International Journal of Innovative Technology and Interdisciplinary Sciences
www.IJITIS.org
ISSN: 2613-7305
Volume 2, Issue 2, pp. 147-159, 2019
DOI: https://doi.org/10.15157/IJITIS.2019.2.2.147-159
Received August 25, 2018; Accepted November 16, 2018

Glove for Augmented and Virtual Reality

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ABSTRACT

This work is focused on developing and prototyping a haptic feedback system glove, which will be able to enable interaction of real arm movements with 3D computer models. This glove will be developed using only IMU for human hand data gathering. This approach should increase accuracy of device and give additional flexibility in interaction with different object. For this purpose, IMU should be tested and calibrated using complementary filters. The design and implementation of hardware and software as well as proof-of-concept experiments are presented.

Keywords: accelerometer; gyroscope; haptic glove; augmented reality; virtual reality; complementary filter.

1. INTRODUCTION

Smart gloves have the potential as an interface for human-machine interaction. In the future, they can replace the usual mouse, keyboard and joysticks. Such kind of devices offers a more intuitive interface. Therefore, engineers are finding ways to improve their efficiency.

In recent years, different augmented and virtual reality gadgets have been developed. It is due to the new virtual reality wave. In the year 2012 new start-up called Oculus was launched on the Kickstarter campaign to raise funds for the production of new virtual reality headset. The developers promised users a "full immersion effect" due to the use of displays with a resolution of 640 by 800 pixels for each eye. The result of this event was the beginning of new VR technologies development and the rapid growth of investments to the industry. Since 2015, virtual reality technologies have become new technological revolution. From year to year, the possibilities of virtual reality are becoming more available to the mass consumer. Well-known companies are engaged in the development of these technologies with as much effort as possible and make it more widely spread.

Virtual reality is the industry in which technologies evolve at the same time with the development of content. After all, if there is virtual reality helmet or glasses, there must be something to interact and to operate. That is why there are various kinds of applications of virtual reality gadgets such as:

- Movies
- Games
- Online streams
- Social networks
- Medicine
- Education

- Trading
- Industry

Virtual reality software development kit gives an opportunity to create and implement different applications and devices. There are various types of gadgets made by commercial and non-commercial developers and companies.

Virtual reality glasses immerse their users into the virtual reality, but different types of interaction with virtual reality, such as gamepads and joysticks, interfere with the effect of presence. The founders of some VR devices often complained that the reason why virtual reality gadgets cannot become wide spread is that there are not well-developed gadgets and tools for interaction with virtual reality. Haptic gloves have become an excellent solution. However, one of the disadvantages of such kind of devices is a high price, which sometimes exceeds even the cost of original glasses for virtual reality. Although, virtual reality gloves can offer the user to feel the objects in the virtual environment using haptic feedback, which gives an in-depth effect of presence. In addition, haptic gloves can have various applications in remote, virtual and human-robot interaction such as manipulation tasks. It is also possible to interact not only with virtual reality but with augmented reality as well. As an example, these gloves can be used together with VR headset and stereo cameras remotely controlling robot arm.

There are many different devices for virtual and augmented reality that were made by commercial and non-commercial companies and developers. Most of the devices have their own advantages and disadvantages in terms of their abilities and use restrictions. The most part of the devices have very similar implementation, but such devices as FESTO ExoHand [1] and DextaRobotics Dexmo Haptic Feedback Exoskeleton Gloves [2] have external mechanical exoskeleton, which makes them bulky and expensive. At the same time, FESTO ExoHand has good accuracy and can be used in different areas such as the robot and virtual reality manipulation and rehabilitation. From the other hand there are various amount of similar and popular solutions as Manus VR [3], Senso gloves [4], Goldfinger Smart Glove. These devices are based on flex sensors [5], which change their resistance by bending. These sensors are expensive and cannot register resistance change in several bending points. That is why in contrast to high-priced haptic gloves, many low-cost gloves do not provide more than one degree of freedom per finger [6], [7]. In order to solve this problem, several sensors are quite often used to increase possible DoFs. In such kind of implementations several resistive sensors per finger [5], which increases DoF. While these gloves provide additional DoFs, they lacks other important features and increase their price due to resistive (flex) sensors cost. Recent references are referred to on [19], [20], [21], and [22].

Currently, different types of sensors know as integrated measurement units are presented on the market. Such kind of IMUs has an embedded 3-axis MEMS gyroscope, a 3-axis MEMS accelerometer and even magnetometers, which gives more features and increases flexibility of device based on these sensors.

2. HUMAN WRIST ANALYSIS

Based on anatomical and medical hand analysis of previous studies and research [8], the hand skeleton model has 23 internal DOFs (Figure 1).

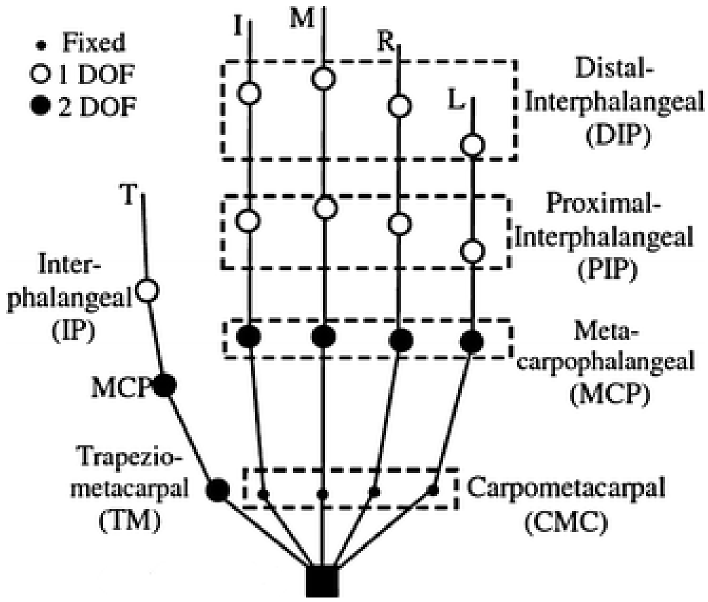

Figure 1. Human wrist model [8]

Each of the four fingers has four DOFs. The DIP and PIP joints both have one DOF, and the remaining two DOFs are located at the MCP joint. Different from the four fingers, the thumb has five DOFs. Two DOFs are at the trapeziometacarpal (TM) joint (also referred to as the carpometacarpal joint), and two are at the MCP joint. The remaining one DOF of the thumb is at the IP joint. The basic flexion/extention (F/E) and abduction/adduction (Ab/Ad) of the thumb and fingers are performed by the articulation of the 21 DOFs just described. As shown in Figure 2, the F/E motions are used to describe rotations toward and away from the palm, which occur at every joint within the hand. The abduction is the movement of separation (e.g., spreading fingers apart), and the adduction motion is the movement of approximation (e.g., folding fingers together). The Ab/Ad only occurs at each finger's MCP joint and at the thumb's MCP and TM joints. Another two internal DOFs are at the base of the fourth and fifth (ring and little finger's) metacarpals, which perform the curve or fold actions of the palm.

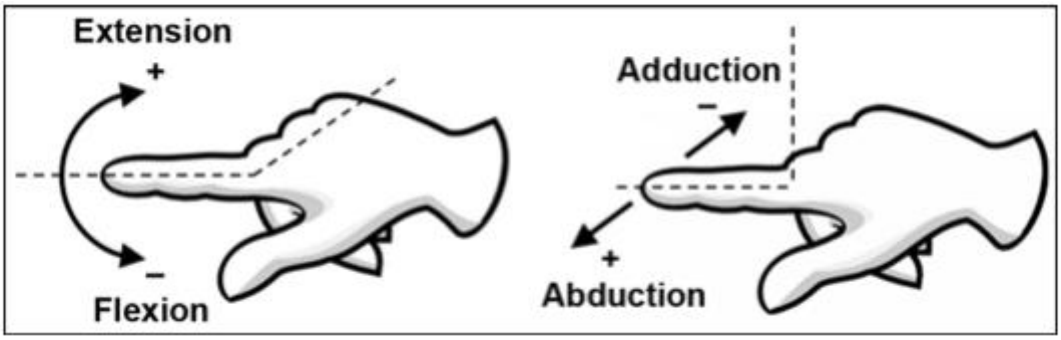

Figure 2. Denotation of flexion/extension and abduction/adduction motions of thumb and fingers. [8]

The main goal of the thesis is develope a device using the IMU sensors and knowledge about human hand physiology, which will provide realistic hand animation. For this purpose MPU6050 was chosen [9]. MPU6050 has accelerometer and gyroscope on his board and its work will be considered in the following sections. Raw data from these two sensors (gyroscope and accelerometer) can be combined and filtered using complementary filter, which gives an opportunity to calculate accurate angle and position of each finger phalange.

3. DESIGN

The main core of the glove is STM32 F413ZH [10]. The microcontroller implements system control. For hand position tracking, an IMU MPU6050 was chosen. MPU6050 has 3-axis accelerometer and 3-axis gyroscope. The sensor provides raw data of gravity acceleration and angular velocity, which can be converted into angles using trigonometric equations. The MPU-6050 features three 16-bit ADCs for digitizing the gyroscope outputs and three 16-bit ADCs for digitizing the accelerometer outputs. For precision tracking of both fast and slow motions, the parts feature a user-programmable gyroscope full-scale range of ±250, ±500, ±1000, and ±2000°/sec (dps) and a user-programmable accelerometer full-scale range of ±2g, ±4g, ±8g, and ±16g. Communication with all registers of the device is performed using I2C communication protocol at 100 kHz or in fast-mode 400kHz. The MPU6050 operates 33 different registers [9].

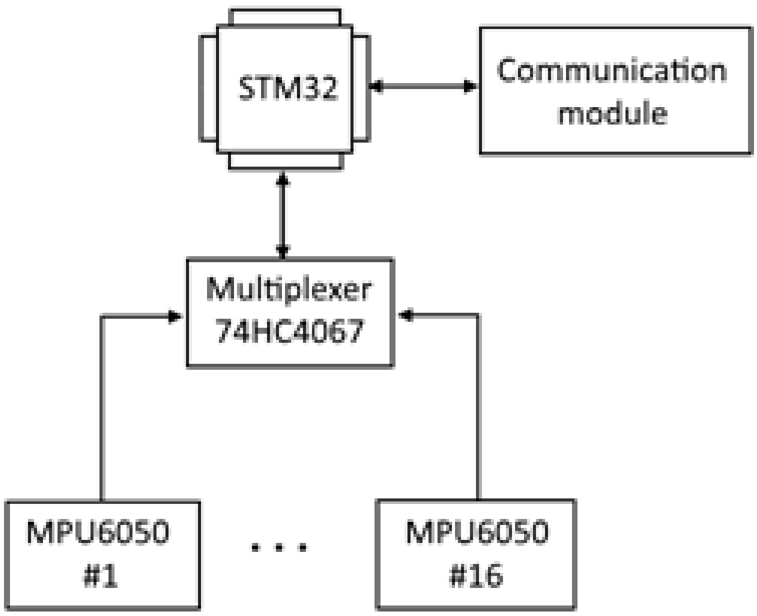

Figure 3. System block diagram

In the current work, 16 IMU sensors have been used. Each sensor has only 2 different addresses, which means that it is needed to find a way gathering data from 16 sensors. For this porpoise a multiplexer can be used. The following model [11] has 16 analog outputs and can work both modes demultiplexing and multiplexing. The presented multiplexer can be controlled by microcontroller, in this case STM32, which will send registers to 4 multiplexer inputs and reads data sequentially from it. Then, the microcontroller gathers data and sends data package to computer over DMA USART communication protocol. The DMA USART can be used in several ways. For example, the microcontroller can be connected using TTL-USB converter or Bluetooth module [12]. The USART communication protocol can be used to debug software, get and send data or commands and connect computer and microcontroller.

Therefore, the following objectives have to be solved in order to get working prototype:

1. Getting raw data from MPU6050
2. Process raw data
3. Formatting data packages from 16 sensors
4. Establish communication between microcontroller and PC
5. Sending processed data to PC

The following sections will show the solution of the objectives.

4. GETTING RAW DATA

In order to act the model to move, it is necessary to prepare data processing from the sensors. The section will focus on the explanation of the algorithms of processing, encoding/decoding data. Methods of obtaining data will be considered using C libraries. Since, the data is raw, it is necessary to convert them into angles, which are understandable for 3D model. In addition, the sensors should be calibrated according to the algorithm proposed below. As it was mentioned above, the chosen sensors only can give information about angular displacement or gravity force vectors. Therefore, it means that these data has to be converted into angles. Getting angles is possible by using Euler angles and integrating in case of gyroscopes. There are different ways how to calculate angles. For example, instead of Euler angles it is possible to calculate them by quaternions. Comparing to quaternions, Euler angles are simple and intuitive and they can be used to perform a simple analysis and control. On the other hand, Euler Angles are limited by a phenomenon called "Gimbal Lock". In applications where the sensor will never operate near pitch angles of +/- 90 degrees, Euler Angles are a good choice. Euler angles provide a way to represent the 3D orientation of an object using a combination of three rotations about different axes.

As soon as MPU6050 are using I2C communication protocol, it is needed to use C generation libraries TM_STM32_MPU6050, which are free available on GitHub [13]. It will make the use of sensors much more convenient and faster, because the I2C workflow means that a lot of work should be performed by sequences and registers. At the same time, the use of libraries makes program code more readable and makes workflow with sensors more suitable for controlling data. For example, only one line is responsible for initializing all 16 sensors, the sensitivity is easily changeable by changing arguments.

As it was mentioned above, the MPU6050 have different sensitivity setting, thus during initialization, the following settings were chosen for sensors:

- Accelerometer +/- 2 g
- Gyroscope +/- 500 °/sec

For initialization, the function TM_MPU6050_Init from TM_STM32_MPU6050 library was used. It should be taken into consideration as well that each operating sensor should be initialized, otherwise the program will not start perform.

Once all sensors are initialized in main function, there is no need to return to this function. After that infinite while loop will start workflow. In this while loop all program code performs and reads data from sensor. All raw data writes to the following variables:

```
TM_MPU6050_ReadAll(&MPU6050_Sensor);

ax = MPU6050_Sensor.Accelerometer_X;
ay = MPU6050_Sensor.Accelerometer_Y;
az = MPU6050_Sensor.Accelerometer_Z;
gx = MPU6050_Sensor.Gyroscope_X;
gy = MPU6050_Sensor.Gyroscope_Y;
gz = MPU6050_Sensor.Gyroscope_Z;
```

Figure 4. Writing raw data to variables

The received values contain information about the gyroscope rotation and forces acting on the accelerometer axes. These data has to be converted to understandable view according to the sensitivity, which has been chosen during initialization. In the other words, the received data has to be divided by the corresponding sensor sensitivity values. On the figure 5 it is seen how processing has been performed. All possible values can be found in datasheet [9].

```
/*==== Processing Accelerometer Data ====*/
gForceX = ax / 16384.0;
gForceY = ay / 16384.0;
gForceZ = az / 16384.0;

/*==== Accellerometer data clamping ====*/
gForceX = clamp(gForceX, -1.0, 1.0);
gForceY = clamp(gForceY, -1.0, 1.0);
gForceZ = clamp(gForceZ, -1.0, 1.0);

/*=== Processing Gyroscope Data ===*/

rotX = gx / 131.0;
rotY = gy / 131.0;
rotZ = gz / 131.0;
```

Figure 5. Raw data processing

In addition, the clamping function has been written in order to cut excessive information from accelerometers to prevent and clamp instabilities when rotation axes happen to become aligned with gravity. The clamp function restricts values in +/- 1g range.

5. ANGLE CALCULATING

Inertial measurement unit is an electronic device, which indicates changing orientation in smart phones, video games remote control joysticks, quadcopters, etc. These devices contains several sensors such as accelerometers, gyroscopes or magnetometers. The number of sensor inputs in an IMU are referred to as DoF. Therefore, a chip with a 3-axis gyroscope and 3-axes accelerometer will be a 6-DoF IMU.

Accelerometers are sensitive to both linear acceleration and the local gravitational field. There are different types of accelerometers. During this study, digital accelerometers will be used, which communicate over I2C communication protocols. . The most common use is in consumer electronics, such as smartphones, portrait frames, etc.

The working principle of MEMS accelerometers gives a displacement orientation of accelerometers according to suspended mass. The deflection of the proof mass is measured from the change in capacitance between the fingers of the proof mass and the sensing plates. Each accelerometer has a zero-g voltage level. To produce the final reading it is needed to divide the zero-g level by the sensitivity as it was shown on the figure 5. Computing orientation from an accelerometer relies on a constant gravitational pull of 1g (9.8 m/s^2) downwards.

Once get these accelerometer axes orientation data, it is possible to calculate angle. As it was mentioned above, there exist several possible ways how to calculate angle using either Euler angles or quaternions. Euler angles were chosen since their simplicity and as possibility of proof of concept justification.

The approach how to find angle of various objects with respect to gravity of the earth is executed by an instrument called an inclinometer. It is also known as a tilt indicator, tilt sensor, tilt meter and etc. There are several physical principles, on the basis of which an inclinometer can be created. Most often, the slope is determined by the gravity force, geomagnetic field, gyroscopic effect or indirect measurements. Any of the listed principles has its pros and cons.

If the gravity force is the only force acting on the object, then in this case the MEMS-accelerometer, an instrument that measures the projection of acceleration on its axis, can be used to determine the angle of inclination of the object. The magnitude of the measured projection determines the angle of inclination.

In the real life, besides the force of gravity the other forces can act on the object, such forces caused by rotation, jolting, shaking, etc. Since the force of gravity has a constant value, any additional forces acting on the object will change the output value of the accelerometer, and consequently an error will appear during the calculation of the inclination angle. By applying preliminary processing of the output signal of the accelerometer, it is possible to reduce the influence of the other forces.

In the ideal case, where the force of gravity is always in the same plane of X axis of the object, it is possible to calculate and obtain an expression of the projection of the gravity force on the axis using simple trigonometry equations.

In a single-axis case, achievement of high resolution on a wide range of measurements is possible only using a high-resolution accelerometer. In addition, such circuit cannot operate in a full range of angles (0º - 360º), because the sine values are the same for angles from Nº to 180º-Nº.

To get rid of these disadvantages, the additional axis y, orthogonal to x, should be included. Two axes using gives an opportunity to find all possible angles. In the starting position the x and y axis are in the horizontal plane and the z axis is orthogonal to the x and y axes (Figure 6).

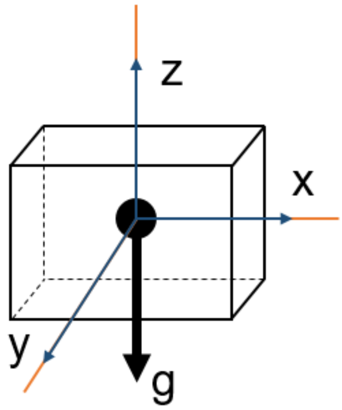

Figure 6. Initial position of accelerometer

In the initial position, when the gravity force acts only in the opposite direction along the z axis, it is seen that all angles are equal to 0. From the properties of the sine and cosine functions it follows that while the sensitivity along one axis will decrease, it will also increase on the other. Moreover, the angles can be calculated by the following formulas:

$$\alpha = \arctan\left(\frac{A_x}{A_z}\right) \#$$

$$\beta = \arctan\left(\frac{A_y}{A_z}\right) \#$$

$$\gamma = \arctan\left(\frac{A_y}{A_x}\right) \#$$

where Ax – gravity force vector along x axis, g,
Ay – gravity force vector along y axis, g,
Az – gravity force vector along z axis, g.

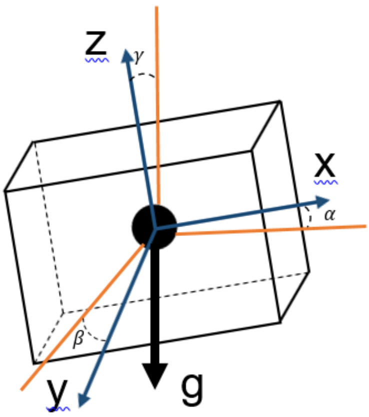

Figure 7. Rotation position of three axes

The second step is getting angles using gyroscope. The gyroscope measures not the acceleration and not the angle, but the angular velocity. Therefore, it is much less sensitive to the noise vibrations. To obtain the angle from the angular velocity, the gyroscope readings must be integrated and an initial angle (i.e., zero angle of the gyroscope) added to them. Integration is performed according to the algorithm.

$$\alpha(t) = \alpha(t-1) + \text{rawData} * dt$$

where, $\alpha(t)$ - current angle, deg,
$\alpha(t-1)$ - angle at the previous time period, deg,
rawData - raw data from the accelerometer, deg/ms,
dt – step time, ms.

At the same time the gyroscopes have the other types of problems. It is seen on the figure 8 if the sensor, that has both built-in gyroscope and accelerometer, is in the stable position and it does not move, the angle from accelerometer is also stable, but received angle from gyrosope has static error called "drift".

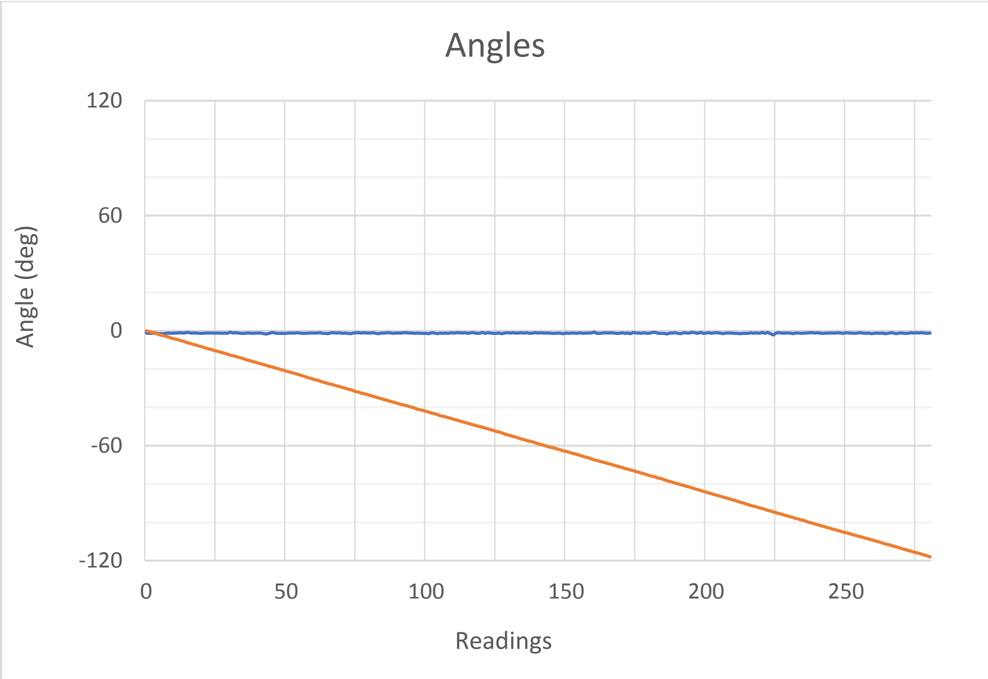

Figure 8. Compering data from accelerometer and gyroscope

Averaging the data that comes from the accelerometers and the gyroscopes can produce a better estimate of orientation than obtained using accelerometer data only. In order to solve the problem, a complementary filter has been chosen. The complementary filter is a combination of two or more device data that combines the information from different sources and gets the best value. In this case, the filter combines and estimates readings from accelerometer and gyroscope. The following algorithm performs an integrating and adding part:

$$\theta_{filtered} = FK * \theta_{accel}(t) + (FK - 1) * \theta_{gyro}(t - 1)\#$$

where θ_{accel} – angle from the accelerometer, deg,
θ_{gyro} – angle from the gyroscope, deg,
$\theta_{filtered}$ – filtered angle, deg,
FK – complementary filter coefficient can be adjusted from 0 to 1.

As a result the final graph was plotted in order to justify that filtered angle has advantages of both devices and lack of disadvantages.

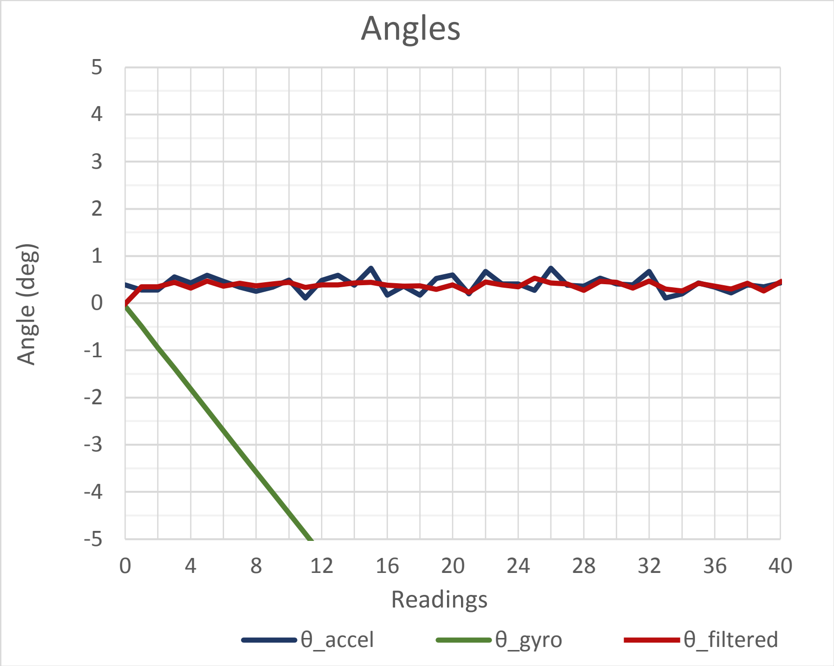

Figure 9. Three angles

6. MATLAB Simulation

For the visualization of the prototype, it is needed to make simulation in appropriate software. Such kind of programs as MATLAB/Simulink have simulation features for such kind of issues. Using Simulink it is possible to visualize and implement received data in Simscape add-on [SIMSCAPE WEBSITE REFERENCE]. The 3D arm is representation of human arm should be make in order to transfer it into MATLAB. The design of the following prototype is made corresponding to the human hand analysis. The model must correspond and have sufficient DoFs according to the analysis of the human hand, which was considered in previous paragraphs.

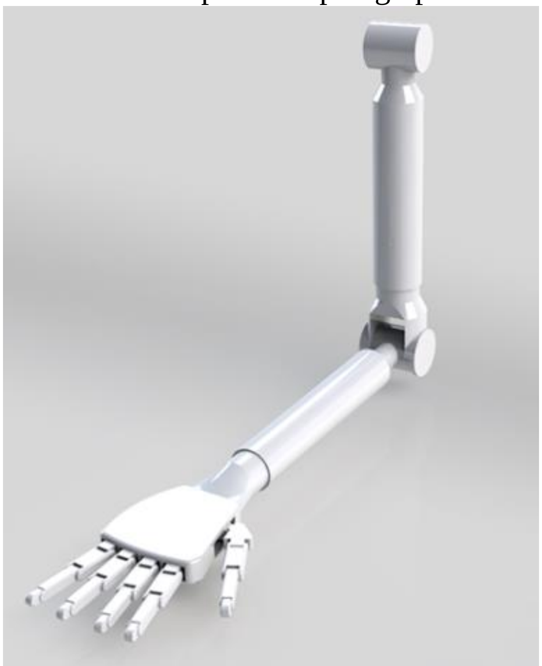

Figure 10. 3D hand

The 3D hand was modelled also based on previous studies [14] and modified according to the current objectives. All modifications were performed by SolidWorks software.

7. PROTOTYPING

In order to justify all presented theoretical algorithms and math, a primary prototype has been made. The prototype has been created using presented sensors. In addition, the glove was bought and the sensors were placed on it by double-sided tape. STM32 F413ZH microcontroller was used for performing software.

Figure 11. Glove prototype

A breadboard was used to wire sensors and connect multiplexer to the microcontroller. All sensors should be connected in parallel in order to prevent voltage and current drop along the circuit.

8. EXPEREMENTAL RESULTS

This section is dedicated to experimental results and performed tests based on the presented prototype and 3D model. . As soon as the current work is focused on virtual reality, the result should be presented graphically, which means that different hand angles and finger phalanges positions will be plotted. All tests were performed using MATLAB Simscape.

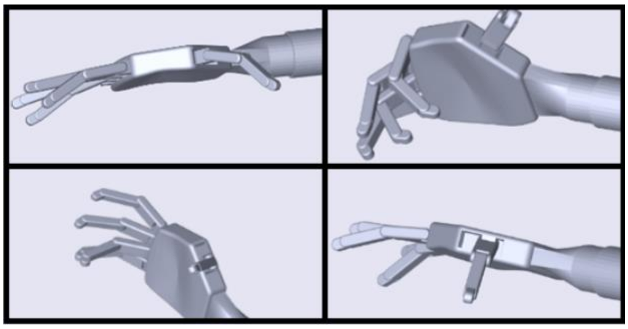

Figure 12. Hand positions

On the figure 12 are presented different hand positions which correspond to real arm movements.

9. CONCLUSION

One of the advantages of the system is that it can provide 23 degrees of freedom, which equals to the real human arm DoFs and it was the main goal. The glove can fit the different people with different hands. The ability to change software for the personal needs depending on the desired degrees of freedom of model. The same applies to the flexibility of measuring angles. The final cost of prototype is approximately 40 euros, which can be considered as low-cost project. The most difficult part was dedicated to sensor readings, as soon as these sensors are using rather difficult communication protocol and given number of sensors. However, the use of analog multiplexer allows solving this problem.

ACKNOWLEDGMENT

The author would like to thank Tallinn University of Technology (TalTech) for supporting this research project.

CONFLICT OF INTERESTS

The author would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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