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Intelligent GNSS/INS integrated navigation system for a commercial UAV flight control system

Guohao Zhang, Li-Ta Hsu *

Interdisciplinary Division of Aeronautical and Aviation Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

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ABSTRACT

Owing to the increase in civil applications using quadcopters, commercial flight control systems such as Pixhawk are a popular solution to provide the sensing and control functions of an unmanned aerial vehicle (UAV). A low-cost global navigation satellite system (GNSS) receiver is crucial for the low-cost flight control system. However, the accuracy of GNSS positioning is severely degraded by the notorious multipath effect in mega-urbanized cities. The multipath effect cannot be eliminated but can be mitigated; hence, the GNSS/inertial navigation system (INS) integrated navigation is a popular approach to reduce this error. This study proposes an adaptive Kalman filter for adjusting the noise covariance of GNSS measurements under different positioning accuracies. The adaptive tuning is based on a proposed accuracy classification model trained by a supervised machine-learning method. First, principal component analysis is employed to identify the significant GNSS accuracy related features. Subsequently, the positioning accuracy model is trained based on a random forest learning algorithm with the labeled real GNSS dataset encompassing most scenarios concerning modern urban areas. To reduce the cases of misclassifying the GNSS accuracy, a fuzzy logic algorithm is employed to consider the GNSS accuracy propagation. Additionally, the process noise covariance of the INS is determined using the Allan variance analysis. The positioning performance of the proposed adaptive Kalman filter is compared with both a conventional Kalman filter and the positioning solution provided by the commercial flight control system, Pixhawk 2. The results show that the proposed adaptive Kalman filter using random forest with fuzzy logic can achieve a better classification of GNSS accuracy compared to the others. The overall positioning result improved by approximately 50% compared with the onboard solution.

1. Introduction

Unmanned aerial vehicle (UAV) is increasingly used in civilian applications, such as disaster search and rescue [1], package delivery [2], and mapping of three-dimensional (3D) city models [3]. Localization is essential in UAV guidance, navigation, and control (GNC). Almost all outdoor UAVs are equipped with a global navigation satellite system (GNSS) receiver to provide their absolute location. A GNSS receiver receives and processes all the satellite signals to obtain the distances between the receiver and satellites, known as a pseudo-range. Subsequently, the pseudo-ranges are operated in conjunction with the satellite positions to determine the UAV position. The performance of the GNSS positioning is affected by several factors, including satellite clock/orbit bias, atmospheric delay, and receiver thermal noise [4]. Currently, the biases caused by atmosphere and satellite orbit and clocks can be significantly corrected using a satellite-based augmentation system (SBAS) correction to achieve 1–2 m of positioning error in open-sky areas [5]. Inevitably, the low-attitude operating environment for a UAV becomes closer to civilians. In other words, it operates in the vicinity of urban cities or even inside urban areas. Compared to an open field, the urban configuration is denser and more complex. The urban configuration has caused many researchers to focus on using active sensors, including monocular/stereo cameras and light detection and ranging (LiDAR). Similar to the research development of autonomous driving vehicles, the LiDAR- and vision-sensor-based perception and localization became a major research stream in the UAV development. In 2012, a comprehensive survey focused on the GNC of an unmanned rotorcraft system was released [6]. It indicated that the actives sensors demonstrated their capabilities in obstacle detection [7], 3D mapping [8], and landing area detection [9]. In terms of localization, the LiDAR-based simultaneous localization and mapping could achieve submeter accuracy in a GNSS-denied area such as indoor environments [10]. With the 3D point cloud map in absolute coordinates, the LiDAR can also provide absolute localization. However, owing to the ex-

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* Corresponding author.
E-mail address: lt.hsu@polyu.edu.hk (L.-T. Hsu).

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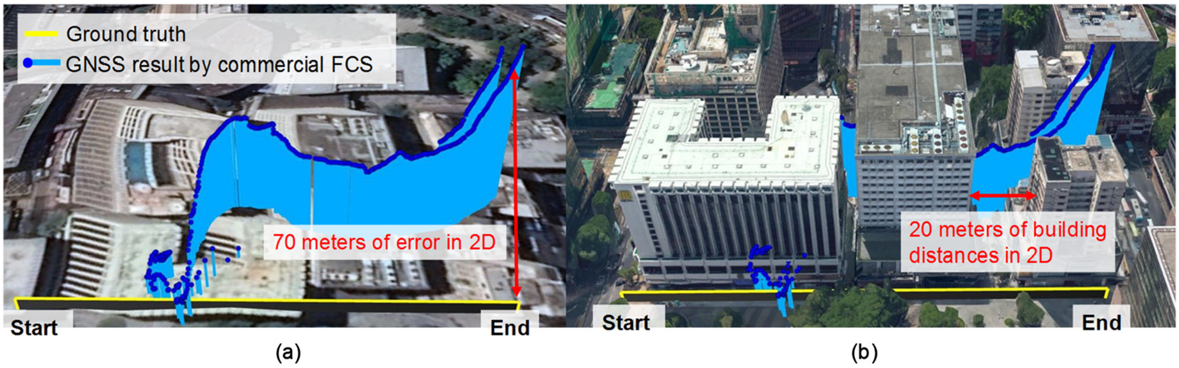

Fig. 1. Demonstration of GNSS positioning error in urban areas (a) without and (b) with the appearances of 3D building model. The yellow and blue lines indicate the true trajectory and position solution of a GNSS receiver embedded in a commercial FCS, respectively. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

cessive computational load and memory expense, it is very difficult for the LiDAR-based rotorcrafts to perform well in applications that require a large area and long lifetime. In addition, the construction or preparation of the absolute 3D point cloud in a wide area requires expensive equipment and heavy manual calibration. Finally, the active sensor itself is too costly to be implemented in mass-market applications, including window-to-window parcel-delivery service. Vision odometry is also a popular option to provide a motion model to assist the dead reckoning (DR) of the UAV [11]. Vision odometry is similar to MEMS INS but with a slower accumulated error, i.e., it cannot estimate the absolute position [12]. Aerial mapping vehicles typically apply highly accurate GNSS/INS integrated receivers to provide submeter navigation service [13]. However, these high-end equipment require a geodetic grade dual-frequency GNSS antenna with a choke-ring design to mitigate multipath effects, high sampling rate dual-frequency GNSS receiver to eliminate ionosphere delay and tactical, and fiber optics INS to provide stable DR. Collectively, the price of the high-end equipment is within the range of 30,000 to 100,000 US dollars. In addition to the high cost, the weight of such equipment is approximately 2 kg to 4 kg. Therefore, it is clearly not suitable for consumer UAV in terms of the price budget and payload. Considering the factors listed above, the ideal sensor to provide absolute positioning is the consumer-grade GNSS receiver with single-frequency patch antenna that merely costs approximately 10 US dollars and 10 g of weight. For example, the popular Pixhawk flight control system (FCS) for quadcopters are embedded with a low-cost GNSS receiver and MEMS inertial measurement units (IMUs). The goal of this research is to improve the GNSS positioning performance for the low-cost FCS even in the highly urbanized HK central business district areas.

Hence, the cause of GNSS localization error must be addressed. GNSS satellites broadcast signals containing information of the satellite clock/orbit, and the transmit time. The signal passes through the atmosphere and is received by the receiver on Earth. Finally, the receiver's position can be estimated using the triangulation theory. In general, the triangulation is linearized by considering the first-order Taylor series and subsequently applying least squares to estimate the receiver position [14]. Several errors arise in the process, including ionospheric delay, tropospheric delay, satellite orbit/clock error, receiver thermal noise, and multipath effects. Differential GNSS (DGNSS) and real time kinematics (RTK) are technologies based on the principle that most error sources are differentiable between the GNSS reference station and aircrafts [15]. Thus, submeter or even centimeter levels of GNSS positioning can be achieved [16]. Unfortunately, in urban canyons, the GNSS signal suffers from signal blockages, diffraction, and reflection by buildings and skyscrapers, resulting in several tens of localization errors. These effects cannot be eliminated by differential technologies because the base station does not share the same signal reflection as the aerial rover. Currently, a universal model or a solution to solve this multipath effect and non-line-of-sight (NLOS) reception does not exist. Therefore, this phenomenon is the current impediment of the application of GNSS localization in an urbanized area [17]. The multipath and NLOS are currently the dominant errors of GNSS positioning in mega cities such as Hong Kong, Tokyo, and New York [18]. They can be severe and cause 70 m of GNSS positioning error, as shown in Fig. 1(a). Compared with the distances between buildings in an urban area, this level of positioning performance is hazardous for UAVs, as shown in Fig. 1(b). The UAVs risk crushing on buildings owing to the erroneous GNSS positioning solutions. Hence, the multipath and NLOS error must be handled to achieve a safe and reliable UAV operation in urban areas [19]. The multipath effect can be mitigated by sophisticated GNSS antenna arrays [20–22], receiver correlator designs [23–25], and 3D city models [26–28]. However, a complete solution to eliminate this error does not exist. An effective solution is to integrate the onboard GNSS receiver with the inertial navigation system (INS) owing to their complementary [29].

The Kalman filter is widely employed to integrate the GNSS and INS with a balance between the two systems. Typically, the INS is used as a prediction, and the GNSS as a measurement. The tuning of both processes and measurement noise covariances will affect the Kalman gain, implying the weighting between system prediction and measurement update [30]. In general, the process noise covariance ($\boldsymbol{Q}$) and measurement noise covariance ($\boldsymbol{R}$) are fixed values, resulting in a constant weighting between the INS and GNSS. However, the operating environment (implying GNSS accuracy) is different in urban areas. Subsequently, constant tuning cannot yield an optimal performance. An adaptive tuning algorithm is required to describe the noise of the measurement model of the GNSS. A loosely coupled GPS/INS integration that tuned its $\boldsymbol{R}$ of the Kalman filter by the innovation/residual between the measurement and propagation is proposed [31]. To improve the residual-based adaptive Kalman filter (AKF), a quasi-accurate detection method is proposed to solve the noise generated by abrupt motion changes [32]. Hajiyev and Soken developed a robust AKF to isolate sensor/actuator faults by assigning multiple adaptive factors for both $\boldsymbol{Q}$ and $\boldsymbol{R}$ [33]. A cubature Kalman-filter-based multipath mitigation tracking system is developed for land-based navigation systems to remove the reflection components for distance measuring equipment (DME) measurement [34]. An initial alignment for the Strapdown INS/GNSS integrated system using AKF is recently proposed [35]. Gao et al. proposed a maximum posterior and random weighting approach to conquer the deficiency of the unscented Kalman filter for the INS/GNSS integrated navigation [36]. Recently, a fuzzy logarithmic least-squares method is proposed to handle the traditional analytic hierarchy of GPS accuracy