Measuring angular coordinates in Unmanned Aerial Vehicles (UAVs) positioning systems and developing a new phase-metric method for goniometric control of UAVs

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Abstract.- For the safe operation of Unmanned Aerial Vehicles (UAVs), an effective Automatic Control System (ACS) is necessary, which for successful operation requires high accuracy of the initial information about the UAV's position in space. Based on the analysis of the shortcomings of the known orientation systems, a phase-metric method of goniometric (angular) control based on accelerometric and gyroscopic transducers for positioning the UAV is proposed, which has a higher accuracy and a wider range of measurement angles. The conducted study showed that in a wide range of rotation angles from 10 to 90 degrees, the root mean square error (RMS) of the results of calculating the rotation angle using the phase-metric method is 8,78 times less than the RMS of the results of calculating the rotation angle using the arctangent function. Reducing the error determines the effectiveness of the proposed method in UAV control systems.

Keywords: unmanned aerial vehicles (UAV); orientation system; goniometer control; phase-metric method; accelerometer; gyroscope.

Medición de las coordenadas angulares en los sistemas de posicionamiento de Vehículos Aéreos No tripulados (VANT) desarrollando un nuevo método fase-métrico para el control goniométrico de los VANT

Resumen.- Para la operación segura de los vehículos aéreos no tripulados (VANT), es necesario un sistema de control automático (SCA) efectivo, que para una operación exitosa requiere una alta precisión de la información inicial sobre la posición del VANT en el espacio. Basado en el análisis de las deficiencias de los sistemas de orientación conocidos, se propone un método de control gonométrico (angular) de fase métrica basado en transductores acelerométricos y giroscópicos para posicionar el VANT, que tiene una mayor precisión y un rango más amplio de ángulos de medición. El estudio realizado mostró que en un amplio rango de ángulos de rotación de 10 a 90 grados, el error cuadrático medio (RMS) de los resultados de calcular el ángulo de rotación usando el método de fase métrica es 8,78 veces menor que el RMS de los resultados de calcular el ángulo de rotación usando la función arcotangente. La reducción del error determina la efectividad del método propuesto en los sistemas de control de VANT.

Palabras clave: vehículos aéreos no tripulados (VANT); sistema de orientación; control de goniómetro; método fase-métrico; acelerómetro; giroscopio.

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1. Introduction

The effective functioning of unmanned aerial vehicles (UAVs) is provided by an automatic control system that performs the tasks of ensuring the required dynamic properties of the UAV, stabilizing the UAV's angular position and automating trajectory control [1]. An investigation considered the use of ideal control hypothesis for the direction, route and control hypothesis of airplane, shuttle and rockets. A general methodology was adopted that includes modern control strategies based on multi-parameter trajectory optimization for each vehicle [2]. The ideal ways of each UAV were gotten by the hereditary calculation in an equal structure. As indicated by the elements of way arranging, hereditary encoding has a few files. Another hereditary administrator was acquainted with select a suitable pair of chromosomes for hybrid activity. The adequacy of the strategy was appeared by a few reproductions [3]. Another perception technique that utilizes UAVs to overview park-based physical movement was created. Contrasted with these strategies, the UAV perception instrument, covering bigger objective regions, is reasonable for including park clients in an increasingly dependable and effective manner and mapping their utilization designs; in any case, the device is more fragile at gathering itemized client data and looking over under poor climate conditions. In this manner, the UAV technique could supplement existing devices. At long last, this investigation proposed pragmatic ramifications of the UAV perception technique [4].

First of all, the unstable angular position of the UAV causes a decrease in flight safety. In addition, this factor leads to a decrease in the effectiveness of UAV communication systems with narrowly directed antennas due to the deviation of the angular coordinates of the aircraft from the maximum of the receiving antenna's directional diagram [5]. The deterioration of the received signal quality caused by this effect hinders the development of communication protocols for ad-hoc aircraft networks (Flying Ad Hoc Network, FANET) that use directional antennas and increase network performance compared to protocols based on omnidirectional antennas. For instance, a novel MAC convention, LODMAC (Location Oriented Directional MAC), which fuses the use of directional radio wires and area estimation of the neighboring hubs inside the MAC layer was introduced [6, 7]. These aspects determine the relevance of the development of new UAV ACS [8, 9, 10].

A necessary condition for reliable operation of the UAV ACS is high accuracy of the initial information about the UAV position in space. For small-sized UAVs, free-form orientation systems (FOS) based on inertial sensors (micromechanical gyroscopes and accelerometers) are the most common sensors for orientation systems [11]. The main errors of such systems are non-linearity, zero offset, and noise component. These factors have a negative impact on the accuracy of measuring spatial and angular coordinates and, as a result, reduce the safety of the aircraft.

To improve the accuracy of determining the UAV's angular orientation, integration of various types of orientation systems is used, for example, the three-axis magnetometer module, the pyrohoryzon module, and the GPS/Glonass satellite navigation system module [12]. This method of aggregation increases the accuracy of determining pitch and roll angles and eliminates errors associated with the presence of residual uncompensated magnetic interference and an error caused by the UAV's sliding angle. The linear Kalman filter calculation was inferred, the detail of how it is executed and tried was talked about. In addition, the all-encompassing Kalman filter calculation; a rendition of the straight Kalman filter which can be applied to issues in which the perception and procedure models are non-linear was broadened [13].

The purpose of this work is to analyze the known methods for measuring angular coordinates in UAV positioning systems and to develop a new phase-metric method for goniometric (angular) control of UAVs based on accelerometric transformers.

A typical FOS block diagram based on inertial sensors (micromechanical gyroscopes and accelerometers) is shown in Figure 1 [13]. The main errors of such systems are non-linearity, zero offset, and noise component.

The gyroscopic orientation system is based on integrating the signals of three gyroscopes, which are angular velocity sensors. Each of the gyroscopes measures the corresponding angular velocity ω_X, ω_Y, ω_Z. Based on the information about these projections, the yaw angles ψ, pitch

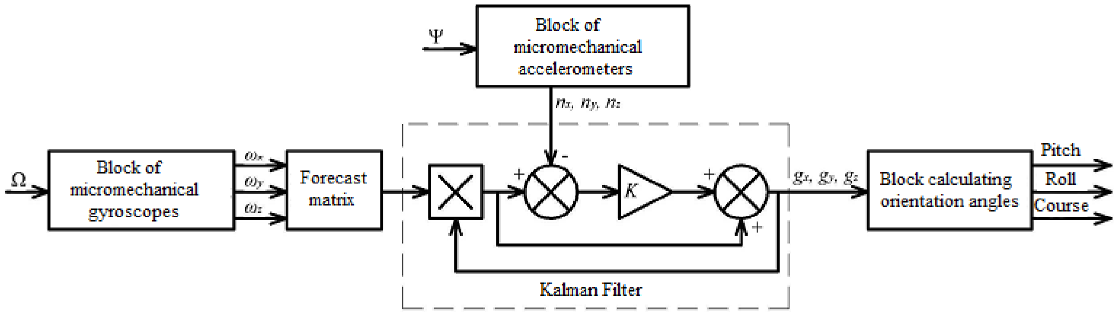


Figure 1: Typical FOS block diagram: Ω-angular velocity of the UAV, Ψ-angular orientation of the UAV

ω, and roll γ can be determined based on the expressions in equation (1) [14]:

$$\begin{aligned} \psi_{k+1} &= \psi_k + T_0 \cdot \omega_{Z_k}, \\ \upsilon_{k+1} &= \upsilon_k + T_0 \cdot \omega_{X_k}, \\ \gamma_{k+1} &= \gamma_k + T_0 \cdot \omega_{Y_k}, \end{aligned} \tag{1}$$

Where T_0 is the discreteness period; $k = 0, 1, \ldots$ are discrete samples.

The problem with gyroscopes when measuring UAV orientation angles is the accumulation of errors over time. This negative effect is caused by the offset of the zero obtained by pre-calibration during the flight, as well as the influence of noise.

The accelerometric orientation system is based on the measurement of accelerometer accelerations A_x, A_y, A_z (or equivalent gravity action) along the three coordinate axes X, Y, Z. Accelerometer readings are determined by projections of acceleration values on the corresponding coordinate axis:

$$\begin{aligned} A_X &= -g \cos\upsilon \sin\gamma, \\ A_Y &= g \sin\upsilon, \\ A_Z &= g \cos\upsilon \cos\gamma. \end{aligned} \tag{2}$$

Where g is the acceleration of gravity. From the ratio in equation (2), the pitch υ and roll γ angles of the UAV are determined with equation (3):

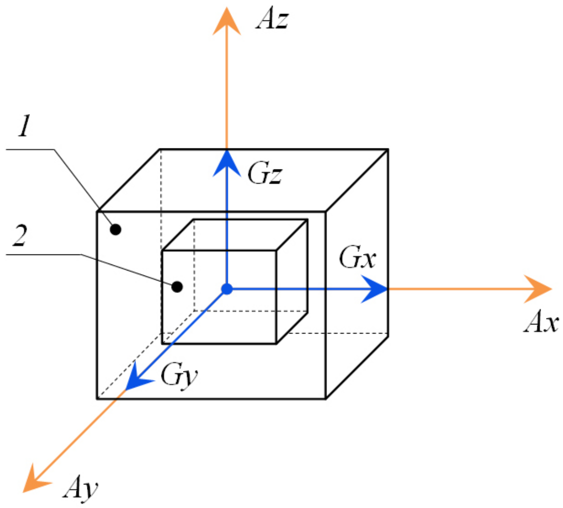
$$\begin{aligned} \upsilon &= \frac{180^\circ}{\pi} \arcsin\left(\frac{A_Y}{g}\right), \\ \gamma &= -\frac{180^\circ}{\pi} \arctan\left(\frac{A_X}{A_Z}\right). \end{aligned} \tag{3}$$

The accelerometric system does not tend to accumulate errors and is selective to the horizon plane, but is subject to accelerated movement, and the output signal contains high-frequency noise. The error in estimating the required output parameters of the FOS (pitch, roll, yaw) can be significantly increased by using accelerometric sensors with improved characteristics as part of the micromechanical accelerometer unit.

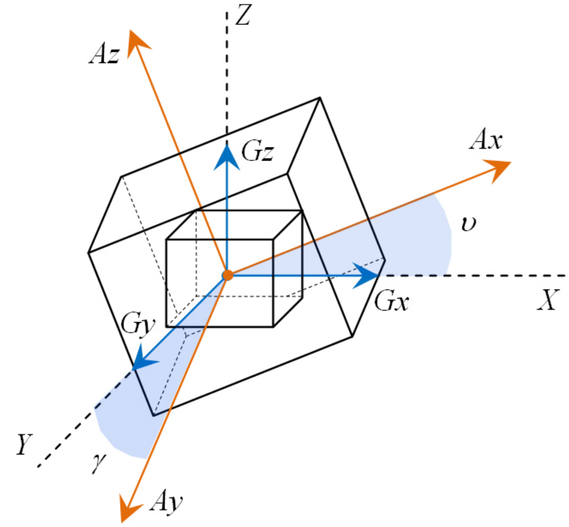
Problems of accelerometric sensors that are significant in the problem of estimating the angular position of the UAV are [15, 16]:

- Insufficient angle measurement range for many commercially available accelerometers designed for inclinometric monitoring of buildings and structures (small deviations from the vertical need to be evaluated);
- High accuracy of accelerometers with wide measurement angles-more than 10 (for UAVs in different flight modes, it takes 30-40 degrees or more);
- Insufficient threshold sensitivity (minimum defined angle) and unacceptable measurement error of small angles less than 10 due to insufficient accuracy of arctangential transformations;
- Significant influence of temperature interference and other external destabilizing factors on the measurement error.

The combined use of gyroscopic and accelerometric measurements based on the phase-metric



(a) in a stable state.



(b) in a state of destabilization.

1 – the symbol of the accelerometer, 2 – the symbol of the gyroscope A_x, A_y, A_z – coordinate system of the accelerometer, G_x, G_y, G_z – coordinate system of the gyro, XYZ geographic coordinate system.

Figure 2: The principle of registering the pitch angle υ and roll angle γ of the UAV

method of goniometric (angular) control [17, 18, 19, 20, 21, 22, 23] for registering the pitch and roll angles of the UAV, as well as spatial positioning of the UAV, will compensate for the main drawbacks of the classical control methods described above, performed on the basis of expressions based on equations (1), (2) and (3). According to what was said, in the current study, it was tried to measuring angular coordinates and to develop a new phase-metric method for goniometric control of UAVS.

2. Proposed method

According to the proposed approach, registration of the UAV pitch angle υ and roll angle γ is performed on the basis of calculating the difference in angular parameters relative to the measurements of the gyroscopic and accelerometric converters whose coordinate axes are coaxially located according to Figure 2.

During the movement of the UAV, the registered values of angular coordinates calculated on the basis of the accelerometer are balanced relative to the registered values of the gyroscope. In contrast to similar solutions for joint accelerometric and gyroscopic measurements, in this case, increasing

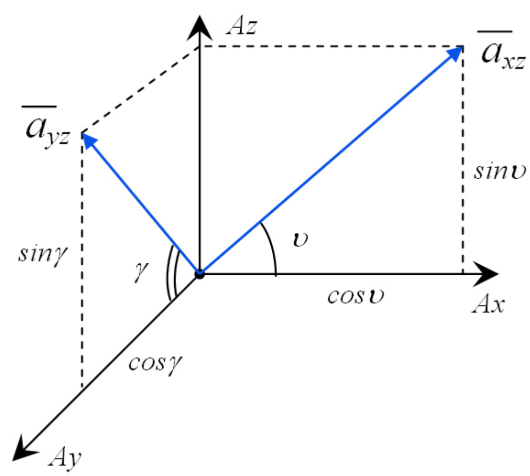


Figure 3: Phase-metric method for the computation of pitch angle υ and roll angle γ of the UAV

accuracy and stability is achieved by using the phase-metric method to calculate the inclination angle of the accelerometric transformer.

According to the phase-metric method, to calculate the pitch angle υ of the UAV and the roll angle γ from the registered values of the accelerometer, it is necessary to convert signals along the axes A_x, A_y, A_z into harmonic signals as is shown in Figure 3 according to equations (4), (5)

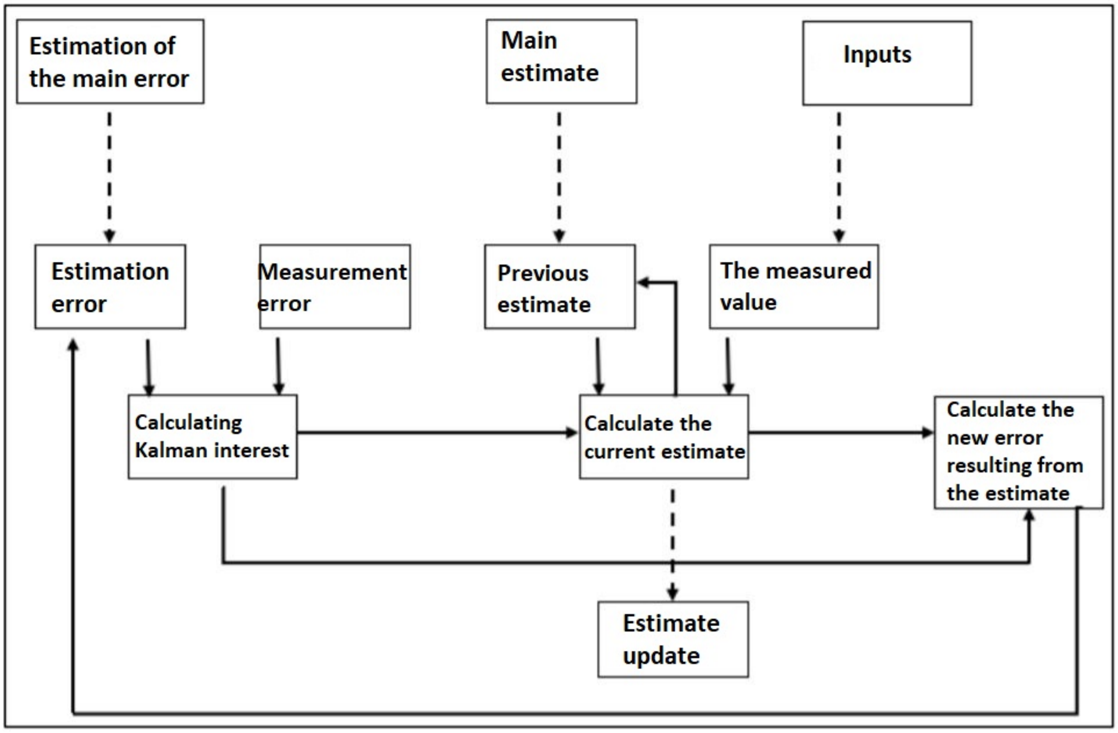


Figure 4: Diagram of Kalman filter implementation steps

and (6):

$$U_x = A_x \cdot U \cdot \cos \omega t \tag{4}$$

$$U_y = A_y \cdot U \cdot \cos \omega t \tag{5}$$

$$U_z = A_z \cdot U \cdot \sin \omega t \tag{6}$$

According to trigonometric laws the pitch angle υ and roll angle γ are determined based on the expressions (7) and (8):

$$U_\upsilon = a_x \cdot \cos \omega t + a_z \cdot \sin \omega t, \tag{7}$$

$$U_\gamma = a_y \cdot \cos \omega t + a_z \cdot \sin \omega t. \tag{8}$$

Then, after performing the conversion, the expressions for determining the pitch and roll angles υ and γ are obtained by (9) and (10):

$$\begin{aligned} U_\upsilon &= a \cdot \sin \upsilon \cdot \cos \omega t + a \cdot \cos \upsilon \cdot \sin \omega t \\ &= a \cdot \sin(\omega t + \upsilon) \end{aligned} \tag{9}$$

$$\begin{aligned} U_\gamma &= a \cdot \sin \gamma \cdot \cos \omega t + a \cdot \cos \gamma \cdot \sin \omega t \\ &= a \cdot \sin(\omega t + \gamma) \end{aligned} \tag{10}$$

3. Results and discussion

At first place, we will take a closer look at the steps of the standard Kalman filter which also represents the overall view of the proposed phase-metric method. First of all, Figure 4 gives a more detailed view of the Kalman filter design process.

As a first step, how to calculate Kalman interest is shown. Kalman interest is a measure to examine the ratio between the accuracy of measurements (observations) and the accuracy of estimates. As can be seen in Figure 4, the calculation of Kalman interest is clearly visible. Based on this, Kalman's interest formula is as equation (11):

$$KG = \frac{E_{est}}{E_{est} + E_{mea}} \qquad 0 < KG < 1 \tag{11}$$

Where KG, E_{est} and E_{mea} are Kalman interest, Estimation error, and Measurement error, respectively. As the measurement accuracy decreases and the estimation accuracy increases, Kalman's interest rate approaches zero value. This indicates that the actual value is approaching. Now to be able to estimate the desired parameter at the present time. Based on previous estimates, is obtained the equation (12):

$$E_{estt} = E_{estt-1} + KG(MEA - E_{estt-1}) \qquad (12)$$

Where t, MEA and Est are time, the measured value, and the estimated value, respectively. The third basic equation of a standard Kalman filter according to the equation (13).

$$\begin{aligned} E_{estt} &= \frac{E_{mea} \cdot E_{estt-1}}{E_{mea} + E_{estt-1}} \\ &= (1 - KG)(E_{estt-1}) \end{aligned} \qquad (13)$$

The equation (13) are the three main equations of the Kalman filter steps. As a result, according to the three equations, we can easily run them backwards and then achieve the desired value.

The resulting angle values must be subtracted from the angle values recorded by the gyroscopic transducer. This will calculate the desired pitch and roll angles υ and γ, which must be compensated for the spatial location of the UAV body using the balancing system and the control system.

The error of the results of calculating the angle of rotation based on two methods (phase-metric and using the arctangent function) was determined by comparing the calculated angle with the preset angle of rotation of the gear shaft (positioning accuracy 0,001°). The rotation angle values were set to 1°, then from 15°to 90°in increments of 15°. The study showed that the standard deviation of calculation results of rotation angle via phase-metric method is 8,78 times less than a standard deviation of calculation results of rotation angle using the inverse tangent.

4. Conclusions

To create effective UAV control systems, it is necessary to ensure high accuracy of the initial information about the UAV's position in space. To improve the accuracy of determining the UAV's angular orientation, various types of orientation systems are integrated. The disadvantage of this approach is the high hardware and algorithmic complexity so the phase-metric method can be a good alternative that does not have these disadvantages. Based on the analysis of the shortcomings of the accelerometric and gyroscopic orientation system, a phase-metric method of goniometric control based on accelerometric and gyroscopic transducers for positioning UAVs is proposed.

The combined use of gyroscopic and accelerometric measurements based on the phase-metric method of goniometric (angle-measuring) control for registering the pitch and roll angles of the UAV, as well as spatial positioning of the UAV, will compensate for the main disadvantages of classical control methods performed on the basis of arctangent transformations by improving the exactness of deciding the UAV's precise direction. (insufficient angle measurement range, high error of accelerometers with wide measurement angles, insufficient threshold sensitivity, significant influence of temperature interference and other external destabilizing factors on the measurement error).

The study showed that in a wide range of rotation angles from 10 to 90°, the results of calculating the rotation angle using the phase-metric method are 8,78 times less than the results of calculating the rotation angle using the arctangent function. Reducing the error determines the effectiveness of the proposed method in UAV control systems.

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