MOTOR FAILURE DETECTION FOR MULTICOPTERS

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Abstract: The contribution is focused on the problem of motor failure detection for multicopters using sensors usually used for state estimation. Such an algorithm is an essential part of the safety system which would mitigate the consequences of single motor failure of multicopter. The detection algorithm is based on set of Kalman filters for state estimation. Each Kalman filter has different prediction model (each models a different motor failure). The magnitude of corrections applied in the update step of Kalman filter is used as a measure of model correspondence. The algorithm was tested on simulated data for two different scenarios and shows sufficient performance in both cases.

Keywords: Multicopter, Safety System, Failure Detection, Kalman Filter

1. INTRODUCTION

Multicopter is very popular aerial platform which is used or planned to be used in many different fields. It consists of even number of motors (at least four) with propellers which produce thrust for hovering. Unbalancing the individual thrusts allows for rotational movement of multicopter. The typical multicopter system and list of its components are on Figure 1. Some of the current or planned applications of multicopters require higher level of safety because of the price of the system or because of the usage near people.

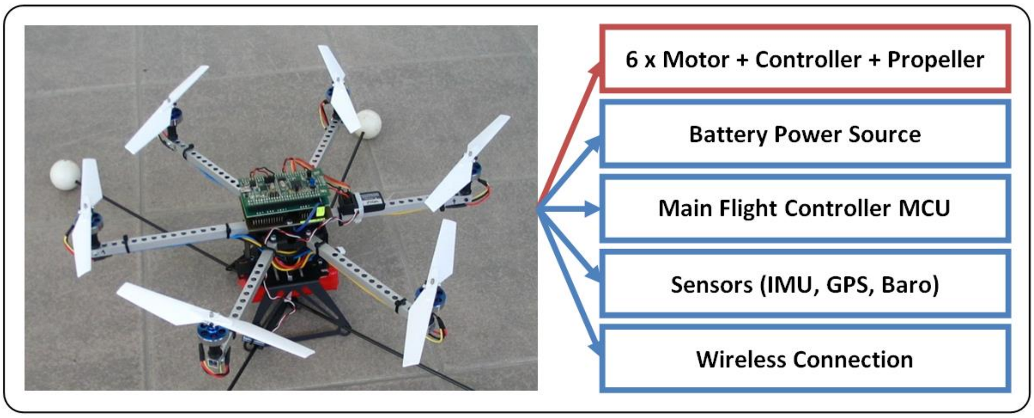

Figure 1 Multicopter with six propellers; list of individual components.

With regards to the components onboard of the multicopter, these are the one which can commonly fail with fatal consequences:

- Battery power source failure (Battery failure, connection failure)
- Wireless connection failure (interference, inappropriate distance) – only in a case of non-autonomous operation,

- Failure of one or more thrust units (mechanical breakage of propeller, motor controller malfunction, motor failure).

Third mentioned failure can be mitigated with advanced control techniques. In this situation the failed motor is excluded from control and the priority is to land as soon as possible in horizontal orientation. This is usually possible only in fast rotation around vertical axis.

To apply such advanced control algorithm, the failure of motor must be quickly and accurately detected. This contribution is focused just on this detection of failed motor on a multicopter.

2. THRUST UNIT FAILURE AND ITS DETECTION

Thrust of individual propellers of multicopter is essential for the normal operation. It provides enough lift to be a counterpart to gravitational force and the small changes in individual thrusts allows for the rotational movement. For example the relation between total thrust and torque vector and the individual thrusts for hexacopter (multicopter with six propellers) is described using this equation:

$$\begin{bmatrix} F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} -1 & -1 & -1 & -1 & -1 & -1 \\ 0 & -L\frac{\sqrt{3}}{2} & -L\frac{\sqrt{3}}{2} & 0 & L\frac{\sqrt{3}}{2} & L\frac{\sqrt{3}}{2} \\ L & \frac{L}{2} & -\frac{L}{2} & -L & -\frac{L}{2} & \frac{L}{2} \\ c_R & -c_R & c_R & -c_R & c_R & -c_R \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} \tag{1}$$

where:

- L is the distance of the propellers from the center of gravity of the hexacopter
- T_i is the thrust of i-th propeller
- c_r is the reactive torque linear coefficient
- M_i are the components of torque vector expressed in the coordinate frame connected with multicopter
- F_z is the total thrust acting along the z-axis connected with multicopter

Using Moore-Penrose pseudo-inverse, inverse relation can be constructed which is used to compute the values of individual thrusts based on the desired total thrust and torque vector. Theoretically, (with unlimited thrust values) for any torque vector the individual thrusts can be computed.

The failure of any of the six thrusts would cause that the torque and thrust would be different than the ones computed using the relation (1). The typical control algorithm for stabilization assumes that torque vector with arbitrary direction can be generated. This is, however, not true in the case of one or more thrusts failures. This is the main reason why this event causes destabilization of multicopter and usually a crash. Any advanced control algorithms which would mitigate the destabilization and allows for safer landing needs a trusted information that the motor failure event occur and which of the total number of thrust units fails. The requirements for such a failure detection system are:

- quick detection (less than 0.5 s) after the failure
- lowest possible number of undetected failures
- lowest possible number of false detections

The failure detection system can be based on many different principles. First intuitive approach is to use speed measurements of individual propellers. Speed measurements can be realized using infrared gate, hall sensor etc. This approach would certainly fulfill all the above mentioned requirements. The drawback is the installing of new sensors which will increase the weight of the multicopter and on some multicopters this extension would be hard or impossible to implement.

Another approach is to process the sensors and data already available on almost every multicopter in order to detect motor failure. Almost each multicopter is equipped with sensors for attitude and heading estimation which is the key knowledge for proper stabilization. The sensors used for this are the three axis gyroscope, the accelerometer and the magnetometer. Additionally the multicopter must be equipped with microcontroller which computes all the algorithms and iteratively generates control signals for individual motors. The digital value, which usually corresponds to electric power driving the motor, is assumed as a control signal for a motor. The control signals shows to be very important information with regards to detecting motor failure.

Implementing of such a new safety algorithm to an existing multicopter would change only to an upgrade of the firmware of microcontroller. This is considered as a huge advantage.

3. FAILURE DETECTION ALGORITHM

The proposed failure detection algorithm is based on the extended Kalman filter which processes the data from gyroscope, accelerometer, magnetometer and the motor control signals in order to estimate the state of the multicopter. Deep description of the above mentioned Kalman filter is out of scope of this contribution. Only the key facts about the Kalman filter will be mentioned.

3.1. KALMAN FILTER

Kalman filter in general is a system state estimator developed by Kalman in 1960 [1]. The original version was designed for linear systems only. But the extended Kalman filter and later many other modification where subsequently developed for use with non-linear systems [2]. The important thing about the Kalman filter with respect to this work is that the one iteration of the algorithm consists of two steps, the prediction and the correction, this fact is illustrated on Figure 2.

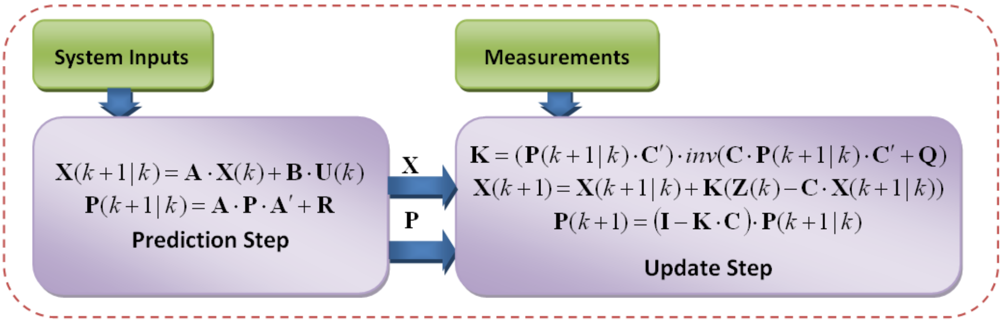

Figure 2 Prediction and update step of Kalman filter.

Generally, in prediction step, the state is predicted based on the previous state estimate and by the model driven by system inputs. In update step, the corrections to the predicted state are applied based on the measurements.

3.2. KALMAN FILTER FOR STATE ESTIMATION OF MULTICOPTER

The Kalman filter for state estimation of multicopter used for the motor failure detection is based on the works [3], [4]. Because the system and measurement model contain nonlinear equation, the extended Kalman filter has to be used. In prediction step, the state is computed based on the previous state and on the full model of multicopter driven by motor control signals. In update step the corrections are computed and then applied to the predicted state based on the measurements (gyroscope, accelerometer and magnetometer). The filter has 19 states in total (attitude quaternion, angular rate, velocity, gyroscope bias, accelerometer bias and specific force).

3.3. ALGORITHM FOR DETECTION OF FAILURE

The detection algorithm use the fact, that if the prediction model is wrong or non precise, the corrections applied in the update step to the predicted state will be large in each iteration. Further, if more Kalman filters, each with different prediction model, are computed simultaneously, the best model can be identified by comparing the magnitude of corrections applied in the update step (the measurements are the same for each Kalman filter). The one with the lowest magnitude is considered as a best model.

This principle is used in the detection of failed motor. According to the number of rotors of the multicopter the main full model and then models with one failed motor (each model with different motor) are used in separate Kalman filters. In each iteration the previous state from the best model is used for every model in the new prediction step. In update step, the corrections for angular rate are compared. Based on this comparison, a conclusion if any motor is failed is made. On the Figure 3, there is a plot of magnitudes of corrections to angular rate for 7 different models (the case for hexacopter, one main model and six with motor failure) during a simulated hover of the hexacopter (no failure). The magnitude is computed as square root of sum of squares of individual components of corrections.

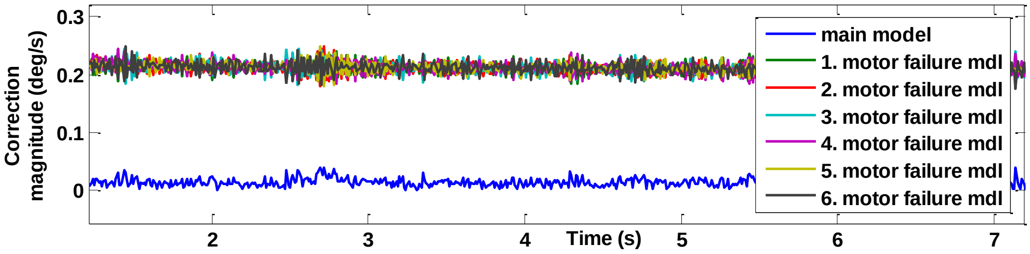

Figure 3 Plot of magnitudes of angular rate corrections for different models for simulated hover of hexacopter (no failure).

To fulfill the requirement for the lowest number of false detection of motor failure, the detection is reported only in the case that the model with failed motor is best (lowest magnitude of angular rate corrections) for a minimum time of 10 ms. This value is a trade-off between the requirement for quick detection and the requirement for low number of false detections.

4. RESULTS OF SIMULATIONS

The algorithm for the detection of motor failure was tested on two simulated scenarios. The first was the failure of 3rd motor during a hover (Figure 4). The second one was the failure of 6th motor during a waypoint navigation mission (Figure 5). The red vertical line indicates the time of failure and the green line indicates the time of proper detection.

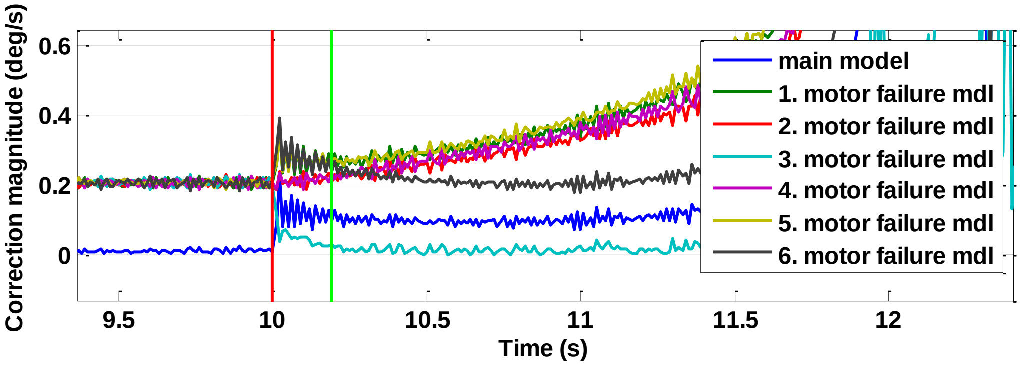

Figure 4 Magnitude plot for angular rate corrections and output of detection algorithm for motor failure during hover.

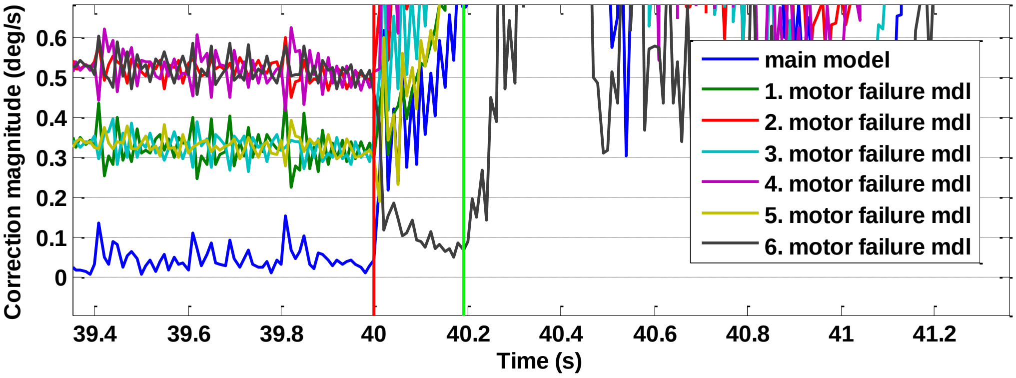

Figure 5 Magnitude plot for angular rate corrections and output of detection algorithm for motor failure during waypoint mission.

5. CONCLUSION

In the presented article the detection algorithm based on multiple Kalman filters with different prediction models was presented. The model correspondence is represented by magnitude of corrections applied in the update step of the Kalman filter. The Figure 4 and Figure 5 show sufficient performance of the algorithms on two simulated failure scenarios. The performance of presented algorithm relies on the good mathematical model of the real multicopter. The required accuracy of the model and its parameters will be subject of the further analysis. The future work will also be focused on the evaluation of the algorithm on a real data and on the real-time implementation to multicopter controller.

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REFERENCES

[1] Kalman, R. E. (1960). A New Approach to Linear Filtering and Prediction Problems. *Transactions of the ASME--Journal of Basic Engineering*, Vol. 82. p. 35-45.

[2] Marins, J. L., Bachmann, E. R., McGhee, R. B., & Zyda, M. J. (2003). An extended Kalman filter for quaternion-based orientation estimation using MARG sensors. *Proceedings 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems. Expanding the Societal Role of Robotics in the the Next Millennium (Cat. No.01CH37180)*, *4*, 2003–2011.

[3] Leishman, R., Macdonald, J. (2011): Utilizing an Improved Rotorcraft Dynamic Model in State Estimation. Proceedings of 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, 5173-5178.

[4] Macdonald, J., Leishman, R., Beard, R., McLain, T. (2013): Analysis of an Improved IMU-Based Observer for Multirotor Helicopters. *Journal of Intelligent and Robotic Systems*.