Complementary of quaternion method and Boole’s rule on IMU sensor to calculate orientation angle of Stewart Platform

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Abstract. This paper discusses the complement of the Quaternion method and Boole’s rules on the IMU sensor aimed to calculate the orientation angle of the Stewart Platform. Orientation angle validity of The Stewart platform is very difficult to recognize by using manual measuring devices. Thus, it requires an IMU sensor to calculate the orientation angle. The IMU sensor consists of three types of sensors, namely the accelerometer, magnetometer, and gyroscope sensors. The Quaternion method is used to calculate the pitch and roll angle of the accelerometer sensor. It is also used to calculate the yaw angle of the magnetometer sensor. Boole’s rule is used to calculate the pitch, roll, and yaw angles of the sensor gyroscope. Moreover, the orientation angle of accelerometer and magnetometer is combined with the orientation angle of the gyroscope using complementary. The test is carried out in six repetitions with angular parameters: 5°, 10°, 15°, 20°, 25°, 30°. Overall, the pitch angle has an average value of error percentage of 2.31%, roll angle has an average value of error percentage of 1.98%, and yaw angle has an average value of error percentage of 1.63%. The measurement results of the orientation angle of the Stewart Platform using the IMU sensor shows that the complementary quaternion and Boole’s rule on the IMU sensor is quite feasible as measuring instruments for the orientation angle of the Stewart Platform.

1. Introduction

The Stewart Platform is a robotic technology used to move a platform using 6 motors, which was first published by Stewart [1,2]. Some potential errors on the Stewart Platform are very likely to occur so that the orientation angle of the Stewart Platform needs to be calculated for validation purpose. Calculation of orientation angle of Stewart Platform is very difficult to recognize by using a manual measuring device, so it requires a sensor aimed to calculate the orientation angle. The Inertial Measurement Unit (IMU) is one of the sensors that can be used to calculate the orientation angle [3-5].

Research on the application of Quaternion method and Boole’s rules to calculate orientation angles has been carried out in several research. In the references [6], Quaternion method was used to calculate the pitch and roll orientation angle of the accelerometer sensor and yaw orientation angle of the magnetometer sensor. The results of these calculation are combined with the orientation angle of the gyroscope sensor. Similar research has also been discussed in paper [7], where the Quaternion method was used to calculate the orientation angle using the IMU sensor, by adding Kalman filters to optimize
the calculation results. In the references [8], indirect Kalman filter is used to calculate adaptive external acceleration so that it can optimize the calculation of the IMU sensor orientation angle.

Besides the accelerometer and magnetometer, there is also a sensor gyroscope inside the IMU sensor [9,10]. Gyroscope sensor is a digital instrument that can calculate angular velocity linearly. The value of the orientation angle of the gyroscope sensor can be calculated using integral calculations [9]. One of the integral methods used to calculate the orientation angle of the gyroscope sensor is Boole’s rule. Research on the application of Boole’s rule to calculate the orientation angle of the gyroscope sensor has been done in the paper [11]. Boole’s rule is an integral method that is included in the Newton Cotes Formula category and the development of the Simpsons method 3/8 [12].

In this research, orientation angles were obtained from the accelerometer, magnetometer, and gyroscope sensors combined using the complementary method. Complementary combines the results of the accelerometer sensor and the gyroscope sensor to obtain a pitch and roll orientation angle. Besides, it also combines the result of yaw orientation calculation of the magnetometer with the yaw angle of the sensor gyroscope [13-15]. Complementary results from the three sensors were used to calculate the orientation of the Stewart Platform in this research.

2. Method
IMU is an electronic module that has several sensor units to be sent to the Central Processing Unit (CPU). There are three types of sensors contained in the IMU sensor, that is the accelerometer, gyroscope, and magnetometer [10,16]. The accelerometer sensor calculates linear acceleration including gravitational acceleration, gyroscope [17] sensor measures angular velocity, and the magnetometer sensor measures the magnetic field from the north pole. In this research, the orientation angle of the IMU sensor is calculated using the complementary equation between the accelerometer sensor, gyroscope, and magnetometer. The calculation of the IMU sensor orientation angle that was designed, presented in Figure 1.

Based on figure 1, the IMU sensor reads data from the accelerometer, gyroscope and magnetometer sensors. gyroscope sensor angular velocity data is calculated using the Boole integral method [11] to reveal pitch, roll, and yaw data, accelerometer gravity acceleration data is calculated by using the Quaternion method due to generate data pitch and roll orientation angles. Meanwhile, magnetic field data from the magnetometer is calculated by using the Quaternion method to get a yaw orientation angle. Afterward, data on orientation angle (pitch, roll, yaw) of the three sensors are combined by using the complementary method [13]. The Boole integral equation is simply presented in equation (1)[11],

$$y_g[i] = y_g[i - 1] + \frac{7 d y_g[i - 3] + 32 d y_g[i - 2] + 12 d y_g[i - 1] + 32 d y_g[i] + 7 d y_g[i + 1]}{90} h$$  \hspace{1cm} (1)

with $d y_g[i]$ is the first derivative from $y_g[i]$, and $h$ is sample time.
The calculation of pitch, roll, and yaw orientation angles from the accelerometer and manometer are calculated using the Quaternion method. In simple terms, the calculation of pitch \((y_{ap})\), roll \((y_{ar})\), and yaw \((y_{ar})\) orientation angles are presented on the equation (2) to equation (4) [6,18],

\[
\begin{align*}
  y_{ar} &= \arctan \frac{2(q_0q_1+q_2q_3)}{1-2(q_1^2+q_2^2)} \\
  y_{ap} &= \arctan \frac{2(q_0q_2-q_1q_3)}{1-2(q_2^2+q_3^2)} \\
  y_{my} &= \arctan \frac{2(q_0q_3+q_1q_2)}{1-2(q_2^2-q_3^2)}
\end{align*}
\]

where \(y_{ap}\) and \(y_{ar}\) are the pitch and roll angle values of the accelerometer sensor, while \(y_{ar}\) is the value of the yaw angle of the magnetometer sensor.

The combination of the three sensors is committed by using the complementary filter, with the gyroscope and the accelerometer sensors that are used to calculate the pitch and roll angle. Meanwhile, the combination of the sensor gyroscope and a magnetometer is used to calculate the yaw angles. The complementary equation for calculating pitch to recognize pitch \((\theta)\), roll \((\phi)\), yaw \((\omega)\), is simply presented in equation (5) to equation (7) [13],

\[
\begin{align*}
  \theta &= ay_{gp} + (1-a)y_{ap} \\
  \phi &= ay_{gr} + (1-a)y_{ar} \\
  \omega &= ay_{gy} + (1-a)y_{my}
\end{align*}
\]

with \(a = 0.98\), \(y_{gp}\) is pitch angle of gyroscope sensor, \(y_{ap}\) is pitch angle of accelerometer sensor, \(y_{gr}\) is roll angle gyroscope sensor, \(y_{ar}\) is roll angle of accelerometer sensor, \(y_{gy}\) is yaw angle of gyroscope sensor, and \(y_{my}\) is yaw angle of magnetometer sensor.

After calculating the orientation angle of the IMU sensor, the IMU sensor was used to measure the orientation sensor of the Stewart Platform. Figure 2 presents a set-up of testing the orientation angle of the Stewart Platform.

![Figure 2. Experimental set-up.](image)

In the experimental set-up, the IMU Gy-88 sensor was placed in the center of the platform surface, then the Stewart Platform was moved in accordance with the predetermined coordinates. Measuring the orientation angle of Stewart Platform (pitch, roll, and yaw) using the IMU sensor is done by manually changing the orientation angle of Stewart Platform according to the specified angle parameters.
Measured orientation angle data are recorded for analysis. Tests are carried out 6 times with angular parameters, which are 5º, 10º, 15º, 20º, 25º, and 30º.

3. Results and discussion
This chapter describes the data from the orientation measurement (pitch, roll, yaw) of the Stewart Platform using the IMU sensor which is presented in the form of tables and error charts (%) along with the analysis. The error angle orientation of the Stewart Platform can be calculated using equation (8) [19].

\[
\text{Error (\%)} = \frac{\epsilon_e - \epsilon_p}{\epsilon_p} \times 100\%
\]

where \(\epsilon_e\) is the experimental result value, and \(\epsilon_p\) is the specified parameter value.

3.1. Measurement of the Stewart Platform’s pitch angle
Table 1 is a measurement of pitch angle on the Stewart Platform using the IMU sensor.

| Trial to | Angle (Degree) |
|---------|----------------|
|         | 5  | 10 | 15 | 20 | 25 | 30 |
| 1       | 5.14 | 10.22 | 15.32 | 20.48 | 25.56 | 30.61 |
| 2       | 5.16 | 10.13 | 15.34 | 20.46 | 25.57 | 30.63 |
| 3       | 5.15 | 10.25 | 15.35 | 20.45 | 25.51 | 30.66 |
| 4       | 5.17 | 10.24 | 15.37 | 20.46 | 25.54 | 30.64 |
| 5       | 5.05 | 10.26 | 15.38 | 20.45 | 25.56 | 30.65 |
| 6       | 5.13 | 10.28 | 15.31 | 20.39 | 25.58 | 30.61 |

Average 5.13 10.23 15.35 20.45 25.55 30.63

The measurement results show that the pitch angle on the Stewart Platform has good value because it has approached the value of the angle parameter. Based on the result, the value of angular errors are 2.64% for the 5º angle, 2.32% for the 10º angle, 2.33% for the 15º angle, 2.22% for the 20º angle, 2.21% for the 25º angle, 2.12% for the 30º angle.

3.2. Measurement of the Stewart Platform’s roll angle
Table 2 is a roll angle measurement on the Stewart Platform using the IMU sensor.

| Trial to | Angle (Degree) |
|---------|----------------|
|         | 5  | 10 | 15 | 20 | 25 | 30 |
| 1       | 5.03 | 10.14 | 15.31 | 20.38 | 25.46 | 30.54 |
| 2       | 5.04 | 10.17 | 15.29 | 20.37 | 25.47 | 30.56 |
| 3       | 5.19 | 10.15 | 15.17 | 20.42 | 25.48 | 30.57 |
| 4       | 5.14 | 10.24 | 15.38 | 20.41 | 25.51 | 30.58 |
| 5       | 5.12 | 10.26 | 15.22 | 20.39 | 25.52 | 30.61 |
| 6       | 5.02 | 10.29 | 15.33 | 20.37 | 25.49 | 30.52 |

Average 5.09 10.21 15.28 20.39 25.49 30.56

The measurement results show that the roll angle on the Stewart Platform has a good value because it has approached the value of the angle parameter. Based on the result, the angle error values in the form of percentages are 2% for the 5º angle, 2.2% for the 10º angle, 1.86% for the 15º angle, 1.96% for the 20º angle, 1.97% for the 25º angle, 1.89% for the 30º angle.
3.3. Measurement of the Stewart Platform’s yaw angle

Table 3 shows yaw angle measurement on the Stewart Platform using the IMU sensor.

| Trial to | Angle (Degree) |
|---------|---------------|
|         | 5  | 10 | 15 | 20 | 25 | 30 |
| 1       | 5.12 | 10.21 | 15.22 | 20.31 | 25.38 | 30.51 |
| 2       | 5.01 | 10.15 | 15.27 | 20.29 | 25.36 | 30.53 |
| 3       | 5.04 | 10.16 | 15.23 | 20.33 | 25.39 | 30.57 |
| 4       | 5.08 | 10.19 | 15.24 | 20.32 | 25.36 | 30.53 |
| 5       | 5.13 | 10.18 | 15.25 | 20.32 | 25.42 | 30.58 |
| 6       | 5.05 | 10.17 | 15.28 | 20.34 | 25.41 | 30.52 |

The measurement results show that the yaw angle on the Stewart Platform has a good value because it has approached the value of the angle parameter. Based on the result, the angle error value is in the form of a percentage, namely: 1.45% for 5° angle, 1.75% for 10° angle, 1.67% for 15° angle, 1.62% for 20° angle, 1.57% for 25° angle, 1.83% for 30° angle.

3.4. Comparison of error percentage from pitch, roll, and yaw angle

Based on the results of calculation of pitch, roll and yaw orientation angles, the error percentage is obtained for each angle parameter. Figure 3 shows a graph of the percentage error ratio of the three axes (pitch, roll, yaw).

![Figure 3. Error charts (%).](image)

Based on Figure 3, the measurement data of pitch angle has an overall average error value in the form of a percentage of 2.31%, the measurement of the angle of roll has an overall error value in the form of a percentage of 1.98%, and the yaw angle measurement has an overall average error value in the form of a percentage of 1.65%. The yaw angle has an error value that tends to be smaller, and the pitch angle has an error value that tends to be higher for each angle parameter. The results show that the complementary quaternion and Boole’s rule on the IMU sensor is quite feasible as measuring instruments for the orientation angle of the Stewart Platform.

4. Conclusions

Based on testing the orientation angle measurement of Stewart Platform using the IMU sensor, it was found that the measurement data of pitch angle has an overall average error value in the form of a percentage of 2.31%, the measurement of the angle of roll has an overall error value in the form of a percentage of 1.98%, and the yaw angle measurement has an overall average error value in the form of a percentage of 1.65%. Based on the results of the orientation angle measurement, it can be concluded that the complementary between the quaternion and Boole’s rule on the IMU sensor is quite feasible as measuring instruments for the orientation angle of the Stewart Platform.
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