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ANALYSIS OF MICRO-ELECTROMECHANICAL INERTIAL MEASUREMENT UNITS FOR UNMANNED AERIAL VEHICLE APPLICATIONS

Summary. Typically, an inertial navigation system (INS) is used to determine the position, speed, and orientation of an object moving relative to the earth's surface. The navigation information (position, speed and orientation) of an unmanned aerial vehicle (UAV) is needed to control its flight. Since the resistance of INS to interferences is very high, it is possible to ensure reliable flights in conditions of high-intensity noise. This article explores the principles of constructing inertial measurement units (IMU) that are part of the INS and indicates perspective directions for their development. Micro-electromechanical inertial measurement units were studied in this work, and functional and principal electrical circuits for connecting units of inertial measurements to the microcontroller were developed. The results of practical measurements of units without calibration and after calibration were obtained using the created laboratory device. Based on the obtained results, the necessity of sensor calibration was revealed, and accuracy was improved by performing calibration with the Kalman filter algorithm. The Kalman filter is the heart of the navigation system. In a low-cost system, IMU errors like bias, scale factor error and random walk noise dominate the INS error growth.

Keywords: unmanned aerial vehicles, inertial measurement unit, gyroscope, accelerometer, micro-electromechanical system, roll, pitch, yaw, acceleration

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1. INTRODUCTION

Imagining the modern world without modern navigation systems is almost inconceivable, that is, without inertial sensors covering all areas of human life. The creation and study of this type of sensor led to their use in modern navigation complexes as part of inertial navigation systems (INS) [1]. The inertial navigation system consists of the inertial measuring module (IMU) or the inertial reference unit (IRU) and the navigation determinants for the calculation of the freelance acceleration [2]. The structural scheme of INS with two sensor types is shown in Figure 1.

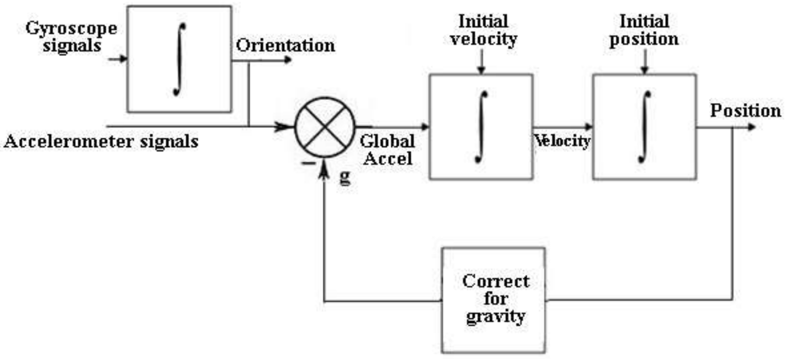

Fig. 1. Structural scheme of INS with two sensor types

When the accelerator measures the motion of the acceleration of the air vehicle, Earth’s gravitation area also affects its work. The navigation system, upon obtaining this value, that is, the freelance acceleration – g, from the measured value of the acceleration, gives the real value.

Here, the navigation system on integrating the signal from the gyroscope and measuring the acceleration of the object’s movement in the moment of integration, 2 time destinies the coordinate. Based on the found coordinates there is determined the g value and deducted from the measured acceleration. The main function of the INS is to calculate the acceleration and information on an aircraft’s roll pitch and yaw angular and linear acceleration and transmit it to the appropriate systems. This information is used for navigation calculation and roll-pitch displays [2].

Due to their complex structures and micro-size, the development of micro-mechanical sensors and inertial measurement units (IMU) requires high technologies from countries with developed industries. Micro-electromechanical systems (MEMS) - inertial sensors include the gyroscope and accelerometer, as well as a combination of gyroscope, accelerometer, and magnetometer [3, 4]. The accelerometer is used to measure inertial acceleration. While the gyroscope, on the other hand, measures angular rotation. Both sensors typically have three degrees of freedom to measure from three axes. The magnetometer measures the bearing magnetic direction, thus it can improve the reading of the gyroscope. MEMS components are small, light, inexpensive, and have low power consumption and short start-up times. Also, their accuracy has significantly increased over the years.

Evaluation of the acceleration and angular velocity of an unmanned aircraft (UA) in the direction of the main axes in space, as well as the determination of the flight direction, is one of the most important parameters characterizing the flight mode. As known [5], INS is used to calculate the flight parameters.

The main function of the INS is to calculate and transmit data to the necessary systems about the coordinates, speed, as well as angles of roll, pitch and yaw, based on the measurement and integration of the acceleration, and angular velocities of the UA in the spatial coordinate system. The processing and application of such data in autonomous transport management systems in recent years allow the achievement of successful results. Examples of this can be the determination of the direction of autonomous vehicles carrying cargo in ports, the successful use of unmanned vehicles with the ability to explore submarines for various purposes, the creation of autonomous vehicles that can move without a pilot in urban and intercity transport or the development of bomb disposal robots. Autonomous vehicles are the types of vehicles equipped with camera systems, sensors, controllers, and wireless communication modules (Global Positioning System (GPS)/INS), produced as a result of the rapid development of digital technology added to the conventional vehicles used today. Inertial sensors are also frequently used for pose estimation of cars, boats, trains and aerial vehicles [4, 6].

Over the years, INS has been improved through the electromechanical devices that control missiles to the semiconductor devices that are now used in many modern vehicles. The INS, developed through inertial sensors, which has passed rapid development in recent times, operating without external influence, has now become a crucial part of aircraft, ships, missiles, and spacecraft, as a standard part of civil and military navigation systems. Furthermore, it seems that the systems developed in this form, especially the autonomous systems applied to various vehicles in recent years, have been developed, with high results achieved.

Presently, the mass production and application of light and ultra-light unmanned aerial vehicles (UAV) tightens the weight and size requirements for inertial navigation systems, making it impossible to use traditional INS. Recently, a sharp increase in demand for drones has led to the expansion and deepening of research in this direction. The development and application of satellite-inertial navigation systems that provide the maximum possible light, small-sized and precise controllability for this type of vehicle are especially critical.

The rapidly developing micro-electromechanical systems (MEMS) - sensor inertial measurement units (IMU) are already been widely used in the navigation and control systems of missiles, and land and air vehicles, in recent years. In particular, MEMS-based IMUs are gaining significant application in unmanned aerial vehicles (UAV) and robotics due to their low cost, low power consumption and small size offered by advanced MEMS manufacturing technology. Although the MEMS-based IMU provides a reduction in size and cost compared to traditional IMU based on fiber optic or laser gyroscopes, it suffers from more non-linear or random errors, which causes navigation solutions in MEMS INS to vary greatly over time [6-8].

Due to failures in the IMU components (gyroscopes and accelerometers), it cannot show the position perfectly. Those failures cause errors in the determined position that increase over time. These failures can be accepted in vehicles making short-term flights. For performing long-term missions, the navigation system needs periodic corrective actions to bring the failures caused by INS as close to zero as possible. Thus, complex filtering algorithms are applied to reduce failures for data processing in navigation systems, as well as algorithms for sensor calibration [9].

2. SUBJECT RELEVANCE

Autonomous vehicles, which are seen as the future of many technological developments, have become a critical element for countries that possess this technology with the advanced features and capabilities provided by technological opportunities. The improvement and production of these vehicles of strategic importance should be determined as a target. We have decided to work toward the development of autonomous systems to participate in the change of this potentially strategic situation. Also, this issue is significant for us, given its applicability to various fields of industry.

The purpose of this study is to analyze and evaluate the results obtained during practical measurements with the installation of MEMS-based IMU that determine the orientation of small-sized aircraft in space on the Arduino platform and its application. Thus, our research work is very relevant for defining and developing the technical parameters of new-generation navigation systems for light and ultra-light aircraft.

MEMS-based IMU containing gyroscopes, accelerometers, and magnetometers, are widely used in position and navigation measurement due to their increasing accuracy, small size and low cost. However, due to various non-linear errors in MEMS-based IMU, errors of MEMS-based autonomous INS have significantly increased over time. Therefore, IMU is calibrated and integrated with GPS to provide reliable navigation solutions through MEMS INS.

Today, there is an extensive choice of inertial sensors and units with different features at different prices. Currently, many companies [10-12] produce inertial measurement units that include gyroscopes, accelerometers, temperature sensors, barometers, and even magnetometers. IMU manufacturers are leading companies such as STMicroelectronics, InvenSense, Analog Devices, Honeywell, XSens, Teknol and others. To improve the accuracy of these types of sensors and IMUs in them, it is necessary to perform an appropriate calibration procedure.

3. ISSUE SOLVING AND DISCUSSION

Based on our previous study, we found it more appropriate to use 3x3x1 mm MPU-9255 with a three-axis gyroscope, accelerometer and magnetometer and 4x4x0.9 mm MPU-6050 MEMS sensors with a three-axis gyroscope and accelerometer manufactured by InvenSense with suitable parameters for creating a sufficiently accurate inertial measurement system that can be applied in UAVs. Currently, the leading company in the development of MEMS inertial sensors, InvenSense [12], manufactures MPUs (Motion Processing Units) with up to 9 axes, installing a magnetic compass (MPU-91xx and MPU-92xx).

Inertial measurement units such as MPU-6050 with a three-axis gyroscope and three-axis accelerometer and MPU-9250 with a three-axis gyroscope, three-axis accelerometer and three-axis magnetometer manufactured by InvenSense were used in the study. The main advantage of these units is providing relatively high characteristics at a low cost.

MPU-6050 type unit with a three-axis gyroscope, three-axis accelerometer and temperature sensor is designed to detect tilt angles in the X, Y and Z axes. The supply voltage of the unit is 3.3-5 V, the measuring range of the accelerometer is ±2, ±4, ±8 and ±16 g, and the measuring range of the gyroscope is ±250, ±500, ±1000 and ±2000 0/sec. When the unit is placed on a flat surface, it will measure 0 g on the X and Y axis, and +1 g on the Z-axis.

Another unit used in the study is InvenSense’s second-generation MPU-9250, with the smallest nine-degree-of-freedom. Two crystals are connected in the body of the microchip. One crystal houses a three-axis gyroscope and a three-axis accelerometer, and the second crystal houses a three-axis magnetometer. Accordingly, the MPU-9250 incorporates a nine-axis motion tracking unit.

MPU-9250 unit supply voltage is 3-5 V, the interface is I2C (400 kHs)/SPI (1 MHs), accelerometer measurement ranges are ±2, ±4, ±8 and ±16 g, gyroscope measurement ranges are ±250, ±500, ±1000 and ± 2000 0/sec, magnetometer full-scale range is ±4800 μT, the size is 15x25mm. In addition, the I2C auxiliary port of the MPU-9250 unit is designed to connect several non-inertial digital sensors, such as pressure sensors. MPU-9250 unit uses a total of nine 16-bit analog-to-digital converters to digitize the output data of the gyroscope, accelerometer, and magnetometer. The data received from the sensors is digitized in a 16-bit analog-to-digital converter, processed by the DMP (Digital Motion Processor) signal processor using Motion Fusion algorithms and transmitted to an external microcontroller via the I_2C/SPI bus interface. Motion Fusion algorithms work with all internal sensors to collect complete data [13]. In addition, a programming digital filter and temperature sensor are also placed in the unit. Communication with all device registers is done using either 400 kHs I2C or 1 MHz SPI.

To conduct this study, the assembly diagram of connecting the IMU to the microcontroller and the display was developed. According to the initial connection structure on the breadboard, the microcontroller that performs the function of the "brain" and each of the other intelligent sensors are added to the first breadboard and connected to the digital pins by appropriate protocols through buses in the abovementioned diagram. Pins are assigned in the corresponding structure to the columns and rows with holes on the breadboard, which is considered the first experimental diagram.

In addition, the main electrical diagram for connecting inertial measurement units to the microcontroller was built using the EasyEda online program (Figure 2).

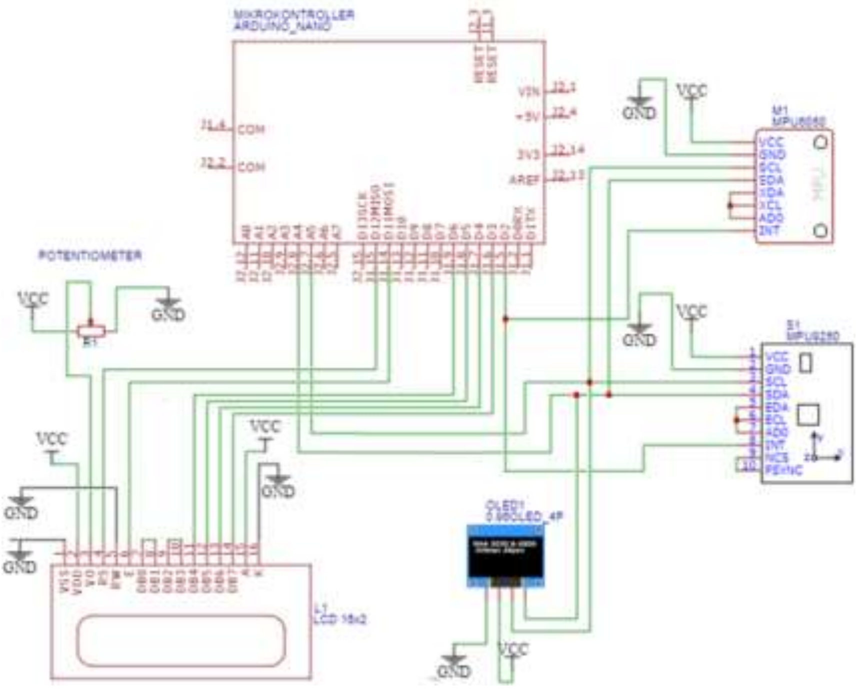

Fig. 2. Main electrical diagram of the IMU connection to a microcontroller and display

Arduino Nano platform was used as a microcontroller to process data from MPU-6050 and MPU-9250 units, and LCD and Oled displays were used to display the processed values in this diagram. Arduino Nano board with an Atmega328 microcontroller from Atmel was used in the functional diagram. It has 14 digital I/O pins (6 of which can be used as PWM outputs), 8 analog inputs, 16 Mhs crystal, a USB port, an ICSP connector and a reset button. It can be connected to a computer via a USB cable equipped with an adapter or battery. FTDI FT232 USB-serial converter was also included for downloading programs and connecting with a computer.

Since the Oled display, MPU-9250 and MPU-6050 units used in the diagram use the i2c protocol, each is connected to the analog inputs A4 and A5 of the microcontroller. LCD 16x2, which is capable of displaying 16 lines 2 columns data, is connected with its 6 digital d7, d6, d5, d4, e, rs outputs into the controller inputs d2, d3, d4, d5, d11, d12, respectively.

Figure 3 shows the external view of the laboratory stand, assembled based on the scheme given in Figure 1 for the research of inertial measurement modules.

Fig. 3. Laboratory stand

After loading the created code to the microcontroller, the time diagrams of the output values of the accelerometer and gyroscope without calibration in the MPU-6050 unit are obtained, as depicted in Figure 4.

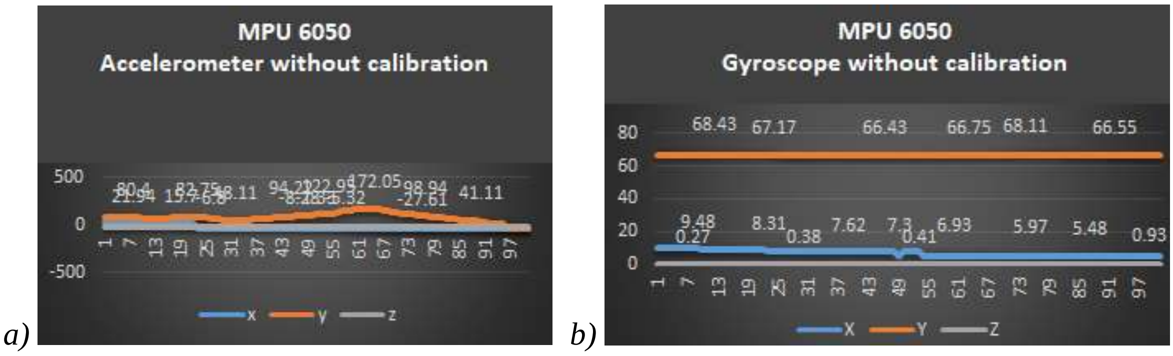

Fig. 4. Uncalibrated characteristic of the MPU-6050 unit on the X, Y, Z axes:
a) accelerometer; b) gyroscope

As seen from the characteristics, the output values of the gyroscope and accelerometer gradually decrease along the time axis X and Z axes, while along the Y-axis, the value of the output signal first decreases slowly, then increases at a high rate and finally decreases again at the same rate. Unit calibration is required to obtain more stable and accurate output signals. Thus, a Basic AHRS calibration code was used in the unit. The calibrated characteristics of the gyroscope and accelerometer on the X, Y and Z axes in the MPU 6050 unit are presented in Figure 5.

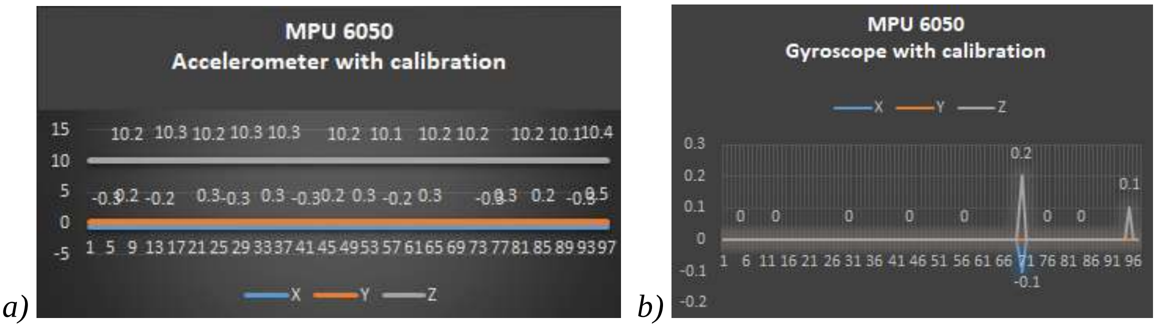

Fig. 5. Calibrated characteristic of the MPU-6050 unit on the X, Y, Z axes:
a) accelerometer; b) gyroscope

According to the results of practical measurements, the average shift of the accelerometer values of the unit without calibration was determined to be 0.0872 m/sec2 on the X-axis, 0.06 m/sec2 on the Y-axis, 0.277 m/sec2 on the Z-axis, and after calibration, the average shift value 0.04 m/sec2 (4.7 mg) on the X-axis, 0.026 m/sec2 (2.65 mg) on the Y-axis and 0.038 m/sec2 (3.87 mg) on the Z-axis, which means 46% improvement as a result of the calibration. In the output signals of the gyroscope, the average shift of the gyroscope without calibration was determined to be 0.66 deg/min on the X-axis, 1.88 deg/min on the Y-axis, 4 deg/min on the Z-axis, and after calibration, the average shift 0.0040 deg/min on the X-axis, 0.0038 deg/min on the Y-axis and 0.0065 deg/min on the Z-axis, then it is indicated that the zero shift of the gyroscope is ±20 rpm (±1200 rpm) and the shift of the accelerometer is ±50 mg on the X and Y axes and ±80 mg on the Z-axis in the technical characteristics of the MPU-6050 unit.

Thereafter, measurement results were obtained without calibration by connecting the MPU-9250 module to the stand (Figure 6).

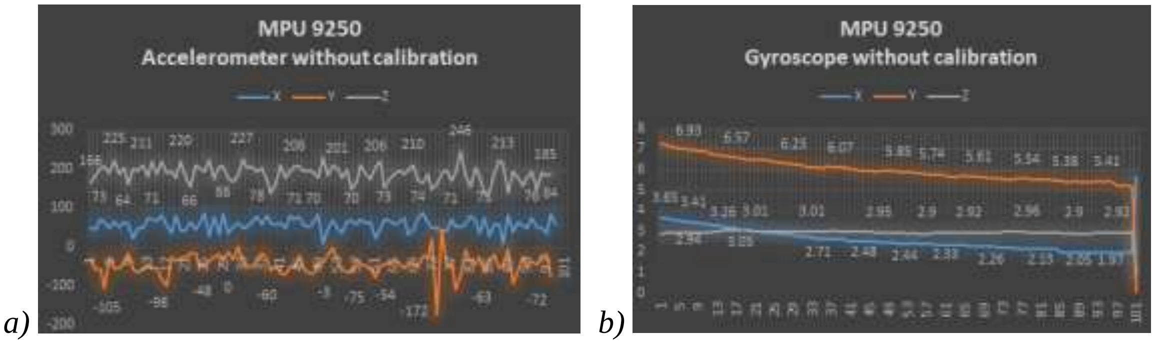

Fig. 6. Uncalibrated characteristic of the MPU-9250 unit on the X, Y, Z axes:
a) accelerometer; b) gyroscope

Based on the results obtained from the MPU-9250 unit, the output signals were found to be unstable and inaccurate. Therefore, using the unit without any calibration will make its application in a UAV inconvenient. If we run the unit without any calibration and read the output values, the accuracy and stability of the result will be low. Unit calibration is required to obtain more stable and accurate output signals. After using the calibration code, the three-axis output characteristics of the unit were obtained (Figure 7).

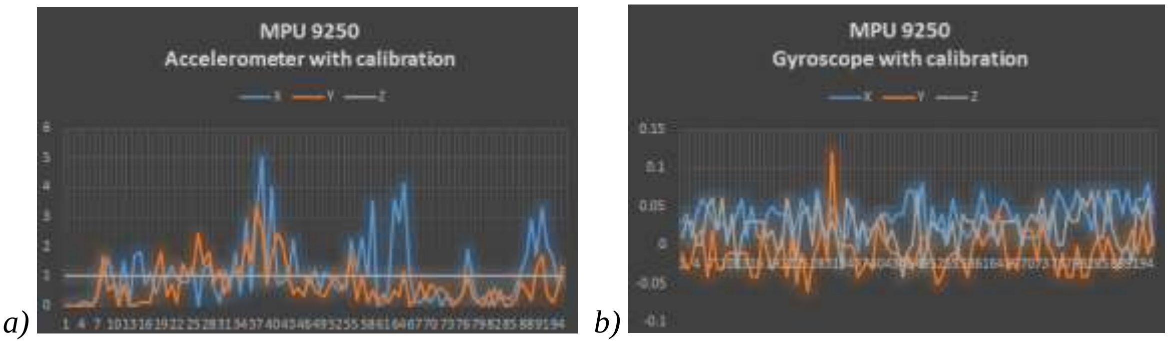

Fig. 7. Calibrated characteristic of the MPU-9250 unit on the X, Y, Z axes:
a) accelerometer; b) gyroscope

Based on the results of practical measurements, the average shift of the accelerometer values on the X-axis without calibration was determined to be 0.0568 m/sec2, on the Y-axis 0.0355 m/sec2, on the Z-axis 0.6506 m/sec2, and after calibration, the average shift value is 0.0207 m/sec2 (2.11 mg) on the X-axis, 0.0238 m/sec2 (2.43 mg) on the Y-axis and 0.4206 m/sec2 (42.8 mg) on the Z-axis, which is 28% improvement as a result of the calibration. In the output signals of the gyroscope, the average shift of the gyroscope without calibration was determined to be 1.68 deg/min on the X-axis, 1.52 deg/min on the Y-axis, 0.02 deg/min on the Z-axis, and after calibration, the average shift 0.0321 deg/min on the X-axis, 0.0286 deg/min on the Y-axis and 0.0064 deg/min on the Z-axis, then it is indicated that the zero shift of the gyroscope is ±5 rpm (±300 rpm) and the shift of the accelerometer is ±60 mg on the X and Y axes and ±80 mg on the Z-axis in the technical characteristics of the MPU-9250 unit.

As can be clearly seen from the characteristics obtained as a result of comparative analysis during the research measurements of the MPU-6050 and MPU-9250 units on the stand for 1 hour, all values of the output values of both inertial units after calibration on the time axis Accx, Accy, Accz, GyX, GyY, GyZ can be considered stable within the indicated limits (Figure 8).

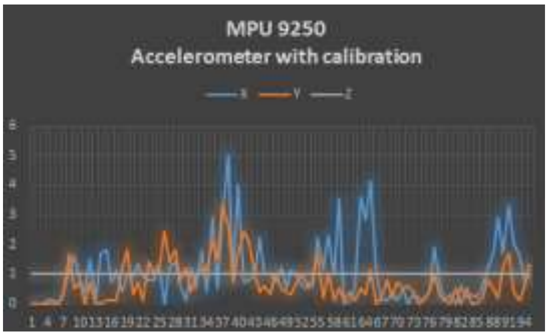

Fig. 8. Output values of MPU-9250 and MPU-6050 units after calibration

As observed from the simulation, the change of angular states on all three axes after calibration is more stable and smoother, which shows us the possibility of applying these modules in small-sized UAVs. From the study, IMU could be used in many applications. For future projects, this study of IMU would be applied to small-sized UAVs, which will be used as flight stabilizer controllers.

4. CONCLUSION

The parameters of MEMS-based IMU for light and ultra-light aircraft are defined, and the algorithm and software of inertial navigation system management are created. The function of IMU, which can measure the pitch, roll and yaw of a UAV, is the main type of sensor that must be used for that application. Besides, it can be implemented with the autopilot system.

Practical measurement results of the unit before and after calibration were obtained using the Arduino platform. Based on the obtained results, the necessity of sensor calibration was revealed, and the accuracy was improved to 46 and 26% by performing calibration with the created Kalman filter algorithm.

The main advantages of the proposed MEMS-based IMU are autonomy, universality and durability to obstruction. IMU sensors can also be combined with other sensors, such as GPS, for accurate navigation, guidance and controlling system. Based on the results of this study, the calibration herein can be considered appropriate for the use of the reviewed unit in the integrated navigation system of light and ultra-light aircraft.

References

1. Manon Kok, Jeroen D. Hol, Thomas B. Schon. 2017. ”Using Inertial Sensors for Position and Orientation Estimation”. *Foundations and Trends in Signal Processing* 11(1-2): 1-153. DOI: 10.1561/2000000094.
2. Набиев Р.Н., А.З. Маммадов. 2021. “Модели построения инерциальной навигационной системы для беспилотных летательных аппаратов” *Авиакосмическое приборостроение* 1: 12-22. DOI: 10.25791/aviakosmos.1.2021.1197. [In Russian: Nabiyev R.N., A.Z. Mammadov. 2021. “Models of construction of inertial navigation system for unmanned aerial vehicle”. *Aerospace Instrument-Making*].
3. Ishak Ertugrul, Ulkir Osman. 2020. “Analysis of MEMS-IMU Navigation System Used in Autonomous Vehicles”. In: *Autonomous Vehicle and Smart Traffic*. Edited by Sezgin Ersoy, Tayyab Waqar.London, UK: IntechOpen. DOI: 10.5772/intechopen.92985.
4. Ahmad N., R.A.R. Ghazilla, N.M. Khairi, V. Kasi. 2013. “Reviews on various inertial measurement unit (IMU) sensor applications”. *International Journal of Signal Processing Systems* 1(2): 256-262.
5. H. Chao, Cao Y., Chen Y. 2010. “Autopilots for small unmanned aerial vehicles: A survey”. *The International Journal of Control, Automation and Systems* 8(1): 36-44.
6. Skog I., P. Handel. 2009. “In-car positioning and navigation technologies – A survey”. *IEEE Transactions on Intelligent Transportation Systems* 10(1): 4-21.
7. Hardy J., et al. 2016. “Unmanned aerial vehicle relative navigation in GPS denied environments”. In: *2016 IEEE/eION Position, Location and Navigation Symposium (PLANS)*: 344-352. Savannah, GA. DOI: 10.1109/PLANS.2016.7479719.
8. Perlmutter M., L. Robin. 2012. “High-performance, low cost inertial MEMS: A market in motion!” In: *Proceedings of the IEEE/ION Position Location and Navigation Symposium (PLANS)*: 225-229. Myrtle Beach, South Carolina, USA.
9. Choe N., H. Zhao, S. Qiu, Y. So. 2019. “A sensor-to-segment calibration method for motion capture system based on low cost MIMU”. *Measurement* 131: 490-500.
10. Analog Devices. 2021. Available at: http://https://www.analog.com/en/parametricsearch/11172#/.
11. Xsens Technologies. 2021. Available at: http://www.xsens.com.

12. İnvensense. 2021. Available at: https://invensense.tdk.com/products/motion-tracking.

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