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Data Fusion Algorithm for the Altitude and Vertical Speed Estimation of the VTOL Platform

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Abstract An approach to the autonomous of the realization VTOL platform take-off and landing significantly simplifies the operator labor to control such device. At the same time, implementation of these control scenarios allows to perform these tasks under failure conditions (for example communication breakdowns). One condition of proper operation of the vertical movement control system is the ability to provide reliable information about the altitude of the controlled platform. In this paper one of the solutions for obtaining estimate of the altitude based on sensor data fusion is presented. Proposed scheme uses information obtained from pressure sensor, inertial measurement unit, ultrasonic sensor and GPS, all of these instruments are nowadays very often mounted on VTOL platforms.

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1 Introduction

In several recent years, there has been a great boom on many kind of an unmanned aerial vehicles (UAVs), especially vertical take-off and landing platforms with multirotor actuators. They have become very popular and have a few advantages over other types of drones e.g. unmanned planes. The ability to start and land vertically allows them to operate in a small, hard to reach and hazardous areas. The applications of small flying machines cover the fields of many domains such as security, inspections and management of the large infrastructures, ground installations and also some emergencies and natural disasters [4, 10]. A VTOL (Vertical Take-off and Landing) platform with a different number of rotors is a complex system, structurally unstable that needs to fly with the use of a modern embedded control systems [10, 11]. Development of Micro Electro- Mechanical Systems gave the opportunity to design very small in size and powerful electronic circuits that consist of miniature sensors and high performance microprocessors [5]. Despite that fact, the problems with accurate measurements and proper data processing still exist. One of them, addressed in this paper is an altitude estimation issue. The altitude control is an important feature because it allows the flying platform to maintain at a certain height. Having on-board altitude stabilization relieves the operator from the continuous throttle operation while flying in the manual mode. On the other hand it also provides the possibilities of autonomous take-off and landing operation. The reference value can be either a constant value for vertical speed or a trajectory along the vertical axis direction. An altitude control problem has been reviewed by several researchers and many techniques have been used to deal with the control strategies based on different measurement devices [1–3, 7].

This paper has both conceptual and practical meanings for the altitude control that can be implemented upon an algorithm presented in the contribution. The idea that stands behind assumes to combine different kind of sensors such as ultrasonic range finder, barometric pressure module, accelerometers and for an outdoor use GPS device. Two of them are the absolute height measure device and two other give relative information about the position above the ground and linear acceleration. Once performing the data fusion one can obtain a measurement signal that is suitable for both low and high levels of altitude. The accuracy of such measurements satisfies the requirements of precise maneuvers such as taking-off and landing not being confined to the flying at a certain altitudes only.

The paper is organized as follows. First the measurement instruments are shortly described, their characteristics, sources of the errors and their impact on the estimation process. Then the description of the algorithm that has been used for the altitude estimation is presented. The fourth section presents an implementation of the algorithm and some results which are obtained with processing synthetic data obtained by the means of simulation. Finally, the results of experiments together with the conclusions are briefly discussed.

2 Measurement System

Let us formulate at the beginning the measurement system in the sense of its error/noise characteristics. We assume that VTOL platform is equipped with the following instruments:

- Accelerometer measuring acceleration along z-axis of VTOL platform,
- Pressure sensor which measures static pressure of surrounding air,
- Ultrasonic range finder which is pointing downwards along VTOL z-axis,
- GPS module.

Details of each of the instruments will be shortly discussed in separate paragraphs.

2.1 Accelerometer

The triaxial accelerometer has been used for the altitude estimation algorithm. It has been a part of a triaxial inertial sensor with magnetometer ADIS 16400. The range of the accelerometer is about $+/-$ 18 g. Factory calibration coefficients allow to obtain for each sensor its own dynamic compensation in order to provide accurate sensor measurements over a wide range of temperatures (-40 °C to $+85$ °C). The misalignment of the sensor axis is about 0.2°. Nonlinearity of the sensor is a 0.1 % of a full scale while the sensor output noise is less than 9 mg rms.

One of the basic issues related to the acceleration measurement, is high vulnerability of the measurement to the VTOL frame vibrations which results in a high variance noise. At the same time, assumption about zero mean value of this noise is too optimistic, which can result in a drift, when one would like to obtain a linear velocity based on the integration of the accelerometer measurements.

2.2 Pressure Sensor

The MS5611 is a piezo-resistive sensor based on leading MEMS technology that includes 24 bit sigma-delta analog-to-digital converter with an altitude resolution about 10 centimeters and temperature readings. The sensing operation completes long term stability and both pressure and temperature compensation. This sensing element gives the measurements relative to the atmospheric pressure. The pressure range of the sensor is between 10 to 1200 mbar with an accuracy about +/− 1.5 mbar. Measurements of the sensor (pressure and temperature) is highly depended on the conversion time (0.6 to 9.04 ms). The faster conversion time the worse resolution. The pressure sensor has been optimized for altimeters and variometers.

In order to calculate altitude using pressure sensor measurements, there appear a need for a knowledge about pressure on the ground level. Without this reference measurement, one has to take into account measurement drift which is result of the changing air pressure.

2.3 Ultrasonic Range Finder

An ultrasonic sensor is a distance measuring unit which consists of an integrated ultrasonic waves transmitter, receiver and signal processing circuit. The sensor XL-EZ0 that has been used in the autopilot electronics detects object from 20 to more than 700 centimeters with a 1 centimeter resolution. Sonar series is capable to operate in a variable conditions such as temperature, voltage and acoustic or electrical noise changes. It has been provided with an auto-calibration function. Sensor operates at 42 kHz frequency and measurements are available every 100 miliseconds.

In case of ultrasonic sensor, the main problem is related with reflections of the beam emitted by the sensor itself, these reflections results in a high amplitude pulses in the altitude readings. Some solutions to this issue were proposed, for example, by employing fault detection like schemes in [6]. This behavior is very undesirable especially when such measurement is used as feedback signal in control loop, attempt of overcoming this problem by use of downpass filter introduce large phase lag in the control loop. Another issue in case of ultrasonic sensor is its short range.

2.4 GPS Module

To provide altitude data for the unmanned aerial robots some different approaches are possible. It is very common to use GPS (Global Positioning System) but it is insufficient because of its accuracy and hardly possible to operate in buildings and closed areas. Despite that fact the GPS module can be used as a one of the signals that gives explicitly the coordinates of the vehicle and its height above the reference ellipsoide. In the autopilot electronics design the LEA6 module has been used with the 5 Hz navigation update rate. The accuracy in position is 2.5 meters CEP.

While GPS module allows to obtain measurements of the position without any drift and with high reliability when GPS signal has sufficiently high quality, due to artificial noise with high variance added to the measurements, GPS on its own cannot be used for landing/takeoff tasks. Other drawback of this instrument is low sampling frequency which can be insufficient for control tasks.

3 Altitude Estimation Algorithm

Because of different noise/error characteristics of measurements which in case of ultrasonic sensor and pressure sensor cannot be modeled as a white noise, common filtering techniques like Kalman filter cannot be used directly. In order to cope with this problem, we choose to build estimation algorithm in a sequential manner so it is possible to solve problems related to the given measurement sources step by step.

In the first step it is desirable to attenuate spike errors present in ultrasonic sensor measurements. These spikes are results of the beam reflections, such reflection can occur when emitted beam hits for example walls when flight takes place indoor or leaves when VTOL is starting from the ground in outdoor environment. Measurements from ultrasonic sensor are filtered with use of a nonlinear filter. Task of this nonlinear filter is to limit the rate of change of the signal coming from the ultrasonic sensor. With this approach it is possible to remove high amplitude pulses present in the measurement. This filter consists of saturation, gain and integral, these elements are enfolded by a negative feedback loop. Rate of change limiter can be written using a nonlinear differential equation (1) where e is a difference between actual ultrasonic sensor readings and the output of rate of change limiter.

$$\dot{h}_{US}^F = k_{ROCL} sat_B(e) = \begin{cases} k_{ROCL} B_{ROCL}; & e > B_{ROCL} \\ k_{ROCL} e; & |e| \le B_{ROCL} \\ -k_{ROCL} B_{ROCL}; & e < -B_{ROCL} \end{cases} \quad (1)$$

From this point, gain inside the filter will be denoted as k_{ROCL} , saturation limits will be denoted as B_{ROCL}. From the Eq. 1, it is clear, that the derivative of the output is bounded by the values $k_{ROCL} B_{ROCL}$ and $-k_{ROCL} B_{ROCL}$. At the same time, when signal e is not affected by the saturation function (because of its low absolute value), whole filter acts as a first order lag. By use of sufficiently high gain k_{ROCL} and adequately to it choosen saturation level B_{ROCL} , it is possible to obtain low values of phase lag between signal before and after filtering, while being able to filter out the high amplitude pulses found in ultrasonic sensor readings.

Taking into account fact that measurements coming from ultrasonic sensor are more reliable at low altitudes (because of lower reflections probability), while measurements taken from GPS module on higher altitudes (because of possibly better GPS signal quality on higher altitudes), more weight is given to the filtered ultrasonic sensor readings at low altitudes and less weight on higher ones. Weights given to each of two data sources, are summed up to one. Linear combination of these two signals is given according to the following formula (2).

$$h_w = w_{US}\left(h_{US}^F\right) h_{US}^F + w_{GPS}\left(h_{US}^F\right) h_{GPS} \quad (2)$$

Where w_{US} is weight given to the filtered altitude readings based on ultrasonic sensor, h_{US}^F are altitude readings based on ultrasonic sensor after filtering using rate of change limiter, w_{GPS} is weight given to filtered GPS readings based on h_{US}^F and h_{GPS} are altitude readings based on GPS. Weights are functions of h_{US}^F because it was assumed that the phase lag related to this signal will be negligible due to the high value of gain k_{ROCL}.

In the implementation weighting function had the following form (3):

$$w_{GPS}(x) = \min(x/r, 1)$$
$$w_{US}(x) = 1 - w_{GPS}(x) \quad (3)$$

Where r is the maximum range of the ultrasonic sensor. By choosing this form of the weighting functions, weights are linearly changing when there is no saturation in ultrasonic measurement, at the same time, when range finder measurement is in the half of its range, the equal weights are given to both of the measurements.

Up to this stage, we were able to cope with the problems related to pulse errors, limited range of the ultrasonic sensor and to overcome situations when GPS signal has low quality, for example because of the fact that the flight takes place indoor. Next instrument widely used in the problem of altitude measurement is the pressure sensor. We assume following model of the altitude measurements when the pressure sensor is used Eq. 4.

$$h_{PS} = h + \eta + \beta(t) \quad (4)$$

Where η is uncorrelated noise with normal distribution and zero mean, $\beta(t)$ is a slowly changing bias. Appearing bias is related to the changes of the surrounding air pressure which without some reference instruments (for example mounted on the ground control station) results in changes of the altitude readings. Use of pressure sensor readings as a main source of information can be advantageous because it is more reliable than GPS or ultrasonic sensor. We would like to compensate drift present in the pressure sensor measurement, one possibility to accomplish this task, is to use a reference pressure sensor, one of drawbacks of this solution is the need for more complicated system (additional sensor and more data being send to the VTOL). By assuming that the drift changes are relatively small comparing to the altitude, instead of using reference pressure sensor, quantity h_w can be used along with explicit complementary filter [8] for bias compensation. Set of equations describing this stage of altitude estimator is given below (5).

$$
\begin{aligned}
e &= h_w - h_{PS} \\
\hat{\beta}(t) &= \frac{1}{T_i}\int edt \\
h_{PS}^F &= h_{PS} - \hat{\beta}(t)
\end{aligned} \tag{5}
$$

Where altitude measurement based on pressure sensor information, after compensation is denoted by h_{PS}^F. This kind of filter is commonly used in attitude estimation applications, where there exists a need for some solution of the problem related to integration of the gyroscope measurements which have non zero bias [8, 9]. Up to this point it was possible to obtain altitude measurements which have compensated bias component. If we assume, that bias changes are much slower than vertical movement and that this error can be compensated up to the point where it has negligible value, then we can treat pressure sensor readings as a measurements where only source of error is zero mean Gaussian white noise.

In order to implement control algorithm which can be used in the task of altitude stabilization, it would be very beneficial to have the estimate of the vertical speed, with use of the speed information, cascade control scheme can be deployed or control techniques which make use of higher derivatives of the process value [14]. To obtain this estimate discrete Kalman Filter will be used.

Vertical movement can be described by a simple linear model (6).

$$
\begin{aligned}
\dot{v} &= F_z/m - g \\
\dot{h} &= v
\end{aligned} \tag{6}
$$

which can be expressed in the state space formulation (7):

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \tag{7}$$

with the $\mathbf{A}$ and $\mathbf{B}$ matrices of the form (8):

$$\mathbf{A} = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \quad \mathbf{B} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \tag{8}$$

and state vector and input vector (9):

$$\mathbf{x}^{\mathbf{T}} = [v, h] \quad \mathbf{u} = [F_z/m - g] \tag{9}$$

Where h is altitude of the platform, v is vertical speed, F_z is force acting along z-axis of the VTOL platform which is the effect of proplusion system, mass is denoted as m and gravity acceleration by g.

In order to implement discrete Kalman Filter, we have to use discrete formulation of the system. For the discretization of the state equations first order approximation will be used Eq. 10:

$$
\begin{aligned}
\mathbf{x}(k+1) &\approx (\mathbf{I} + \mathbf{A}T_s)\mathbf{x}(k) + T_s\mathbf{Bu}(k) + \nu(k) \\
&= \mathbf{\Gamma x}(k) + \mathbf{\Psi} u(k) + \nu(k)
\end{aligned} \tag{10}
$$

For the modeling purposes, additional term $\nu(k)$ was added which express the impact of unknown external forces, non zero pitch/roll angles and non perfect measurements of accelerometers.

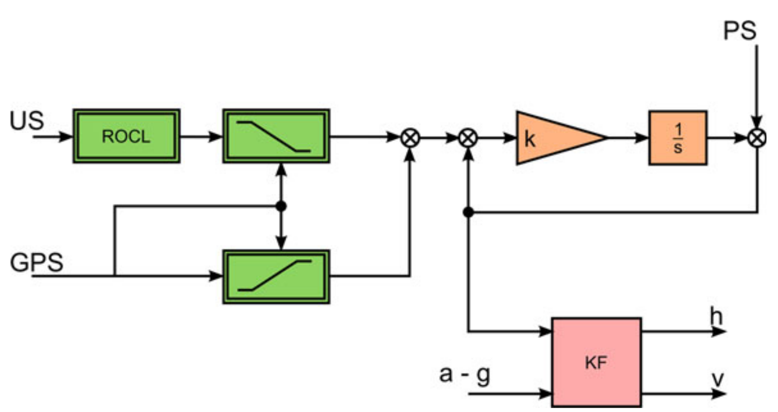

Fig. 1 General scheme of the altitude estimation algorithm

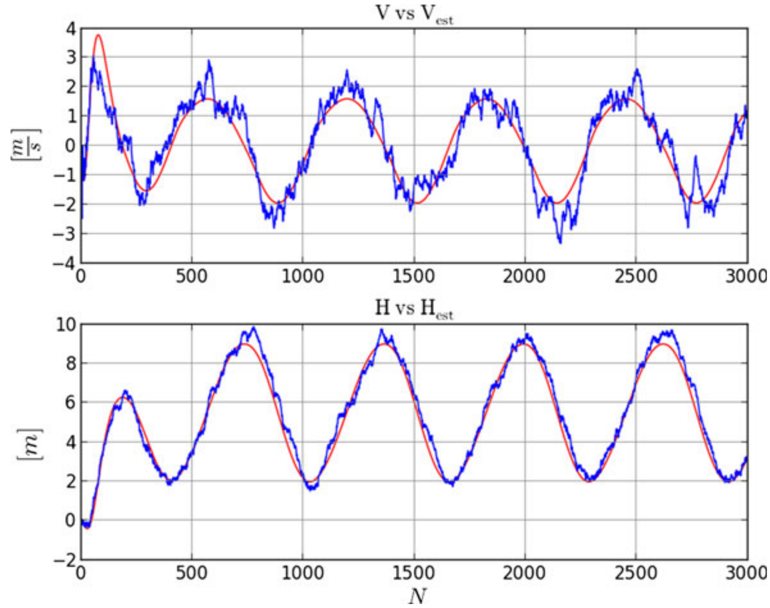

Fig. 2 Comparison between actual values and their measurements

We assume that $\nu(k)$ is white Gaussian with zero mean and unknown covariance matrix $\mathbf{Q}$. Discretization of equations (6) results in the discrete system with matrices (11).

$$\mathbf{\Gamma} = \begin{pmatrix} 1 & 0 \\ T_s & 1 \end{pmatrix} \quad \mathbf{\Psi} = \begin{pmatrix} T_s \\ 0 \end{pmatrix} \tag{11}$$

Measurement model is represented by discrete state space equation (12) and matrix (13), $\mu(k)$ is the measurement noise with covariance matrix R.

$$y(k+1) = \mathbf{H}x(k) + \mu(k) \tag{12}$$

$$\mathbf{H} = \begin{pmatrix} 0 & 1 \end{pmatrix} \tag{13}$$

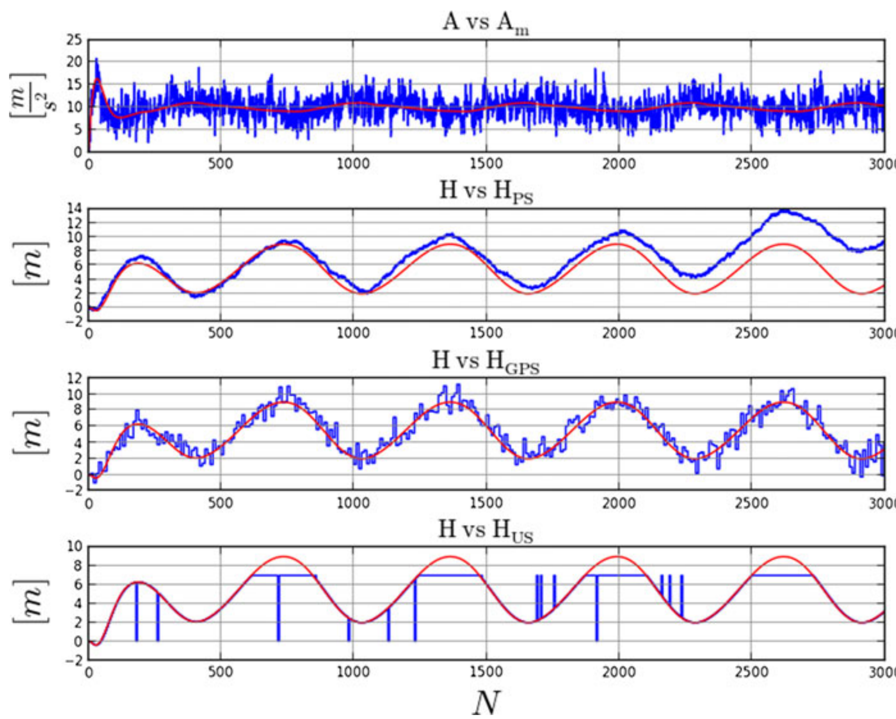

Fig. 3 Comparison between actual velocity and altitude, and their estimates

In order to measure F_z/m accelerometer will be used, altitude information will be obtained from previously constructed explicit complementary filter. For altitude, vertical velocity estimation discrete Kalman Filter described by the Eq. 14 is used.

$$\begin{aligned}
\mathbf{\hat{x}_{k|k-1}} &= \mathbf{\Gamma \hat{x}_{k-1|k-1} + \Psi u_{k-1}} \\
\mathbf{P_{k|k-1}} &= \mathbf{\Gamma P_{k-1|k-1} \Gamma^T + Q} \\
\mathbf{e_k} &= \mathbf{z_k - H\hat{x}_{k|k-1}} \\
\mathbf{S_k} &= \mathbf{HP_{k|k-1}H^T + R} \\
\mathbf{K_k} &= \mathbf{P_{k|k-1}H_k^T S_k^{-1}} \\
\mathbf{\hat{x}_{k|k}} &= \mathbf{\hat{x}_{k|k-1} + K_k e} \\
\mathbf{P_{k|k}} &= \mathbf{(I - K_k H)P_{k|k-1}}
\end{aligned} \tag{14}$$

Where $\mathbf{\hat{x}_{k|k-1}}$ is a priori estimate of the state vector, $\mathbf{\hat{x}_{k|k}}$ is a posteriori estimate, by $\mathbf{P_{k|k-1}}$ we denote a priori estimate covariance, a posteriori estimate covariance is denoted by $\mathbf{P_{k|k}}$. Matrix $\mathbf{S_k}$ is residual covariance and $\mathbf{K_k}$ is the Kalman gain.

Comprehensive discussion on Kalman Filtering techniques can be found in [12, 13]. We will treat output of Kalman Filter, as our final estimate of altitude and vertical velocity.

Graphical representation of discussed altitude estimation algorithm, is depicted on Fig. 1.

On the Fig. 1 rate of change limiter with weighting function are marked with green color, output of this part is treated as the input for explicit complementary filter. Kalman filter is feeded with output of the explicit complementary filter (altitude measurement after bias compensation) and with accelerometer measurements.

4 Simulation Results

Proper operation of proposed algorithm, was checked by means of the simulation. In the simulation, set of differential equations (6) was used in a character of the plant. Then sine like changes of vertical velocity were forced and errors of the measurement instruments were modeled. Gaussian white noise was added to the acceleration. In case of pressure sensor, besides Gaussian noise, also slowly changing bias was introduced. In order to simulate behavior of GPS module, high variance noise was added together with the effect of low sampling rate (5[Hz]). Ultrasonic measurements were saturated above the range of 7 meters, also spike errors were introduced to this measurement.

On Fig. 2 comparison between simulated measurements (blue lines) and actual values (red lines) have been shown. Starting from the upper subplot one can see accelerometer measurement, altitude based on the use of pressure sensor, altitude measured by the use of GPS module and ultrasonic sensor information.

On Fig. 3 comparison between actual value of altitude and velocity and their estimates is depicted. Actual values are marked with red color, while their estimates with blue. It can bee seen, that even with strongly disturbed measurements, both of these quantities can be relatively well estimated.

5 Summary

Presented algorithm, allowed for successful estimation of both altitude and vertical speed by use of four different information sources. Each of these sources, was corrupted by noise/ errors with each own characteristics. This enforced the step by step technique of estimator design. On each of these steps, consecutive issues related to each of the measurement instruments were solved.

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