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Adaptive complementary filter using fuzzy logic and simultaneous perturbation stochastic approximation algorithm

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ABSTRACT

This paper addresses the problem of attitude estimation using low cost, small-sized inertial sensors under dynamic maneuvers. An adaptive complementary filter with fuzzy logic and simultaneous perturbation stochastic approximation (SPSA) algorithm is proposed. By recognizing the situation of dynamic condition via fuzzy logic, the cut-off frequency of the complementary filter is determined adaptively under varying vehicle dynamics. Also, the SPSA algorithm is used to tune the parameters of fuzzy system. Simulation results based on the test data show that the proposed SPSA-based fuzzy complementary filter exhibits a significant performance improvement for attitude estimation during dynamic maneuvers.

1. Introduction

Attitude estimation is required in many different applications. Currently, such systems are typically realized using mechanical, fiber-optic or ring laser sensors. Though these sensors are capable of providing the high performance required for attitude estimation systems, they are too expensive for wider applications [1]. With the recent electro-mechanical development, more and more low-cost micro electro-mechanical system (MEMS) sensors with the advantages of small size, light weight and low-power consumption have been applied to the commercial market, such as antenna stabilization, walking robots and unmanned vehicles [2,3].

Due to MEMS gyroscope suffers from high drift and noise, attitude calculated from gyroscope will deteriorate over time. On the other hand, attitude derived from accelerometer will not diverge with time in the absence of motion acceleration. Thus, accelerometer can be used as an aiding sensor for correcting the drift of the gyroscope [4]. Traditionally, fusion algorithms such as the extended Kalman filter (EKF) [5,6] and complementary filter (CF) [7,8] are widely implemented to integrate these information sources. However, accelerometer cannot clearly distinguish inclination and acceleration. When the system has maneuver acceleration, attitude estimation based on these methods will be less accurate [9].

To overcome this problem, it is feasible to remove non-gravitational acceleration from accelerometer output with the aiding of GPS velocity information [10]. By removing the GPS-derived acceleration from the specific force sensed by the accelerometer, attitude can be determined by relating the body orientation to the gravity vector. But this method is not available during GPS outages. Another alternative fusion scheme based on switch criteria [11–13] is developed. It combines gyroscope and accelerometer measurements in low acceleration state, and adjusts parameters to rely mostly on the gyroscope outputs for dynamic conditions. However, this method should build up a detection process for the existence of motion acceleration on the basis of normalized acceleration vector, which may be invalid in low external acceleration due to the noise of accelerometer. More recently, adaptive system with fuzzy logic has attracted attention as a promising way to raise the accuracy in high dynamic maneuvers

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[14–16]. A fuzzy system has a characteristic to represent human knowledge or experiences as fuzzy rules, which can be used to identify the dynamic condition. However, the performance of a fuzzy system depends on its control rules and membership functions. Hence, it is important to tune the appropriate parameters for the fuzzy system.

In this paper, an adaptive complementary filter is proposed using fuzzy logic and simultaneous perturbation stochastic approximation (SPSA). The fuzzy logic is used to automatically adjust the weighting factor for cut-off frequency according to dynamic states. With this filtering structure, the SPSA algorithm is to find the optimal scaling parameters and position of the membership function for the fuzzy system.

The rest of this paper is organized as follows. Section 2 gives a brief description of the attitude determination from inertial sensors. In Section 3, a complementary filter based on fuzzy logic is constructed, and the parameters of the fuzzy system are tuned by SPSA algorithm. In Section 4, simulations are provided to demonstrate the detailed implementation procedures and the validity of the proposed approach. Finally, Section 5 presents a brief conclusion.

2. Attitude determination from inertial sensors

In this paper, the navigation frame and the body frame are used as the reference and moving frames, respectively. The navigation frame is called North-East-Down (NED) frame whose axes are aligned to the local north (x), east (y) and down (z), respectively. The inertial measurement unit (IMU) is aligned with the body frame consisting of three orthogonal axes where x is in the direction of forward motion of the vehicle, z is in the down direction, and y is in the direction of transverse motion of the vehicle. The transformation between the navigation frame and the body frame can be accomplished by a sequence of elementary rotations about the Euler angles.

2.1. Attitude determination based on gyroscope

The angular velocities of the vehicle are typically measured by gyroscopes fixed to the body axis. Then the relationship between Euler rates and gyroscope measurements can be determined using the following equation:

$$\begin{bmatrix}\dot\phi\\ \dot\theta\\ \dot\psi\end{bmatrix} = \begin{bmatrix}1 & \sin\phi\tan\theta & \cos\phi\tan\theta\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta\end{bmatrix}\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix} \tag{1}$$

where ω_i represents the angular rate of the i axis in the body frame. ϕ, θ and ψ are three Euler angles, which represent the roll, pitch and yaw, respectively. The Euler angles can be obtained by directly integration of Eq. (1), given a known initial condition.

2.2. Attitude determination based on accelerometer

Accelerometer measures the absolute acceleration with respect to an inertial frame. Thus, the total acceleration caused by the specific force impacting on an accelerometer can be formulated as [15]:

$$\mathbf{f} = \dot{\mathbf{v}}^b + \boldsymbol{\omega}\times\mathbf{v}^\mathbf{b} - \mathbf{g}^\mathbf{b} = \begin{bmatrix}\dot u - \omega_z v + \omega_y w\\ \dot v + \omega_z u - \omega_x w\\ \dot w - \omega_y u + \omega_x v\end{bmatrix} + \begin{bmatrix} g\sin\theta\\ -g\sin\phi\cos\theta\\ -g\cos\phi\cos\theta\end{bmatrix} \tag{2}$$

where $\mathbf{v^b} = [u, v, w]^T$ is translational velocity vector, $\boldsymbol{\omega}$ denotes the gyroscope outputs and $\mathbf{g^b}$ the gravitational acceleration relative to the body frame, g is the local gravitational constant. The velocity v and w is small for vehicle, the main disturbance for maneuvering vehicle are longitudinal acceleration $\dot u$ and centripetal acceleration.

If we ignore disturbances and assure IMU is in steady state, the accelerometer can serve as an inclinometer to measure the roll and pitch angles.

$$\mathbf{f} = \begin{bmatrix} f_x\\ f_y\\ f_z\end{bmatrix} \approx -g\begin{bmatrix} -\sin\theta\\ \sin\phi\cos\theta\\ \cos\phi\cos\theta\end{bmatrix} \tag{3}$$

where f_x, f_y and f_z are the components of the acceleration measured by accelerometers in the body coordinate frame. Under this assumption, the tilt angles can be estimated by the following equations:

$$\theta_a = \arcsin\left(\frac{f_x}{g}\right), \quad \phi_a = \arctan\left(\frac{f_y}{f_z}\right) \tag{4}$$

where θ_a and ϕ_a are pitch and roll angle estimated from the accelerometer outputs, respectively.

3. Adaptive complementary filter

To make the filter more robust to maneuvering acceleration disturbances, an adaptive complementary filter augmented by a fuzzy logic is proposed in this paper. The fuzzy logic is designed to identify the dynamics of the vehicle and change the parameters of filter. For choosing the most suitable membership functions of the fuzzy rules, the fuzzy parameters are optimized by SPSA algorithm. In this way, the complementary filter can adjust adaptively depending on the dynamic states of the vehicle.

3.1. Complementary filter

The high frequency response of the gyroscope is reliable, but its low frequency response is poor due to the drift. On the contrary, the accelerometer is drift-free, but it may be contaminated by the vibrations which are generally of high frequency. In short, the measurements of accelerometer and gyroscope have contrary characteristics that are suitable to combine them by a complementary filter [17].

The block diagram of the conventional complementary filter is depicted in Fig. 1. The gyroscope angular rates are transformed from the angular rates of body frame to Euler rates $\dot\phi_g$ by the Eq. (1). ϕ_a is directly calculated from the accelerometer outputs by the Eq. (4). The filter is to compare attitude angle from the integration of the gyroscope with the attitude angle from the accelerometers.