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Model of inertial navigation system for unmanned aerial vehicle based on MEMS

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Abstract. The article presents data on the software and hardware implementation of the algorithm for determining Euler angles (roll, pitch and yaw) based on MEMS using a complementary filter. The yaw angle is calculated from the readings of the magnetometer. The angles of roll and pitch are calculated from the accelerometer and gyroscope readings with their subsequent integration to improve the determination accuracy. A prototype model of an inertial navigation system was assembled using the GY-9250 module and the Arduino UNO board, which have high performance at low cost and low power consumption.

1. Introduction

Unmanned aerial vehicles have become an integral part of modern warfare. They are used for conducting reconnaissance, targeting high-precision weapons, electronic warfare and can themselves be shock weapons of destruction. However, today the majority of unmanned aerial vehicles can not independently perform all of the above operations, being, in fact, remotely controlled aircraft that are critically dependent on commands from the ground and signals from navigation systems. It is against these communication systems that the enemy actions are directed — control channels and ground and satellite navigation signals are jammed with interference, while attempts are made to “climb” into the control circuit of the device in order to send him false commands or coordinates. As a result, the unmanned aerial vehicle either crashes or lands in an automatic mode, which often leads to its falling directly into the hands of the enemy.

The use of inertial navigation is a prerequisite for the use of unmanned aerial vehicles in an environment of active electronic countermeasures from the enemy. They allow unmanned aerial vehicles performing reconnaissance and attacking tasks even in the event of complete loss of communication with the control center and the absence of signals from ground-based and satellite navigation systems.

Therefore, a reliable solution for preserving unmanned aerial vehicles in the context of countering modern electronic warfare is to install on its board a free-form inertial navigation system (FINS) integrated with special devices that recognize interference with the control of the device and transfer it fully offline. Autonomy, independence from the human factor and resistance to external influences is decisive factors for the success of the tasks of an unmanned aerial vehicle. In this case, navigation is carried out at the expense of the coordinates issued by the FINS, and the device continues to perform a



pre-programmed task - for example, flying at certain points for conducting reconnaissance of the area [1-6].

2. Means and methods for determining the position of an object in space

MEMS is a device that combines microelectric and micromechanical components. The advantage of such inertial systems is their small weight and compact dimensions, but their autonomous use is difficult due to the instability of the characteristics of microelectromechanical gyroscopes and accelerometers, which leads to a rapid accumulation of errors in the definition of navigation data. The integration algorithm makes it possible to use serial MEMS gyroscopes and accelerometers as sensitive elements and to improve the accuracy of the navigation solution both in the presence and in the event of a signal failure of the satellite navigation system. The main purpose of the study is to determine the accuracy of an inertial navigation system built on budgetary inertial measurement modules.

2.1 Devices used in the study

As devices for the implementation of the algorithm for determining the Euler angles were used inertial measurement module GY-9250 on an MPU – 9250 microchip, which is a 9-axis device (3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer) and an ArduinoUNO microcontroller, which consists of an Atmel AVR microcontroller and an element strapping to enable the microcontroller to function and to provide Input/Output. The board used in the work is programmed via USB, which is done through the converter chip USB-to-serial FTDI FT232RL. In addition to programming, it allows exchanging data with a PC. There are a large number of ready-made libraries for solving various kinds of tasks that simplify software development. There are also many different expansion cards.

2.2 Calculation of the angles of orientation of the object in space

The term "orientation" implies the presence of any initial coordinate system, relative to which the orientation will be determined. Terrestrial (navigation) and connected coordinate system are used.

Mutually perpendicular to the axis of the earth's coordinate system X and Y lie on the surface of the Earth, the Z axis is directed to the center of the Earth. The terrestrial coordinate system (TCS) is used in research and study of the trajectories of the body in space, relative to which body position is determined.

The X axis of the CSC coincides with the direction to the north, Y – east, and the Z axis is directed to the center of the earth.

Connected coordinate system (CCS) is most often used in aviation and is used to analyze the movement of aircraft in flight mechanics. The X axis coincides with the longitudinal axis of symmetry of the object.

Euler angles — roll, pitch, and yaw — are three angles that define a triple, sequential rotation of a connected coordinate system around its three axes so that the axes coincide with the GCS. Most often in this work, these angles are denoted by φ , θ and ψ , respectively. This type of rotation is the most common. However, it has a significant drawback - the impossibility of calculating angles at $\theta = \pm 90^\circ$. Working with Euler angles, one has to make a correction for a particular case [7].

2.3 Calculation of Euler angles from readings of MEMS sensors

According to the accelerometers, it is possible to calculate the values of the pitch and roll angles [7]:

$$\theta_a = \arcsin \left(\frac{a_x}{\sqrt{a_x^2 + a_y^2 + a_z^2}} \right); \quad (1)$$

$$\varphi_a = -\arcsin \left(\frac{\frac{a_y}{\sqrt{a_x^2 + a_y^2 + a_z^2}}}{\cos(\theta_a)} \right), \quad (2)$$

where θ_a – pitch angle, rad; φ_a – roll angle, rad; a_x, a_y, a_z – accelerometer readings along the respective axes, m/s²; $\sqrt{a_x^2 + a_y^2 + a_z^2} = g$ – acceleration of gravity, m/s². The signal from the output of the accelerometer, in addition to the useful signal a_x, a_y, a_z includes A_{cor} – Coriolis acceleration, A_{vib} – component due to vibration of the object, V – component due to vibration of the object, component, due to the linear acceleration of the object, as well as components, due to its own noise μ_n and zero accelerometer drift $b(t)$.

In a state of rest or uniform motion, using accelerometers, it is possible to accurately calculate the angles, but when solving the navigation problem, it is necessary to take into account that the object will move with linear acceleration. This leads to significant errors in accelerometer readings. Therefore, the navigation system can not be built using only accelerometers.

Using the readings of the gyros, on the basis of the Euler equations, calculate the derivatives of the pitch and roll angles [7]:

$$\dot{\theta}_g = g_y \cdot \cos \phi - g_z \cdot \sin \phi; \quad (3)$$

$$\dot{\phi}_g = g_x + \tan \theta \cdot (g_y \cdot \sin \phi + g_z \cdot \cos \phi), \quad (4)$$

where $\dot{\theta}_g$ – pitch derivative; $\dot{\phi}_g$ – roll derivative; g_x, g_y, g_z – gyro readings relative to the respective axes, rad·s⁻¹.

By integrating $\dot{\theta}_g$ and $\dot{\phi}_g$, it is possible to get the desired angles. However, the signal coming from the output of the angular velocity sensor on each axis, in addition to the useful signal (g_x, g_y, g_z), includes components due to its own noise and zero level drift $b(t)$. When integrating such a signal, an error quickly accumulates.

Using a separate accelerometer or a separate gyroscope will not give the desired result, only their combined use with filtering, taking into account the readings of two sensors, gives an acceptable result [8].

2.4 Ways of combining the readings of MEMS gyroscopes and accelerometers

To combine the data obtained from gyroscopes and accelerometers, it is proposed to use a complementary filter (CF), a block diagram of which is shown in figure 1.

The complementary filter (CF) is a combination of filters of the first order of low frequency filter (LFF) and high frequency filter (HFF), having the same time constant T_{CF} . If both inputs CF give the same signal, then the transfer function $W_{CF}(s) = 1$.

The signal, calculated through the accelerometer reading, is fed to the LFF input.

The signal, calculated through the gyroscope readings, comes after the integration to the HFF input, which does not miss the error due to the integration of the intrinsic noise and the drift of the gyroscope.

Below there are expressions for combining readings through a complementary filter:

$$Pitch[1] = Pitch[0] + (\theta_a - Pitch[0] + \dot{\theta}_g \cdot T_{CF}) \cdot \left(\frac{T_s}{T_{CF}} \right); \quad (5)$$

$$Roll[1] = Roll[0] + (\phi_a - Roll[0] + \dot{\phi}_g \cdot T_{CF}) \cdot \left(\frac{T_s}{T_{CF}} \right); \quad (6)$$

$$Pitch[0] = Pitch[1]; \quad (7)$$

$$Roll[0] = Roll[1], \quad (8)$$

where T_{CF} – time constant CF = 2 s, T_s – quantization period, s; $Pitch[0]$, $Roll[0]$ – pitch angle (θ) and roll angle (φ) at the previous stroke, rad; $Pitch[1]$, $Roll[1]$ – the pitch and roll angle at the current stroke, rad.

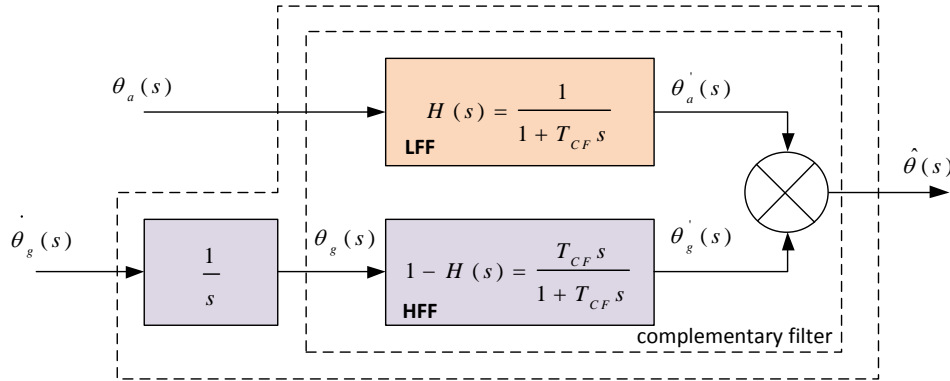


Figure 1. Scheme of the complementary filter

When choosing a T_{CF} , it is necessary to take into account the nature of the object movement; the higher this coefficient, the more significant the gyroscope readings during CF operation. This coefficient was chosen experimentally.

2.5 Course angle calculation

The course angle is calculated from the readings of the magnetometer, the input vinertial measuring module. According to the readings of the magnetometer, it is possible to calculate the values of the course angle [8]:

$$\psi = -\arctg \left(\frac{m_y \cdot \cos \phi + m_z \cdot \sin \phi}{m_x \cdot \cos \theta + m_y \cdot \sin \phi \cdot \sin \theta + m_z \cdot \cos \phi \cdot \sin \theta} \right), \quad (9)$$

where ψ – yaw angle, rad; ϕ , θ – roll and pitch angles after operation of the complementary filter, rad; m_x , m_y , m_z – projections of magnetic field lines on the axes x , y , z , obtained from a magnetometer, μT .

The course angle is measured from 0 to $\pm 180^\circ$: 0° – north, $\pm 180^\circ$ – south, 90° – east, -90° – west.

To accomplish the task, the MPU-9250 module was used - it is a 9-axis device (3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer). The microcircuit is intended for use in smartphones, trackers, quadcopters and other robotic objects. The main advantage of the module is its relatively high performance at low cost, and low power consumption.

Figure 2 shows the developed scheme of the algorithm for calculating the Euler angles. In this case, the accelerometer and gyro readings were used combined with a complementary filter. A magnetometer was also used to calculate the course angle.

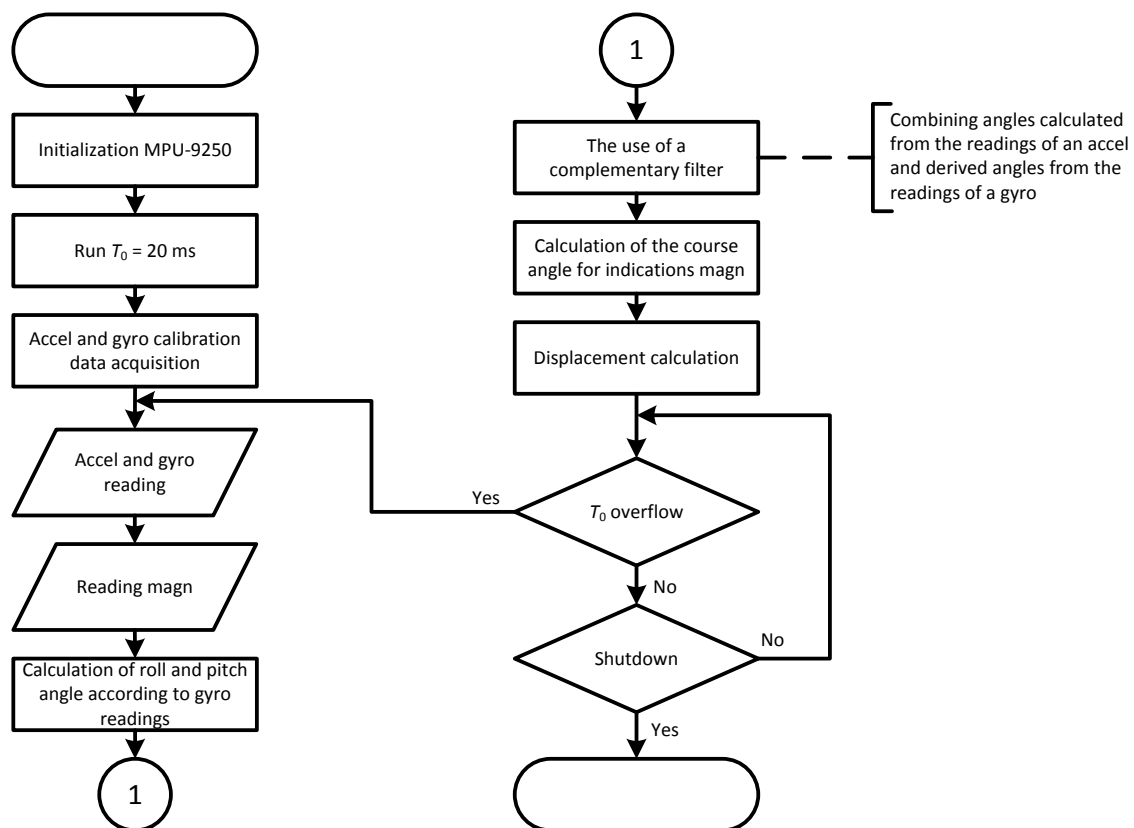


Figure 2. Algorithm for calculating the Euler angles

After adjusting the accelerometer, gyroscope and magnetometer, T_0 is initialized to 20 ms, this value can be changed by writing the required value in ms to the variable T_s .

Then the necessary information is collected for calibration.

Accelerometer reading occurs from the corresponding registers. On each axis 2 bytes are allocated, the high byte comes first, then the low byte. The readings of the gyroscope are read in the same order as in the case of the accelerometer.

The readings of the magnetometer reads from the registers, only the data comes in a different order (first low byte, then high).

After reading all the measurements using formulas (1) and (2), the authors calculate the angles of heel and pitch from the accelerometer. Then, using formulas (3) and (4), the derivatives of the roll and pitch angles using the gyroscope readings are found. The combination of the calculated values occurs using a complementary filter, according to formulas (5)-(8).

The course angle is found using the readings of the magnetometer using the formula (9).

3. Practical part of the study – measurement of Euler angles

For checking the corners of Euler, the available tools were used: goniometer, building level, compass. To begin with, the module was installed on a flat horizontal surface, measured with a building level. The X axis was directed north using a compass (course angle = 0 °). The module was fixed and tested for 11 s. The output of the corners on the computer screen was carried out using a special program.

The experiment showed that the readings of the angle of heel and pitch fluctuate within hundredth readings, but the course angle varies from -0.62 to 6.73 , this is due to the fact that the magnetometer installed in the GY-9250 has a low sensitivity. In addition to the Euler angles, the program interface displays the values read from accelerometers, gyroscopes, and magnetometers. Depending on the

settings, these values can be displayed either in units of measurement (accelerometer – m/s^2 , gyroscope – rad/s , magnetometer – μT), or in codes read from registers.

4. Conclusion

From the experiments, it can be concluded that the formulas for finding the Euler angles are correct, but the course angle is unstable and fluctuates within 6° . This demonstrates the need to apply new approaches in measuring the course angle.

To build an inertial navigation system (INS) in the course of the work, it was proposed to use the budget inertial measurement module GY-9250. An INS prototype was assembled using the GY – 9250 and the Arduino UNO board.

A block diagram of the algorithm and a control program that realizes taking readings from sensors and calculating the parameters of the angular position of an object in space was developed. Based on the collected prototype, experimental investigations of the INS were carried out.

After the application of algorithms for the integration of data obtained from various sensors, as well as calibrations, the calculated Euler angles became suitable for use as part of an integrated navigation system.

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