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Fuzzy adaptive integration scheme for low-cost SINS/GPS navigation system

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Due to weak stand-alone accuracy as well as poor run-to-run stability of micro-electro mechanical system (MEMS)-based inertial sensors, special approaches are required to integrate low-cost strap-down inertial navigation system (SINS) with global positioning system (GPS), particularly in long-term applications. This paper aims to enhance long-term performance of conventional SINS/GPS navigation systems using a fuzzy adaptive integration scheme. The main concept behind the proposed adaptive integration is the good performance of attitude-heading reference system (AHRS) in low-accelerated motions and its degradation in maneuvered or accelerated motions. Depending on vehicle maneuvers, gravity-based attitude angles can be intelligently utilized to improve orientation estimation in the SINS. Knowledge-based fuzzy inference system is developed for decision-making between the AHRS and the SINS according to vehicle maneuvering conditions. Inertial measurements are the main input data of the fuzzy system to determine the maneuvering level during the vehicle motions. Accordingly, appropriate weighting coefficients are produced to combine the SINS/GPS and the AHRS, efficiently. The assessment of the proposed integrated navigation system is conducted via real data in airborne tests.

1. Introduction

Advances in micro-electro mechanical system (MEMS) technologies have led to significant developments in low-cost strap-down inertial navigation systems (SINSs). When cost or weight is an important issue in application of navigation systems, heavy accurate inertial sensors are excluded and instead, low-cost systems like MEMS-grade gyroscopes and accelerometers are proposed. However, by use of the current generation of low-cost inertial measurement units (IMUs), the navigation error of stand-alone SINS intensively increases over time owing to sensor noise, bias and drift of the MEMS-grade IMUs [1]. The global positioning system (GPS) and the SINS have very complementary characteristics. As the main benefit of gathered GPS receiver with a SINS, online calibration of the SINS sensors is performed through the GPS absolute and drift-free measurements. On the other hand, the low frequency 1 (up to 20) Hz update rate of GPS data are compensated by the high frequency SINS to provide accurate position and orientation data at high update rate [2]. SINS is a self-contained unit which provides position, velocity and orientation regardless of external environment. In contrary, the GPS performance depends on external environment and satellite accessibility. Hence, the above-mentioned complementary characteristics motivate the design of integrated SINS/GPS navigation system to obtain combined superior performance with respect to the individual subsystems SINS and GPS.

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Several documented researches can be addressed in the literature concerning integrated navigation systems. For example, Kubo et al. proposed combination algorithms of INS/GPS based on nonlinear techniques comprising quasi-linear optimal filter and Gaussian-sum filter [3]. Wang et al. proposed a quadratic extended Kalman filter for INS/GPS integration by considering the second-order terms of Taylor approximation of nonlinear INS dynamics in propagation of estimation covariance matrix [4]. A nonlinear sliding-mode observer has been proposed for a low-cost attitude-heading reference system (AHRS) [5]. Using infinite impulse response (IIR) digital low-pass filter, a new algorithm for initial alignment of marine SINS has been developed in [6]. Magnetic calibration of strap-down magnetometers for the INS heading angle correction has been conducted in [7]. Jaradat and Abdel-Hafez proposed auto-regressive neural network-based data fusion architecture for the integration between low-cost INS and GPS systems [8]. Nourmohamadi and Keighobadi developed a direct decentralized integration scheme for low-cost INS/GPS system in which QR-factorized cubature Kalman filter has been used as the state estimation algorithm [9].

In practical applications, particularly in aerospace engineering, orientation estimation accuracy is an important challenge of low-cost SINS/GPS systems. Some valuable efforts have been conducted to enhance the performance of the integrated inertial navigation systems. However, most of the documented researches merely concentrated on data fusion and state estimation algorithms. Therefore, as the main topic of the proposed research work, the adaptive combination of the SINS/GPS and the AHRS is considered to take advantages of both systems simultaneously. Considering this fact, in this paper an adaptive integration scheme is presented based on fuzzy logic. Unlike crisp sets, fuzzy sets allow partial membership assignment which means that an element may partially belong to more than one set. Therefore, fuzzy logic-based algorithms are much closer in spirit to human thinking than the traditional Aristotelian logical systems [10]. Nowadays, fuzzy logic has become a powerful tool for optimizing the performance of many practical systems, especially in the field of estimation and control [11–16]. For example, Petkovic et al. used adaptive neuro-fuzzy inference system (ANFIS) to estimate optimal power coefficient value of wind turbines [14]. Musavi and Keighobadi proposed an adaptive fuzzy neuro-observer to enhance the performance of integrated INS/GPS positioning systems [15]. Boada et al. proposed a new observer using fuzzy inference system in combination with an unscented Kalman filter which enhanced the estimation accuracy of vehicle sideslip angle [16].

In the current research work, through intelligent fuzzy implications an adaptive integration scheme is developed for SINS/GPS navigation system. Using knowledge-based Mamdani-type fuzzy inference, the inertial measurements comprising gyroscopes and accelerometers outputs are examined to detect the maneuvering level of the vehicle. Accordingly, appropriate weighting coefficients are obtained to combine the SINS/GPS and the AHRS, efficiently. In low-accelerated intervals of motion, the AHRS algorithm data take larger weighting coefficients. However, when the vehicle undergoes non-gravitational accelerations, the orientation results will mostly tend to get the SINS data.

The long-term performance of the proposed approach is assessed through real field test. Low-cost ADIS-16407 IMU is used as the MEMS-grade inertial sensors and the measurement data of the estimation algorithm is provided through Garmin-35 GPS receiver. Furthermore, highly accurate Vitans navigation system is used to produce the reference data for evaluation.

2. Integrated SINS/GPS navigation

This section deals with developing a fifteen-state SINS/GPS navigation algorithm. Following deriving dynamics of the SINS error, the appropriate estimation filter is designed to integrate the SINS with the GPS, efficiently. Fifteen states of error dynamics system include five triple sets of misalignment error, velocity error, position error, accelerometer bias and gyroscope drift components. The measurement vector of integration filter is constituted by the GPS position, velocity and heading angle.

2.1. SINS dynamics

A strap-down inertial system benefits a major hardware simplification of the old stable-platform navigation systems. Strap-down navigation overcomes the problems encountered with the stable-platform navigation systems, and most importantly reduces the size, cost and power consumption [17]. Several reference frames are used in the inertial navigation comprising of inertial frame (i-frame), Earth-fixed frame (e-frame), navigation frame (n-frame) and body frame (b-frame). In the paper, the coordinate frames are defined based on Fig. 1.

Here, the n-frame is considered the local level navigation frame with north-east-down (NED) geodetic axes. Dynamical equations of the SINS position, velocity and orientation components are summarized as follows [18].

$$\begin{aligned} &\dot{L} = \tfrac{v_N}{R_N+h}, \quad \dot{l} = \tfrac{v_E}{(R_E+h)\cos L}, \quad \dot{h} = -v_D \\ &\dot{\boldsymbol{v}}^n = \boldsymbol{C}_b^n \boldsymbol{f}^b - (2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n) \times \boldsymbol{v}^n + \boldsymbol{g}^n \\ &\dot{\boldsymbol{C}}_b^n = \boldsymbol{C}_b^n \boldsymbol{\Omega}_{nb}^b \end{aligned} \tag{1}$$

where L, l and h are the position coordinates comprising latitude, longitude and altitude; $\boldsymbol{v}^n = [v_N\ v_E\ v_D]^T$ stands for the velocity vector represented in the n-frame, $\boldsymbol{C}_b^n$ is the direction cosine matrix (DCM) from b-frame to the n-frame; $\boldsymbol{f}^b$ is the specific force measured by the accelerometers in b-frame and $\boldsymbol{g}^n = [0\ 0\ g]^T$ is the gravity vector in the n-frame. R_N and R_E