Advancing High-Precision Navigation: Leveraging Homogeneous Sensors in Tightly Coupled PPP-RTK/IMU Integration

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***Abstract*—As Global Navigation Satellite Systems (GNSS) and Inertial Measurement Units (IMUs) are gradually emerging as ubiquitous, utilizing redundant sensors to achieve accurate and robust large-scale navigation holds great promise. In this paper, we propose a tightly coupled (TC) PPP-RTK/IMU system with multiple homogeneous sensors to enable high-precision and high-availability vehicle navigation. In it, a stacked Kalman filter is employed to fuse raw pseudorange and carrier phase measurements from all GNSS terminals, driven by a core IMU designated randomly. In PPP-RTK processing, precise atmospheric and bias corrections from a GNSS server are leveraged to quickly resolve carrier phase ambiguity, thus ensuring centimeter-level positioning. Besides, rotation and translation constraints from redundant IMUs are imposed on the estimation pipeline to further improve the state estimation. Real-world experiments show the proposed method can achieve an availability of 98.7% (horizontal position error $<$ 0.1 m) in a half-open-sky case, which is far better than the state-of-the-art methods. Also, redundant sensors not only contribute significantly to the integer ambiguity resolution, but are also able to promise continuous state estimation in case of sensor failure.**

***Index Terms*—GNSS/INS, Tightly coupled integration, Ambiguity resolution, Homogeneous and heterogeneous sensors, State estimation.**

I. Introduction

ACCURATE, continuous and robust position and attitude estimation is a prerequisite for the safe operation of autonomous devices such as unmanned aerial vehicles and unmanned ground vehicles [1]–[3]. The integration of heterogeneous sensors, such as inertial navigation systems (INS), global navigation satellite systems (GNSS), cameras, etc., are widely employed for land vehicle navigation due to their complementary and their adaptability to different scenarios [4], [5].

Typically, the GNSS/INS system, as the core component of an intelligent vehicle, can not only deliver continuous position and attitude services, but also derive enriched information on vehicle motion, such as acceleration and steering angular rate [6]. In it, GNSS positioning is implemented by rendezvous methods using received pseudorange and carrier phase observations from satellites, which ensures that users can obtain all-weather, all-day, large-area ($>$ tens of kilometers) positioning capabilities. INS can not only compensate for discontinuities in positioning services due to satellite signal interference or interruptions, but also contribute to cycle slip detection and ambiguity resolution (AR) of carrier phase [7]. The tightly coupled (TC) GNSS/INS derived from raw measurements has proven outstanding estimation capability and consistency, as it can maximize the usage of all available information to achieve a global optimal state estimation [8].

As an emerging positioning technology, GNSS PPP-RTK unifies two traditional GNSS positioning techniques [9], [10], namely, precise point positioning (PPP) [11] and real-time kinematic (RTK) positioning [12]. It makes use of the widely accessible continuously operating reference stations (CORS) to extract precise atmospheric delay corrections to be sent to users to calibrate their observations, thus significantly enhancing their positioning performance [13]. Fig. 1 illustrates the operation of a complete PPP-RTK system, including the server side and the user positioning side. On the one hand, PPP-RTK technology is not restricted by operating range compared to RTK (requires a nearby base station) and has the capability of seamless positioning over large areas similar to PPP [14]. Furthermore, empowered by precise atmospheric products, PPP-RTK users can expect to successfully resolve carrier phase ambiguity within seconds and obtain centimeter-level position estimation comparable to RTK [15]. However, PPP-RTK is still susceptible to interference from obstructions such as buildings and overpasses in real traffic scenarios. Therefore, a tightly coupled PPP-RTK/INS method with atmospheric augmentation was proposed in [16], which showed excellent positioning performance, but in which the carrier phase ambiguity was not resolved. In our previous study [17], an INS-enhanced PPP-RTK tightly coupled prototype system was presented, indicating a significant gain in carrier phase ambiguity resolution and position estimation, etc. from heterogeneous sensor integration. Subsequently, sensors commonly involved in vehicle navigation, such as wheeled odometers and cameras, were also tightly integrated to further improve the performance in PPP-RTK degradation scenarios [18]–[20].

Nevertheless, as stated in the above study, while such methods can cover most urban scenarios with open sky, their service capability will be significantly diminished in challenging scenarios [20]–[22]. Layh and Gebre-Egziabher [23] designed a decentralized parallel filter to mitigate the performance degradation caused by challenges such as satellite signal interference or loss. Shen et al. [24] also proposed an adaptive federal Kalman filter that utilizes time-varying

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