

A MATLAB Graphical Interface to evaluate the CC2650 Sensor Tag

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Abstract – This paper presents a MATLAB based graphical interface to evaluate the Bluetooth Low Energy (BLE) CC2650 Sensor Tag. Although this module contains more sensors, this paper considers the movement sensor which is composed of a gyroscope and an accelerometer. This sensor communicates by BLE with a PC that contains a USB BLE Dongle. Our contribution is to implement the application that allows using several scenario tests to evaluate this movement sensor. Thus, the accelerometer can be used to measure the pitch and roll angles when the sensor is not moving linearly. The gyroscope is used to measure these angles as well as the yaw angle when the sensor is performing a linear movement. The graphical interface allows scanning of the BLE devices, establishing the link with one device, configuring the parameters of the device and displaying the time variation of angular rate, angular position and accelerations among others. There is the possibility of these measurements to be displayed in real time or off line, when all the data were acquired and processed. In this way the sensor can also be used to determine the trajectory of a person in an indoor environment.

Keywords – gyroscope, accelerometer, Bluetooth Low Energy, MATLAB

I. INTRODUCTION

Microelectromechanical sensors (MEMS), such as gyroscopes and accelerometers are used to determine the trajectory of a mobile in indoor environment when the GPS signal is weak [1-4]. Such devices are available as integrated circuits that must be connected by serial interfaces to a host [5]. The obtained device has a significantly large dimension and therefore it is difficult to be employed to monitor people. Accelerometers are included in any smart phone however the gyroscope can only be found in more expensive smart phones. Recently, small devices that contain these sensors as well as a wireless connection such as Bluetooth Low Energy were launched. They are powered by small coin-type batteries, are light, and therefore can be introduced in people's

pockets or be attached on mini-vehicles. In this way, the evaluation process of this type of sensors could be greatly simplified. Two examples of these devices are CC2650 [6], [7] and, respectively, CC2451 Sensor Tag.

The manufacturer of the Sensor Tags has presented two applications that can be used to evaluate the sensors if a USB BLE Dongle is introduced in a PC. BLE Device Monitor [8] is implemented as a graphical interface that allows scanning of BLE devices and being connected to one of them. Following this, the current value measured by each sensor can be displayed. B Tool also allows scanning and connecting to the sensor. Each sensor must be configured to send measurement data. However, the received message contains raw data together with other information such as checksums, delimiters, packet type identification, among others. To use this tool, knowledge of the internal architecture of the sensor and Bluetooth protocol is necessary.

In this paper an application that allows evaluation of the gyroscope and accelerometer of CC2650 Sensor Tag is presented. The application configures the two sensors, receives data from them and processes this data to extract information about the movement of the CC2650 Sensor Tag.

The paper is organized as follows. Section II presents basic information about the gyroscope and accelerometer and some characteristics of the CC2650 Sensor Tag. The experimental setup and the proposed graphical interface are presented in Section III. Experimental results are presented in Section IV and the conclusions are presented in Section V.

II. BASICS ABOUT GYROSCOPE AND ACCELEROMETER

The gyroscope and the accelerometer are MEMS sensors. They are manufactured as integrated circuits either as separate devices or even in the same chip. Both of them have three axes. The gyroscope generates a voltage which depends on its angular rate $\omega(t)$. This is true for each of the three axes. By integrating the angular rate, the current angular position $\alpha(t)$ can be obtained,

$$\alpha(t) = \int \omega(t)dt \quad (1)$$

Equation (1) can be evaluated at time moments when the samples of $\omega(t)$ are available by using the trapezoidal method. A major problem of the gyroscope is its offset. As a consequence, when the gyroscope is not moving its output (for each of three axes) is not zero. By integrating this it follows a variable position that is unacceptable. Therefore, this offset must be compensated.

The accelerometer generates a voltage which depends on the linear acceleration as well as on the local gravitational field. Also in this case this is true for all of the three axes; therefore the outputs of the accelerometer are denoted as a_x , a_y and a_z .

Each manufacturer provides the position and the sign of the axis of the accelerometer and similar information about the gyroscope on the sensor package.

Thus, fig.1 presents these axes for the MPU-9250 movement sensor which is included in the CC2650 Sensor Tag. The sensor package is placed on the side of the Sensor Tag which is presented in Fig. 1 such as the pin 1 identifier of the package points to the upper left corner of the CC2650 Sensor Tag.

The rotation angles around x , y and z axes are named *roll*, *pitch* and *yaw* angles, respectively and they can be measured by the gyroscope by integrating the angular rate on each of the three axes.

On the other hand, considering the influence of the gravitational acceleration on its three axes, the accelerometer can measure the inclination of the sensor in comparison with its x axis (this is the rotation around y axis or *pitch* angle) and the inclination in comparison with its y axis (this is the rotation around x axis or *roll* angle) as follows[9],

$$pitch = \text{atan} \frac{a_x}{\sqrt{a_y^2 + a_z^2}} \quad (2)$$

and

$$roll = \text{atan} \frac{a_y}{\sqrt{a_x^2 + a_z^2}} \quad (3)$$

Expressions (2) and (3) are true only if the pitch and roll angles have values in the range $(-90, 90)$ degrees. Otherwise, some corrections must be applied to (2) and (3).

Moreover, a_x , a_y and a_z must depend only on gravitational acceleration, which means that the sensor does not execute a linear movement. The difference is that the gyroscope measures these angles whether the sensor executes a linear movement or not.

Apart from the 3-axes gyroscope and 3-axes accelerometer, MPU-9250 contains a magnetometer. However, this feature is beyond the scope of this paper. Each of them generates 16-bit numbers at each output. The accelerometer has the ranges $\pm 2g$, $\pm 4g$, $\pm 8g$ and $\pm 16g$, where $g = 9.81 \text{ m/s}^2$. The gyroscope has the ranges ± 250 , ± 500 , ± 1000 , ± 2000 , all in degrees/sec.

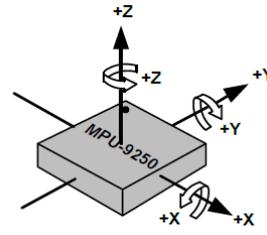


Fig. 1. The axes on the package sensor and the CC2650 Sensor Tag

III. CC2650 SENSOR TAG AND THE EXPERIMENTAL SETUP

CC2650 Sensor Tag contains, apart from the MPU-9250 movement sensor, the temperature, pressure, humidity and optical sensors. They are connected by an I2C interface to a CC2650 microcontroller which is also connected to a Bluetooth antenna. In this way, the CC2650 Sensor Tag can be a BLE slave device.

In order to implement the communication with CC2650 Sensor Tag, a CC2540 USB Bluetooth Dongle is connected to a PC. In this way we have a BLE master device. This is seen by the PC as a COM port.

During the experiments, the CC2650 Sensor Tag can be placed on a rotary platform with a scale where the rotation angle can be read. The Sensor Tag can also be placed in the pocket of a person that walks in the room around the PC with the USB Bluetooth dongle.

The CC2650 microcontroller of the CC2650 Sensor Tag contains preinstalled software that can respond to Bluetooth messages.

Our software application was implemented in MATLAB by using the Graphical User Interface (GUI). This application mainly accesses the COM port to send and receive messages.

The measurement information of the MPU-9250 is sent by the CC2650 Sensor Tag as a 29 bytes string. Out of the 29 bytes, 18 contain the measurement data. Of these 18 bytes, 6 belong to each of the three sensors. The 12 bytes, which correspond to the gyroscope and the accelerometer, are used by the application in this paper.

The measurement rate was set to 10 Hz, which is the maximum value accepted by the preinstalled software. The range of the gyroscope was set to ± 250 degrees/sec while the accelerometer range was set to $2g$.

Fig.2 presents the interface of the application software. It contains a number of push buttons which are listed as follows:

- START-initializes the serial communication with COM
- STOP-ends the serial communication with COM
- HOST-configures the USB Bluetooth dongle
- SCAN-scans for Bluetooth Low Energy devices

- ESTABLISH-connects with the CC2650 Sensor Tag
- TERMINATE-ends communication with CC2650 Sensor Tag
- CONFIGURE-configures the parameters of the MPU-9250 movement sensor (rate, enable sensors)
- DATA-enables the sensor to execute one measurement
- NOTIFICATION-enables the sensor to start the measurement, that is, executes a number of repetitive measurements, according to the rate.

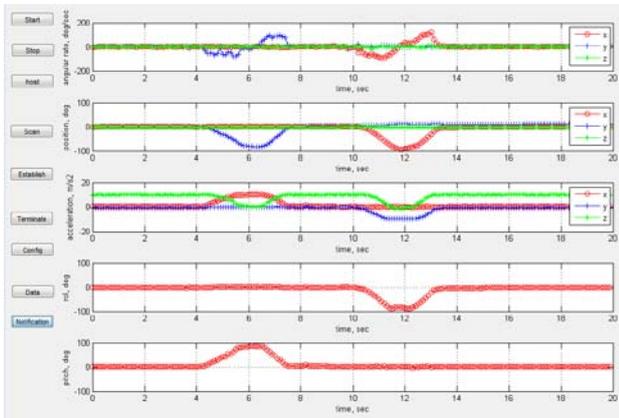


Fig. 2. The graphical user interface of the application

After pressing the NOTIFICATION button, 800 samples of each of the 6 axes (3 for the gyroscope and 3 for the accelerometer) are acquired while the Sensor Tag is not moving. The mean of each of the three gyroscope axes is then computed. This represents the offset. Then, a number of samples (200 that means 20 sec., but this parameter can be modified to have other value) for all the 6 axis are acquired. Each time a new set of 6 samples is acquired, the 3 values of the offset are subtracted from their corresponding gyroscope samples. Following this, the angular position is updated using the gyroscope data. The pitch and roll angles are also updated using the accelerometer data.

After finishing this process, in the graphical part of the application the following measurements are displayed, as time variation:

- the angular rate on each of the three axes of the gyroscope;
- the angular position of each of the three axes of the gyroscope;
- the acceleration on each of the three axes of the accelerometer;
- the pitch angle, computed by (2);
- the roll angle, computed by (3).

There is the possibility of such results to be saved in MATLAB files so that they can be displayed in larger figures. Additionally, there is a similar graphical interface that can be run in real-time. This means that it can display the most recent 100 samples of the gyroscope and

accelerometer and the corresponding angles.

IV. EXPERIMENTAL RESULTS

In this Section some tests are performed using the experimental setup and the software application presented in the previous section.

The first experiment handles the offset of the three axes gyroscope. Thus, if the gyroscope is not moving it is expected that the outputs of the three axes to be zero degrees/sec. However, in practice this does not happen. Fig. 3 (upper panel) presents the outputs generated by the gyroscope - angular rate - while it is not being moved for 8 sec. These amounts represent the offset. The lower panel of the Fig. 3 presents the angular positions of the gyroscope computed using (1) by previous angular rates. It can be observed, for instance that the angular position of z axis is about 90 degrees after 40 sec. These values are unacceptable and must be compensated. According to [2] this can be done by subtracting the curves such as those from the lower panel of Fig.3 by the position which is computed by (1). It can be observed that the curves are linear, and therefore they can be expressed as $pos_offset(t)=angular_offset \cdot t$, where $angular_offset$ represents the average value of the gyroscope output when it is not moving. In [2], this value is obtained as an average of the 15 tests. In our case it was observed that the average has significant variations. Fig. 4 presents the average of the offset for sets of 800 samples (80 sec.). It follows that an average value cannot be a reliable solution. Thus we adopted the method to acquire a number of samples at the beginning of each measurement and the $angular_offset$ is obtained as average of those values. Fig. 5 presents the position after compensating the offset. We observed acceptable values for the x axis (-0.5 degrees) and for the z axis (0.5 degrees) while the value of the y axis was higher (-1.75 degrees). However the results were different for other experiments.

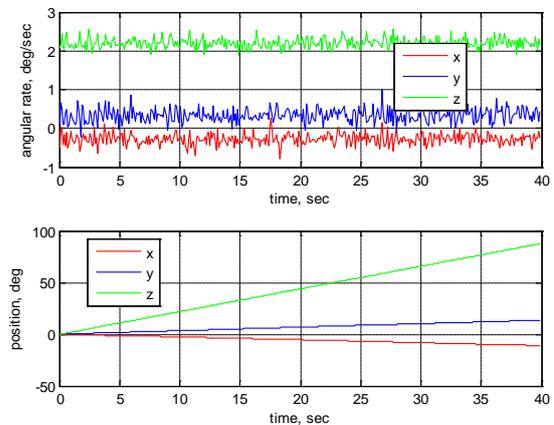


Fig. 3. Angular rate and angular position when gyroscope is not moving

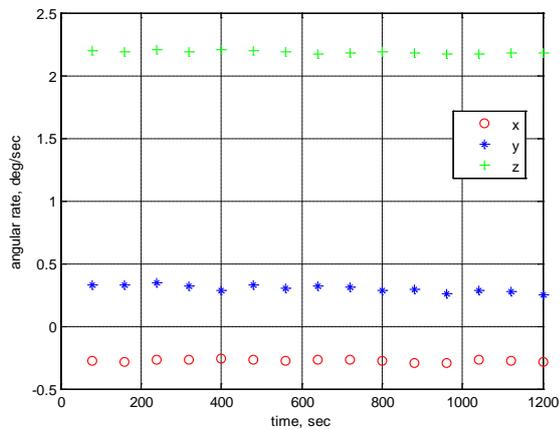


Fig. 4. Average value of angular rate for sets of 80 samples (80 sec.) when gyroscope is not moving

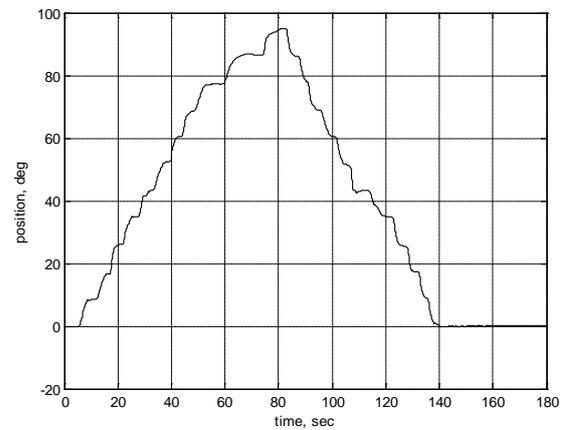


Fig. 6. The angular position of z axis during clockwise and counterclockwise moving of the gyroscope

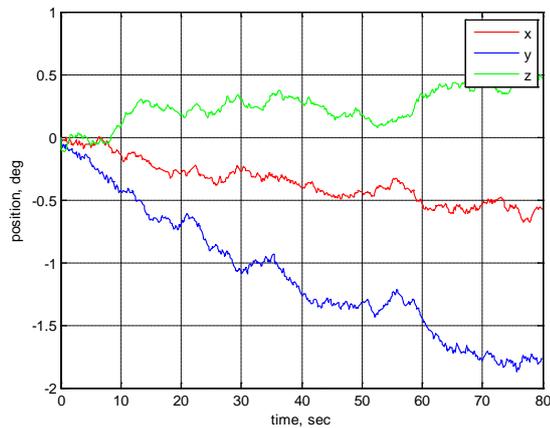


Fig. 5. The angular positions after compensating the offset when gyroscope is not moving

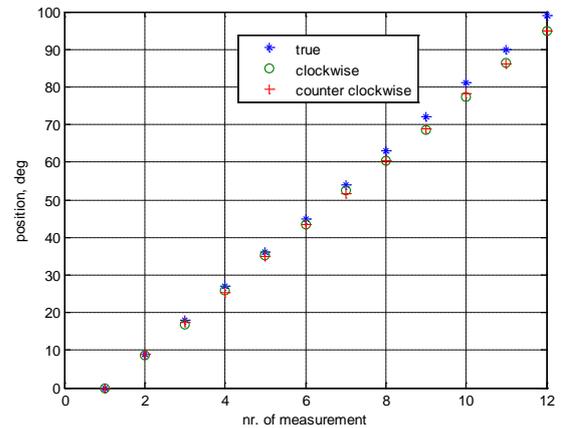


Fig. 7. The angular position of z axis during clockwise and counterclockwise moving, compared with true values

The purpose of the second experiment was to verify how precisely the gyroscope measures the angular position. For this purpose, the CC2650 Sensor Tag was placed on the rotary platform with its z axis up wards. The rotary platform was rotated clockwise from 0 until 99 degrees and counterclockwise to 0 by steps of 9 degrees.

Fig.6 presents the variation of the angular position on the z axis. It can be seen that after finishing the counterclockwise movement, at about 140 sec, the position is close to 0; therefore the offset was successfully compensated. Fig. 7 presents the measured positions compared to the true ones (as they have been read on the rotary platform). It can be seen that the positions of the clockwise moving correspond with similar positions of counterclockwise movement. A gain error was also observed, which was the difference between the true values and the values measured clockwise and counterclockwise, respectively. The value of the gain error was determined as 1.04. It can be compensated by multiplying by 1.04 of each of the angular position.

The purpose of the third experiment was to verify the computation of the pitch and roll angles by using both the accelerometer and the gyroscope. For this purpose the CC2650 Sensor Tag was held in hand. Firstly, it was rotated around the x axis in positive sense and then in negative sense. Secondly, the same procedure was followed, however around the y axis. Fig. 8 presents the results.

By examining the first two diagrams, it can be seen that when angular position around x axis is modified and becomes positive, acceleration y becomes positive too. When the angular position around y axis is modified and becomes positive, acceleration x becomes negative. These two results are in agreement with the signs of the angular rate (gyroscope) and accelerations (accelerometer) of Fig. 1. Thus it follows that the angular position x of the first diagram corresponds to the roll angle (the third diagram) while the angular position y of the first diagram corresponds to the inverted pitch angle (the fourth diagram).

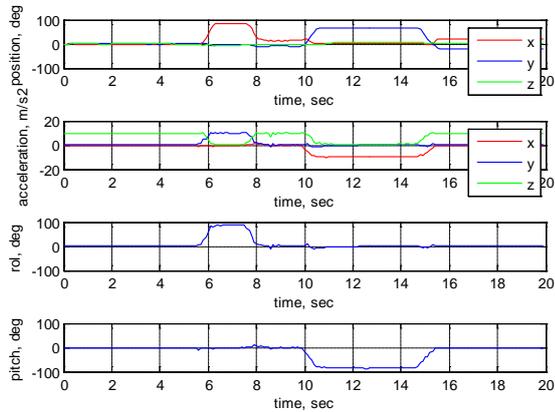


Fig. 8. Angular positions computed by the gyroscope, accelerations, pitch and roll angles computed by the accelerometer

The fourth experiment had the purpose to verify how the gyroscope can detect turns of a person that keeps the CC2650 Sensor Tag in their breast pocket. For this purpose, the individual made a number of steps, turned by 180 degrees clockwise, then, after another number of steps the individual made another turn by 90 degrees counter clockwise. Finally, the individual made another turn by 90 degrees counterclockwise sense too. This test was performed in two ways: firstly, the CC2650 Sensor Tag was placed in the pocket horizontally (the larger side was parallel with the ground, see Fig. 1) and secondly, vertically (the smaller side was parallel with the ground, see Fig. 1). The results of the first part of the fourth experiment are presented in Fig. 9. Thus, in the first diagram it can be observed that the angular rate x is modified, having positive values for the first turn (180 degree clockwise) and negative values for the next two turns (counterclockwise). These results are in agreement with the axis of Fig. 1. The three turns can be seen in the second diagram: the angular position x has values of 180 degrees, then 90 degrees and finally 0 degrees.

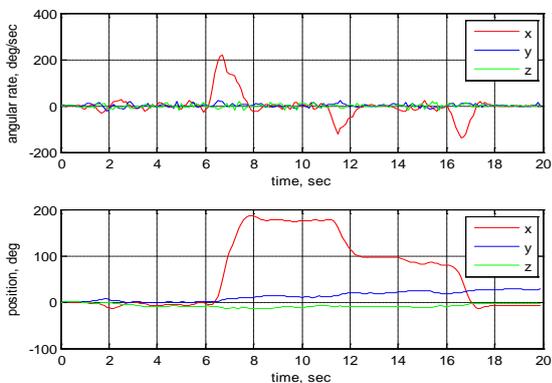


Fig. 9. The position for detecting the turns when CC2650 Sensor Tag was horizontally placed in the breast pocket

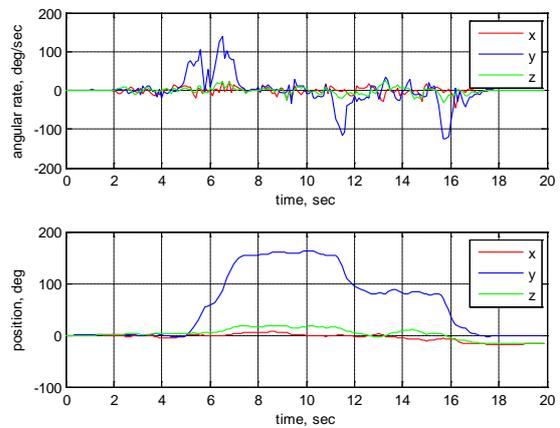


Fig. 10. The position for detecting the turns when CC2650 Sensor Tag was vertically placed in the breast pocket

The results of the second part of the fourth experiment are presented in Fig. 10. In this case the angular rate y (see the first diagram) and the angular position y are modified (the second diagram) however the conclusions are identical.

V. CONCLUSIONS

The paper presents a MATLAB application to evaluate the gyroscope and the accelerometer of the CC2650 Sensor Tag. The presented experiments indicate that the gyroscope has offset errors and gain errors, however both of them can be compensated. The accelerometer can measure the pitch and roll angles only when the sensor does not execute a linear movement. The gyroscope can measure the two angles as well as the yaw angle even if the sensor is moving. As a consequence, the gyroscope can be used to detect the turns of people who walk and keep the sensor in their breast pocket. As a future work, by employing the data for both the gyroscope and the accelerometer, an indoor trajectory could be determined.

VI. ACKNOWLEDGMENT

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