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Optical flow-aided navigation for UAV: A novel information fusion of integrated MEMS navigation system

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ABSTRACT

Due to low precision and weak stability, MEMS micro inertial navigation system installed in MAV cannot work alone and achieve high-performance navigation for a long time. In order to improve MEMS performance, it is proposed to fuse MEMS-IMU information with optical flow, and correct MEMS attitude when it is diverged. Then, image coordinate of optical flow is proposed to be firstly transformed to body one for better vehicle attitude calculation. The Allan variances of MEMS sensors are used in KF filter to replace the regular white noise. The algorithm is finally testified by simulation results, which is shown that vehicle attitude modified by combining with optical flow is of good performance, with smaller error, slow divergence and better robustness.

1. Introduction

Featured by small volume, low cost and power, and easily-portable, MEMS inertial sensors are widely concerned and applied in many areas like navigation research, environmental monitoring, military and so on. However, MEMS inertial sensor is originally low-precision and impressionable. It sometimes goes against accurate navigation or even become seriously unstable when working for a period of time, more worse the initial alignment and calibration are invalid.

Optical flow is paid extensive attention and used for a variety of purposes, such as motion detection and estimation, collision detection and avoidance, shape reconstruction and object segmentation, etc. [1–6]. Specifically, dynamic variation of pixel frame received from optical flow is captured and used to calculate vehicle position, further to reckon vehicle attitude.

So, it is proposed to combine MEMS-IMU with optical flow, and correct MEMS attitude when it is diverged. Image coordinate of optical flow is proposed to be firstly transformed to body one before calculating vehicle attitude. KF filter is used, and the Allan variances of MEMS sensors are used to replace the regular white noise. Simulation results show that vehicle attitude modified by combining with optical flow is of good performance, with smaller error, slow divergence and better robustness.

2. Methodology

According to Allan variance principle, there are five basic noise terms mostly related with MEMS stochastic errors, such as angle random walk, rate random walk, bias instability, quantization noise, and rate ramp. The main source and physical process are represented below.

- Angle random walk

Gyro angle random walk is induced by high frequency signal with much shorter period than the sample time. These noise is characterized by white noise spectrum on the gyro output, most of which can be eliminated through compensation.

The associated rate noise PSD is represented by:

$$S_{\Omega}(f) = N^2 \tag{1}$$

where N is the angle random walk coefficient.

The corresponding variance is:

$$\sigma^2(\tau) = \frac{N^2}{\tau} \tag{2}$$

According to formula (2), it indicates that a log–log value of $\sigma(\tau)$ versus T has a slope of $-1/2$.

- Rate random walk

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This is a random process of uncertain origin, possibly a limiting case of an exponentially correlated noise with a very long correlation time. The rate PSD associated with this noise is:

$$S_\Omega(f) = \left(\frac{K}{2\pi}\right)^2 \frac{1}{f^2} \tag{3}$$

where K is the rate random walk coefficient.

The corresponding variance is:

$$\sigma^2(\tau) = \frac{K^2\tau}{3} \tag{4}$$

According to formula (4), it indicates that a log–log value of $\sigma(\tau)$ versus T has a slope of $-1/2$.

- Bias instability

The origin of this noise is the electronics or the components that are susceptible to random flickering. Because of its low-frequency nature, it is shown as the bias fluctuations in the data. The rate PSD associated with this noise is:

$$S_\Omega(f) = \begin{cases} \left(\frac{B^2}{2\pi}\right)\frac{1}{f} & f \le f_0 \\ 0 & f > f_0 \end{cases} \tag{5}$$

where B is the bias instability coefficient; f_0 is the cutoff frequency.

The corresponding variance is:

$$\sigma^2(\tau) = \frac{2B^2}{\pi}\left[\ln 2 - \frac{\sin^3 x}{2x^2}(\sin x + 4x\cos x) + Ci(2x) - Ci(4x)\right] \tag{6}$$

where x is $\pi f_0 \tau$; Ci is the cosine-integral function.

A log–log plot of formula (6) shows that the Allan variance for bias instability reaches a plateau for τ much longer than the inverse cutoff frequency. Thus, the flat region of the plot can be examined to estimate the limit of the bias instability.

- Quantization noise

This quantization noise is caused by the small differences between the actual amplitudes of the points being sampled and the bit resolution of the analog-to-digital converter.

For a gyro output, the angle PSD for such a process is

$$S_\theta(f) = \tau Q^2\left(\frac{\sin^2(\pi f\tau)}{(\pi f\tau)^2}\right) \approx \tau Q^2 \quad f < \frac{1}{2\tau} \tag{7}$$

where Q is the quantization noise coefficient.

The rate PSD is related to the angle PSD through the equation:

$$S_\Omega(2\pi f) = (2\pi f)^2 S_\theta(2\pi f) \tag{8}$$

and is

$$S_\Omega(f) = \frac{4Q^2}{\tau}\sin^2(\pi f\tau) \approx 2(\pi f)^2\tau Q^2 \quad f < \frac{1}{2\tau} \tag{9}$$

The corresponding variance is:

$$\sigma^2(\tau) = \frac{3Q^2}{\tau^2} \tag{10}$$

This indicates that the quantization noise is represented by a slope of -1 in a log–log value of $\sigma(\tau)$ versus τ.

- Rate ramp

It could be due to a very small acceleration of the platform in the same direction and persisting over a long period of time. The gyro input is given by:

$$\Omega = Rt \tag{11}$$

where R is the rate ramp coefficient.

The variance is obtained as:

$$\sigma^2(\tau) = \frac{R^2\tau^2}{2} \tag{12}$$

This indicates that the rate ramp noise has a slope of +1 in the log–log value of $\sigma(\tau)$ versus τ.

The rate PSD associated with this noise is:

$$S_\Omega(f) = \frac{R^2}{(2\pi f)^3} \tag{13}$$

It should be aware that there may be a flicker acceleration noise with $1/f_3$ PSD that leads to the same Allan variance τ dependence.

3. Orientation from optical flow

In analysis, the world and camera coordinate systems are assumed to be right-hand rectangular coordinate systems. It is also assumed that the world points have already been converted into the camera coordinate system. So, in two images, a point $p_1 = (x_1, y_1, z_1)$ in one image corresponds to another point $p_2 = (x_2, y_2, z_2)$ in the other image, the relation between p_1 and p_2 is:

$$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = R\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} + t = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \tag{14}$$

where R represents rotation and t represents translation[7,8].

According to Euler angle method, orientation from motion coordinate to reference coordinate can be calculated by three different angles successively rotating the reference coordinate. If the three angles as set as γ, θ and φ (roll, pitch and head), each around the x, y and z axes, then the rotation matrix R can be rewritten as follows.

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & \sin\gamma \\ 0 & -\sin\gamma & \cos\gamma \end{bmatrix}\begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}\begin{bmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{15}$$

Simplifying the above equation,

$$R = \begin{bmatrix} \cos\gamma\cos\varphi + \sin\gamma\sin\theta\sin\varphi & -\cos\gamma\sin\varphi + \sin\gamma\sin\theta\sin\varphi & -\sin\gamma\cos\theta \\ \cos\theta\sin\varphi & \cos\theta\cos\varphi & \sin\theta \\ \sin\gamma\cos\varphi - \cos\gamma\sin\theta\sin\varphi & -\sin\gamma\sin\varphi - \cos\gamma\sin\theta\cos\varphi & \cos\gamma\cos\theta \end{bmatrix} \tag{16}$$

As the frame sampling period is quite short, it can be assumed that these rotation angular deviations are small. So, the approximations are set.

The principle of camera perspective projection is shown in Fig. 1.

The image coordinates (u_1, v_1) of the point $p_1(x_1, y_1, z_1)$ are given by

$$u_1 = f\frac{x_1}{z_1}, v_1 = f\frac{y_1}{z_1} \tag{17}$$