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Design of an adaptive Kalman filter to eliminate measurement faults of a laser rangefinder used in the UAV system

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ABSTRACT

The Kalman filter is a valued method of signals filtration having the possibility of a sensors fusion, which is commonly applied in aerospace technology. Mainly, it eliminates random noises, improves the accuracy of a measurement system and their resistance to unexpected faults. Small unmanned aerial vehicles (UAV) are a challengeable area for various applications of the Kalman filter, because their high dynamics makes them highly sensitive to external disturbances acting on the on-board sensors. The paper discusses an application idea of the Kalman filter, whose purpose is to reduce the quantity of accidental incorrect measurements reported by a miniature laser rangefinder fixed to the UAV's wing. To verify the filtration effectiveness, real distance measurements recorded during real flights were applied. The results compare two approaches: an optimization using a reference signal from the second sensor mounted to the same UAV, and an adaptation of the covariance matrix R based on innovation. We can observe that the measurements of the laser rangefinder are corrected significantly, especially for the adaptation method, what is visible as the reduced amount of the incorrect distance measurements. Hence, the reliable detection and localization of an obstacle can be achieved by the usage of the miniature laser rangefinder.

1. Introduction

Unmanned aerial vehicles (UAV) became very popular in the last decade. Improved technology increases continuously the possibilities of this kind of vehicles and makes them more available in various everyday applications. In many cases, such vehicles are able to eliminate the need for a direct human involvement. While the knowledge about controlling and designing of large vehicles with high Reynolds numbers is perfectly recognized, this seems to be totally useless for small unmanned aerial vehicles, because in their case low Reynolds numbers should be applied. Hence, the principle of changing the scale cannot be used. Small time constants of their dynamics cause a series of difficulties starting from an uncertainty in the control process and ending at disturbances in the navigational measurements. Everything together creates a real barrier for the development of fully autonomous small unmanned vehicles. Of course, this issue is continuously solved little by little, in accordance with the growth of aerospace technology.

One of the major problems, which can be found in designing of any UAV system, is the limited accuracy of the on-board measurement systems [1,3,15]. Firstly, the problem is a side effect of the miniaturization of sensors, which makes them well suited to the sizes of unmanned aerial vehicles. Secondly, these vehicles require a much better precision in the navigational measurements, just due to their small sizes. The most typical example of this problem is GPS localization that is commonly applied in UAVs. The accuracy of available small GPS receivers is inadequate for such vehicles, whose wing span is approximately one or two meters. Hence, the integration of GPS with the inertial navigation system (INS) through the Kalman filter is highly expected. Therefore, many researchers try to develop an appropriate Kalman filter as the response to this problem [1,4,10–12,14,15].

Another issue is the presence of faults of sensors or actuators, which destabilizes the vehicle's dynamics and what practically makes it difficult to control [2]. The traditional Kalman filter is unable to handle this issue as these faults are related to the change of matrices R and Q. Therefore, an adaptive Kalman filter should be developed respectively to the problem [5,15,17].

Adaptive filters become to be robust against sensor or actuator faults. We are able to find easily other measurement systems, which are also essential for UAVs, and where the Kalman filter could be applied with a good result [3,6,13]. For example, reliable distance measurements are a crucial factor in applications such as estimating local ground level (AGL) or detecting of obstacles' po-

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sitions. To achieve long-range, high-accuracy measurements, laser rangefinders are a perfect match. Unfortunately, even the use of this kind of sensor does not prevent from accidental measurement errors or random noises. This issue was revealed during the experimental research on the system of obstacle avoidance for small fixed wing UAVs, which was based on two miniature laser rangefinders [8,9]. Thus, an efficient filtering algorithm is of course necessary.

The survey is addressed to the problem of measurement errors and faults, which do not form a permanently present noise, but they are accidental, momentary incorrect values, caused by unknown internal or external disturbances. Those errors or faults have nothing in common with the uncertainty arising from the nature of a considered measurement. Most of the filtration methods will manage to remove those errors, but without no impact on the correct measurements due to changes made in the signal's spectrum. Exactly such problem was found during a research on the laser rangefinders application for the obstacle avoidance purpose. The errors found are the same as the value corresponding to the case, when the measured distance is out of range, and this should be treated as no obstacles in the vicinity. Obviously, we must eliminate these errors, without losing any information relating to the uncertainty of the flight environment. Therefore, we present design of Kalman filters, whose purpose is to reduce these random faults in the measurements made by the miniature laser rangefinder. We compare two approaches. The first uses a reference signal to estimate values of the matrices R and Q that satisfy the best correlation between the filtered signal and the reference. The second uses an adaptive technique to modify values of the matrix R, what improves the robustness of KF (the Kalman Filter) against sensor faults. In the adaptation algorithm we formulate a gain factor for the matrix R defined as the absolute value of the innovation vector. It is a completely different approach than the estimation of matrix R based on innovation sequences, which is dependent on windows sizes and does not guarantee the positive definite nature of matrix R. Our adaptation algorithm based on the innovation vector allows eliminating more random errors without distorting the correct measurements, in contrast to the first approach. This is the main contribution of our survey, which can be applied to similar issues in other measurement systems. To verify the effectiveness of the filtration of both approaches, we applied data recorded in a real flight.

2. Motivation and problem formulation

The system of obstacle avoidance for small fixed wing UAVs was designed and constructed in a separate research project. The research is described thoroughly in the following articles: [8,9]. The principal purpose of the system is to realize inter alia a special case of obstacle avoidance – the flight in urban canyons. To detect obstacles, we chose a miniature laser rangefinder (MLR100 from FLIR) (Fig. 1). The advantages of this sensor are as follows: small resolution (lower than 20 cm), high repetition rate (500 Hz), low power consumption at lower repetition rates (321 mW at 1 Hz), built-in filtering routines, and serial interface (UART). Hence, the possibilities of the sensor overcome other distance measurement techniques, such as optical flow sensors or ultrasonic sensors. The laser of MLR100 meets the 1M class of laser safety at lower operating frequencies. At higher frequencies, the class is only 3B. The spot of the laser beam is an ellipse, and the large diameter is 1 meter at a distance of 100 meters. This will most likely affect the real measurement range because the greater spot of the laser beam can be easily scattered by any heterogeneous surface. Thus, we decided to verify this issue experimentally, and we found that the maximum, achievable range is limited to 150 meters. The selected parameters of MLR100 are listed in Table 1.

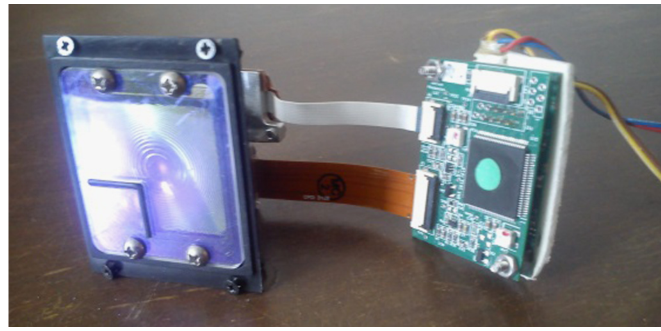

Fig. 1. MLR100 – miniature laser rangefinder (FLIR).

Table 1
MLR100 parameters.

Feature	Value
Weight	36.8 g
Power rating	$<$400 mW at 500 Hz
Size	$32 \times 38 \times 40$ mm
Pulse repetition	500 Hz
Resolution	$<$0.2 m
Range	$\sim$0.1 m to $>$100 m
Divergence angle	10×10 mrad
Output	UART
Filters	averaging and median filters

Serial interface (UART) is very useful in our case, because it makes easier to set up the communication between MLR100 and the UAV's on-board computer. Simultaneously, serial interfaces are more resistant to external electrical noises, in contrast to analogue signals. The sensor has its own microprocessor, so it is possible to modify the measurement parameters and the overall configuration via commands sent as text through serial interface. MLR100 is able to operate in two modes: continuous and single-shot mode. Moreover, the measurement result can be received in two formats: regular format and NMEA-type format. The data frame in NMEA format contains two additional characters, and it looks similar to the messages sent by any GPS receiver. Regardless of the selected format, the distances can be presented as formatted text or binary numbers. When the sensor sends the measurement result as formatted text, it is already given in meters, but the checksum is unavailable. The binary data contain three bytes, and the first two of them are the measured value expressed as a number of clock counts (Eq. (1)). The third byte is the checksum (Tab. 2). All available output formats of MLR100 are presented in Table 2.

$$D = 0.1875 \cdot I + R \tag{1}$$

where:
- I – clock counts,
- D – a range in meters,
- R – a user range offset.

To reveal the real performance of MLR100, we made test flights. We installed two of them, one for each wing of the UAV, in a way that makes possible to measure the altitude above ground level (in the obstacle avoidance system they will operate in a horizontal plane). It was a very important experiment, because it allows assessing not only the capabilities of the sensor, but also it compares the distance measurement to the barometric altitude measured by the sensor of static pressure. Data from the experiment demonstrate that the measurement of one of the sensors is unacceptable for use in the obstacle avoidance system. We can find a lot of accidental measurement errors produced by the sensor fixed to the left wing. These disturbances are visible as the values nearby zero or greater, equal to 800. The second sensor on the right wing is