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A correction in feedback loop applied to two-axis gimbal stabilization

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Abstract. A two-axis gimbal system can be used for stabilizing platform equipped with observation system like cameras or different measurement units. The most important advantageous of using a gimbal stabilization is a possibility to provide not disturbed information or data from a measurement unit. This disturbance can proceed from external working conditions. The described stabilization algorithm of a gimbal system bases on a regulator with a feedback loop. Steering parameters are calculated from quaternion transformation angular velocities received from gyroscopes. This data are fed into the input of Proportional Integral Derivative (PID) controller. Their input signal is compared with earned value in the feedback loop. The paper presents the way of increasing the position's accuracy by getting it in the feedback loop. The data fusion from a positioning sensor and a gyroscope results in much better accuracy of stabilization.

Key words: gimbal stabilization, feedback loop, Kalman filter.

1. Introduction

The paper presents the way of increasing the position's accuracy by getting it in the feedback loop. This corrects also the accuracy of stabilization. The data fusion from a positioning sensor and a gyroscope results in much better accuracy of stabilization. The solution was applied where size, weight and power consumption are severely constrained, such as in the cramped space of small unmanned aerial vehicles (UAV), video gimbals, and man portable devices. Mainly it can be applied to UAV mini and micro class.

2. Feedback control loop

Using a feedback loop an accuracy of value is important. For gimbal stabilization, where weight, power consumption and size are restricted, there occurs a very common problem with the resolution of a position sensor. That parameter is responsible for accuracy of gimbal stabilization. The capability of gimbal to compensate for vibration is typically specified by minimum angular movement that can be mechanically stabilized. It is measured in micro-radians. High performance gimbals can provide stabilization as good as 10 micro-radians, however, this kind of optical system is very expensive. There are known more affordable gimbal systems. They typically feature a mechanical stabilization approximately 100 micro-radians [1, 2].

The presented algorithm of correction improves an accuracy of stabilization where it cannot be achieved by the applied sensors. The algorithm of a gyro stabilization system is used as in the diagram (Fig. 1).

The algorithm is implemented with a small weight gimbal (up to 2 kg). In that kind of environment the size and weight are restricted. So that, the largest resolution of encoders, which can be used is 1024 lines per revolution. Feedback velocity ω measured in a rate per minutes can be calculated by microcontroller using Eq. (1) [3, 4]:

$$\omega = \frac{60f}{N}, \tag{1}$$

where f is a frequency of encoders' pulses and N is a number of lines per revolution. Counting angular velocity measured by an encoder with that resolution, mounted on a DC motor equals approximately 2 deg/sec. Diagrams show the angular velocity measured by optical encoders and gyroscopes.

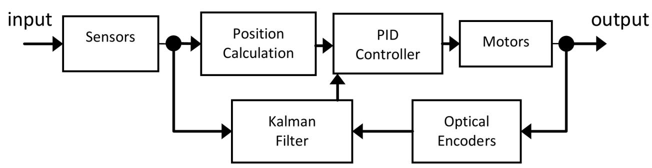

Fig. 1. The stabilization algorithm with feedback loop

Figure 2 shows two angular velocities – measured by gyroscopes and encoder – in the same axis of gimbal. Because a measurement is done statically, Fig. 2 shows just a drift of gyroscope and a velocity of encoder equals zero. There is a lot of methods enabling drift compensation [5]. Figure 3 shows angular velocities measured by a gyroscope and calculated from frequency of encoder signal using Eq. (1). A rotating gimbal in one axis with a low frequency gives us an unacceptable resolution of angular velocity. As a result no better than the 1 mili-radians accuracy of stabilization can be achieved [6].

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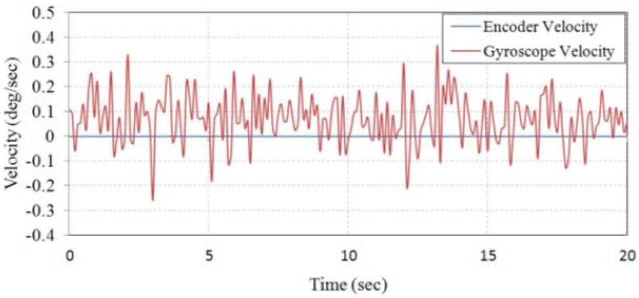

Fig. 2. The angular velocity measured statically

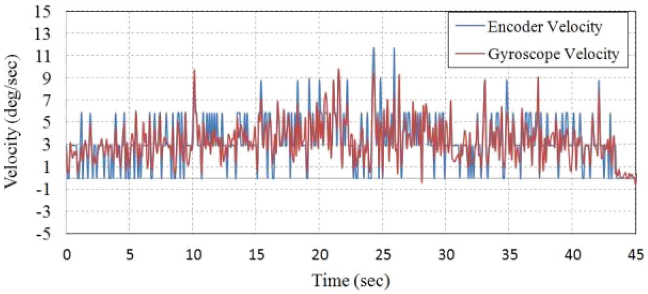

Fig. 3. The angular velocity measured dynamically

3. Data fusion of velocities

The presented algorithm tends to improve the accuracy of gimbal stabilization. Therefore, a data fusion of two angular velocities is made [7]. The first is measured by encoders and the second comes from the gyroscope Micro Electro-Mechanical Sensor (MEMS).

The complementary features of the encoder and the gyroscope are fully exploited to a correction in a feedback loop to stabilization [8]. The block diagram is shown in Fig. 4.

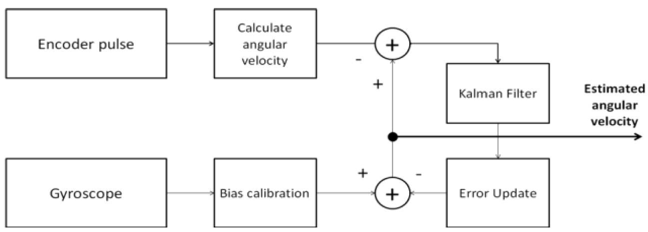

Fig. 4. Angular velocity composed of optical encoder and gyroscope

The input data of the system are angular velocities from gyroscopes (which are oriented parallel to the axes of gimbals) and optical encoders. The encoder's and gyro's measurements are jointly processed using a complementary Kalman Filter (KF) working in a closed-loop configuration [9]. The results of estimation are subsequently used to calculate the estimated angular velocity in feedback in order to make correction in PID controller in every stabilization axis.

The measurement vector of the Kalman Filter is formed as a difference between the encoder and the gyroscope velocities. As they both are composed of true angular velocities and respective errors, the difference between encoder and gyroscope consists in a combination of errors. The Kalman Filter estimates a residual velocity of encoder and provides it to the input of the error updater. The error updates, accumulates it and calculates the total estimated velocity error, which is subsequently subtracted from the encoder velocity, providing estimated velocities [9].

The Kalman Filter in the algorithm is based on a discrete model of an algebraic equation of observation and a difference equation of dynamics [9]:

$$x(k+1) = \mathbf{\Phi}(k+1,k)x(k) + w(k) - \delta\hat{x}(k), \tag{2}$$

$$z(k) = \mathbf{H}(k)x(k) + v(k), \tag{3}$$

where x is a state vector, w is a vector of random process disturbances, $\delta\hat{x}$ is a vector of deterministic inputs, $\mathbf{\Phi}$ is a state transition matrix, z is a measurement vector, v is a vector of measurement noises, $\mathbf{H}$ is an observation (measurement) matrix. The state transition matrix $\mathbf{\Phi}$ has the following form:

$$\mathbf{\Phi} = \begin{bmatrix} 1 & \Delta\psi_{\mathrm{g}} & T \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{4}$$

where $\Delta\psi_{\mathrm{g}}$ is representing a change of angular velocity between kT and $(k-1)T$, from gyroscope. The measurement matrix $\mathbf{H}$ can also be determined as:

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}. \tag{5}$$

The Kalman Filter consists of initialization and steps of prediction and correction.

Prediction is as follow [9]:

$$\hat{\mathbf{x}}(k+1\,|k) = \mathbf{\Phi}\cdot\hat{\mathbf{x}}(k\,|k) - \delta\hat{\mathbf{x}}(k), \tag{6}$$

$$\mathbf{P}(k+1\,|k) = \mathbf{\Phi}\cdot\mathbf{P}(k\,|k)\cdot\mathbf{\Phi}^{\mathrm{T}} + \mathbf{Q}, \tag{7}$$

where $\mathbf{P}(k+1|k)$ is a covariance matrix of prediction errors, $\mathbf{Q}$ is a covariance matrix of random process disturbances.

$$\begin{aligned}\mathbf{K}(k+1) &= \mathbf{P}(k+1\,|k)\cdot\mathbf{H}^{\mathrm{T}} \\ &\cdot\left[\mathbf{H}\cdot\mathbf{P}(k+1\,|k)\cdot\mathbf{H}^{\mathrm{T}} + \mathbf{R}\right]^{-1},\end{aligned} \tag{8}$$

where $\mathbf{K}(k+1)$ is a Kalman gains matrix and $\mathbf{R}$ is a covariance matrix.

Correction is as follow [9]:

$$\begin{aligned}\hat{\mathbf{x}}(k+1\,|k+1) &= \hat{\mathbf{x}}(k+1\,|k) \\ &+\mathbf{K}(k+1)\left[\mathbf{z}(k+1) - \mathbf{H}\cdot\hat{\mathbf{x}}(k+1\,|k)\right],\end{aligned} \tag{9}$$

$$\begin{aligned}&\mathbf{P}(k+1\,|k+1) \\ &= [\mathbf{I} - \mathbf{K}(k+1)\cdot\mathbf{H}]\cdot\mathbf{P}(k+1\,|k) \\ &\cdot[\mathbf{I} - \mathbf{K}(k+1)\cdot\mathbf{H}]^{\mathrm{T}} + \mathbf{K}(k+1)\cdot\mathbf{R}\cdot\mathbf{K}^{\mathrm{T}}(k+1),\end{aligned} \tag{10}$$

where $\hat{\mathbf{x}}(k+1\,|k+1)$ is a filtered state vector at a time $(k+1)T$, $\mathbf{P}(k+1\,|k+1)$ is a covariance matrix of filtration errors.

Figures below present the result of the filtering depending on parameters: measurement covariance $\mathbf{R}$ and process covariance $\mathbf{Q}$. Figures show influence angular velocities of gyroscope on the estimation of the system's angular velocity.

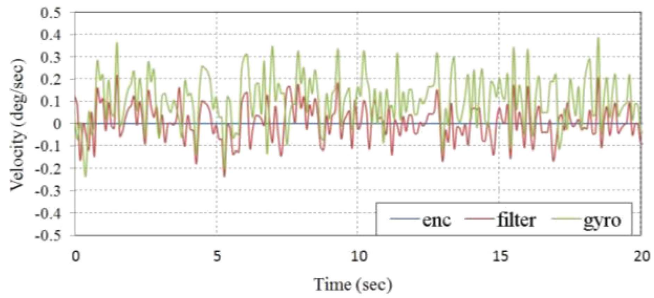

Fig. 5. Estimated velocities for filter parameters $\mathbf{R} = 0.1$, $\mathbf{Q} = 0.01$

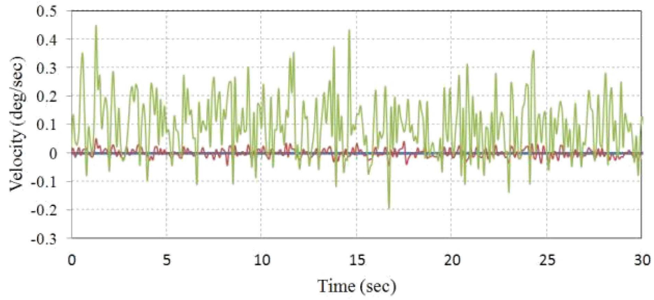

Fig. 6. Estimated velocities for filter parameters $\mathbf{R} = 0.1$, $\mathbf{Q} = 0.5$

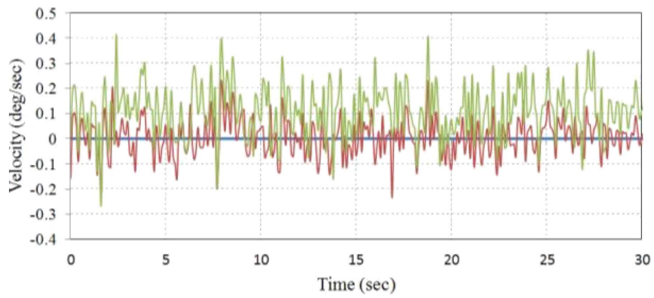

Fig. 7. Estimated velocities for filter parameters $\mathbf{R} = 1$, $\mathbf{Q} = 0.1$

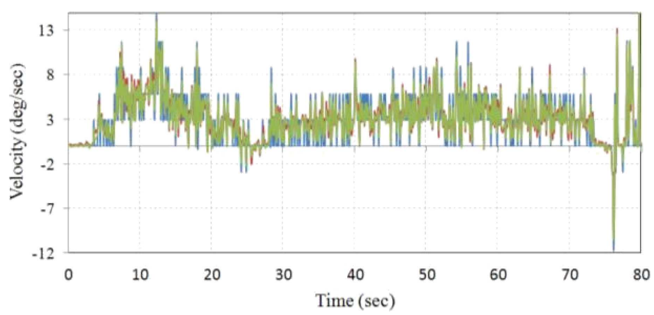

Fig. 8. Estimated velocities during movement

4. Results discussion

To compare the accuracy of stabilization the root mean squared (RMS) errors are determined by the following formula:

$$RMS = \sqrt{\frac{1}{k}\sum_{i}^{k}\delta\upsilon_i^2}, \tag{11}$$

where k represents the number of samples and $\delta\upsilon_i$ – error of gimbal position.

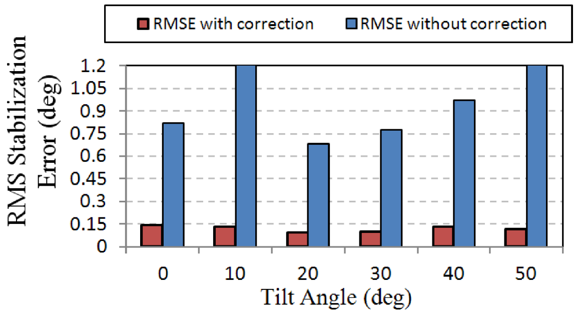

Fig. 9. Root Mean Squared Errors in stabilization

The presented algorithm works in real-time in the gyroscope stabilization gimbal. The RMSE value shows that data fusion increase accuracy of stability. Some of the value without correction in several slopes get even 1.2 deg. After implementing the presented algorithm this value decreases 10 times.

5. Conclusions

The results of research enabled to draw a conclusion that presented corrections are more accurate than a value measured only by one sensor. Showed data fusion improved accuracy of an angular velocity given by optical encoders. This fusion also eliminated the influence of bias from gyroscopes on the estimated angular velocity. The presented solution was adjusted to work in real-time and to correct angular velocity while the two axis gimbal system is being stabilized simultaneously.

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