IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 18 October 2022, accepted 22 October 2022, date of publication 26 October 2022, date of current version 4 November 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3217494

APPLIED RESEARCH

MEMS Gyro and Accelerometer as North-Finding System for Bulk Direction Marking

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This work was supported in part by the School of Engineering, Monash University Malaysia, under SEED, under Grant-2020; and in part by the Centre for Collaborative Innovation (PIK), Universiti Kebangsaan Malaysia (UKM), under Grant INOVASI-2017.

ABSTRACT The ability to seek the accuracy of the true north direction is essential in determining the direction of the ground vehicle, sea, and air and as a reference point in the determination of Qibla direction as well. Theodolite is mainly used for surveying applications in measuring angles, including determining the direction for Muslims to perform ritual prayers, Qibla. However, transferring point-by-point from outdoor to indoor via theodolite requires many experts and is a complicated process. In this paper, we present the development of a highly accurate and compact north-finding prototype for bulk direction marking based on a Micro-Electro-Mechanical System (MEMS) gyroscope and accelerometer sensor. The system consists of two modules; a GPS-based transmitter module to obtain latitude and longitude information and a MEMS gyroscope and accelerometer-based receiver module to detect the geographic north and mark the direction. We accomplish the accuracy by implementing a 4-point static rotation method to compensate for the gyroscope bias and a digital complementary filter system to filter out drift error and fluctuations in the data. We tested the developed prototype on different geographic landscapes, weather conditions, and various building types. The field test results prove that the developed system achieves an accuracy of ±7' 06'', verified by the Department of Survey and Mapping Malaysia.

INDEX TERMS Accelerometer, direction marking, geographic north, GPS, gyroscope sensor, MEMS gyroscope, north-finding, static rotation method, true north.

I. INTRODUCTION

Geographic north (also known as true north) is the point on the north pole in the middle of the Arctic Ocean where all the earth's longitude lines converge. Unlike magnetic north, which is created by the earth's magnetic field and constantly moves due to magnetic changes and flux lobe elongation, geographic north never changes. And thus, knowing the geographic north is crucial in applications that need absolute north orientation, such as geodetic surveying, mapping, topography, attitude determination, trajectory verification, and military applications [1]. Even in essential navigation tools such as compass and GPS (Global Positioning System), geographic north plays the crucial role of fixed reference point; magnetic declination (the angle on the horizontal plane between magnetic and true north) is applied to determine the actual direction when using a compass [2]. In contrast, while the GPS geographic coordinates are defined relative to the latitudes of the north pole (90°N), south pole (90°S), and the equator (0°) [3].

Regarding finding direction in modern society, the readily available electronic compass and GPS-based technologies is the most popular choice, commonly used in navigation apps, maps, and digital compasses [4]. To correct the magnetic declination and ensure precise direction, the World Magnetic Model (WMM) is used, which comes pre-installed on Android and iOS devices. The WMM is a spatial-scale geomagnetic model of the earth's magnetic field [5]. It keeps track of the changes in the magnetic field and is updated every five years as the magnetic north drifts towards Siberia

The associate editor coordinating the review of this manuscript and approving it for publication was Santosh Kumar.

at around 50 – 60 km a year. The next WMM update was supposed to be at the end of 2020. However, the European Space Agency (ESA) recently reported that the magnetic north is drifting unexpectedly, thus rendering the WMM data too inaccurate to wait for the next scheduled update. An out-of-cycle update for the WMN has been issued around mid-2020 [6] showing that electronic compass and GPS-based technologies are unstable for permanent direction-marking applications. In addition, the heading accuracy of digital compasses can be degraded by electromagnetic interference and ferrous materials. At the same time, GPS signals can be easily obstructed inside buildings in geographically isolated locations, challenging landscapes, and harsh weather conditions [7], [8]. Due to all these factors, it is safe to say that electronic compass and GPS-based technologies cannot be used if the goal is to find and mark the accurate direction in varying geographic situations.

Because of the issue with drifting magnetic north and inaccurate WMM data, 19.5 million Muslims in Malaysia face a severe problem; the Qibla direction they have marked using mechanical and digital compasses is entirely wrong. Qibla is the direction of the Kaaba building in Mecca, Saudi Arabia, -It is used for daily prayers and various religious practices, including burying the dead with the head in line with the Qibla direction. This practice helps archaeologists determine the remains of Muslim cemeteries if no other signs are present [9].

The Department of Islamic Development Malaysia (JAKIM) is fully responsible for determining the exact Qibla direction for prominent mosques and principal infrastructures across the country. Their primary method to determine the Qibla is using a mixture of theodolite and GPS to create high precision, quasi-solar compass system [10]. Meanwhile, the general public and non-principal businesses such as hotels and shopping malls rely on mechanical and digital compasses to mark their Qibla [11]. And as stated earlier, these personal markings are inaccurate. JAKIM has to complete a country-wide bulk Qibla direction marking correction in many high-rise buildings and geographically isolated locations within the next three years. Such a task is very challenging with their current system and workforce numbers.

Looking at this situation, it is clear that there is a pressing need for a high-accuracy, compact, and mobile direction-finding and marking system based on geographic north that is low in cost and easy to use for non-experts. The design must be robust and versatile for use inside and outside high-rise buildings and in varying geographic landscapes. Micro-Electro-Mechanical System (MEMS) gyroscope can fulfill all these criteria because it does not have rotating parts that use bearings and thus can be miniaturized to fit a small printed circuit board (PCB). MEMS gyroscope utilizes the Coriolis acceleration effect on the vibrating mechanical element to detect the velocity of the Earth's angular rotation rate [12]. MEMS gyroscope can provide precise readings and is initially used for military navigation. As the demand soars in the civilian market, it is now fully adapted for low-cost applications in the automotive, industrial, medical, and mobile device industries. The cost of production is expected to decrease further as MEMS gyroscope technology gradually reaches its commercial maturity [4], [13].

In this paper, we proposed the development of a highly accurate yet affordable north-finding and directing marking system using MEMS gyroscope, accelerometer, and GPS. The developed system comprises two modules: indoor and outdoor. The outdoor module includes a global positioning system (GPS) to provide location information (latitude and longitude) fed into the indoor module inside the building via wireless communication technology medium on 433MHz radio frequency waves. The location information is then processed using vector algebra formulas for Qibla angle determination. The indoor module consists of a MEMS gyroscope and accelerometer on the horizontal rotating laser mounted on a stepper motor to detect the geographic north and mark the desired direction. This paper is structured as follows: Section 2 describes the theoretical background of the proposed system, while Section 3 describes the development of the prototype. Section 4 discusses the analysis and field-testing results, and Section 5 concludes the paper.

II. THEORETICAL BACKGROUND

A. TRANSMITTER AND RECEIVER MODULES

We came up with the concept of two separate modules for the north-finding system instead of a single device commonly reported after a thorough discussion with The Department of Islamic Development Malaysia (JAKIM). They raised concerns over the reliability of the GPS reading on a single device for direction marking inside closed-off buildings with multiple rooms and high-rise infrastructures [14]. While the geographical north determination only needs to be done once per location, the bulk Qibla direction marking based on geographical north requires personalized marking at each sub-location. Thus, we devised with a separate transmitter module stationed outside the building and a receiver module placed inside the building. The two modules will communicate via a specialized wireless medium. Fig. 1 shows the block diagram of the two-modules concept for the system.

The transmitter module is solely responsible for obtaining the accurate latitude and longitude data of the measurement location. As it has a more straightforward function and thus a less complex design than the receiver module, we focused on ensuring the transmitter module has a compact and very light design yet maintains high accuracy even in poor environments. The receiver module bears an enormous burden in the whole system; it is responsible for receiving and processing the data from the transmitter while simultaneously controlling the MEMS gyroscope and accelerometer data and filtering their inputs, so they are free from errors. After the gyroscope and accelerometer find the geographic north direction, the transmitter module then needs to compute the transmitter latitude and longitude data against the geographic north angle to obtain the desired direction [15] and drive the laser marker towards that direction.

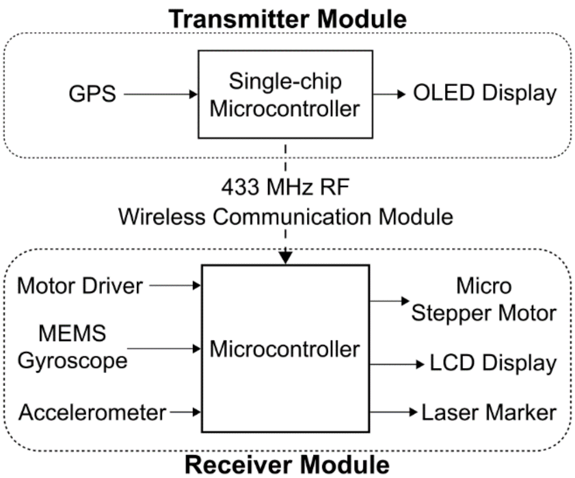

FIGURE 1. Block diagram of the transmitter and receiver modules concept for the north-finding system.

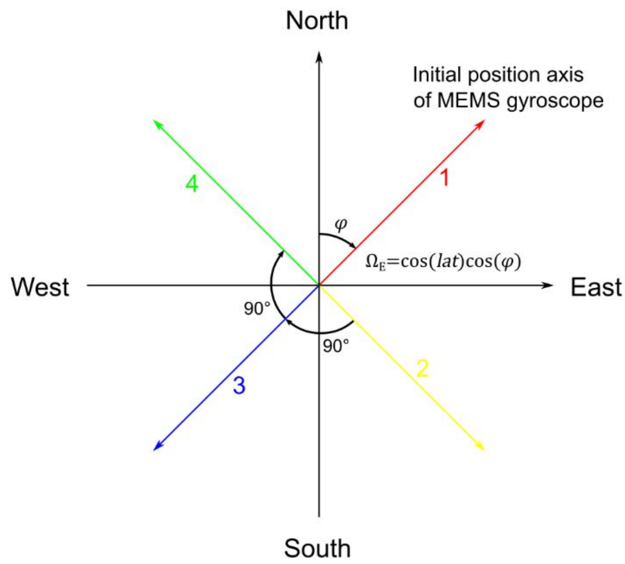

FIGURE 2. 4-points static rotation method.

This is why the MPU6050 sensor combines a 3-axis MEMS gyroscope and a 3-axis accelerometer was chosen as the geographic north-finder because, despite its affordable price, it can give very accurate readings [16]. The 3-axis accelerometer of the MPU6050 acts as an auxiliary sensor that counter the errors experienced by the MEMS gyroscope sensor. This is done by feeding the data from both sensors into a filter system. The accelerometer also helps the MEMS gyroscope differentiates between the system's rotation and the Earth's rotation when the system is rotated without moving. The angular velocity of the system's rotation will be measured by the accelerometer and subtracted from the gyroscope data to obtain the Earth's rotation velocity and geographic north direction [17].

The wireless communication medium between the two modules must be at a frequency band specific to that system and will not be disrupted by nearby signals. We achieved this by choosing 433 MHz radio frequency (RF) modules that only communicate within that frequency band [18].

B. 4-POINTS STATIC ROTATION METHOD

The geographic north's orientation is obtained by observing the horizontal component of the earth's rotation vector. And in the case of using MEMS gyroscope to find north, this sensor type tends to show long-term drift and thus requires bias compensation. In the static north-finding model, a standard method of 2-point static rotation is applied to mitigate the additive bias errors through differential azimuth measurement. The sensitive gyroscope axis needs to be discretely turned by $\pm 180°$ (also known as maytagging) to detect the azimuth [19].

An improvement to the static rotation method is introduced in this paper. Instead of the standard 2-points rotation, we used a 4-points static rotation method [19] in which the sensitive gyroscope axis was discretely turned by $\pm 90°$ in the 1-2-3-4-1 clockwise direction, followed by 1-4-3-2-1 counterclockwise movement, as shown in Fig.2. Measurement of the four points (one full rotation) for each order are represented by the following equations

$$V\left(0°\right) = \Omega_E \cos(lat) \cos(\varphi) V° \tag{1}$$

$$\begin{aligned} V\left(90°\right) &= \Omega_E \cos(lat) \cos\left(\varphi - \frac{\pi}{2}\right) \\ &= \Omega_E \cos(lat) \sin(\varphi) \end{aligned} \tag{2}$$

$$\begin{aligned} V\left(180°\right) &= \Omega_E \cos(lat) \cos(\varphi - \pi) \\ &= -\Omega_E \cos(lat) \cos(\varphi) \end{aligned} \tag{3}$$

$$\begin{aligned} V\left(270°\right) &= \Omega_E \cos(lat) \cos\left(\varphi - \frac{3\pi}{2}\right) \\ &= -\Omega_E \cos(lat) \sin(\varphi) \end{aligned} \tag{4}$$

where Ω_E is the rotation rate of the earth's magnitude, which is 15.0411 °/hr (approximately 0.0042 °/s), lat is the latitude angle of the measurement location, and φ is the azimuth angle. Thus, the azimuth angle will be

$$\varphi = \tan^{-1}\left(\frac{V(90°) - V(270°)}{V(0°) - V(180°)}\right) \tag{5}$$

C. DIGITAL COMPLEMENTARY FILTER SYSTEM

While the basis of the static north-finding model is modulating discrete rotation of the sensitive gyroscope axis, the dynamic north-finding model is based on modulating the continuous process of the axis to measure the Earth's rotation rate (also known as carouseling). A Kalman filter is commonly used in many pieces of research to reduce the effect of bias drift when using the dynamic method [19]. However, some literature argues that the Kalman filter's algorithm is too complex, has a long computational time, and is difficult to program on specific 8-bit microcontrollers [20, 21]. Reference [21] suggests that the filter can have simpler algorithms and fewer sensors. As our receiver module takes data from the MEMS gyroscope and accelerometer, the filter

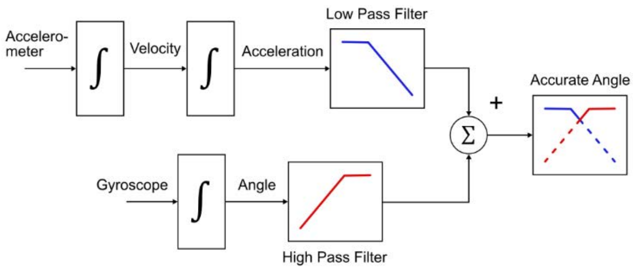

FIGURE 3. Block diagram of the digital complementary filter system.

must be able to smoothly integrate both inputs, keep drift error at a minimum, and has a less complex algorithm for faster computational time.

Hence, we developed our own digital complementary filter system that uses the strength of one sensor (MEMS gyroscope) to overcome the weakness of the other sensor (accelerometer), and vice versa. This is achieved by combining high-pass and low-pass filters that work simultaneously. The high pass filter will filter out the drift error from the gyroscope, while the low pass filter will filter out the fluctuations in the accelerometer's input data [22]. Based on Fig. 3 below, the gyroscope angle rate input will be integrated first to produce the attitude angle before it passes through the high pass filter to overcome the drift angle error. Meanwhile, the accelerometer input will go through the integration process twice to obtain the output angle before being filtered by the low pass filter. Both filters work simultaneously, and the sum from both filtered data will give a more accurate angle.

For this system, a mathematical algorithm is developed for the high pass and low pass filters using an integrated development environment (IDE) based on (6) as follows

$$Angle = a \times (gyro\_data \times dt) + (1 - a) \times (acceleerometer\_data) \quad (6)$$

where $a =$ coefficient value. Position data obtained from the MEMS gyroscope and accelerometer will undergo a simulation process simultaneously through the high pass and low pass filters to obtain the output angle value. The low pass filter allows frequency signals lower than the cutoff frequency to pass through, and gyroscope signals with higher frequencies than the designated cutoff frequency will be blocked. Similarly, the high pass filter will only allow frequency signals higher than the cutoff frequency to pass through, and accelerometer signals lower than the cutoff frequency will be blocked. Filtered signals from both sensors are then combined to get the best signal and angle value. The coefficient value from (6) will be tuned throughout the experiment to get the best value. The coefficient value for the filters will always add one so that the resulting angle is always accurate and linear.

D. ALLAN VARIANCE

Measuring the bias stability of a gyroscope can help determine its stability over a period of time, with the bias stability coefficient commonly denoted in units of a degree per hour (°/hr) or degree per second (°/s). A common approach to measuring bias stability is using the Allan Variance, a method to characterize noise and stability by analyzing a time sequence and describing the intrinsic noise as a function of the averaging time [23]. The calculation begins by splitting a long data sequence into bins based on averaging time τ. The Allan variance calculation is as follows

$$AVAR^2(\tau) = \frac{1}{2 \cdot (n-1)} \sum_i \left(y(\tau)_{i+1} - y(\tau)_i\right)^2 \quad (7)$$

where $AVAR^2(\tau)$ is the Allan variance as a function of the averaging time τ, y_i is the average value of the measurements in bin i, and n is the total number of bins.

Uncorrelated noise in the output influences the Allan variance at a short averaging time τ. At first, the Allan variance gradually decreases as the average time increases until it levels off due to $1/f$ noise. As the power of $1/f$ noise can be used to define bias stability, the minimum value of Allah variance represents the bias stability of the gyroscope. The Allan variance increases again as the averaging time gets longer due to bias drift or angular rate random walk error in the output [24].

III. PROTOTYPE DEVELOPMENT

A. GPS-BASED TRANSMITTER MODULE

A compact 81 mm × 64 mm printed circuit board (PCB) was specifically developed for the transmitter module, consisting of several main components, namely an ATMega328 integrated circuit, a wireless transceiver communication device that operates at 433 MHz radio frequency (RF) waves, an organic light emitting diode (OLED) display, and a GPS module. The transmitter module was placed outside the building (where the GPS signal was clear) to receive only the latitude and longitude coordinates of the location. The GPS module used was a GPS SKM53 series with an embedded GPS antenna that can function well even in poor GPS signal environments. In addition, this module uses the high-performance single MediaTek 3329 chip architecture. No electronic compass and geomagnetic model are integrated with the GPS module. Fig. 4 shows the complete assembly of the GPS-based transmitter module.

The ATMega328 microcontroller functioned as a processor unit that retrieved location data from the SKM53 GPS module and then displayed the latitude and longitude coordinates of the location via the OLED display. This processing unit received data continuously while, at the same time, the location information was transmitted to the receiver module inside the building through the wireless 433 MHz RF wave communication medium.

B. MEMS GYROSCOPE AND ACCELEROMETER (MPU6050)-BASED RECEIVER MODULE

The developed receiver (and marker) module consists of Arduino Mega 2560 microcontroller, RFBee wireless communication device at 433 MHz radio frequency, 16 × 2 light emitting diode (LED) display, micro stepper motor, laser

FIGURE 4. GPS-based transmitter module.

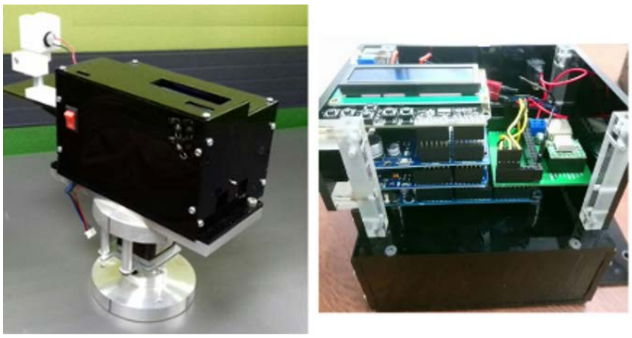

FIGURE 5. MEMS gyroscope and accelerometer (MPU6050)-based receiver module.

marker, and a MPU6050 sensor module that combines 3-axis MEMS gyroscope and a 3-axis accelerometer in a single sensor. Fig. 5 shows the complete assembly of the transmitter module.

Location data sent by the transmitter module was detected by the receiver module placed inside the building via the RFBee communication medium in real-time. The data was processed and displayed on the 16 × 2 LED display in the latitude and longitude coordinate format. At the same time, those latitude and longitude data were processed inside the C programming software with the help of the Arduino Mega microcontroller.

Meanwhile, the MEMS gyroscope and accelerometer inside the MPU6050 sensor were rotated horizontally on a rotating laser marker. The stepper motor turned into micro-motion mode under the control of the Arduino Mega 2560 to collect the output data from the gyroscope and accelerometer. The data were fed into the microcontroller for simultaneous simulation through the digital complementary filter system to filter out errors and obtain an accurate direction angle of the geographic north. Once the geographic north was successfully detected, it was set as the reference point for the direction determination and marking.

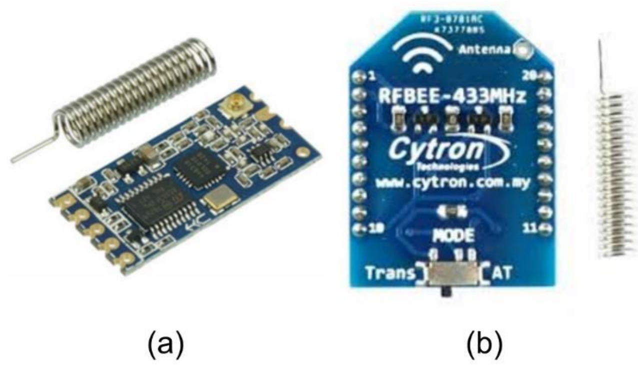

FIGURE 6. a) 433 MHz v1.1 RF transceiver module installed in the transmitter module. b) RFBee 433 MHz UART wireless module (1km) installed in the receiver module.

TABLE 1. Bias stability measurement for mpu6050 with Allan variance.

Random Error	Gx Measurement	Ax Measurement
Bias stability coefficient, B (°/s)	0.001241	0.00004280

C. WIRELESS COMMUNICATION MEDIUM BETWEEN MODULES

A wireless communication medium that functions at 433 MHz radio frequency (RF) waves was chosen as the specialized communication method between the two modules because it operates under a similar concept as the wireless sensing network. The transmitter module was equipped with a 433 MHz v1.1 RF transceiver module, as shown in Fig. 6a, while the receiver module was equipped with RFBee 433 MHz UART wireless module (1km), as shown in Fig. 6b. Both 433 MHz modules were chosen because of their smaller size and thinner design. In addition, both modules operate at a frequency band between 433.4 MHz and 473.0 MHz for 1 km. Unless signals with the same frequency band are nearby, the communication medium cannot be disrupted.

IV. RESULTS AND DISCUSSION

A. BIAS STABILITY COEFFICIENT

Static measurement was done for 4 hours on MPU6050 to collect the output data. The data was then processed using MATLAB software for Allan variance analysis. Fig. 7 shows the Allan variance plot for MEMS gyroscope output, while Fig. 8 shows the same plot for accelerometer output, both on the x-axis at a sample rate of 100Hz. Table 1 presents the bias stability measurement for MPU6050 with Allan variance.

The bias stability coefficient for MPU6050 is the key feature to be considered before the geographic north-finding experiment can be carried out. Based on the measurement in Table 1, the bias stability coefficient for the MEMS gyroscope of the MPU6050 sensor is 0.001241°/s, which equals 4.47°/h. This coefficient value is smaller than the earth's angular

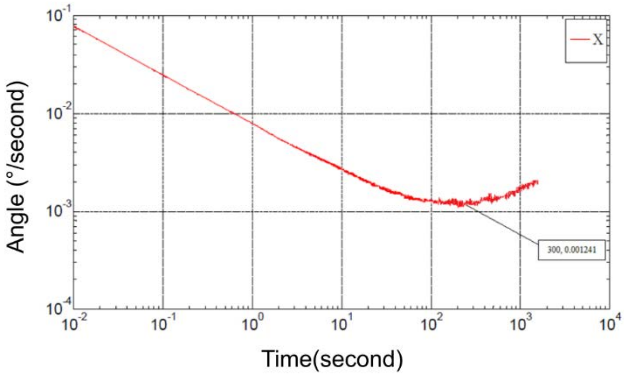

FIGURE 7. Allan deviation of the MEMS gyroscope on the x-axis.

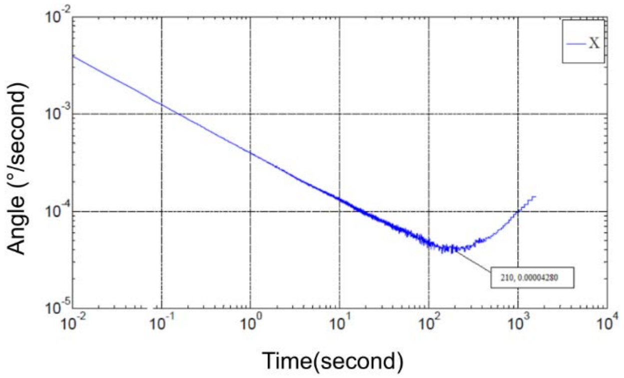

FIGURE 8. Allan deviation of the accelerometer on the x-axis.

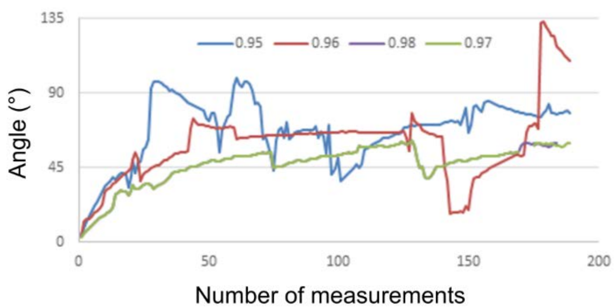

FIGURE 9. Output measurement at four coefficient values for 90° angle position experiment.

velocity at 0.0042°/s, and thus the MPU6050 is deemed capable of measuring the angular rotation of the earth's axis [25].

B. COEFFICIENT VALUE FOR DIGITAL COMPLEMENTARY FILTER SYSTEM

At first, the coefficient value a from (6) for the digital complementary filter system was randomly assigned in the algorithm code. Then, the angle measurement was done when the MPU6050 was at a 90° position to narrow down the potential coefficient value. Fig. 9 shows the output angle for coefficient values of 0.95, 0.96, 0.97, and 0.98.

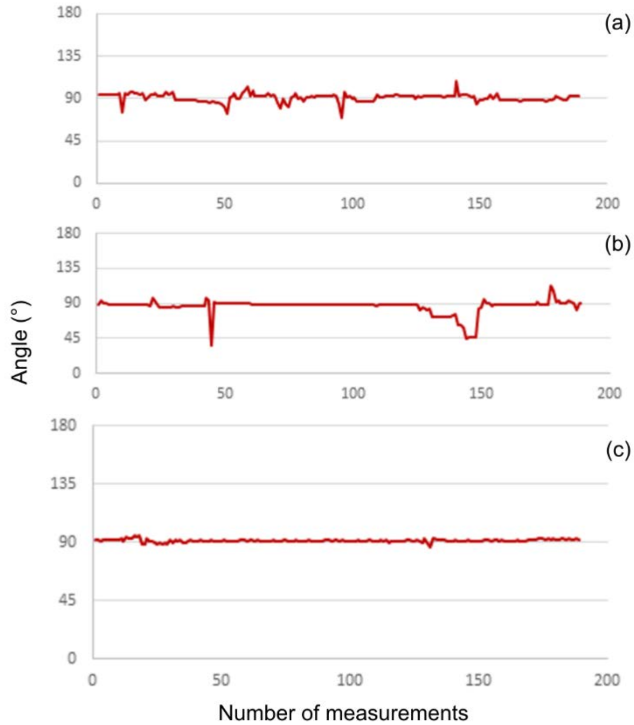

FIGURE 10. Output measurement at a) 0.958 b) 0.956 and c) 0.954 coefficient values for 90° angle position experiment.

Based on Fig. 9, the 0.95 and 0.96 coefficient values are the closest to a 90° angle. Thus, the subsequent measurement focused on the values between 0.95 and 0.96. Fig. 10 shows the results for three values, namely 0.958, 0.956, and 0.954. From the three values, Fig. 10c clearly illustrates that the coefficient value of 0.954 gives the highest output angle accuracy at the 90° position, compared to 0.958 and 0.956 values.

Fig. 11 shows the performance of 0.954 coefficient value when tested at angle of 0°, 90°, and 180°, respectively, for 200 measurements.

Due to its stable performance and accurate output, 0.954 was chosen as the coefficient value for our digital complementary filter system and used in the subsequent experiments to determine geographic north.

C. GEOGRAPHIC NORTH FINDING USING 4-POINTS STATIC ROTATION METHOD

The experiment to find geographic north using 4-points static rotation method was done under 300 seconds for one direction, in which 50 measurements were recorded. During the investigation, the initial position of the MEMS gyroscope headed geographic north. After that, the rotator was turned 90° clockwise heading east for the second cycle of measurement, another 90° clockwise, heading south for the third cycle, and finally heading west for the last measurement cycle. Fig. 12 shows the output measurement of the rotations with Fig. 12a for the geographic north heading, Fig. 12b for the east heading, Fig. 12c for the south heading, and Fig. 12d for the west heading.

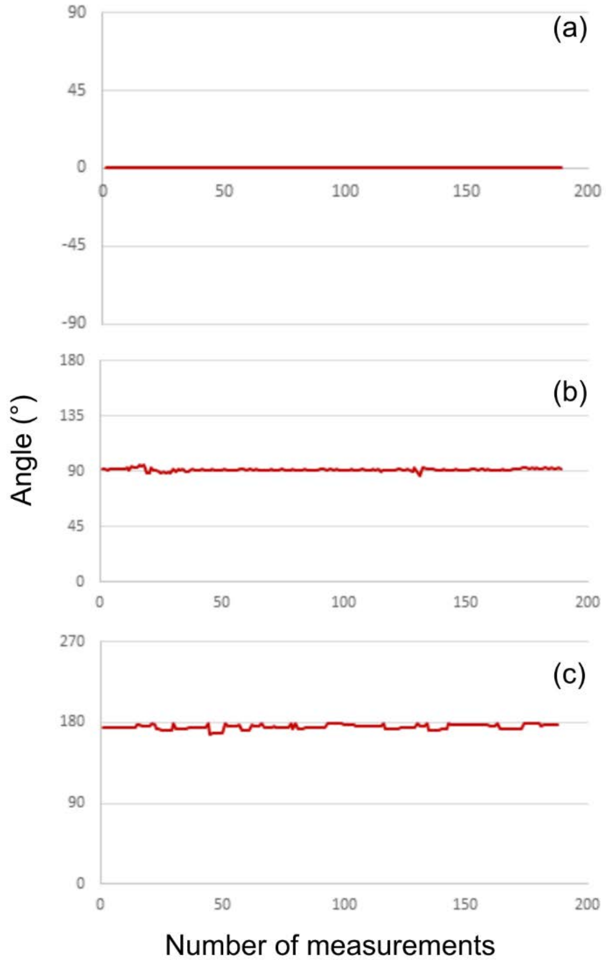

FIGURE 11. Performance of 0.954 coefficient value at a) 0° b) 90° and c) 180°.

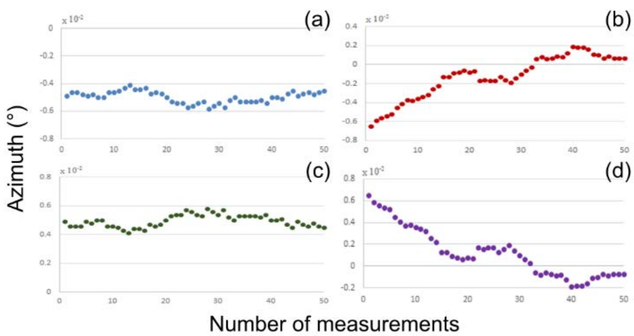

FIGURE 12. Output measurement when MEMS gyroscope headed towards a) geographic north b) east c) south and d) west.

Measurements were continued for five complete rotations. Fig. 13 shows a total of 1000 recorded measurements that took 1.7 hours. Each measurement point in Fig.13 represents the average azimuth of 50 measurements in each direction.

The experimental results in Fig. 13 show that the azimuth approaches zero value when the MEMS gyroscope sensor is either in the east or west direction. Meanwhile, the azimuth

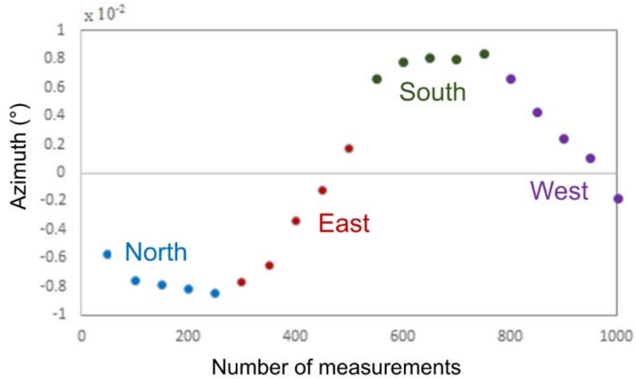

FIGURE 13. Measurement results with each measurement point represent the average azimuth of 50 measurements in each direction.

reaches a minimum value in the geographic north direction and a maximum value in the south direction. The measurement results also show that the gradient of the graph in the east and west directions is steeper, meaning they are easier to detect accurately compared to the north and south directions [26].

D. FIELD TESTS OF PROTOTYPE FOR BULK DIRECTION MARKING

A field test to determine the communication distance between the transmitter and receiver modules via the wireless radio frequency at 433MHz (RFBee 433MHz) was first conducted. We found that the maximum distance when both modules are at the same level is 600 meters. In contrast, when the receiver module was placed at a different story inside the building, the communication distance can cover a maximum height of 14.58 meters.

Field tests were carried out throughout Malaysia to find the geographic north, the feasibility of the north-finding system, and whether it can accurately detect and mark the desired Qibla direction based on the geographic north. The locations of the field test were selected based on different geographic landscapes, weather conditions, and various building types, namely:

1) SITUATION 1

Inside a closed building in the Collaborative Innovation Center (PIK), UKM Bangi, at latitude 2.9273 °N.

2) SITUATION 2

In a semi-open area at latitude 2.9228 °N, located in IMEN, UKM Bangi.

3) SITUATION 3

In an open area located on the hill at Sheikh Tahir Astronomical Center, Penang, at latitude 5.4115 °N and an altitude of 40 m above sea level.

4) SITUATION 4

In a semi-open area in Kubang Kerian Mosque, Kota Bharu Kelantan, at latitude 6.0945 °N.

TABLE 2. Comparison in measuring geographic north between the mpu6050 north-finder prototype and jupem's marking.

Situation	Prototype	JUPEM	Deviation	Percentage of Accuracy
1	359.8816°	0°	0.1184	99.88%
2	359.8816°	0°	0.1184	99.88%
3	1.5013° (first marking)	0°	1.5013 (first marking)	98.50% (first marking)
	358.5668° (second marking)	0°	1.4332 (second marking)	98.57% (second marking)
4	359.3767°	0°	0.6233	99.38%

TABLE 3. Comparison in measuring the Qibla direction between mpu6050 north-finder prototype and JUPEM's marking.

Situation	Prototype	JUPEM	Deviation	Percentage of Accuracy
1	292.6944°	292.6261°	0.0683	99.98%
2	292.6944°	292.6261°	0.0683	99.98%
3	293.1569° (first marking)	291.5878°	1.5691	98.43% (first marking)
	290.2382° (second marking)	291.5878°	1.3496	98.65% (second marking)
4	292.0467° (first marking)	291.0372°	1.0095	98.99% (first marking)
	292.2594° (second marking)	291.0372°	1.2222	98.78% (second marking)

Representatives from the statutory bodies (JUPEM, JAKIM, and the State Mufti Department) were present during the field tests to check the system's accuracy by comparing the detected geographic north and Qibla direction with the one they obtained, as shown in Table 2 and Table 3 below.

The prototype underwent four situations at each field test to assess its feasibility and robustness. Table 2 and Table 3 show that the mean absolute deviation is 0.57. The prototype achieved an average accuracy of 99% in determining the geographic north and marking the Qibla directions with a slight error of $0^\circ\ 7'\ 6''$.

At the end of the experiment, we concluded that the MEMS gyro MPU6050 north-finder prototype has four distinct strengths. Firstly, the prototype can handle different field situations and still give highly accurate readings due to properly suppressed errors. Secondly, the two-module configuration where the GPS-based transmitter module is placed outside the building, and the MEMS gyroscope and accelerometer-based transmitter module is placed inside the building, allows for more flexibility in the measurement process. Thirdly, the prototype is easy to use for non-expert as all the computation and detection are automatically done by the system. The user only needs to place modules and ensure they can communicate properly. And lastly, the transmitter module is very compact and light, while the larger receiver module only weighs around ~1.5 kg. Hence, the developed prototype makes it easily portable for bulk direction marking at multiple sub-locations.

V. CONCLUSION

This paper reports the development of a high-accuracy north-finding and direction-marking system prototype consisting of a GPS-based transmitter module and a MEMS gyroscope and accelerometer-based receiver module. The bias stability coefficient for the prototype's MEMS gyroscope sensor was found to be at 0.001241°/s, and it is smaller than the Earth's angular velocity at 0.0042°/s, and thus suitable for north-finding measurement. A 4-points static rotation method for bias compensation is introduced in this paper as an improvement to the commonly used 2-points method. A digital complementary filter system is also developed for the receiver module consisting of a high pass filter that filters out the drift error from the gyroscope and a low pass filter that filters out the fluctuations in the accelerometer's input data. The data from both sensors are summed with a 0.954 coefficient value to produce the most accurate angle. The prototype underwent field tests in three locations throughout Malaysia with varying geographic landscapes and four situations at each site. Based on the field tests, the two modules could communicate at a maximum distance of 600 meters and a maximum height of 14.58 meters. The field test results were reviewed by statutory bodies (JUPEM, JAKIM, and the State Mufti Department). It proved that the prototype system for determining the direction of Qibla based on true north has achieved an average accuracy of 99% in determining the geographic north and marking the desired directions with a slight error of $0^\circ\ 7'\ 6''$. Future work will be focused on decreasing the time needed to find the north direction and designing the receiver module to be more compact and robust.

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