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A cascaded Kalman filter-based GPS/MEMS-IMU integration for sports applications

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ABSTRACT

Nonlinear Kalman filtering methods are the most popular algorithms for integration of a MEMS-based inertial measurement unit (MEMS-IMU) with a global positioning system (GPS). Despite their accuracy, these nonlinear algorithms present a challenge in terms of the computational efficiency for portable wearable devices. We introduce a cascaded Kalman filter for GPS/MEMS-IMU integration for the purpose of trajectory determination in sports applications. The proposed algorithm uses a novel orientation filter, cascaded with a position/velocity filter. By using cascaded linear Kalman filtering, this method avoids the need to propagate additional states, resulting in the covariance propagation to become more computationally efficient for ambulatory human motion tracking. Additionally, the use of this separate orientation filter helps to retain the orientation accuracy during GPS outage. Results of the field experiments reveal that the proposed algorithm is computationally much faster compared to the available non-linear approaches and demonstrates improved trajectory tracking during GPS outages.

1. Introduction

For athletes, access to quantitative performance variables can significantly improve overall performance, allowing them to share information with coaches, record performance over time, and even provide real-time feedback of how they are doing. Currently available video-based or camera-based motion capture approaches provide few quantitative variables and are limited by meteorological conditions [1]. Additionally, these techniques are restricted to the use of pre-set confined areas that are not suitable for motion capture of outdoor sports such as skiing, snowboarding and mountain biking that take place over large distances.

The global positioning system (GPS), which provides position and velocity trajectories, might be a good alternative for chronometry or video recordings. A number of commercial products are available on the market, for example, Ripxx, and ShadowBox, provide performance parameters derived from satellite-based position [2]. However, the GPS sampling rate is typically too low to detect complex kinematic motions in sports competitions. Additionally, some other factors such as satellite signal attenuation in athletes' environment, and the number of satellites and their positions may also affect the accuracy of GPS position/velocity calculation [3].

Alternatively, an inertial navigation system (INS) can be integrated with GPS to detect rapid movements and bridge the gap between GPS blockage periods [4]. An INS is a navigation system based on an inertial measurement unit (IMU), which consists of accelerometers, gyroscopes and sometimes magnetometers to calculate orientation, position and velocity via dead reckoning [5]. In fact, since its emergence, INS is widely used in various motion capture (MOCAP) applications such as pedestrian [6], ship [7,8]

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aircraft [9–11] land vehicle [12,13] navigation, hand-held surgical devices [14], fastening tools [15] and pen [16] tracking, in addition to robotics [17–19], to provide navigation information such as orientation, velocity, and position.

Recently, miniature MEMS inertial devices have become commonplace, resulting in the emergence of INS for human body motion tracking using wearable MOCAP devices [20]. These devices typically make use of a MEMS inertial measurement unit (MEMS-IMU) and a GPS receiver for localization. As a result of its more accurate and robust MOCAP performance, the GPS/MEMS-IMU integration algorithms have received increased attention recently for trajectory determination in sports. In [1], the performance of the two widely-used nonlinear Kalman filtering methods, the unscented Kalman filter (UKF) and extended Kalman filter (EKF), for GPS/MEMS-IMU integration in sport trajectory determination is compared, finding the performance of the two algorithms comparable but the UKF incurring a higher computational cost. In [2], the EKF is utilized for jump trajectory determination in ski and mountain biking applications. In [21], a combination of GPS, MEMS-IMU and pressure sensitive insoles sensors has been used in a fusion algorithm to capture 3-D kinetics and kinematics of alpine ski racing.

Despite their excellent sensor fusion capabilities in terms of accuracy, the above mentioned nonlinear Kalman filtering methods demand relatively high computational time that is not desirable in low-cost, battery-powered, and lightweight wearable/portable navigation systems worn by athletes. The model complexity and the large amount of computation required for the available inertial MOCAP methods are also reported in [22]. To reduce this high computational cost, [22] proposes a two-step Kalman filter for orientation estimation in inertial MOCAP applications. However, it does not address the navigation and tracking issues that are highly relevant in sports applications.

In addition to high computational cost, the available GPS/IMU Kalman filter-based fusion approaches rely on GPS observations to correct the otherwise drift prone orientation calculated by the gyroscope [23]. They make use of the fact that errors in the attitude solution of an INS propagate into errors in velocity. Therefore, errors in attitude can be observed through as independent measurement of velocity under particular motion conditions that include acceleration, which is non-parallel to the velocity vector in the navigation frame [23]. However, the accuracy and speed of attitude correction by this method depends on frequency and magnitude of acceleration maneuvers [24]. Additionally, using GPS position and velocity observations to correct orientation is problematic for long GPS outage periods.

To address the shortcomings of available GPS/MEMS-IMU fusion algorithms mentioned above, this paper introduces a cascaded Kalman filter to integrate GPS/MEMS-IMU for trajectory determination in sports applications. This cascaded Kalman filter consists of a separate and novel orientation filter cascaded with a position/velocity filter. By using cascaded linear Kalman filtering, the proposed method avoids the need to propagate additional states, resulting in reduced matrix operations and more computationally efficient covariance propagation. Additionally, the use of a separate orientation filter results in more robust orientation estimation during GPS attenuation/blockage periods. The proposed orientation filter uses two linear Kalman filters consisting of a tilt angle Kalman filter followed by a yaw angle Kalman filter. Accurate orientation obtained from the orientation Kalman filter are fed to a gyroscope error Kalman filter and a navigation Kalman filter to estimate navigation parameters in addition to inertial bias errors.

The remainder of the paper is organized as follows. In Section 2, theory behind the proposed GPS/IMU fusion algorithm for trajectory determination in sports applications is introduced. The experimental setup and experimental protocol are explained in Section 3. In Section 4, the proposed method is assessed based on downhill snowboarding experiments and benchmarking the results against those obtained from tactical grade IMU fused with real-time kinematic GPS using commercial software. The performance of the algorithm under GPS outage intervals and the computational efficiency of the proposed method are also investigated in this section. Finally, Section 5 concludes the paper.

2. Theoretical method

In an INS, the navigation parameters, i.e. position and velocity, are estimated by solving strapdown inertial navigation equations through integration of the external acceleration [25]. Thus, it is important for the INS to accurately estimate external acceleration during dynamic conditions by subtracting the gravitational acceleration from the accelerometer signal. To realize this, an accurate estimation of orientation is needed. Additionally, due to their light weight and their fabrication process, MEMS sensors have large bias instability and noise, which consequently affect the obtained navigation accuracy. Therefore estimating the variations in inertial biases is extremely important in a MEMS-based INS.

To accurately determine navigation parameters including orientation, position and velocity in addition to inertial bias errors, a cascaded Kalman filter fusion algorithm is proposed here. The cascaded structure simplifies the mathematical model by removing the calculations related to orientation states in the position/velocity Kalman filter. Thus, the cascade formulation has much less computational overhead than a global Kalman filter [26]. Even though the cascaded filter is suboptimal, the accuracy is comparable to the global Kalman filter [26]. In addition to the improved computational cost, the cascaded implementation allows for increased flexibility and easier implementation and tuning with relatively small performance loss. The structure of these filters is explained in this section.

2.1. Orientation filter

In the orientation filter, Euler angles and the gyroscope's bias error are estimated using three cascaded Kalman filters: tilt Kalman filter, yaw Kalman filter and gyroscope bias error Kalman filter. The orientation of the