A Novel Portable Tracking Device with Kalman Filter for Hand and Arm Rehabilitation Applications

Veselin Lalov and Agata Manolova(✉)

Faculty of Telecommunications, Technical University of Sofia,
blvd. Kliment Ohridski 8, 1796 Sofia, Bulgaria
veselinlalov@mail.bg, amanolova@tu-sofia.bg

Abstract. Utilising MEMS technology motion sensors and algorithms for motion data processing, a prototype device is proposed as a viable solution for movement diagnostics during sports or rehabilitation activities, based on the documented in the medical journals benefits of eccentric resistive training with full range of motion. The proposed device evaluates the quality of the movement by measuring the range of motion and both eccentric and concentric phases of the movement.

Keywords: Kalman filter · Tendopathy · Rehabilitation · Signal processing

1 Introduction

A lot of research from different fields experts is put into regaining or increasing the human body functionalities with the use of emerging technologies such as robotics, computer vision, virtual reality and braincomputer interfaces to enhance the user's independence or fitness level. These arising fields will make possible for a better living by allowing remote assistance from the medical personnel, which in turn may reduce the stress of a visit to the hospital [1] or the pain patients with mobility impairments experience [2]. The patients will benefit from the possibility of remote interaction with their doctors without going outside their comfort zone and also carry out the training from their home, under remote supervision, reducing the cost to the healthcare system. For doctors, these types of assistive rehabilitation mobile devices provide online remote monitoring of the rehabilitation process with possibility to record patient's history.

A connected wearable device with appropriately designed interface will enable therapists to engage with an increasing number of patients without the physical burden of providing the therapy in the hospital. Therapists would then be able to perform a more prescriptive role whilst the device takes care of the manual tasks. From the data gathered from research that has been made in the previous years in the physical medicine and rehabilitation branches of medicine, the

V. Poulkov (Ed.): FABULOUS 2019, LNICST 283, pp. 67–75, 2019.
https://doi.org/10.1007/978-3-030-23976-3_7

results for wearable devices have shown an emergence of a correlation with positive effects such as improved tendon healing and decreased rehabilitation time in patients suffering from tendinopathic conditions such as tendonitis and tendinosis when eccentric based exercises are used in the rehabilitation regimes of the patients [3–6].

Based on the numerous evidence in support of the eccentric training regimes in rehabilitation, it has led the authors of this study to the development of a device with a supportive purpose during rehabilitation or in aid of the research activities in the medical fields. This papers main objective is to provide a brief overview and description of the software and hardware parts of the developed device. Research and testing has been made on the algorithm for calculating the range of motion and angular velocity regarding it's accurate calculations and reliable use, during the intended operation of the device.

The main goal of this paper is to present a development of a prototype of a A novel portable tracking device with Kalman filter for hand and arm rehabilitation applications based on low-cost sensors with mobile interface.

The rest of the paper is organized as follows: the next section describes the device in details. Section III introduces the data analysis to evaluate the device's performance. The final section draws the conclusion and suggests the scope of future work.

2 Device Description

The device consists of an Arduino Micro-Pro as a processing unit, a three-axis accelerometer and gyroscope MPU-6050 and a HC-06 Bluetooth 2.0 module. The communications between the device and smartphone is established via Android application which shows in real time the range of motion in degrees and the corresponding phase of the movement (eccentric or concentric), measured by the angular speed with degrees per second. The prototypes modules are shown on the Fig. 1.

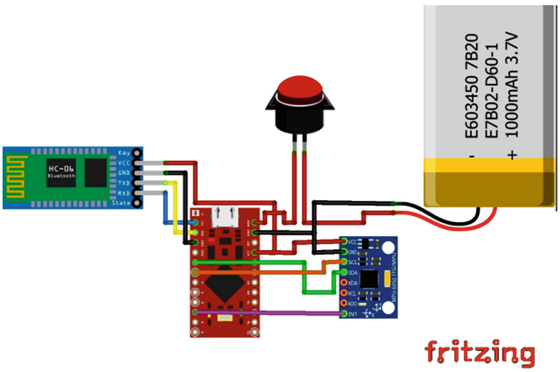

Fig. 1. Device overview.

The MPU-6050 measures raw data for the acceleration on the x, y and z axis (pitch, roll and yaw) and the angular velocity on the above described axes in the form of 16 bit words and transmits it to the Arduino Micro-Pro trough I2C interface. The orientation of the axes are shown on the figure below, provided in the data sheet of the manufacturer of the MPU-6050 (Fig. 2).

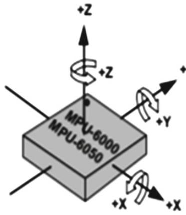

Fig. 2. Axis orientation of the MPU-6050 accelerometer and gyroscope

The processing unit calculates the acceleration and angular velocity trough the mathematical equations: Eq. 1 describes the Eulers angle on the y axis and Eq. 2 represents the rotation on the z axis with a constant provided by the data sheet of the manufacturer.

$$tan^{-1}\theta_y = \frac{-Acc_X}{\sqrt{(Acc_y)^2 + (Acc_z)^2}} \quad [deg] \tag{1}$$

$$Yaw_{rotation} = \frac{Gyro_Z}{32.8} \quad \left[\frac{deg}{s}\right] \tag{2}$$

Acc_x, Acc_y, Acc_z and $Gyro_Z$ represent the raw data readings from the MPU-6050.

After the raw data is converted to measurable units with Eqs. 1 and 2 the $Yaw_{rotation}$ angular velocity and the pitch angle are ran through a filtering algorithm.

The output data from the filter is then ran through an algorithm which describes the exercise done by the user. The algorithm in the processing unit is an if-else type state machine, which switches its conditional statements depending on the exercise selected by the user with the smartphone application. Each exercise is described with different conditional statements in order to ensure the correct execution of the movement by measuring the range of motion (ROM) and the quality of the movement as well by measuring the angular velocity (Yaw rotation). The pseudo code below illustrates an example algorithm flow of the exercise known as Bicep curl:

Algorithm 1. Range of motion and quality of movement

while ∞ **do**
  if $pitch > 45$ **then**
    $flagCon = 1$ {Concentric phase completed}
  end if
  if $pitch < -60 \quad and \quad flagCon = 1$ **then**
    $flagEcc = 1$ {Eccentric phase completed}
    $repetitions++$ {One repetition of set is completed}
  end if
  if $GyroZ < -650 \; or \; sensorValue < 0 \; and \; GyroZ > 650 \; and \; flagCon = 1$ **then**
    $(bluetoothSendFailSet)${Exits Loop}
  end if
  if $repetitions = targetRepetitions$ **then**
    $(bluetoothSendSetCompleted)$ {Exits Loop}
  end if
end while

The algorithm detects if the user has reached the end of both phases of the movement by measuring the pitch angle, verifying if the exercise is executed with proper range of motion. There is a condition for ensuring the quality of the movement (e.g. the user is making the movement in a controlled manner) by measuring the angular velocity on the yaw axis. If the conditions are met then a counter, representing the number of repetitions is incremented until it is equal to the number of selected repetitions from the user, sending a Successful set. notification to the user. In case the user has not made the movement with the required range of motion conditions or if the movement is made in a fast manner, the device sends a Failed set. notification to the smartphone of the user.

The smartphone is used as a terminal between the user and the prototype device, with which the user can select the exercise, number of repetitions to perform and receive notifications from the device. Other functions of the application is to show the status of the connection and a test command to evaluate the connection between the device and the smartphone. The figure below shows the basic interface of the application.

Regarding the numerous research indicating correlation with faster healing of connective tissue, the constructed device could be used for sports and medical applications as a tool for doctors and medical personnel for diagnostic purposes [7] (Fig. 3).

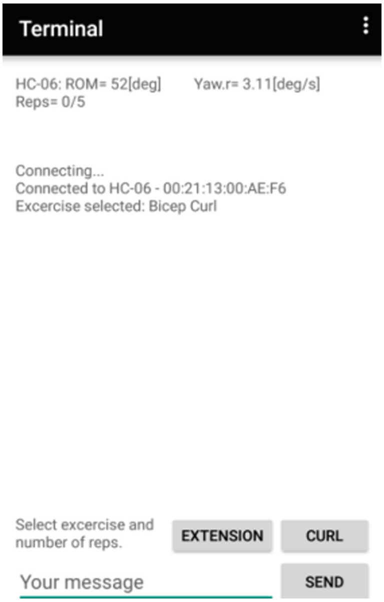

Fig. 3. Smartphone application overview.

The next picture shows the developed prototype of the device (Fig. 4).

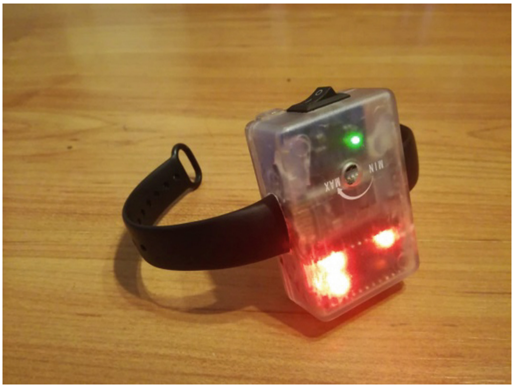

Fig. 4. Prototype of the device.

3 Data Analysis

In this chapter a comparison of the output data is made between the filtered and non-filtered data. The filtering algorithm is a Kalman filter [8], which filters the noise of the pitch angle data and corrects gyroscope data drift coming from the

MPU-6050. The point of this experiment is to show the key role of the application of a filtering algorithm to the device. Isometric contractions during an exercise performed by the user are a natural part of the movement when a muscle group is experiencing resistive load. These isometric contractions can lead the device being subjugated to vibrations (Fig. 5).

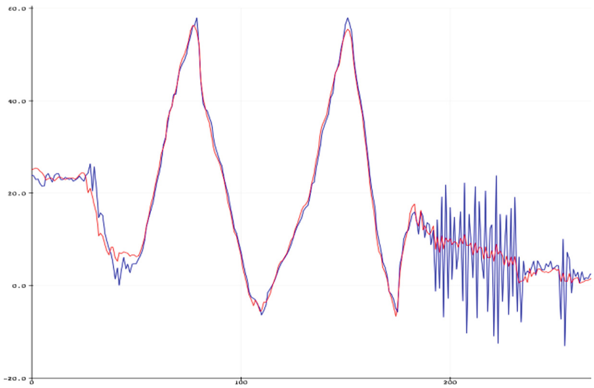

Fig. 5. Filtered data using Kalman filter versus no data filtration. (Color figure online)

On the graph above it is shown the output data from the accelerometer, illustrating the pitch angle. The red line represents the output data from the Kalman filter and the blue line, the data when there is no filtration applied. In the end of the graph the non-filtered data shows a large swing of the amplitude when there is vibration applied to the device. The red line representing the Kalman filtered data shows little variance of the pitch angle when there is vibration applied to the device. Thus, the implementation of a Kalman filter is crucial for achieving more accurate data for the pitch angle and preventing faulty notifications to the user, which can be a result of the inaccurate readings from the accelerometer when there is vibration applied to the device.

The next graph shows the second role of the Kalman filter, implemented in the device. Gyroscope data drift is a common problem of the MEMS technology based gyroscope devices. It is represented by linear increase or decrease of the angular velocity even though the device is not in motion. With the red line, the Kalman filter output data of the angular velocity is shown and with the blue line when there is no filtrating algorithm applied (Fig. 6).

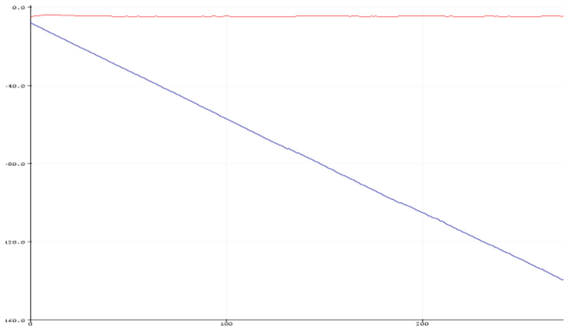

Fig. 6. Gyroscope data correction using Kalman filter. (Color figure online)

On the graph above it is shown that the corrected data is static and does not show any significant variance. When there is no filtration applied, it is shown linear change of the angular velocity. This would make the algorithm for quality of movement detection unusable, due to the inaccurate data for the eccentric and concentric phase of the movement, based on the angular velocity provided by the gyroscope. The next following pictures demonstrate the basic principle of operation of the device. On the left we see the subject reaching the end of both phases of the movements of the exercise. On the right it is shown the displayed information on the application in the smartphone of the corresponding phases of the movement.

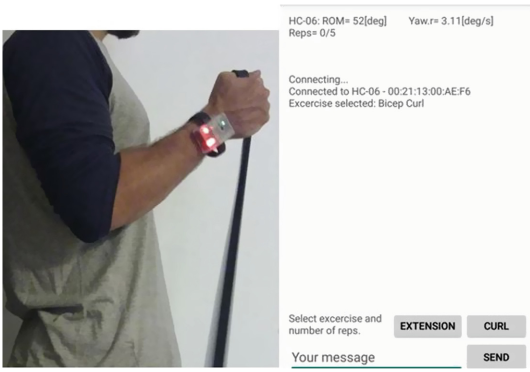

Fig. 7. Concentric phase reached.

Fig. 8. Eccentric phase reached.

On the right side of the figures, we can see on the terminal application the current angle of the arm, which measures the range of motion of the user, denoted as "Range of motion" (Figs. 7 and 8) and the angular velocity, which measures the quality of the movement by how well the movement is executed in a controlled manner. The angular velocity is denoted as "Yaw rotation" on the display of the smartphone. Negative values of the angular velocity correspond to the eccentric phase of the movement, hence the eccentric phase representing the negative portion of the movement (Fig. 8) and suchlike interpretations can be made for the concentric, positive phase of the movement (Fig. 7).

4 Conclusion and Future Work

The proposed device could be used in aid of the rehabilitation process of patients, suffering from tendinopathy or similar conditions, when eccentric or concentric based rehabilitation regime is utilized, by helping the patient maintain proper form during the rehabilitation process, which is crucial for the effective treatment. The developed device can be used for further research about the effectiveness on eccentric based recovery regimes or similar as an useful tool in aid of researchers during their studies and investigations regarding the mentioned above techniques for rehabilitation.

The observed data from the data analysis provides evidence in the utility of the algorithm in the developed device as a practical and functional method of calculating the range of motion and the quality of the movement during exercise in a reliable and accurate way.

Future endeavours would include a better graphic user interface, graphing the movement as an useful insight of the history of the achieved range of motion for each executed repetition of the set. Statistical database showing the improvements of the range of motion of the patient over time. Improved hardware with an aim to decrease the dimensions of the device. Further software improvements would include faster algorithm calculations and the previously mentioned GUI improvements.

Acknowledgements. This work was supported by European Regional Development Fund and the Operational Program "Science and Education for Smart Growth" under contract UNITe- BG05M2OP001-1.001-0004-01 (2018–2023). The authors of this study would like to thank Michel Aflak and Kristian Lauszus. The base application "Bluetooth-Terminal", developed by Michel and the Kalman filter algorithm and blog post about the algorithm, developed and written by Kristian, proved to be of great use throughout the development of the device. The authors of this study would like also to thank the associate professors of the faculty of Telecommunications at Technical University of Sofia, Bulgaria for their recommendations, review and feedback, during the writing of this research paper.

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