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Measurement data fusion with cascaded Kalman and complementary filter in the flight parameter indicator for hang-glider and paraglider

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ABSTRACT

The research on an assistive instrument for hang-gliders and paragliders resulted in the three prototypes of the integrated device for sensing, processing and displaying data to the pilot. The data processing contains innovative data fusion and filtration algorithms with cascaded filter build with Kalman and complementary filters. The developed prototypes have been successfully tested in the laboratories and during flight tests.

1. Introduction

Hang-gliding and paragliding are the forms of a sport or recreation aviation, which attract dozens of new fans who want to develop their piloting skills every year. The main reason is, that this course of action is much easier in comparison to the other aviation sports such as gliding, parachuting, touristic airplanes piloting, or even ultralight aircraft piloting. Hang-gliding and paragliding do not require specialized technical support such as airdromes, airsheds or maintenance crew and maintenance actions consist of only periodical surveys. Hang-gliders and paragliders are non-self-propelled aircraft, which are able to fly after taking-off from a hill or after being towed by a static towline, a car, a motorboat or by another aircraft (hang-gliders only). Increasing of endurance during a free flight can be implemented by the reasonable usage of atmospheric phenomena such as thermals (convection) or sea breeze. During the flight, the pilot bases mainly on his senses and feelings. Instruments should only facilitate navigation tasks and help to use environmental conditions for flying in an optimal way. The instruments are especially helpful during the free flights with thermals, it means when the vertical airstreams occur. The thermals result from various properties of heat absorption and emission in various parts of the earth surface. The instruments can considerably prolong the flight by sensing and indicating updrafts – vertical airstreams directed upward (also known as thermal columns) and downdrafts – vertical airstreams directed downward (also known as subsidence). During the flight, pilot tries to find and use thermal columns as well as he tries to avoid downdrafts in order to gain altitude.

There are the modest devices on the market equipped with the static pressure sensors (integrated variometer and altimeter) and GPS receivers for navigation, flight data and flight path recording. However, such devices are reasonably expensive. Therefore, the smartphone and tablet apps became recently more and more popular in that field. Unfortunately, commercial mobile devices cannot replace dedicated aviation devices for many reasons. The main reason is that the off-the-shelf mobile devices' sensors are not accurate enough to meet exacting requirements of various conditions in the air. Moreover, the applications are not stable enough since the operating systems of the contemporary mobile devices are mostly not real-time operating systems (RTOS) which result in unrestricted usage of device computing and memory resources by various applications. The dedicated device, which has been designed, provides the pilot with the high accuracy data owing to the implementation of the high precision sensors as well as real-time received data fusion and filtration in the 32-bit microcontroller. Moreover, all the units have been picked in a manner that the overall cost of the device is a few times lower than the cost of commercial counterparts.

2. Design concept

While flying by hang-glider or paraglider the most important parameters for the pilot is information about the vertical speed, altitude and magnetic heading. Additionally, useful parameters are ground

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speed, wind direction and the gliding ratio (for a free flight, the glide ratio is the ratio of the ground speed – measured relative to the earth – to the vertical speed measured with a positive sign towards the Earth during descent). Knowledge of these parameters and the appropriate skills allow the pilot to use optimally weather conditions to complete the flight. These values, especially the vertical speed and altitude, should be determined with the highest possible accuracy. To do this, a system consisting several sensors, using the chosen method of data fusion, and filtering should be applied to determine the required parameters and minimize measurement errors. The chosen signal processing algorithm should be implemented in a microprocessor system.

In such integrated measurement devices, it is critical that information on the flight parameters is passed to the pilot in an accessible and transparent way, and the device does not absorb pilot's attention excessively. The best solution is a graphical representation, commonly used in many aviation instruments. Vertical speed can be imaged by a sliding scale with marked values, and the course can be represented by a rotary graphics simulating the compass rose, where can also be wind direction indicated. In contrast, there is no need for a graphical presentation of the altitude, although the devices dedicated for hang-gliders and paragliders sometimes offer drawing the altitude in time.

Due to the fact that the pilot must observe the situation around him (especially other pilots), navigate and predict where potential heat fluxes are occurring, observing the indications can only be performed from time to time. For this reason, an acoustic presentation of vertical speed is used. Climbing is signaled by shorter high tones whose transmission frequency is proportional to the speed value. Descent below a certain set value is signaled by continuous low-frequency sound. This value should be set based on the specific rate of descent of the glider and the pilot's will. In addition, in order to facilitate the pilot's documentation of his achievements and to keep records of his and his glider's hours in the air, it is useful to equip the measurement system with the flight data acquisition module, i.e. measurement time and geographic coordinates and altitude.

3. Measurement sensors

The last requirement is the size limitation, as the device should have the smallest external dimensions and mass. The proposed device is assumed to use a digital barometer, inertial unit (three-axis accelerometer and three-axis gyroscope), a three-axis magnetometer produced using MEMS technology and a miniature, SBAS enabled GPS receiver. The idea of correcting the measurements of altitude and vertical speed by integrating data from these modules is based on a concept developed and verified at the Polish Institute of Aviation [1,2].

3.1. *The measurement of the barometric altitude and vertical speed*

The classic onboard instrument used for measuring the altitude of the aircraft is a barometric altimeter, which uses the dependence of absolute pressure change with altitude [3]. The barometric altitude is determined from the measured pressure from the hypsometric formula (1):

$$H = \frac{T_0}{t_{gr}}\left[1-\left(\frac{p_H}{p_0}\right)^{t_{gr}R}\right] \tag{1}$$

where

T_0 – level 0 temperature,
t_{gr} – gradient of the temperature,
R – gas consolidation,
p_0 – level 0 pressure,
p_H – level H pressure.

The first measurement data come from the barometric MEMS sensor. That type of barometers has good sensitivity and linearity, but its drawback is the high susceptibility to interference. In addition, barometric altitude measurement method is affected by errors due to changes in atmospheric pressure, the change of the average temperature of the air column, variable humidity and various temperature gradient [1]. Nevertheless, it is commonly used in aviation a method of measuring the altitude and it was selected as the base value, which is to be corrected by filtration and fusion with data from the other sensors.

3.2. *Altitude, vertical speed and magnetic heading determined from the inertial unit and magnetometer*

Altitude and vertical speed can also be obtained by the vertical component of acceleration acting on the aircraft, measured in the coordinate system related to the Earth. The gravitational acceleration should be removed from the vertical component of the acceleration then, the acceleration should be integrated in order to obtain a vertical speed and after another integration the altitude is to be obtained.

A device for measuring the acceleration is a three-axis accelerometer, but it measures the acceleration components in the coordinate system related to the device. In order to transfer the vector coordinates from one coordinate system to another the relative position of these systems must be known. The relative position of the systems can be represented by Euler angles, rotation matrix or quaternion [4]. The transformations in the research were based on quaternion to calculate the mutual position of the systems. Implementing the quaternion transformations has been found beneficial especially in low-cost navigation devices [5] but it is also an encouraging option in newly designed concepts of navigation modules [6] as well as in complex autopilot systems [7].

The quaternion transformation is based upon the Euler's Principal Rotation so any arbitrary orientation can be represented with just a vector and an angle. The vector defines the direction of rotation, and the angle is the amount of rotation about this axis to go from initial to final attitude. Quaternions form a class of four-component hyper-complex numbers. A quaternion q is often represented as a scalar q_0 and a vector **q**:

$$q = q_0 + q_1\mathbf{i} + q_2\mathbf{j} + q_3\mathbf{k} = \{q_0,q_1,q_2,q_3\} = q_0 + \mathbf{q} = \{q_0,\mathbf{q}\} \tag{2}$$

where q_0, q_1, q_2, q_3 are real numbers, and **i**, **j**, **k** are components of a unit vector in the reference frame.

The elements of the quaternion representing the relative position of the measurement module in relation to the Earth reference frame can be derived from Euler Angles as follows:

$$q_0 = \cos\left(\frac{\Psi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Phi}{2}\right) + \sin\left(\frac{\Psi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Phi}{2}\right) \tag{3}$$

$$q_1 = \cos\left(\frac{\Psi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Phi}{2}\right) - \sin\left(\frac{\Psi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Phi}{2}\right) \tag{4}$$

$$q_2 = \cos\left(\frac{\Psi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Phi}{2}\right) + \sin\left(\frac{\Psi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Phi}{2}\right) \tag{5}$$

$$q_3 = \sin\left(\frac{\Psi}{2}\right)\cos\left(\frac{\Theta}{2}\right)\cos\left(\frac{\Phi}{2}\right) - \cos\left(\frac{\Psi}{2}\right)\sin\left(\frac{\Theta}{2}\right)\sin\left(\frac{\Phi}{2}\right) \tag{6}$$

The inertial measurement sensors are characterized by measurement errors, whose sources are mostly: bias error, axis alignment error, scale factor and scale factor nonlinearity [8]. The error sources are multiple and are coupled, making the sensor calibration a non-trivial task. Even if no physical input is applied, the bias error occurs. Furthermore, the scale factor error is the uncontrolled noise of the ratio of the sensor output change to the measured physical variable change. Additionally, gyroscopes experience g-dependent bias errors, which are proportional to the applied acceleration [8].

Due to an integration error of the vertical speed and altitude, determined by the vertical acceleration, begin to differ significantly from