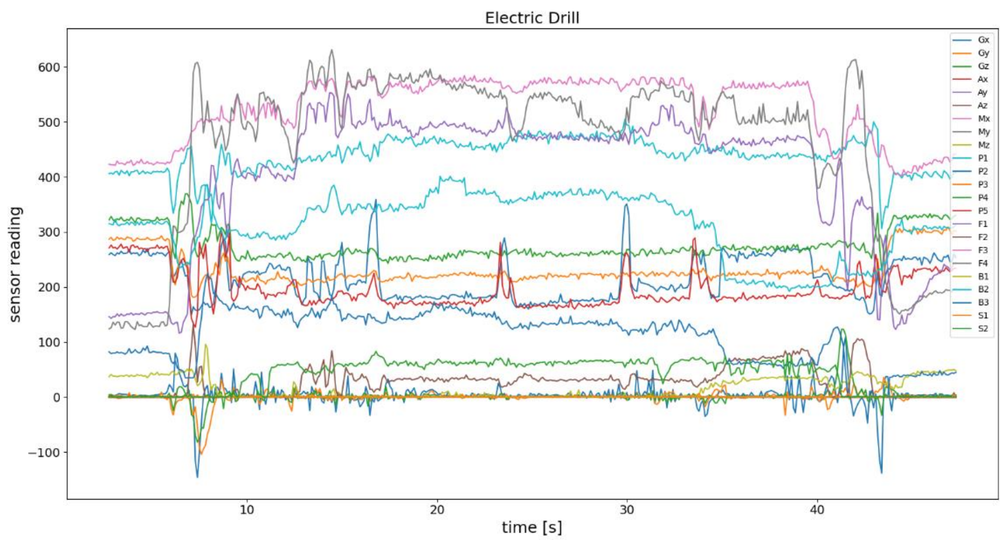

Figure 49 - Electric drill

4.2.4. Hand Gestures

This chapter will present the results of gestures Based on hand gestures as described in Figure 50 . each test will be conducted as follows: ~5 seconds of the rested arm (idle) followed by ~12 seconds of a static gesture, as described in Figure 50**Error! Reference source not found.**, and returning to idle for ~5 more seconds.

Figure 50 - Hand gestures [35]

- Open and Close

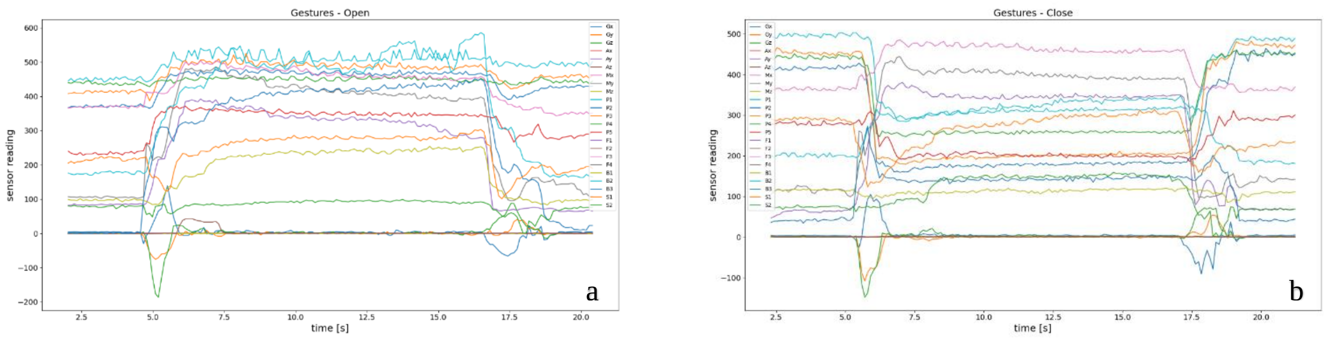

Figure 51 - Gestures - close & Open

These two gestures are rather similar, and the only difference is in the tip of the fingers. In “Open” all four fingers are aligned and with distance from the thumb, while in “Close” that gap no longer exists resulting in some curvature in all 5 fingers. As can be seen in Figure 51a and Figure 51a, P1 and P5, for example, changed their behavior, while in Figure 51a P1 is straight, in Figure 51b it is curved and it can be seen in the read values. If comparing to the idle state P1 reading is around 450 and P5 is ~250 when no action is performed, in “Open” P1 goes to ~550 and P5 to ~350 while in “Close” P1 goes to ~300 and P5 to ~200.

- Home and Back Home

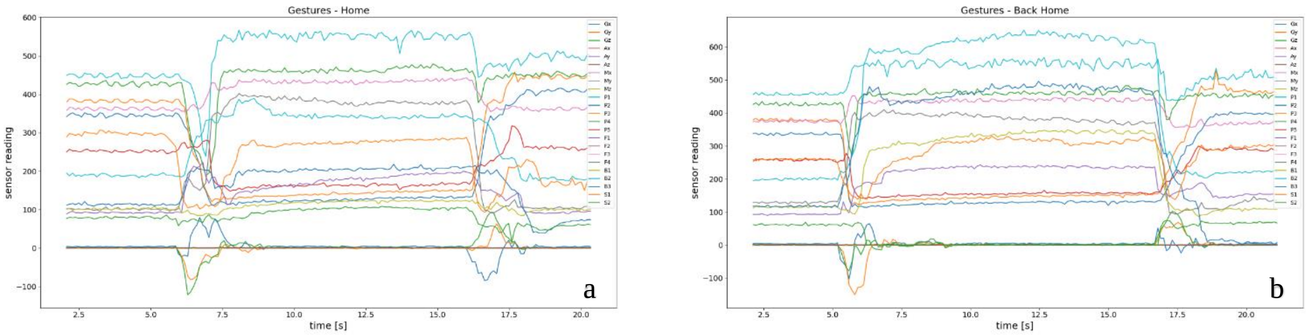

Figure 52 - Gestures – Home and Back Home

Home and Back-Home are very similar gestures regarding finger activity. The expected difference, in this case, is the forearm activity and the biceps activity since the palm remains in the same state and the arm is rotating causing a significant change in the arm muscles (B and F). As can be seen in Figure 52a & b, in the case of examining B2, in both cases the start value, for the idle state, is ~200 and when changing the position to "Home" B2 goes to ~330 while in "Back Home" it goes to ~600.

- Up and Down

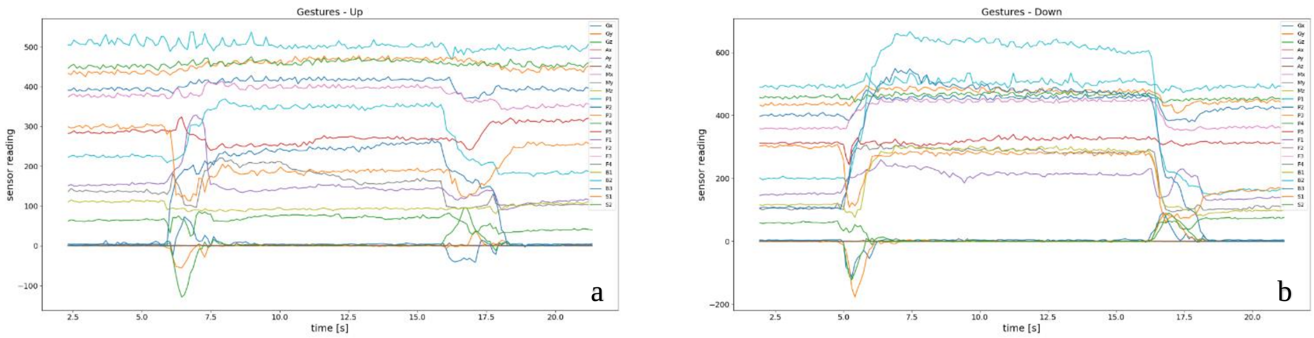

Figure 53 - Gestures - Up and Down

This case is similar to the previous gestures regarding the expected muscle activity changes, the palm state remains relatively constant while the arm is rotating causing a significant change in the forearm and biceps muscles. For example, if examining F4, in both cases the read value is ~130, and when performing the "Up" gesture the value goes up to around peaking ~200 then drops back to idle values, while in "Down" the value goes up to ~300 and remains there for the entire measurement.

- Roll Left

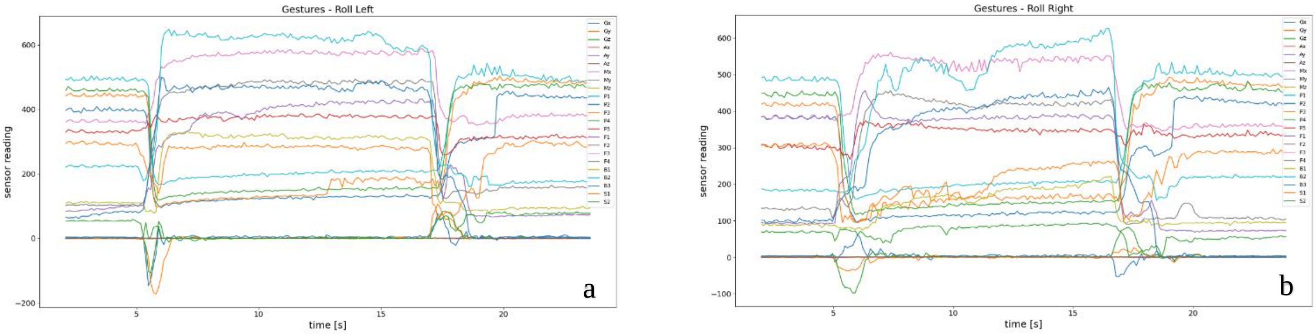

Figure 54 - Gestures - Roll Left and Roll Right

The following gesture is also presenting a more significant change in read values of the arm and similar measurements of the palm. If examining P1, in both cases, starts in an idle state with a value of ~500, and while performing the gesture the value changes to ~200. But if examining B2, the value starts at ~200, and in “Roll Left” climbs to over 600 while in “Roll Right” the value fluctuates around 500 for ~5 seconds and then climbs to ~600.

4.2.5. Pointing

- Relaxed Arm

This phase of testing will compare the behavior and differences between different pointing gestures: left, right, up, and forward. As seen in the previous chapters, the first measurement is of an idle state, relaxed arm while no action is being performed, and the results are presented in Figure 55.

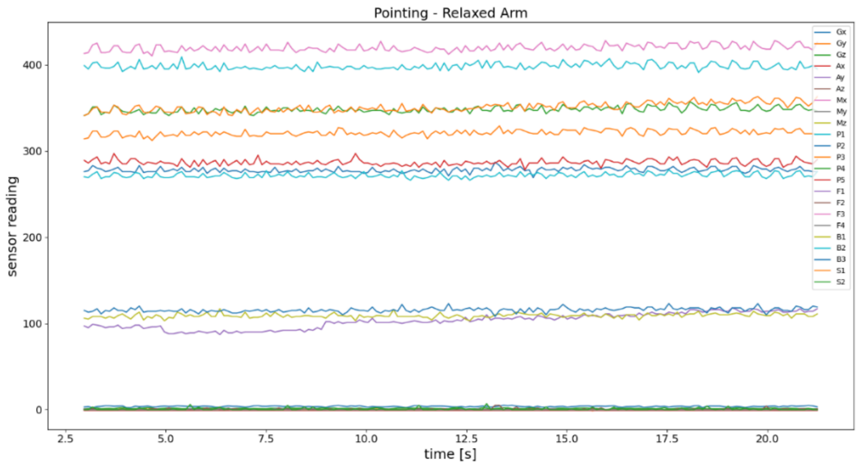

Figure 55 - Pointing - relaxed arm

- Pointing Left, Right, Forward, Up

the following testing occurred in a similar way as on 4.2.4 Hand Gestures, starting with ~5 seconds of idle, continuing to ~15 seconds of pointing, and concluding with another ~5 seconds of idle. The results of the four tests are presented in Figure 56.

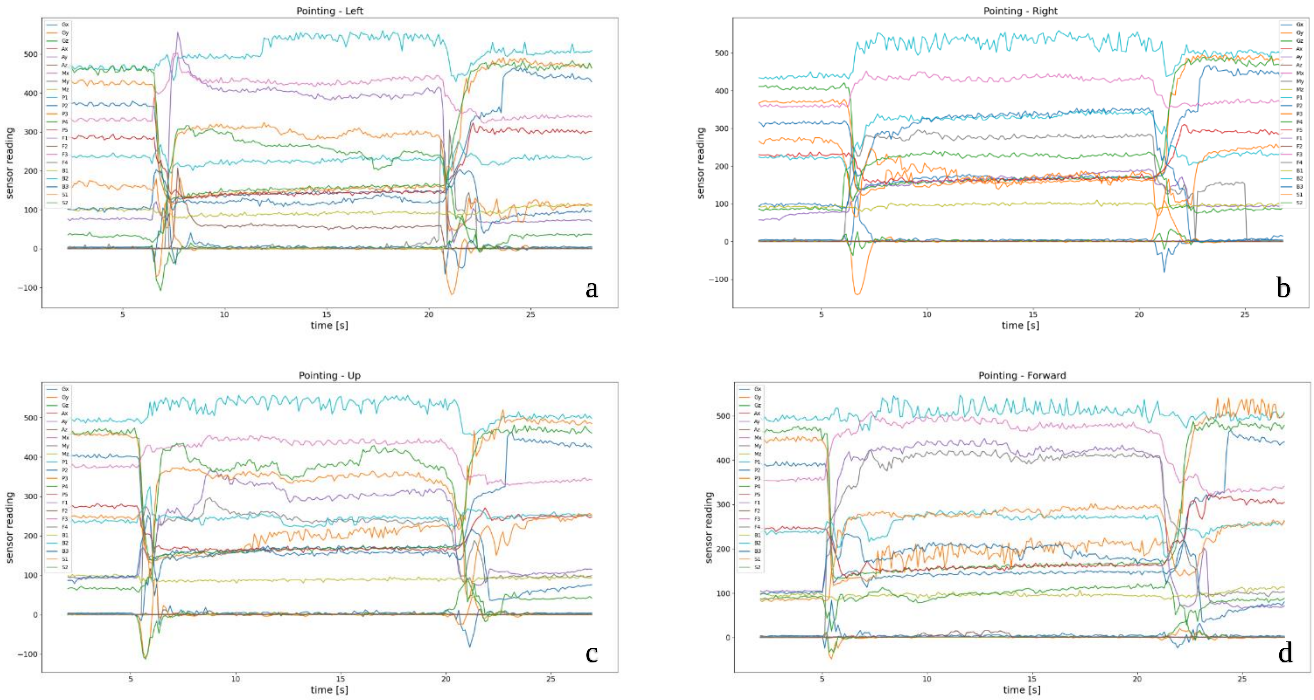

Figure 56 - Pointing

Naturally, the results are showing a significant change in the muscles over the arm, excluding the palm, since those muscles are at a pointing state that is similar in all four. if looking at P1 its values are in the range of ~500-600 in all the tests. While examining F1, which starts at ~70 in all tests, in Figure 56a the value peaks at ~600 and then goes down to ~400 for the rest of the measurement, in Figure 56b the value of F1 goes up to ~180, in Figure 56c the value is ~300 and in Figure 56c the value of F1 is steady at ~400.

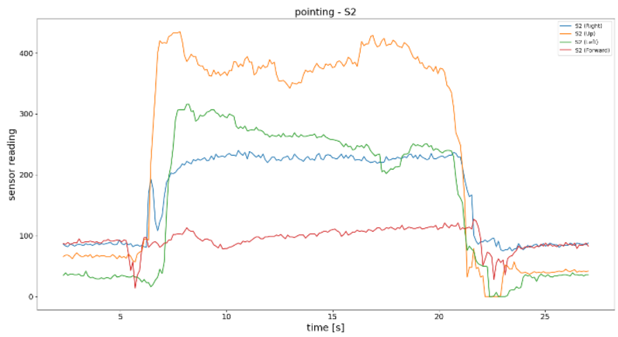

Figure 57 - Pointing, S2 sensor comparison

the shoulder muscles showed the most measurable activity during the pointing testing, S2 for example, as can be seen in Figure 57 (isolated the readings of S2 from all tests in a single chart), in “right” the value goes to ~220, in “up” it goes to ~400, in “left” it goes to ~280 and in “forward” the value is not changing significantly and peak at ~120.

5. Conclusions and summary

In this project, a system for muscle activity and arm positioning was designed. The system is constructed of five flex sensors that measure the bending of the fingers, 9 FSR sensors that measure the force applied by the arm sensors (shoulder to hand wrist), and an IMU unit that measures the linear acceleration, angular acceleration, and relative change of the magnetic field.

This project is following the previous generation, a similar system that measured only the forearm muscles using FSR-400 and IMU. The changes in the second generation are the addition of the flex sensors, for the finger bending measurement, the broad FSR sensors distribution over the entire arm, and improving the robustness of the FSR casing alongside ease of maintenance. For improvement of the data transmission rate, the total amount of sensors in the system decreased to 14 (instead of 28), thus the FET module (its purpose was to switch between sets of sensors, 14 on each set) from the first system was also removed from the new system.

the second generation used most of the first generation's components, the FSR-400, PMOD-NAV IMU, and Teensy 4.1 microcontroller. All those components were connected to a PCB designed for the first-generation system. The new system was designed to work while connected to a computer (for both power supply and data transmission), as opposed to the first generation one that was powered by a battery and transmitted the read data over a wireless communication module. The parts for the entire system structure were 3D printed from PETG using a Prusa MK3S+.

The entire array of sensors together with the IMU were worn on an arm and a series of tests were performed, the tests were constructed of actions with various items such as a screwdriver or a bottle of water, a set of gestures, and from pointing action. Those tests' goal was to validate the full system, while ultimately the purpose of it is to teach deep learning programs to operate manipulator robots in coordination with a human wearing this system, all as a part of research in the robotics lab at Tel-Aviv University. The system is designed to fit on the entire left arm and to be connected to a PC for data recording. The data recording was done by a Python script, the script communicated with Teensy via a serial communication port and wrote the entire data to a CSV (comma-separated values) file, per test. After the data recordings file was created another Python script was used to process the data and create the chart with the plotted measurement values.

the measurements for this project were made with the new improved system. The changes that were made in the second generation are the measurements of the entire arm, in comparison to the first system which used to measure the forearm only as well as the ease of maintenance (maintaining a single sensor when needed instead of the entire strap of 7 sensors). The test results showed a measurement for every sensor and every IMU value as well. The positioning of the sensors on the arm wasn't repeated between testing sessions due to a lack of validation methods.

As described, an issue that rose during the testing, that can be solved in the next generation of the system, there is no way to validate the positioning of the sensors on the arm, this might affect the measurement's repeatability over time, and a solution for that might be a more robust and fixed structure for the entire sensor array.

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8. תקציר

כחלק ממחקר במעבדת הרובוטיקה באוניברסיטת תל-אביב, יש צורך במערכת שתאפשר למפעיל אנושי לעבוד בתיאום עם רובוטים מניפולטורים. יש צורך שהרובוטים "יבינו" את הפעולה או הכוונה של המפעיל ויסייעו לו בפעולה ספציפית מבלי שהמפעיל יעשה דבר נוסף מלבד הפעולה.

המערכת הלבישה מיועדת עבור ביצוע פעולות שונות בעוד שרובוט המשתף פעולה לוקח חלק בפעולה, יחד עם המפעיל. המערכת נבנתה מתשעה חיישנים שהוצבו כנגד שרירים ומדדו את הכוח שכל שריר מייצר על החיישן במהלך הפעולה. חמישה חיישנים נוספים משמשים למדידת כיפוף האצבעות ביד במהלך הבדיקות ויחידת IMU מודדת את התאוצה הליניארית, המהירות הזוויתית והשינוי היחסי של השדה המגנטי.

מהמערכת נדרש להיות לבישה על ידי מספר משתמשים ולשדר את הנתונים למחשב שיתעד את המדידות. תכונה חשובה נוספת היא מארז החיישן, מארז נפרד לכל חישן ומבנה עמיד, כדי לוודא שיש מינימום אירועים של ניתוק של המגעים במהלך הבדיקה, וקלות תחזוקה בעת הצורך.

באמצעות המערכת תתבצע סדרת בדיקות, כל בדיקה תפיק נתונים ועבור כל מדידה והנתונים יוצגו על גבי גרף. כפי שיוצג בהמשך, נראה שהמערכת עובדת בצורה אמינה ורציפה עם קריאה עבור חיישן ולכל קריאות ה-IMU.

אוניברסיטת תל אביב

הפקולטה להנדסה ע"ש איבי ואלדר פליישמן

בית הספר לתארים מתקדמים ע"ש זנדמן סלנר

מערכת לבישה לחישה של פעילות שרירים ומיקום הזרוע

חיבור זה הוגש כעבודת גמר לקראת התואר "מוסמך אוניברסיטה" בהנדסה מכנית

על ידי

אסף הראל אלשוחט

תשרי התשפ"ג

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בהנחית ד"ר אבישי סינטוב

תשרי התשפ"ג