Autonomous MEMS Gyroscope and Accelerometer for North Finding System

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***Abstract*—The precision in detecting the north direction and estimate orientation is highly important. Excellent standard of gyroscopes, such as ring laser gyros, are capable of maintaining measurement at a high level. However, the device and technology required for it are bulky and high in cost. The accuracy of common instruments in detecting direction such as compass and electronics magnetometer can be easily reduced due to electromagnetic interference. Therefore, a continuous rotation method of the Micro-Electro-Mechanical System gyroscope and accelerometer is proposed, in order to seek true north angle. With this method, the issues regarding gyroscope will be solved. Moreover, the autonomous system consists of gyroscope and accelerometer which function in mounting the horizontal shape of the rotating laser controlled by the microcontroller. Moreover, it has been proven that the developed prototype provides an accuracy with complementary filter factor, a = 0.97. In addition, besides the fact that the rotator displays a successful rotation at ±0.02° for a rotation angle ranging from 0° to 360°, an autocollimator has also calibrated the rotator. Apart from that, it has been proven from the field test results that an accuracy of ±1°, is acquired by the developed system, regarding the true north angle that is verified by the Department of Survey and Mapping Malaysia.**

***Index Terms*—Complementary Filter; MEMS Accelerometer; MEMS Gyroscope, North.**

I. INTRODUCTION

The efficiency of many navigation and location systems [1-5] is determined by their capability of precisely and autonomously detecting the geographic location and orientation information. In fact, the North end is the main point for the rotation of the Earth on its axis. Aside from it being located along the surface of the Earth, which is facing towards Geographic North Pole, it is also the reference point used for the detection of any other directions. In general, several instruments are utilized for detecting the information regarding the north and geographic location. Examples of the instruments are hand bearing compass, magnetometer, inertial gyroscope compass, digital compass, and Global Positioning System (GPS) [6-8].

The information regarding the North location is traditionally acquired through magnetic compass, where the measurement of the magnetic field of the Earth and geomagnetism takes place. However, due to the dependency of the compass on the Earth's magnetic field for the production of heading, its performance is highly determined by where it is installed. This also applies to the digital compasses installed on smartphones.

It is a fact that, due to the inconsistency of the Earth's magnetic field, obtaining accurate information is difficult. This is also due to the man-made or natural magnetic anomalies, which will lead to the unpredictable distortion of the local magnetic field. This occurs especially in the indoor areas. In addition, the degradation of the compass system can easily occur under the influence of nearby ferrous materials, electromagnetic interference, and weather [9-12]. Due to these factors, the compass cannot be effectively used inside buildings. Besides, it takes a high amount of effort to correct the impact brought by magnetic field distortions. Therefore, in order to curb the problems related to electromagnetic interference, a total station (theodolite) have been used. The purpose of this approach is to keep the reading accuracy at a high level. However, the device and technology used for this instrument are bulky, and they will cost a tremendous amount of money. During the recent years, in order to measure the angular rate of rotation [13-15], Microelectromechanical system (MEMS) gyroscope has been widely used. Besides, this instrument is capable of determining the Earth's rotation rate [16,17]. Furthermore, there are numerous advantages found within MEMS gyroscope, as in [18,19]. However, it is necessary that the angular rate signal of MEMS is integrated in terms of time, as this will result in the creation of readable angles. These angles will lead to several drift problems [20-22]. Therefore, it has been suggested by [23-25] that a preventive method should be used. In this method, the merging of the outputs of two sensors is conducted through digital signal filtering to curb the problem regarding the drift of the gyroscope.

Furthermore, the use of Kalman digital filter is involved in [26-28], order to reduce drift. However, [29] refutes this point by saying that the mathematical algorithm of Kalman Filter is too complicated. On the other hand, [30,31] claims that provided the complexity of the systems is due to many sensors and the tendency of inaccuracy, the angle can be acquired when using fewer sensors with a simpler algorithm.

Thus, referring to the information above, there has been a degradation of the MEMS gyroscope in terms of its performance. Therefore, a method of continuous rotation produced by the MEMS gyroscope and accelerometer is proposed for the acquirement of the north location. This method is conducted by merging both sensors output, which is performed through the complementary filter. In fact, the digital complementary filter is developed with the main purpose of utilizing the strength of one sensor in the effort of overcoming the weaknesses of the other sensor. Furthermore, the position of MEMS gyroscope and accelerometer will be frequently changed by the rotation technique. In this process, the error that occurs within the sensor's bias will be displayed. Therefore, subtracting the obtained bias error with the measured output is a necessity in utilizing it. The purpose of this is to ensure the compensation of the MEMS gyroscope and accelerometer data.

The other sections of this paper are displayed as follows. Precisely, system hardware design and testing setup are displayed in Section 2. Furthermore, the measurement results are displayed in Section 4, the summary regarding the results of this work and the conclusions are drawn in section 5.

II. METHODOLOGY

A. System Hardware Design

This study used a six degrees of MPU6050 freedom board (three-axis gyroscope and three-axis accelerometer). The power supply of 5V from the microcontroller Arduino Mega was utilized to generate the angular rate rotation from gyroscope and acceleration force signal from the accelerometer. Communications were usually held through the I2C protocol. Following that, the I2C lines were labeled. This step required the pin to be labelled as Serial Data (SDA) on the MPU 6050, in order for it to be connected to the Arduino's analog pin 20. Apart from that, the labeling of the 12C lines was also performed by labeling the port. The labeling of the port can be performed anywhere, which is from Serial Clock (SCL) of the sensor to the Arduino's analog port 21, SCL.

Based on the experiment, the impacts of temperature were controlled. This was conducted by maintaining the MPU6050 unit of at ambient temperature, in order to warm up the sensor before the experiments started. This step was followed by the sensor being warmed up before the experiment. Moreover, Figure 1 displays the circuit connection of sensor MPU050.

Apart from that, the development of customized shield of stepper driver (Figure 2) was conducted in this study. Besides, in order to control the rotation of the micro rotator, the development of micro stepper driver began. The purpose of these was to the wiring connection was suitable for the Arduino Mega. Aside from the precise rotation displayed by the rotator, which was in control, it was configured in micro-step. To illustrate this, MPU6050 was placed horizontally on the rotator with the use of A4988 micro-step driver. The purpose of doing this was to put control on the rotation in micro mode, which was 0.1125° per step. Last but not least, another purpose of doing this was to switch between different positions. Based on Figure 3, a complete setup of MEMS gyroscope and the accelerometer for north location finder was displayed.

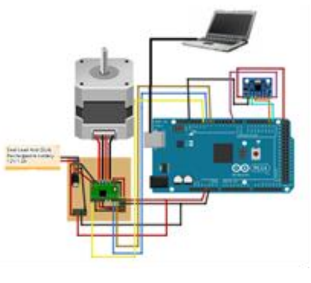

Figure 1: Schematic diagram of the North location detector system

Figure 2: Custom-made shield for micro stepper motor circuit

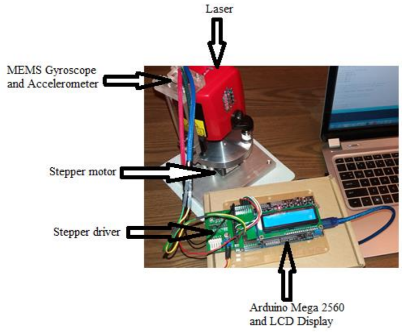

Figure 3: A complete system of MEMS gyroscope and the accelerometer for the North location detector

B. Testing Setup for The Accuracy of Micro Rotator Using Optical Polygon and Autocollimator

In order to perform angular calibration [32,33], two industry standard methods were required. In these methods, a polygon mirror and autocollimator were involved. These instruments consisted of two optical polygons with a similar number of faces, followed by one autocollimator and one polygon with two autocollimators.

In order to acquire the accuracy of the angular displacement of the rotator, calibration was performed using one polygon (six faces) and one autocollimator. Furthermore, this process was performed at Angle Laboratory National Metrology Institute of Malaysia. During this process, the rotator was firstly placed on a flat table, where the six faces of optical polygon were concentrically mounted on top of the rotator. An autocollimator was put in a standing position, facing the polygon, albeit being separately set. Furthermore, the face of the polygon was aligned at 0º of the reading of the rotator's position angle, followed by the recording of the reading of the autocollimator. Then, the rotation of the rotator was performed, until it corresponded to the nominal angle of the polygon. During the end of this process, the autocollimator reading was again noted.

This method continued until all measurements were acquired. Following that, the repetition of the reading process was performed, where the rotation of the rotator in reverse direction was involved. Moreover, the setup of the rotator's calibration, where optical polygon and autocollimator were involved, is presented in Figure 4.

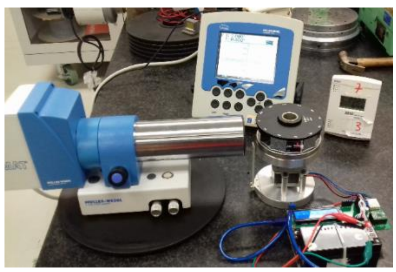

Figure 4: Setup of the rotator calibration using optical polygon and autocollimator

C. *Testing Complementary Filter for MEMS Gyroscope and Accelerometer*

As displayed in Figure 5, the implementation of the digital complementary filter was conducted. During this process, the benefit of one sensor will be employed, in order to defeat the delicacy of the other sensor that complemented the former. Based on the block diagram in Figure 5, two inputs are displayed. They consisted of the accelerometer angle estimation and the gyroscope angular rate. In respect of the accelerometer, the high-frequency signals were filtered by the high-frequency signals when the condition of vibration was sensed by this input. Then, before the input of gyroscope angular rate was fed into the high pass filter, which disabled the effects of drift, it was merged. The purpose of this process was in order to emerge an attitude angle. Moreover, after a simultaneous function produced by both high-pass and low-pass filters, both signals were combined altogether.

The adjustment of both gyroscope and accelerometer data, which was performed by the offset, would be conducted after the scaling process of both. This was followed by the feeding process of the gyroscope and accelerometer data into the complementary filter. Then, with the current position of the gyroscope data, it was constantly integrated during each step. Moreover, the constant value, which was 0.97 and 0.03 needed in order for it to be summed up to 1. Besides, both constant values would be changed throughout the whole experiment, so that a suitable value could be acquired. For example, the constant value of *a* was always added to one, in order to produce an accurate and linear estimate of the output. The equation (1) below displays the mathematical relation of the complementary filter.

$$Angle = a\times(Gyro\_angle\times dt) + (1-a)\times(Acce\_angle) \qquad (1)$$

Based on the equation:

a = Constant value

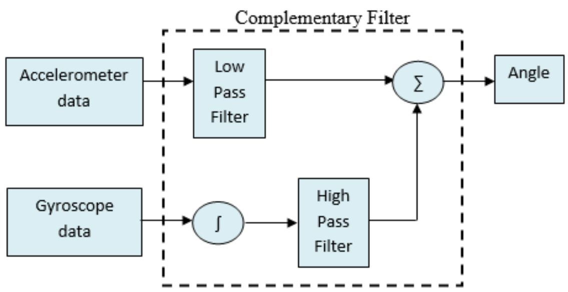

Figure 5: Block diagram of digital complementary filter system for MEMS gyroscope and accelerometer

D. *MEMS Gyroscope and Accelerometer Based North Finding System*

In order to control the rotation of the MPU6050, it was configured to be aligned to the plane of the horizon, which was situated uppermost part of the spinning laser of the stepper motor. This configuration was conducted by the A4988 micro-step driver. Furthermore, in order to maintain the consistency of the g-sensitivity throughout the measurement process, the position of MPU6050 was fixed and the setup was rotated in clockwise direction. Moreover, each step of the rotation amounted to 0.1125 degrees of angle, which was displayed by the horizontally rotating micro stepper motor. Last but not least, all field tests, which are reported in this study, were performed at Bangi, Malaysia, with a latitude of φ = 2.9300° N. The measurement model was represented by the following equation:

$$\omega_{position1} = \Omega_e \cos\varphi \cos\psi + \varepsilon(t_1) \qquad (2)$$

$$\omega_{position2} = -\Omega_e \cos\varphi \cos\psi + \varepsilon(t_2) \qquad (3)$$

Based on this equation:

- Ωe = Rotation rate of earth
- φ = Angle of the latitude
- ψ = Difference of the detected axis and north
- ε(t1) = Bias of gyroscope at t1
- ε(t2) = Bias of gyroscope at t2

An angle was formed by both Equation (2) and (3) to obtain the North direction:

$$\psi = \arccos[(\omega position1 - \omega position2)/(2\omega e \cos\varphi)] \qquad (4)$$

III. Result and Discussion

A. *The Accuracy of Equation Testing of Micro Rotator Using Optical Polygon and Autocollimator*

The accuracy of the rotator, which was tested on, was collected. Following that, there were six samples of the rotator in total that coincided with the angle of the polygon's faces, which were 90°, 180° - 360°. Moreover, the angle of the polygon's faces was 0° with each rotation of the rotator. Based on Table 1, an accuracy of ± 0.02 ° was found in the micro rotator. This accuracy was tested in clockwise and counterclockwise rotation ranged from 0° to 360°. Last but not least, these findings have proven the accuracy of the developed rotator in this system.

Table 1
Calibration Results of Micro Rotator

Expected Angle (°)	Reading of Autocollimator (°)					
	1	2	3	4	5	6
0	0.00	0.00	0.00	0.00	0.00	0.00
90	89.68	89.93	89.77	89.90	89.73	89.89
180	179.48	179.88	179.62	179.81	179.56	179.81
270	269.66	269.96	269.79	269.94	269.77	269.94
360	359.61	360.00	359.80	360.00	359.80	360.00

B. *Complementary Filter for MEMS Gyroscope and Accelerometer*

A connection was established between the signal conditioning and the input device of Arduino Mega. The connection was done via an I2C communication medium. Furthermore, data was imported from the microcontroller to Microsoft Excel (at the actual time) through Parallax Data Acquisition tool (PLX-DAQ) software. Through this process, the measurement graph was successfully captured. Therefore, based on [17], the results regarding the raw data accelerometer and gyroscope, which took place in real-time captured via PLX-DAQ, has been displayed.

Based on the graph in [17], a clear trend of accelerometer sensibility to noise could be seen. On the other hand, a drift angle occurred within the gyroscopes, in which it was in a static condition with zero degrees of angle. Based on this finding, it could be proven that a filter was required for both gyroscope and accelerometer, in order to ensure that the output was not affected by interference. Moreover, in order to gain the desirable value, a simple rotation along X-axis was appropriately performed from the beginning to the end of the experiment where the factor value, a, will be tuned in. Based on the results and analysis in [17] for the various setting of coefficient complementary filter, 0.97, which was the best factor value, was chosen.

C. Outdoor and Semi-Open Field Test for North Location Finding System

There were 24 experiments held at three different locations, with each of them being conducted outdoor at a latitude of φ = 2.9300° N. The purpose of this experiment was to find the North direction. Following that, the comparison was done between the collected results from this experiment and the ones from Pedoman Suria, developed by Unisza which was certified by Islamic National Council Malaysia due to its accuracy. The comparison results from this experiment are displayed in Table 2.

Table 2
Comparison Results Between True North Direction of The Developed Systems and SCA

Time	Differences of angles in different locations (°)		
	FKAB	KBH	FPEND
1000	1.5	1.4	1
1030	1.5	1	1
1100	1	1.5	1.5
1130	1.5	1	1
1200	0.5	1.3	1.5
1230	1.5	1	1.1
1300	1	1	1.5
1430	1.5	1.2	1.2

Based on the experimental results in Table 1, the developed low-cost system was proven accurate. To illustrate this, the systems displayed an accuracy of approximately ±1.5°, in comparison to the accuracy of the true north orientation produced by the certified SCA. Therefore, in terms of the measurement of time and stability of accuracy, a better performance was shown by the developed system, in comparison to the performance displayed by the universal north-seeking scheme.

On 14th March 2017, through a collaboration with the Department of Survey and Mapping Malaysia (JUPEM), a semi-open field test was accomplished at Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (FKAB UKM). Furthermore, with the Theodolite, the true North direction was determined and marked by JUPEM officers, as presented in Figure 6. These procedures are dependent on the concept of points and degree calculations. Not only that, they should be performed outdoors, with an exposure to the sun. Firstly, before the transfer of the true north direction, which was done point-by-point to the semi-open space, it was marked outside. Following that, comparison was performed with the direction of true north obtained through the prototype. Consequently, the results from the comparison were successfully verified, with an error less than ±1.0°. These results are presented in Figure 8.

Figure 6: JUPEM officers equipped with Theodolite observing the sun, in order to determine the true north direction

Figure 7: The direction of true north, which was transferred point-by-point to the semi-open space, and the marked difference of true north direction, which was done by a prototype, was observed

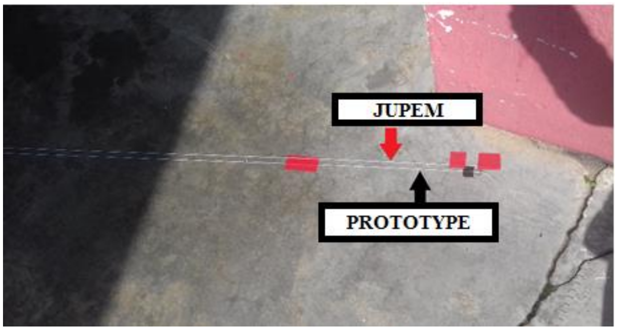

Figure 8: A comparison performed between the developed system and JUPEM, in terms of true north direction

IV. Conclusion

Based on this study, it can be seen that the combination between the microelectromechanical system of the gyroscope and accelerometers, which was done via digital complementary filter factor, a = 0.97, was successfully performed. The purpose of this combination was to determine the accurate direction of north. Based on the industry standard testing, where autocollimator and polygon were involved, the precise rotation of the rotator could be seen, whereby it rotated at ±0.02° for a clockwise and counterclockwise rotation angle from 0 ° to 360 °. Last but not least, it was proven from the field test results that an accuracy of ±1° can be acquired by the developed system, in terms of the true north direction.

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