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Improving The Accuracy of Displacement Profile from Inertial Measurement Unit Sensor (IMU)

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Abstract:

This research involves discovering in improving the accuracy of the displacement profile from the inertial measurement unit sensor (IMU). Since Global Positioning System (GPS) is not precise to detect small displacement readings, an IMU is used to identify and monitor the displacement reading. Therefore, the objectives of this project are to measure the displacement reading from IMU by evaluating the speed and position as well as developing a motion tracking device on Arduino. To obtain the acceleration, this project used Arduino Uno and MPU6050 which are connected together to process the data. Then, the data will be recorded in Cool Term Software and imported into Microsoft Excel to perform the kinematics equation to get the displacement. However, IMU produces a lot of noise. Thus, a complementary filter is introduced on the MATLAB to reduce the noise. Finally, the displacement reading from IMU for the GPS signal will be measured and evaluated by using Arduino and Excel.

***Keywords:** IMU, GPS, Arduino, MATLAB, Wireless*

I. INTRODUCTION

This paper is focusing on research of Inertial Measurement Unit sensor (IMU), which this sensor is an essential part of motion tracking systems. It is usually used in the airspace, watercraft, satellites as well as guided missiles. An IMU is a combination of accelerometers and gyroscope which works as a sensor motion of force, angular rate and direction [1]. A variety of applications is commercially utilized by using this device as an alternative tool. However, there are few works need to be done to determine the reliability of this device.

This is corresponding to another researcher which states that IMU consists of tri-axial accelerometers, gyroscopes, and magnetometers with static and dynamic conditions along the accuracy and precision [2] . The function is to detect the contemporary rate of acceleration along with the changes of orientation, velocity, pitch, roll, and yaw [3]. This data will be integrated on Arduino Uno which acts as a microcontroller for further processing which is calculating the current speed and position with a given initial speed and position so that the output from IMU can be recorded and synthesized.

To determine the location of the exact body using IMU is quite challenging as it gives errors during the measurement of acceleration. This is because the IMU sensor is inadequate to measure the location precisely. Hence, only angular velocity and acceleration measurements can be estimated [4] [5].

This research used Arduino Uno as a platform to process the data and it will be transmitted and read by the Arduino Software (Arduino IDE). The final step is to add a filter to obtain an accurate reading of acceleration as well as processing the data to determine the distance by using Microsoft EXCEL and MATLAB which are completely designed.

II. LITERATURE REVIEW

A. Previous Studies

Accuracy and quality affect the step detection [6]. By using a smartphone, the combinations of device pose and the step modes variation can be detected by analyzing the inertial and magnetic sensors measurements. However, the classifier is not needed and the filters will adaptively tune. In order to reduce the motion noise in the signal while preserving crucial walking information, an adaptively low-pass filter that continuously tunes the cut-off frequency was proposed.

According to [7], they claimed that the accuracy of accelerometer-based inclinometers is much lesser when the motion speed arises. It cannot measure the gravity vector accurately. In theory, to overcome the limitations, the addition of sensor fusion algorithms in IMU is introduced (Kalman filter or complementary filter). This correlates with the research who recommends that laboratory settings of IMU-based motion capture can be greatly precise [8]. When the IMU-based inclinometers are implemented using a Kalman filter, the results shown can improve the accuracy of the inclinometer.

This is equivalent to [9] in their journal which estimates the Euler angles containing yaw angle, the pitch angle and the roll angle by using the quaternion-based indirect Kalman filter. The updated reading data of magnetometer an estimated magnetometer bias are corrected through the yaw angle and it shows the accuracy with the averaged displacement error of less than 3%.

Another way to help the displacement accuracy in low-grade IMU is by introducing a zero velocity update algorithm (ZUPT) [4]. ZUPT is an algorithm where it identifies the specific location in time when the incremental speed should be zero. In easy language, it is one of the methods where it calculates human footsteps.

In fact, the data received from the inertial sensor is vital to estimate without any extra information obtained from another device [10]. The sensors are small in size to be able to minimize the errors. Considering that the errors are negligible or tolerable, they create a full test benched-independent algorithm of calibration.

However [11] states that the ground reaction sensor array (GRSA) output profile may be able to determine by placing the foot on the ground. The results can be satisfying as it gives the accurate location of calculation as well as achieving a greater navigation accuracy.

III. METHODOLOGY

A. Block Diagram

Referring to Fig. 1, the Inertial Measurement Unit (IMU) which are Accelerometer and Gyroscope is attached to the Arduino input port. Arduino Uno will process the signal which has been collected and measured from IMU by the user. Arduino Software needs to be installed in the Arduino Uno as a library to process the data and convert them into the output signals. The data will be recorded and saved by using Cool Term Software and kinematics equation will be applied in Microsoft Excel. Next, the complementary filter will be used to reduce the noise of accelerometer by using a low pass filter while gyroscopic noise is used by integrating numeric and high pass filter. Lastly, the result will be displayed on the MATLAB view as the displayed outputs.

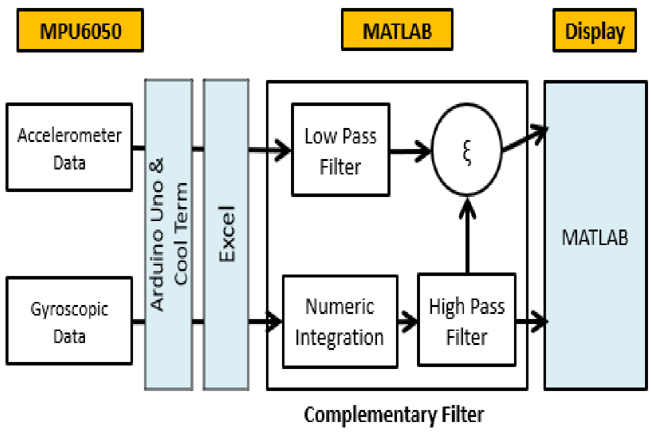

Fig. 1. Block Diagram of IMU Project

B. Flow Chart of the project

The flowchart in Fig. 2 shows the operation of this project from the beginning until the final results. First, connect the Arduino to the computer and then connect the IMU to the Arduino by following the circuit diagram connection. The program is ready to start by turning on the Arduino. It has the coding of the IMU which has been a program. Then, run the program to give a signal. The IMU starts at 0 degrees of point. When the IMU starts to move and rotates, it will give a signal and reading to the Arduino. When the output value displays '1°' it will go to the next stage. If '0°' it will repeat over again. Next, open the serial plotter of the Arduino and the acceleration results will be obtained. However, Arduino serial plotter cannot

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record the display results. So, Cool Term software is used to record and store the data. The imported data which has been save from the computer will be transmitted into the EXCEL software to perform a kinematics equation for obtaining the velocity and displacement. Last, implement the complementary filter and display the results on the MATLAB.

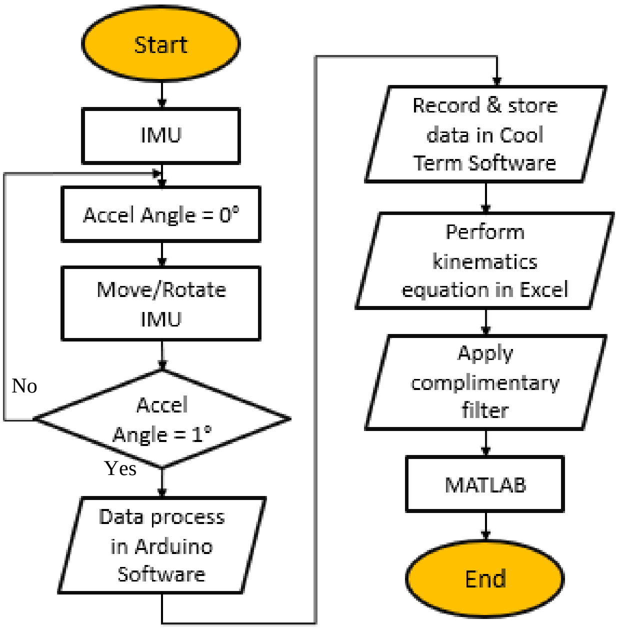

Fig. 2. Flowchart of IMU System.

C. *Kinematics Equations*

Kinematics is well known as a part of the classical mechanism which can explain about the movement of the objects without the dealing with the mass of the forces. It is also a field of study where it is usually referred to "geometry of motion". Hence, it is infrequently identified as a part of mathematics. By claiming that the original conditions of any known values such as position, speed or acceleration might lead to a kinematics problem. Doing this can determine the arguments of a geometry, location, speed, and acceleration of unknown components of the system.

Moreover, kinematics can be defined as the study of interpreting the movement of the body using numbers, graph, diagrams, words as well as equations. The main target of the study of kinematics is to build practical mental models which are served to explain the movement of the body.

There are several symbols applied in the equation. Every symbol has a particular definition. The symbol *d* in all equations stand for the displacement of the body while symbol *t* determines for the period for the body to move. Basically, Equation (1) and Equation (4) are used to determine the displacement [12]. Meanwhile, symbol *a* stands for acceleration of the body and symbol *v* used to determine for the velocity of the body. v_i indicates that the initial velocity value and v_f indicate final velocity value. Equation (2) and Equation (3) are used to examine the final velocity of the body movement. These four equations applicable to define the mathematical relationship between the limit of the body's motion.

$$d = vi * t + \frac{1}{2} * a * t^2 \quad (1)$$

$$vf^2 = vi^2 + 2 * a * d \quad (2)$$

$$vf = a * t \quad (3)$$

$$d = \frac{vi + vf}{2} * t \quad (4)$$

IV. RESULTS AND DISCUSSIONS

A. *Arduino & Coll Term Tests*

This paper showed the results by using Arduino which connected to the computer and Inertial Measurement Unit (IMU) sensor, MPU6050. The Arduino application is run while the hardware is connected to the computer to check whether the coding has errors or not. The connection of the circuit also is checked. The Arduino application will be fully running to launch a command "Connect". The command then allows the Arduino test the coding hence shows the reading from the IMU sensor. The results are obtained by viewing them at the serial monitor.

After the coding was completely uploading, the serial plotter is opened in order to get the data. Fig. 3 shows the results of the acceleration value that has been run and shown in the Arduino Serial Monitor. The results are shown in X-axis, Y-axis, and Z-axis of acceleration of IMU. Doing this test can only monitor the acceleration value and cannot perform advanced mathematical formula. This is because of the limitation of arithmetic of Arduino. To achieve the objectives of this project which is to obtain the value from acceleration to displacement, it can be done by using another software which is Microsoft Excel where it can perform an advanced mathematical formula.

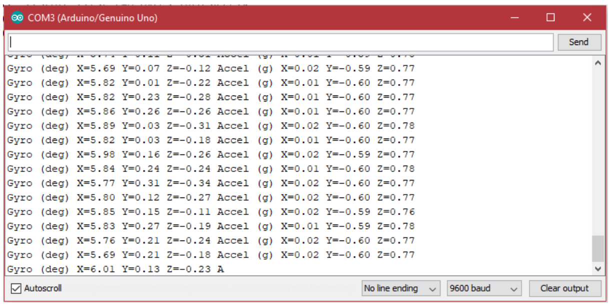

Fig. 3. Serial Plotter Test.

The Arduino and IMU are connected to process the data value. Referring to Fig. 4, Cool Term software is run by setting up the port which is similar to the pin of Arduino. The port used is Port 3 while the baud rate is set at 9600. Every time the hardware is connected to the serial port, it must be set up to Port 3. Meanwhile, for the bits, the data is generated at 8 bits. Next, button 'Connect' is clicked to run the software. The acceleration reading will display as similar to the Arduino serial plotter.

The results shown in Fig. 4 is the acceleration data and gyroscopic data which are generated and recorded by Cool Term software. The results now can be recorded by using this software. However, it is not in real time. A mathematical equation needs to be done to get the displacement value. The acceleration must be divided by time to obtain displacement value. The acceleration value of IMU shows in 3 dimension X-axis, Y-axis, and Z-axis. The time difference between the acceleration results is 1 second. The results are taken for a couple of seconds to show the acceleration result differences.

The result of Cool Term software and Arduino Serial Plotter is successfully acquired. By using the Cool Term software, the results can be recorded and stored into TXT file. This way helps to do for more steps to collect the displacement results.

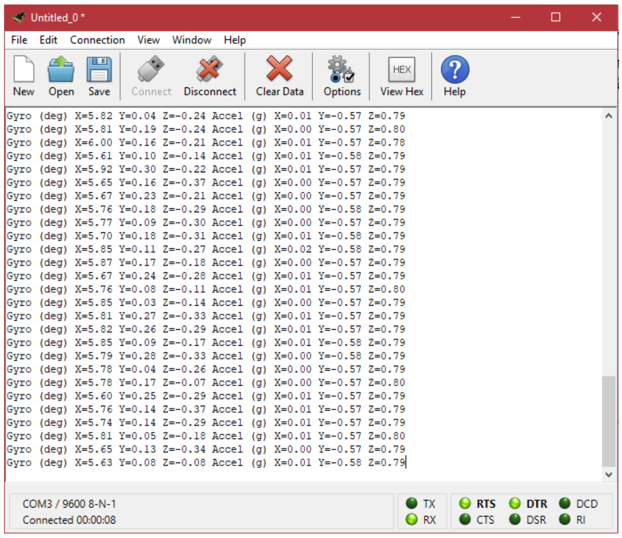

Fig. 4. Cool Term Test

B. Acceleration Result obtained using the 2nd and 4th Kinematic equation

Fig. 5, Fig. 6 and Fig. 7 indicate the results which are acquired completely for the first results. The figures show the acceleration, velocity and displacement results as well as the addition of a plotted graph to get a clear view. The data is imported from the TXT file which is recorded by Cool Term software and are tabulated in Excel. However, the data are not in a real time.

The acceleration values are converted into velocity and displacement by using the 2nd and 4th kinematic formula of physics Kinematic Equations [12] as shown in Equation (5) and Equation (6).

$$V = Afinal - Ainitial \times Tfinal - Tinitial \qquad (5)$$

$$D = \frac{1}{2}((Vfinal - Vinitial) \times (Tfinal - Tinitial)) \qquad (6)$$

Velocity represents as *"V"*, acceleration represents as *"A"*, displacement represents as *"D"* and time represents as *"T"*. The velocity results must be converted to get the displacement values so that the objectives of this project can be achieved. The data are classified into several columns which are the axes (X-axis, Y-axis or Z-axis), the time taken (second), final and initial acceleration, the final and initial time taken, final and initial velocity as well as the displacement of the object. The data was taken for the first 30 seconds to be analyzed.

As shown in Fig. 5, the data represents for X-axis. It was tabulated accordingly. The velocity and displacement are acquired by performing the kinematics equation as mentioned before. It was similar to Y-axis and Z-axis which were shown in

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Fig. 6 and Fig. 7. The data was not similar as the IMU was moved and rotate in different direction and angle. As mentioned before the unit for acceleration is g or meter per second squared while velocity is meter per second and displacement is meter.

time(s)	eration(m	time(s)	Afinal	Ainitial	Tfinal	Tinitial	V=(Afinal-Ainitial)x(Tfinal-Tinitial)	Vinitial	D=1/2((Vfinal-Vinitial)x(Tfinal-Tinitial))
	X1								
0	0	0	-0.03	0	1	0	-0.03	0	-0.015
1	-0.03	1	-0.03	-0.03	2	1	0	-0.03	0.015
2	-0.03	2	-0.03	-0.03	3	2	0	0	0
3	-0.03	3	-0.04	-0.03	4	3	-0.01	0	-0.005
4	-0.04	4	-0.04	-0.04	5	4	0	-0.01	0.005
5	-0.04	5	-0.04	-0.04	6	5	0	0	0
6	-0.04	6	0.05	-0.04	7	6	0.09	0	0.045
7	0.05	7	-0.05	0.05	8	7	-0.1	0.09	-0.095
8	-0.05	8	-0.08	-0.05	9	8	-0.03	-0.1	0.035
9	-0.08	9	0.07	-0.08	10	9	0.15	-0.03	0.09
10	0.07	10	0.1	0.07	11	10	0.03	0.15	-0.06
11	0.1	11	-0.32	0.1	12	11	-0.42	0.03	-0.225
12	-0.32	12	-0.42	-0.32	13	12	-0.1	-0.42	0.16
13	-0.42	13	-0.2	-0.42	14	13	0.22	-0.1	0.16
14	-0.2	14	-0.12	-0.2	15	14	0.08	0.22	-0.07
15	-0.12	15	-0.04	-0.12	16	15	0.08	0.08	-1.38778E-17
16	-0.04	16	-0.3	-0.04	17	16	-0.26	0.08	-0.17
17	-0.3	17	-0.2	-0.3	18	17	0.1	-0.26	0.18
18	-0.2	18	-0.06	-0.2	19	18	0.14	0.1	0.02
19	-0.06	19	-0.31	-0.06	20	19	-0.25	0.14	-0.195
20	-0.31	20	0.06	-0.31	21	20	0.37	-0.25	0.31
21	0.06	21	-0.04	0.06	22	21	-0.1	0.37	-0.235
22	-0.04	22	0.04	-0.04	23	22	0.08	-0.1	0.09
23	0.04	23	-0.09	0.04	24	23	-0.13	0.08	-0.105
24	-0.09	24	-0.03	-0.09	25	24	0.06	-0.13	0.095
25	-0.03	25	-0.06	-0.03	26	25	-0.03	0.06	-0.045
26	-0.06	26	0.02	-0.06	27	26	0.08	-0.03	0.055
27	0.02	27	-0.09	0.02	28	27	-0.11	0.08	-0.095
28	-0.09	28	0.01	-0.09	29	28	0.1	-0.11	0.105
29	0.01	29	-0.07	0.01	30	29	-0.08	0.1	-0.09
30	-0.07	30	-0.02	-0.07	31	30	0.05	-0.08	0.065

Fig. 5. Results of X-axis on the kinematics equation.

time(s)	eration(m	time(s)	Afinal	Ainitial	Tfinal	Tinitial	V=(Afinal-Ainitial)x(Tfinal-Tinitial)	Vinitial	D=1/2((Vfinal-Vinitial)x(Tfinal-Tinitial))
	Y1								
0	0	0	0	0	1	0	0	0	0
1	0	1	0.01	0	2	1	0.01	0	0.005
2	0.01	2	0	0.01	3	2	-0.01	0.01	-0.01
3	0	3	0.01	0	4	3	0.01	-0.01	0.01
4	0.01	4	0	0.01	5	4	-0.01	0.01	-0.01
5	0	5	0	0	6	5	0	-0.01	0.005
6	0	6	0.03	0	7	6	0.03	0	0.015
7	0.03	7	-0.02	0.03	8	7	-0.05	0.03	-0.04
8	-0.02	8	0	-0.02	9	8	0.02	-0.05	0.035
9	0	9	0.01	0	10	9	0.01	0.02	-0.005
10	0.01	10	0.01	0.01	11	10	0	0.01	-0.005
11	0.01	11	-0.01	0.01	12	11	-0.02	0	-0.01
12	-0.01	12	-0.1	-0.01	13	12	-0.09	-0.02	-0.035
13	-0.1	13	-0.04	-0.1	14	13	0.06	-0.09	0.075
14	-0.04	14	-0.01	-0.04	15	14	0.03	0.06	-0.015
15	-0.01	15	0.05	-0.01	16	15	0.06	0.03	0.015
16	0.05	16	-0.05	0.05	17	16	-0.1	0.06	-0.08
17	-0.05	17	0	-0.05	18	17	0.05	-0.1	0.075
18	0	18	-0.05	0	19	18	-0.05	0.05	-0.05
19	-0.05	19	-0.01	-0.05	20	19	0.04	-0.05	0.045
20	-0.01	20	0.09	-0.01	21	20	0.1	0.04	0.03
21	0.09	21	0.04	0.09	22	21	-0.05	0.1	-0.075
22	0.04	22	0.06	0.04	23	22	0.02	-0.05	0.035
23	0.06	23	-0.02	0.06	24	23	-0.08	0.02	-0.05
24	-0.02	24	0.03	-0.02	25	24	0.05	-0.08	0.065
25	0.03	25	0.01	0.03	26	25	-0.02	0.05	-0.035
26	0.01	26	0.03	0.01	27	26	0.02	-0.02	0.02
27	0.03	27	0	0.03	28	27	-0.03	0.02	-0.025
28	0	28	0.01	0	29	28	0.01	-0.03	0.02
29	0.01	29	0.02	0.01	30	29	0.01	0.01	0
30	0.02	30	0.05	0.02	31	30	0.03	0.01	0.01

Fig. 6. Results of Y-axis on the kinematics equation.

time(s)	eration(m	time(s)	Afinal	Ainitial	Tfinal	Tinitial	V=(Afinal-Ainitial)x(Tfinal-Tinitial)	Vinitial	D=1/2((Vfinal-Vinitial)x(Tfinal-Tinitial))
	Z1								
0	0	0	0.98	0	1	0	0.98	0	0.49
1	0.98	1	0.98	0.98	2	1	0	0.98	-0.49
2	0.98	2	0.98	0.98	3	2	0	0	0
3	0.98	3	0.98	0.98	4	3	0	0	0
4	0.98	4	0.98	0.98	5	4	0	0	0
5	0.98	5	0.98	0.98	6	5	0	0	0
6	0.98	6	0.98	0.98	7	6	0	0	0
7	0.98	7	1	0.98	8	7	0.02	0	0.01
8	1	8	1	1	9	8	0	0.02	-0.01
9	1	9	0.95	1	10	9	-0.05	0	-0.025
10	0.95	10	0.99	0.95	11	10	0.04	-0.05	0.045
11	0.99	11	0.94	0.99	12	11	-0.05	0.04	-0.045
12	0.94	12	0.96	0.94	13	12	0.02	-0.05	0.035
13	0.96	13	0.96	0.96	14	13	0	0.02	-0.01
14	0.96	14	0.93	0.96	15	14	-0.03	0	-0.015
15	0.93	15	1	0.93	16	15	0.07	-0.03	0.05
16	1	16	0.91	1	17	16	-0.09	0.07	-0.08
17	0.91	17	0.99	0.91	18	17	0.08	-0.09	0.085
18	0.99	18	1	0.99	19	18	0.01	0.08	-0.035
19	1	19	1.03	1	20	19	0.03	0.01	0.01
20	1.03	20	1.01	1.03	21	20	-0.02	0.03	-0.025
21	1.01	21	0.99	1.01	22	21	-0.02	-0.02	0
22	0.99	22	0.96	0.99	23	22	-0.03	-0.02	-0.005
23	0.96	23	0.95	0.96	24	23	-0.01	-0.03	0.01
24	0.95	24	0.99	0.95	25	24	0.04	-0.01	0.025
25	0.99	25	0.99	0.99	26	25	0	0.04	-0.02
26	0.99	26	0.97	0.99	27	26	-0.02	0	-0.01
27	0.97	27	0.98	0.97	28	27	0.01	-0.02	0.015
28	0.98	28	0.97	0.98	29	28	-0.01	0.01	-0.01
29	0.97	29	1	0.97	30	29	0.03	-0.01	0.02
30	1	30	0.97	1	31	30	-0.03	0.03	-0.03

Fig. 7. Results of Z-axis on the kinematics equation.

Fig. 8 shows the plotted graph of the results on the MATLAB on X-axis, Y-axis, and Z-axis. The graph shows all of the acceleration, velocity, and displacement of all of the axes. After obtaining the measurements for velocity and displacement, let's move to the next step which is adding a complementary filter on the MATLAB. The first column represents for X-axis, the next column is Y-axis and the last column is Z-axis. Meanwhile, for the first row, it stands for the acceleration, the second row stands for the velocity and the last row stands for the displacement. Based on Fig. 8, it shows that the pattern of the results of X-axis almost the same. It was slightly different because of the decimal points obtained. It was so much alike as Y-axis and Z-axis. The pattern of the graph was nearly identical but with different values achieved.

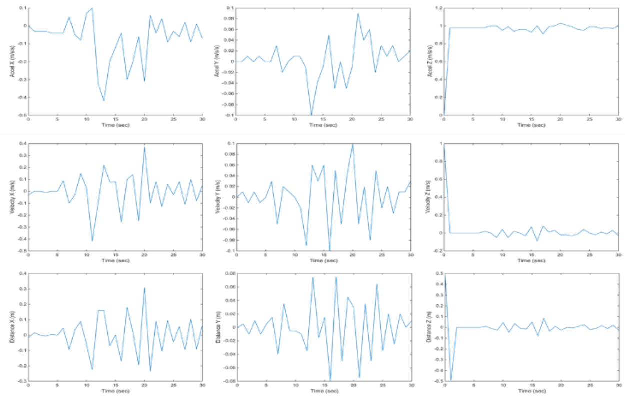

Fig. 8. Plotted graph of the results of acceleration, velocity, and displacement.

Fig. 9 shows the final graph of the roll, pitch, and yaw. The graph shown has 3 lines to be exact. Each of the line represents for acceleration, gyroscope and filtered data. These data were plotted to be evaluated and interpreted. The blue line represents as acceleration where it is in meter per second squared while the red line represents as gyroscope where the unit is in degree per second or in other words, the red line shows gyro turn rate in degree per second which these values are integrated over time to produce the yellow line which is known as filtered data. Lastly, the filtered line which is in yellow color. The unit of roll and pitch were in angle while yaw was in degree per second.

It can be seen in Fig. 9, the graph for gyroscope was not consistent as there was presence of noise. This noise was reduced by adding a complementary filter. To reduce the noise, the gyroscopic value was integrated and added with acceleration data. This complementary filter which consist of high pass filter and low pass filter will cut off the high and low frequency. This will produce the yellow line which the data was filtered.

It is understandable that the pitch angle and roll angle of the accelerometer contained of noise. Furthermore, a complementary filter does not have any information about the data which has been

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filtered. Nevertheless, the angle obtained from the complementary filter is more correct and precise with no fewer errors. There is absent of vibration on the axes when the IMU moves only one single axis. It means that there is absence of signal coupling occurs on pitch and roll axes. In short, this complementary filter is productive, constant and decent in IMU data fusion after the filter coefficient is well tuned.

It can be concluded and proven that the velocity and displacement can be obtained from converting the acceleration by using 2nd and 4th kinematics equation. Thus, by using the complementary filter, a smoother line can be acquired. However, the values obtained are in angle. It cannot be converted into acceleration (meter per squared) as the equation was integrated with values of the gyroscope.

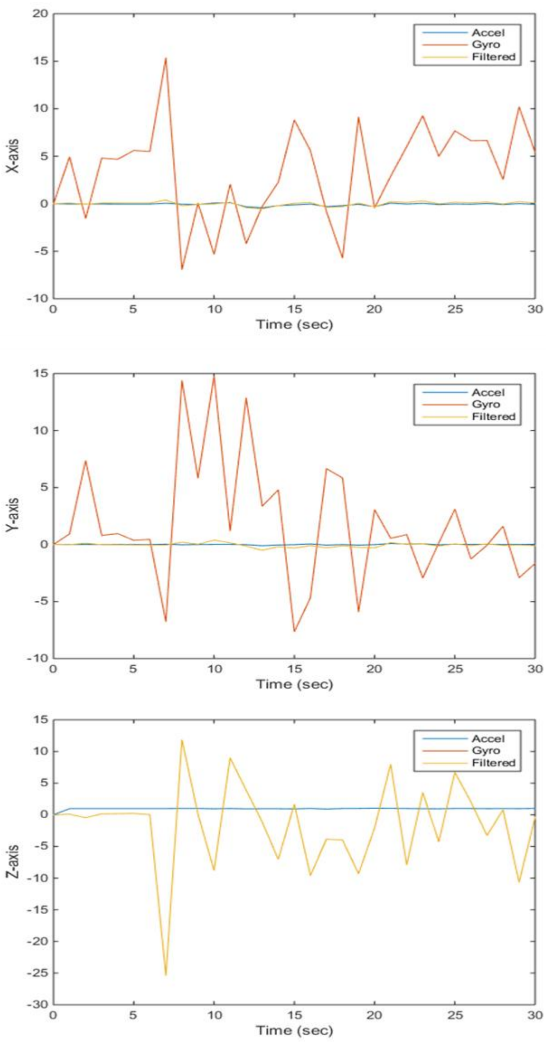

Fig. 9. Plotted graph of roll, pitch and yaw.

V. CONCLUSIONS

In conclusion, the objectives of this paper are achieved where a motion tracking device was developed as well as the velocity and displacement can be measured plus evaluated by using IMU which was developed on Arduino. It has been tested by using some method which is the study of acceleration results obtained using 2nd and 4th kinematics equation. The negative values mean that the direction of the angle was different (anti-clockwise). Accelerometer measured the acceleration of a moving or vibrating body while gyroscope measured angular rate or orientation. Since the values of the acceleration are not consistent, the graph shown was different. The combination of high pass filter and low pass filter produced a complementary filter. Hence, the values for gyroscope should be collected to be integrated for the implementation of a complementary filter. The signal data now are smooth. However, the filtered data was in angle (degree). To convert it again into acceleration, it is impossible as it needs to differentiate and required the gyros data. In short, all of the objectives were achieved where a motion tracking device was developed, the measurement of velocity and displacement were measured and lastly, the implementation of complementary filter was added to improve the accuracy of displacement.

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