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Aircraft attitude calculation with the use of aerodynamic flight data as correction signals

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ABSTRACT

The article presents the problem of attitude calculations in the case of faulty correction signals. The issue is of vital importance especially for small general aviation aircraft and small Unmanned Aircraft Vehicle (UAV) systems, where there is no hardware redundancy (multiplied Attitude and Heading Reference System: AHRS). First, a typical algorithm using complete measurement information and complementary filtering used in AHRS is described. An alternative solution for complementary filtering is the use of Kalman filtering. The attitude is calculated from roll rates measured by rate gyros in the aircraft body frame. As correction signals, pitch and roll gravity angles are used. The angles between the aircraft body frame x (for the pitch angle) and y (for the roll angle) axes and local gravity axis are treated as gravity angles. Gravity angles are usually measured by clinometers or calculated from accelerations. Next, the problem of missing correction signals is discussed. Attitude calculation without correction causes significant errors depending on time (drift). Therefore, for correction estimates of pitch and bank angle were proposed. It is shown that the use of estimated data in the case of missing correction signals does not cause significant attitude errors. For simulation analysis, flight testing data were used.

1. Introduction

1.1. Attitude and heading reference system – general description

The data from attitude and heading measurements are critical for aircraft safety. In older systems the attitude was measured with a unit based on mechanical gyros with gimbal rings, described e.g. in [22]. In modern systems the attitude is measured with the use of an Attitude and Heading Reference System – AHRS. A typical AHRS consists of three rate gyros, accelerometers or clinometers and a magnetometer. Rate gyros measure three rates in the aircraft body frame (p – roll rate: the roll around aircraft x axis, q – pitch rate: the roll around aircraft y axis, r – yaw rate: the roll around aircraft z axis). With the use of a transformation algorithm, the system calculates angular rates in the Earth frame F_V [3]. From integration of angular rates, attitude angles and heading are received. However, if only rate gyros are used, attitude and heading can be burdened with errors, growing in time, caused by gyros drift and its integration. An error depends on the class of sensors, however, even the best sensors do not guarantee error free measurements. For this reason, in order to correct the attitude angles, gravity angles are used. Here, the gravity pitch angle is the angle between the body frame x axis and the local gravity vector. The gravity roll angle is the angle between the body frame y axis and the local gravity vector. Gravity angles are measured by a clinometer or calculated from accelerations. For heading correction, magnetic heading measured by an AHRS is used. It is common knowledge that gravity angles are real angles only during unaccelerated flight. During accelerations caused by e.g. turning, attitude is calculated with the use of gyros only, or with the use of other correction signals. There are several alternative solutions which can be used as correction signals. Frequently, for the attitude estimation GPS signals are used. For example, in [12] the second derivative of GPS position (acceleration estimation) is used for correction of attitude. The use of GPS for attitude estimation is also presented in [8], where a triple antenna is applied. Another solution is to use different kind of sensors, as e.g. in [2], or the detected horizon line for attitude estimation, as described in [6] or [4].

The most popular correction signals are gravity pitch and roll angles measured by clinometer or calculated from measurement of accelerations. Such solution is typical for commercial units. For attitude correction signals which are not burdened with low frequency error can be used. Correction algorithms are another important problem in attitude estimation. Often, different forms of Kalman filtering are implemented, as e.g. in [30,31,24,11,27]. Another frequent solution for the correction of attitude and heading are different forms of complementary filtering [23,2,7,1], or other filtration algorithms [26].

The aim of the article is to describe implementation of aerodynamic flight data for pitch and roll correction. Such application

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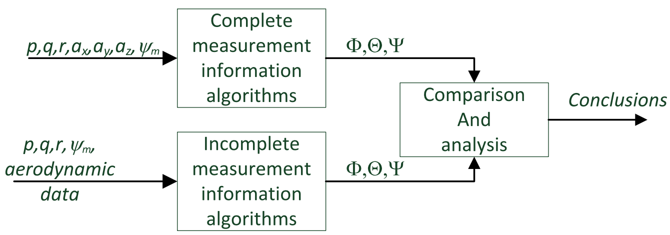

Fig. 1. Methodology of results analysis presented in the article.

is useful e.g. in the partial fault of AHRS sensors (lack of gravity angles). Fig. 1 presents general methodology of results analysis.

First, for analysis, the attitude was calculated with the use of typical algorithms, with complete measurement information (measurement of angular rates in body frame, measurement of gravity angles). Next, with the use of the same data, attitude was calculated with non-gravity correction signals, and the difference between results obtained was taken into consideration. It means that reference attitude was obtained from AHRS algorithms, with correction signals obtained from gravity sensors. Next, data from AHRS algorithms with the use of aerodynamic flight data for correction were analyzed. For simulation analysis, flight testing data recorded on the board of PZL-110 *Koliber* were used [17]. The flight was realized in low level of atmospheric turbulences. During the flight, typical maneuvers were realized (non-aerobatic flight), with limitations characteristic for general aviation aircraft. Roll angle did not exceed 25 degrees, pitch angle did not exceed 20 degrees. The flight was realized with the use of indirect control system (fly-by-wire) for general aviation aircraft [29]. Fiber optic gyros µFORS 36 were used as angular rates sensors [20]. Sensors were implemented in an AHRS designed at the Department of Avionics and Control Systems of the Rzeszow University of Technology [16,28]. The attitude calculated for the case of incomplete measurement information was compared with attitude calculated from the same sensors, but in the case of complete measurement information. For aerodynamic data, Air Data Computer (ADC) designed at the Department of Avionics and Control Systems of the Rzeszow University of Technology was used [25].

The practical contribution of this article is the implementation of known estimates of pitch and roll angles for AHRS correction algorithms, and testing the proposed solution by means of collected in-flight testing data.

2. Typical algorithms used for attitude calculation

2.1. Tait–Bryan algorithm

In some publications the Tait–Bryan algorithm is called the Euler angles algorithm. The relations between angular rates measured in the body frame F_B and the angular rates in the Earth frame F_V are as follows:

$$\dot{\bar{\Phi}} = L_{VB} \times \bar{\Omega}_K \tag{1}$$

where:

$$\bar{\Omega}_K = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$ – angular rates in the body frame F_B (roll rate, pitch rate, yaw rate)

$$\bar{\Phi} = \begin{bmatrix} \Phi \\ \Theta \\ \Psi \end{bmatrix}$$ – Euler angles in the Earth frame F_V (roll, pitch, yaw angle)

$$L_{VB} = \begin{bmatrix} 1 & \sin\Phi\tan\Theta & \cos\Phi\tan\Theta \\ 0 & \cos\Phi & -\sin\Phi \\ 0 & \frac{\sin\Phi}{\cos\Theta} & \frac{\cos\Phi}{\cos\Theta} \end{bmatrix}$$ – matrix allowing derivation of the Euler angle rates from the body rates body frame to the Earth frame

Eq. (1) is the base for attitude calculation. Its description is shown e.g. in [3,21]. The solution presented is implemented in many attitude and heading reference systems, also those designed at the Department of Avionics and Control Systems of the Rzeszow University of Technology. The use of the Tait–Bryan algorithm leads to a point of discontinuity for pitch angle $\Theta = 90$ [deg] (see L_{VB} matrix), which is a serious disadvantage. An alternative solution is the use of an algorithm based on quaternion algebra [3,9].

2.2. Quaternion based algorithm

The relationship between a quaternion and angular rates measured in the body frame F_B is as follows:

$$\dot{\varepsilon} = \frac{1}{2} L_e \times \bar{\Omega}_K \tag{2}$$

where:

$$\varepsilon = \begin{bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{bmatrix}$$ – quaternion

$$L_e = \begin{bmatrix} -e_1 & -e_2 & e_3 \\ e_0 & -e_3 & e_2 \\ e_3 & e_0 & -e_1 \\ -e_2 & e_1 & e_0 \end{bmatrix}$$

The relationship between quaternion and attitude and heading angles in the earth frame is as follows:

$$e_0 = \cos\left(\frac{\Phi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Psi}{2}\right) + \sin\left(\frac{\Phi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Psi}{2}\right) \tag{3}$$

$$e_1 = \sin\left(\frac{\Phi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Psi}{2}\right) - \cos\left(\frac{\Phi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Psi}{2}\right) \tag{4}$$

$$e_2 = \cos\left(\frac{\Phi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Psi}{2}\right) + \sin\left(\frac{\Phi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Psi}{2}\right) \tag{5}$$

$$e_3 = \cos\left(\frac{\Phi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Psi}{2}\right) - \sin\left(\frac{\Phi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Psi}{2}\right) \tag{6}$$

The relationship between attitude and heading angles and a quaternion is as follows:

$$\tan\Phi = \frac{2(e_0e_1 + e_3e_2)}{e_0^2 - e_1^2 - e_2^2 + e_3^2} \tag{7}$$

$$\sin\Theta = 2(e_0e_2 - e_3e_1) \tag{8}$$

$$\tan\Psi = \frac{2(e_0e_3 + e_1e_2)}{e_0^2 - e_1^2 - e_2^2 + e_3^2} \tag{9}$$