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Development of Knee Angle Estimation System based on Internet of Things Method

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Abstract:
Gait analysis plays an important role in diagnosis and treatment of patients with gait disorders. Since this analysis is done in a closed area with a determined space such as a laboratory, patients could be affected negatively from this environment. Consequently, correct results would not be obtained. Lately, there is an increase in the use of wearable, remote viewable, controllable systems with the increasing interest to wearable sensor technology and the development of web and sensor technologies. This study worked on knee angle estimation, a part of gait analysis, via 3-axis inertial measurement unit (IMU) and aimed graphically viewing accessible anywhere through the Internet. Sensors used in the study are 3-axis gyroscope, 3-axis accelerometer and 3-axis magnetometer. NodeMCU development card including WiFi module used to connect Internet and import values. After calibrating sensors, the study benefited from DCM coordinate transformation method, Euler angles and quaternion methods for orientation estimation and angle calculation. Angle is saved in database through internet of things and graphically presented in web interface.

Keywords: Inertial Measurement Unit, Internet Of Things, DCM Coordinate Transformation, Euler Angles, Quaternion.

I. INTRODUCTION

Today, the internet of things is used in many areas of daily life as it provides technological convenience. Despite the increasingly widespread usage area, there is no common definition for the term. ITU (International Telecommunication Union) defines the internet of things as a global infrastructure for the information society, which connects all kinds of things, based on existing and interoperable information and communication Technologies [1].

The development of sensor and networking technology and "anytime, anywhere, under any conditions" understanding of communication has enabled people as well as the objects to communicate with each other.

The internet of things is used in health [2-4], agriculture [5-7], sports [8-10], education [11-13], industry [14-16] and many other areas [17-20] and applications are being developed.

We can examine the internet of things in three parts: (i) industrial applications, such as production, logistics, banking, service sector; (ii) environmental applications in areas used, such as recycling, environmental management, energy management, agriculture, which aims to protect and monitor the continuity of natural resources; (iii) social applications including services in areas such as health, management, transportation, regulation of community and city life, intelligent services that enable people to live more comfortably and quality and use their time efficiently.

Similarly, wearable sensors with the Internet of things which used in healthcare are a system that provides convenience especially for doctors, plays an important role in treatment outcomes and patient follow-up mechanism, and make things easier.

Gait is one of the human body functions that wearable sensors are used. Gait is a highly complex function controlled by the nervous system, with many centers of the body involved.
Gait analysis systems are necessary to identify the walking phases, determine the kinetic and kinematic parameters of walking situations and evaluate the musculoskeletal functions numerically [21].

In general, in gait analysis are carried out by getting patients walk on a certain length of platform equipped with cameras. The images recorded with cameras are processed with various techniques and gait analysis is defined. However, the patient cannot walk naturally on the platform since she/he is affected by the environment. The most suitable places to observe the gait are places where the patient spends her/his time, such as streets, shopping centers and houses. Therefore, remote traceable walking analysis systems have been developed with the development of the Internet and wearable sensor technology.

One of the parameters used in the gait analysis is the knee angle. Disorders of the knee joint and movement limitation can be determined by measuring the angle of the knee through the Internet of things.

This study proposes a wearable system to determine the angle of knee with the inertial sensors using the Internet of Things method.

In this study, as hardware, Pololu 3-axis MinIMU-9 v3 inertial sensor, NodeMCU development board, TCA9548A I2C connection multiplexer was used. As the method, DCM filter, euler angles and quaternion method was used.

II. MATERIALS AND METHODS

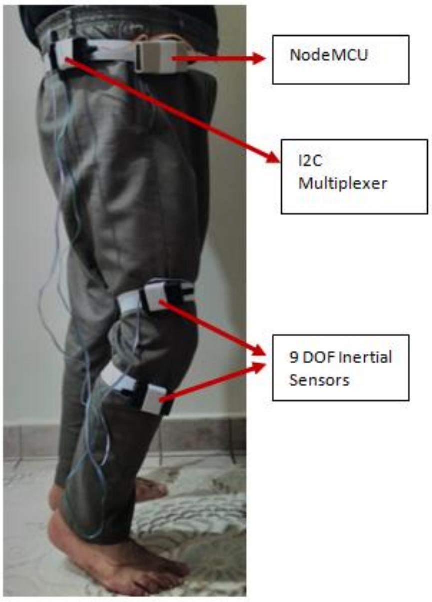

Figure 1.Positioning of Sensors

2.1. Study Materials Used

In this study, MinIMU-9 v3 inertial sensor, NodeMCU development board, TCA9548A I2C connection multiplexer is used.

2.1.1. MinIMU-9 v3 Inertial Sensor

Various sensors are used to measure the angular velocity, direction and gravitational forces of the joints and segments in each extremity. These sensors include accelerometers, gyroscopes and compass / magnetic resistance sensors. The structure that collects these sensors in one module is called IMU. In IMU, these three sensors can be combined or can only be in the form of accelerometer and gyroscope.

In our study, Pololu MinIMU-9 v3 module was used.

MinIMU 9v-3 inertial module consists of L3GD20H 3-axis gyroscope and LSM303D 3-axis accelerometer and magnetometer sensors.

The sensors provide nine independent rotation, acceleration and magnetic reading data (9 DOF- The DOF term refers to the degree of freedom of the IMU. Each axis is 1 DOF.). The gyroscope can be used to monitor rotation on a short time scale sensitively. The accelerometer and compass can help compensate for the gyroscope shift over time by providing an absolute reference frame.

The sensors on the module use the I2C communication protocol.

I2C Communication Protocol

The I2C protocol is a protocol that allows the use of multiple slave digital circuits to communicate with one or more masters. I2C is designed for short distance communication [22].

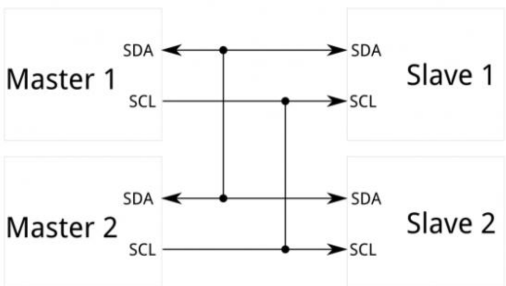

Figure 2. I2C Communication Protocol

Each I2C data bus consists of two signals: SCL and SDA. SDA is the data signal. It is the line of data transfer between the devices. SCL is the clock signal and provides synchronization of data exchange.

2.1.2. NodeMCU Program Developmet Card

On the basis of the Internet of things, there are interconnected and communicating devices. These devices watch and use things in real world like industrial devices, buildings, home applications, people. Design, development, feedback of hardware and software components and communication with each other are very important in applications of Internet of Things. A variety of platforms available such as Arduino and rasperry pi for the quick development of these applications and to modify on a fixed system instead of re-draw circuit boards at each time . Yet, the most important point is connecting to the Internet. Therefore, in this study, NodeMCU development card is used because of the internal wifi module and of its easier usage.

NodeMCU is an open source, interactive, programmable, low cost, easier to use development board with ESP8266 wifi module [23].

Figure 3. NodeMCU

The ESP8266 Wifi module is a module that can be easily connected to a wireless internet network via TTL (serial communication) and allows other devices to connect to this network by sharing this network.

2.1.3. TCA9548A I2C Multiplexer (I2C Connection Multiplexer)

The TCA9548A multiplexes I2C address of the card with one I2C data bus and provides data exchange with multiple sensors at the same time.

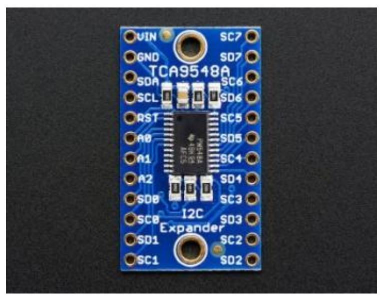

Figure 4. TCA9548A pins

For communication, the SDA and SCL pins of the module are connected to the SDA and SCL pins of the main module. Multi-use is provided by connecting devices to each SD-SC pin on the module. 8 I2C communication devices can be connected at the same time.

2.2. Filters and Methods

2.2.1. DCM (Directional Cosine Matrix) Coordinate Transformation Matrix Filter

DCM coordinate transformation is a method that provides conversion from body coordinates to local coordinates [24].

If we denote the body coordinates with b, and the local coordinates with n in the application of coordinate conversion filter, the display of the filter is as follows:

$$C_b^n = \begin{bmatrix} cos\psi cos\theta & cos\psi sin\phi sin\phi - sin\psi cos\phi & cos\psi sin\phi cos\phi + sin\psi sin\phi \\ sin\psi cos\theta & sin\psi sin\theta sin\phi + cos\psi cos\theta & sin\psi sin\theta cos\phi - cos\psi sin\phi \\ -sin\theta & cos\theta sin\phi & cos\theta cos\phi \end{bmatrix}$$

Euler (orientation angles) are obtained by transformation of C_b^n matrix.

Roll $-\phi$ = arctan ($C^n_{b3,2}, C^n_{b3,3}$)

Pitch $-\theta$ = -arcsin ($C^n_{b3,1}$)

Yaw $-\psi$ = arctan ($CC^n_{b2,1}, C^n_{b1,1}$)

2.2.2. Euler Angles

Euler angles are used to describe the 3D orientation movement of a body in space [25]. It is the angle system used to show the transformation of the body's coordinate system according to a fixed reference coordinate system.
Conversion angles; the turns around the x-axis are called roll (ϕ), the turns around the y-axis are called pitch (θ), and the turns around the z-axis are called yaw (ψ).

2.2.3. Quaternion Method

Quaternions were first used by the Irish mathematician William Rowan Hamilton in 1843. [26].
Quaternion cluster is a 4-dimensional vector defined as H.

$$H = \{w + xi + yj + zk \vee w, x, y, z, k \in R\}$$

Matrix representation is as follows:

$$q_k = \begin{bmatrix} q_w \\ q_x \\ q_y \\ q_z \end{bmatrix} \quad q_k = w + xi + yj + zk$$

Quaternions are widely used in the modeling of robot arms and velocity, orientation and position estimation of three-dimensional movements. At the time of movement, axes overlap in result of rotations in 3-axis plane defined with Euler angles, this problem named "Gimbal Lock". Therefore shifts and losses occur in the data. Quaternions or DCM matrix are used to overcome this problem [27].

Calculation of DCM matrix from quaternions:

$$DCM = \begin{bmatrix} 1 - 2({q_y}^2 + {q_z}^2) & 2(q_x q_y + q_w q_z) & 2(q_x q_z - q_w q_y) \\ 2(q_x q_z - q_w q_z) & 1 - 2({q_x}^2 + {q_z}^2) & 2(q_y q_z + q_w q_x) \\ 2(q_x q_z + q_w q_y) & 2(q_y q_z - q_w q_x) & 1 - 2({q_x}^2 + {q_y}^2) \end{bmatrix}$$

Calculation of Euler angles from quaternions:

ϕ= arctan $(2(q_y q_z + q_w q_x))$

θ= -arcsin $(2(q_x q_z - q_w q_y))$

ψ = arctan $(2\,(q_x q_y + q_w q_z)/1 - 2({q_y}^2 + {q_z}^2))$

2.3. Calculation of Knee Angle

To calculate the knee angle, one of the sensors is positioned at the top of the knee and the other at the bottom of the knee. The NodeMCU development board and TCA9548A I2C multiplexers are connected to the waist.
The raw data from the sensors were converted into local coordinates by the DCM conversion filter method. As a result of this conversion, x (roll), y (pitch), z (yaw) Euler angles were obtained.

Then, in order to avoid Gimbal Lock problem (in other words the problem of overlapping axes as a result of rotations) and in terms of ease of operation, quaternions that 4-dimensional vectors were obtained from these angles.
Calculation of quaternions from Euler angles :

$$q_w = cos\left(\frac{\phi}{2}\right) cos\left(\frac{\theta}{2}\right) cos\left(\frac{\psi}{2}\right) + sin\left(\frac{\phi}{2}\right) sin\left(\frac{\theta}{2}\right) sin\left(\frac{\psi}{2}\right)$$
$$q_x = sin\left(\frac{\phi}{2}\right) cos\left(\frac{\theta}{2}\right) cos\left(\frac{\psi}{2}\right) - cos\left(\frac{\phi}{2}\right) sin\left(\frac{\theta}{2}\right) sin\left(\frac{\psi}{2}\right)$$
$$q_y = cos\left(\frac{\phi}{2}\right) sin\left(\frac{\theta}{2}\right) cos\left(\frac{\psi}{2}\right) + sin\left(\frac{\phi}{2}\right) cos\left(\frac{\theta}{2}\right) sin\left(\frac{\psi}{2}\right)$$
$$q_z = cos\left(\frac{\phi}{2}\right) cos\left(\frac{\theta}{2}\right) sin\left(\frac{\psi}{2}\right) - sin\left(\frac{\phi}{2}\right) sin\left(\frac{\theta}{2}\right) cos\left(\frac{\psi}{2}\right)$$

If we say q_1 the quaternion from the first sensor and q_2 the quaternion from the second sensor, angle of rotation between the quaternions is calculated by the formula [28]:

$$\alpha = \cos^{-1}(2 < q_1, q_2 >^2 - 1)$$

The expression $< q_1, q_2 >$ in the formula refers to the inner product of the quaternions.

$$< q_1, q_2 > = < w_1 + x_1 i + y_1 j + z_1 k, w_2 + x_2 i + y_2 j + z_2 > = w_1 w_2 + x_1 x_2 + y_1 y_2 + z_1 z_2$$

The ESP8266 Wifi module, which is available on the NodeMCU development board, is used to access the Internet. Angle values sent via url are recorded in MySQL database by using PHP programming language. The angle values taken from the database for graphical representation are visualized using the HighChart graphical interface.

III. CONCLUSION AND RECOMMENDATIONS

Gait analysis is a very comprehensive application consisting of 3 parts; kinetic, kinematics and EMG. In this study, the knee angle, which is one of the parts of the kinematic analysis, was measured successfully. The measured angle values are recorded in the database and are shown graphically in the web interface with internet tools. Hospitals doing gait analysis perform gait analysis for various purposes. These purposes are; improving the quality of sports in athletes, finding the cause of the fall in the falling events, finding the cause of gait disturbance in people with walking disorder, drawing treatment plan for people who feel pain when walking and evaluation of treatment. For this reason, gait analysis is very important in the diagnosis and treatment of many diseases.
Gait analysis is carried out in Turkey by using camera laboratory systems. The laboratory systems with camera are quite expensive. Also, it takes a long time to provide a patient to move to normal walking for gait analysis. This makes the cost expensive and leads treatment of less number of patients.
In this study, we aim to reduce the cost and to act in the patient's own daily environment with wearable inertial sensors for the patients who do not behave naturally before the doctor. With the internet of things, we aim to achieve more accurate results by providing the doctor to reach these data from anywhere and thus to treat them with less cost.

Figure 5. Gait Analysis Knee Angle Measurement Graphic

By measuring the angle of the knee by means of this system connected to the patient, the angle values are shown with graphics. The graph can be used as an auxiliary criterion for determining the treatment to be applied by the expert. After the treatment, a repeat measurement can be made and a graph can be drawn and compared before and after treatment.

In further studies, kinematic analysis can be performed by measuring the angles of different joints used in the analysis, such as ankle and hip angle.

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