Avrupa Bilim ve Teknoloji Dergisi
Özel Sayı 26, S. 180-184, Temmuz 2021

Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
Special Issue 26, pp. 180-184, July 2021

Research Article

Test Experiment Design for IMU-Based Angle Measurement Systems

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(3rd International Congress on Human-Computer Interaction, Optimization and Robotic Applications June 11-13, 2021)

(**DOI:** 10.31590/ejosat.955145)

ATIF/REFERENCE: Yavan, L. & Tepe, C. (2021). Test Experiment Design for IMU-Based Angle Measurement Systems. *European Journal of Science and Technology*, (26), 180-184.

Abstract

Inertial Measurement Unit (IMU) sensors are used in many applications that include aviation, vehicle systems, unmanned aircraft, indoor navigation, health, and robotic systems. An IMU consists of accelerometers and gyroscope sensors combined in a single module. However, the accelerometer or gyroscope alone cannot produce reliable data, and so the outputs are combined to determine accurate data for measurements such as direction, velocity, angular velocity and position.

The data collected from IMU sensors may differ due to measurement errors, calibration issues, and errors due to ambient noise. Small errors in IMU sensors can cause large deviations in applications. There is no clear distinction between the performance and area of use of commercially available sensors. Therefore, when selecting a sensor, the requirements for performance should be determined for the area of use and choosen accordingly.

This study investigates the performance of three IMU sensors that have no specific application area and are in common use. An experimental setup was designed and implemented to test the accuracy of the acceleration and gyroscopic information obtained from the IMU sensors. The test apparatus consists of IMU sensor, encoder, stepper motor and Raspberry Pi. The stepper motor and encoder are connected to a shaft, and the IMU sensor is mounted on a rotating moving mechanism. The apparatus is controlled by a Raspberry Pi. The Python programming language has been used for the control software. The apparatus provides rotation of a desired angle and velocity. Acceleration and gyroscopic data received from the IMU sensor are drawn in real time. All sensors were first calibrated and then data were taken. The performance of the sensors was compared using the angular values around the x-axis. The test setup was rotated at a certain angle in the x-axis using a stepper motor. The gyroscopic data on the x-axis for each IMU sensor were then read and processed through a Kalman filter. The accuracy of the IMU sensors was determined with reference to the encoder data.

Keywords: IMU, KalmanFilter, Python, PyQt5, RaspberryPi, StepMotor, Encoder.

IMU Tabanlı Açı Ölçüm Sistemleri için Test Deney Düzeneği Tasarımı

Öz

Atalet Ölçüm Birimi (IMU) sensörleri, havacılık, araç sistemleri, insansız hava araçları, iç mekan navigasyon, sağlık ve robotik sistemleri içeren birçok uygulamada kullanılmaktadır. Bir IMU tek bir modülde birleştirilmiş ivmeölçerler ve jiroskop sensörlerinden oluşur. Ancak, ivmeölçer veya jiroskop tek başına güvenilir veriler üretemez ve bu nedenle çıkışlar yön, hız, açısal hız ve konum gibi ölçümler için doğru verileri belirlemek üzere birleştirilir.

IMU sensörlerinden toplanan veriler, ölçüm hataları, kalibrasyon sorunları ve ortam gürültüsünden kaynaklanan hatalar nedeniyle farklılık gösterebilir. IMU sensörlerindeki küçük hatalar, uygulamalarda büyük sapmalara neden olabilir. Piyasada bulunan sensörlerin performansı ve kullanım alanı arasında net bir ayrım yoktur. Bu nedenle sensör seçimi yapılırken kullanım alanı için performans gereksinimleri belirlenmeli ve buna göre seçilmelidir.

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Bu çalışma, belirli bir uygulama alanı olmayan ve genel kullanımda olan üç IMU sensörünün performansını karşılaştırılmıştır. IMU sensörlerinden elde edilen ivme ve jiroskopik bilgilerin doğruluğunu test etmek için bir deney düzeneği tasarlanmış ve uygulanmıştır. Test aparatı IMU sensörü, enkoder, step motor ve Raspberry Pi'den oluşmaktadır. Step motor ve enkoder bir mile bağlanmış ve IMU sensörü dönen bir hareketli mekanizma üzerine monte edilmiştir. Deney düzeneği Raspberry Pi tarafından kontrol edilmektedir. Kontrol yazılımı için Python programlama dili kullanılmıştır. Deney düzeneği istenilen açıda ve hızda döndürülebilir. IMU sensöründen alınan ivme ve jiroskopik veriler gerçek zamanlı olarak grafik olarak çizdirilmketedir. Karşılaştırılan sensörler önce kalibre edilmiş ve ardından veriler alınmıştır. Sensörlerin performansı, x ekseni etrafındaki açısal değerler kullanılarak karşılaştırılmıştır. Test düzeneği, bir step motor kullanılarak x ekseninde belirli bir açıyla döndürülmüştür. Her IMU sensörü için x ekseni üzerindeki ivme ve jiroskopik veriler okunmuş ve Kalman filtresi aracılığıyla işlenmiştir. IMU sensörlerinin doğruluğu, enkoder verileri referans alınarak belirlenmiştir.

Anahtar Kelimeler: IMU, Kalman Filtresi, Python, PyQt5, RaspberryPi, Step Motor, Enkoder.

1. Introduction

An inertial measurement unit (IMU) contains accelerometer and gyroscopic sensors that can be used to determine the velocity, angular velocity, acceleration and displacement of objects. The IMU has 6 degrees of freedom given by the acceleration and gyroscopic values in 3 axes.

Accelerometers measure linear acceleration of an object. This includes the force of gravity on the sensor, which can be used to determine the posture of the object. For example, Bakhshi et al. observed used IMU sensors placed on the joints of the human body to determine the angle of joints in patients during activities (Bakhshi, Mahoor, & Davidson, 2011). Abhayasinghe et al. used IMU sensors placed on the thigh bone for indoor pedestrian monitoring to recognize the activity of people and detemined moments of walking, sitting and standing (Abhayasinghe & Murray, 2014). Chang et al. used IMU sensors to measure the posture of the human finger (Chang, Cheng, & Chang, 2016).

IMU sensor data can be used to determine position and speed. Yuan and Chen use the IMU sensors in a wearable system to determine the position and speed of people doing sports (Yuan & Chen, 2014). As GPS does not work indoors, it has become very popular to use accelerometers and gyrescopes in location detection. Aydın and Erkmen used acceleration and gypscope values to determine the speed and position of a person moving in a closed environment (Aydin & Erkmen, 2019).

IMU sensors are used in the inernial navigation systems of aircraft to determine the angular changes and to ensure the stability of the flight. Loianno et al. used an IMU sensor and a camera to control a quadrotor through obstacles in a confined space (Loianno, Brunner, McGrath, & Kumar, 2016). IMU sensors are increasingly being used in balance robots. In their study, Çelik and Güneş built a robot that could move in balance on two wheels and recognize objects using a camera (Celik & Güneş, 2018).

Acceleration and gyroscope data include a number of errors caused by the sensor and the external environment that include sensor-induced bias (deviation) and scaling factor error, and external electrical noise. There issues that should be considered in the selection of a sensor to minimize the effect of these errors in an application. Aspects to consider also include if the outputs are analog or digital, the number of axes, sensitivity, bandwidth, and measurement full-scale range. The data read from the data register of a digital sensor are binary, and must be translated to g or m/sec^2 for acceleration and ^{o}/s for gyroscopic data (Jefiza, Pramunanto, Boedinoegroho, & Purnomo, 2017).

Today, IMU sensors are used in many areas and the accuracy of these sensors is of great importance. In this study, an experimental setup was designed to determine the angular change values calculated from the acceleration and gyroscopic data of sensors with the same characteristics from three manufacturers. The accuracy of the angular change values of the sensors was determined using the mean square error (MSE) criteria.

2. Material and Method

This section discusses the experimental design and data acquisition.

2.1. The Experimental Setup

The design and implemention of the experimental setup for this study is given in Figure 1 and Figure 2.

Figure-1 Experimental Setup CAD Design

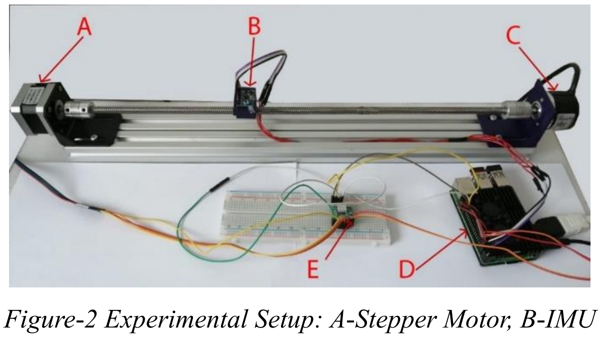

Figure-2 Experimental Setup: A-Stepper Motor, B-IMU Sensor, C-Encoder, D-Raspberry Pi, E-Stepper Motor Driver

The electrical connection diagram for the experimental setup is given in Figure 3, with the connection pin numbers of the Raspberry Pi given in Table 1.

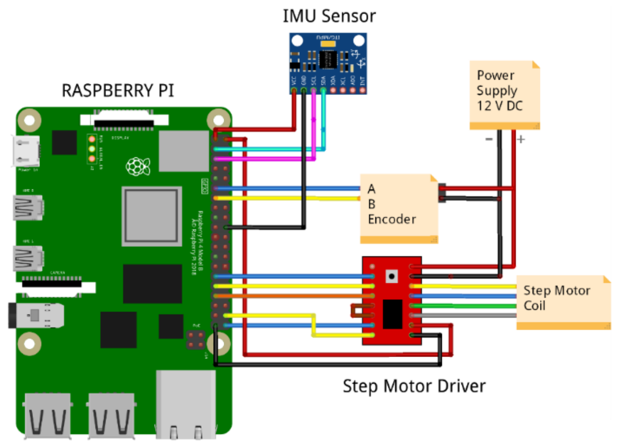

Figure-3 Electrical Connection Diagram for Experimental Setup

Table 1. Raspberry Pi Connection Pin Number

Pin Number	**Connection Name**
GPI02(SDA)	IMU Sensor SDA
GPI03(SCL)	IMU Sensor SCL
GPIO17	Encoder A Channel
GPIO27	Encoder B Channel
GPIO20	Stepper Motor Driver DIR
GPIO21	Stepper Motor Driver STEP
GPIO05	Stepper Motor Driver MS1
GPIO6	Stepper Motor Driver MS2
GPIO13	Stepper Motor Driver MS3
3.3 V	IMU Sensor VDD
5V	Stepper Motor Driver VDD

A Raspberry Pi 4 was chosen as the platform for reading IMU sensor data, display the data on the real time screen and controlling the test setup. The Raspberry Pi can multitask, communicate with electronic equipment and sensors through its input and output pins, and supports many communication protocols and programming languages. The Python programming language was used in this setup to read data from IMU accelerometer and gyroscope sensors using the PyQt5.0 library.

The stepper motor used rotates 1.8° deg per step (MotionKing, 2014) and is driven by a stepper motor driver (Sorotec, 2018). To obtain more accurate values from the IMU sensor, the stepper motor driver is set to complete one complete revolution in 6400 steps in microstep mode. The stepper motor was mounted with a mechanical damper to minimize transmission of mechanical vibrations. An encoder that produces 1024 pulses per revolution (Autonics, 2021) was used to determine the accurate position of the shaft and used as reference angle.

The sensors used in this study were selected from general purpose commercial products that are not intended for a specific application area. The IMU sensors were selected to have the same characteristics including; degrees of freedom, resolution, full-scale range, and acceleration and gyroscopic measurement intervals. Each sensor provided I2C as communication protocol. The characteristics of the selected IMU sensors are given in Table 2.

2.2. Data Acquisition from IMU Sensors

Each sensor was calibrated for offset and gravity before experimental data was taken. The sensor was placed stationary on a flat surface and the acceleration and gyroscopic data in the x, y, and z axes read 1000 times and averaged. The averaged data were added later during testing. The accelerometer and gyroscopic measurement ranges of the sensors were set to the same full-scale range of ± 2 g for acceleration and ± 250 °/s for the gyroscope. In all tests, the stepper motor rotates through an angle of 72°. As the shaft is rotated through this angle, the angle information, encoder information, and data from the x axis of the IMU sensor were read and recorded.

While determining the rotation angle on the x axis, the acceleration values read from the axes and the gyro data read on the x axis were obtained by fusing with the kalman filter. The Kalman filter predicts the next state of the system from the input and output data of a system and minimizes the system status update and measurement errors (Gui, Tang, & Mukhopadhyay, 2015). Figure 4 shows the raw and Kalman filtered IMU data.

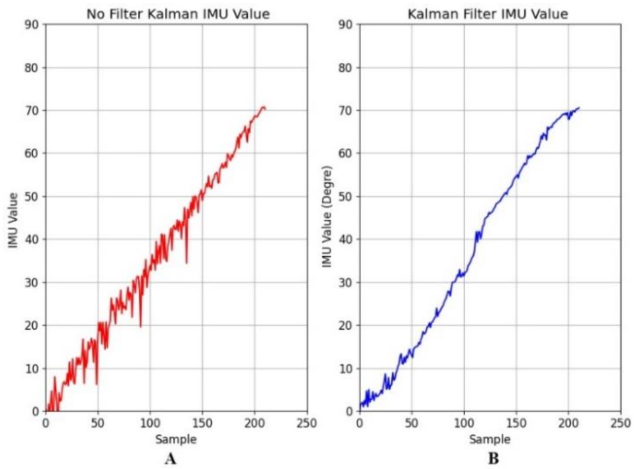

Figure-4 IMU Data. A) Raw Data B) Filtered Data

A graphical interface was created to; control the experiment, read and save the data, and display the acceleration values in the x, y, z axes in terms of g force and the gyroscopic values read in three axes in degrees / second. These data are updated every 10 ms. The angular change values of the IMU sensor mounted on the experimental setup in the x-axis depend on the angular movement of the stepper motor and are determined by passing the acceleration and gyroscopic data through the Kalman filter. At the same time, angular change values are determined from the encoder. These values are plotted and recorded in real time in the interface as shown in Figure 5.

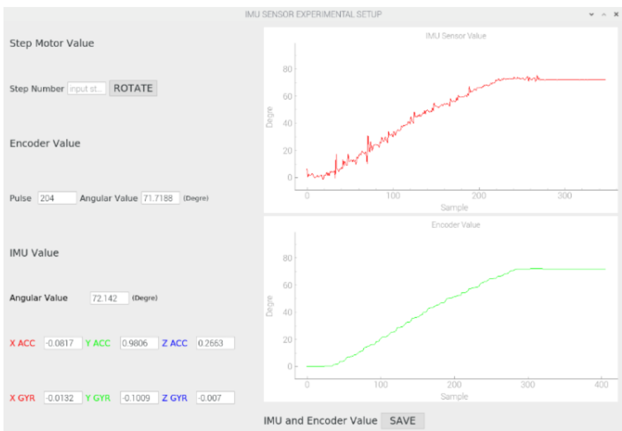

Figure -5 Experiment Setup User Interface

Table 2. Properties of IMU Sensors

IMU Sensor	Operating Voltage	Gyroscope Full-Scale Range (º/s)	Acceleration Full-Scale Range (g)	Communication	Data Out
S1	3 - 5 V	±250, 500, 1000, 2000	±2,4,8,16	I2C	16 Bit
S2	3.2 - 6 V	±125, 250, 500, 1000, 2000	±2,4,6,8	I2C	16 Bit
S3	3 - 5 V	±250,500, 1000, 2000	±2,4,6,8	I2C,SPI	16 Bit

3. Results and Discussion

The angle information taken from the IMU sensors and encoder are shown in Figure 6 after the calibration settings have been applied to the sensor data.

In order to test the accuracy of the angle values taken from these three IMU sensors, the angle values taken from the encoder were used as reference. The Mean Square Error (MSE) criterion (Equation 1) was used to compare the accuracy of the data from the sensors. Individual sample errors from the sensors are shown in Figure 7. The MSE values of these three sensors were S1 = 1.2363, S2 = 6.4147 and S3 = 1.0848, indicating S3 gave the most accurate result, followed by S1 and S2.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$$

Where $y_i = Encoder\ angle\ value$ $\hat{y}_i = The\ IMU\ sensor\ angle\ data.$

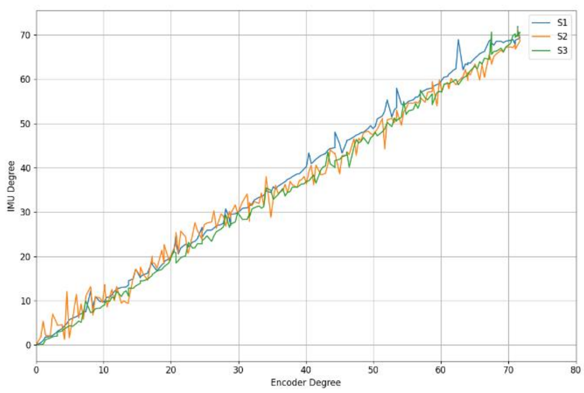

Figure -6 Angle Values of IMU Sensors and Encoder

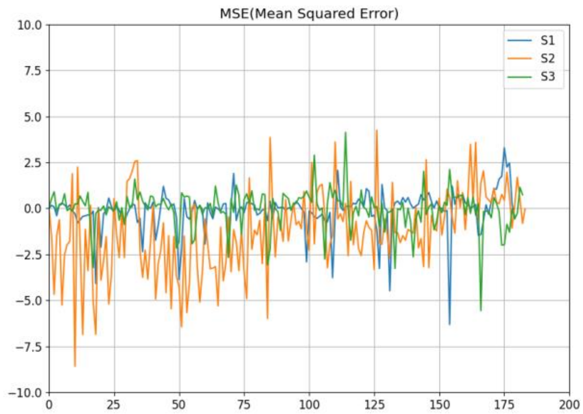

Figure -7 Error Values of IMU Sensors

4. Conclusions and Recommendations

This study determines the accuracy of the angular change from the acceleration and gyroscopic data obtained from the IMU sensors measured on a purpose test setup. Most manufacturers do not provide clear information to the end user regarding measurement errors of IMU sensors. Therefore, problems may be encountered in terms of price / performance when selecting sensors for use in applications. This study has shown that comparable IMU sensors may have significantly different levels of measurement error. In the sensors selected in this study, S3 and S1 had comparable accuracy, with S2 worse.

In future studies, it is aimed to design an open source smart glove that records the position and speed of the five fingers of the hand in real time using IMU sensors. This IMU test will be used in the selection of the most suitable sensor to be used in smart glove design with the experiment setup. In addition, the interface used in this study is planned to be developed and used as the interface of this smart glove.

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