Journal of Global Positioning Systems
Vol. 22, Issue 1:169-172

Journal of Global Positioning Systems
2026
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Research on deep integration technology of vehicle navigation for GNSS observation quality in harsh environment

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Examination Date: 2025-05-27

Abstract

Emerging fields such as autonomous driving and intelligent robotics require continuous and reliable positioning with decimeter-level or even centimeter-level accuracy. However, GNSS signals are highly susceptible to attenuation, obstruction, and reflection in harsh environments such as dense tree canopies and urban canyons, which severely degrades the accuracy and continuity of carrier phase observations and compromises the availability of centimeter-level positioning. Multi-sensor (GNSS, IMU, Camera, etc.) data fusion techniques cannot maintain satisfying long-term positioning accuracy when GNSS carrier phase observations fail. Ultra-tight integration techniques that leverage multi-sensor information can enhance signal tracking performance at the GNSS baseband processing level, radically improving the accuracy and availability of carrier phase observations. However, existing ultra-tight integration techniques based on single low-cost sensors (such as MEMS IMU or camera) cannot provide satisfying assistance accuracy for phase-locked loops (PLLs) when GNSS signals degrade. Although INS/Vision fusion can improve the assistance accuracy, there is currently no research on assisting GNSS baseband using INS/Vision fusion and ultra-tight integration for robust carrier phase measurement and precise positioning.

This paper aims to achieve robust GNSS carrier phase signal tracking and high-precision positioning with superior availability in harsh environments, especially in dense tree canopies and urban canyons. In this paper, a GNSS/INS/Vision ultra-tightly coupled integration system (GIV-UTC) is developed and thoroughly tested using a wheeled robot in harsh environments. The overall diagram of the proposed GIV-UTC is shown in Fig. 1, which integrates GNSS baseband signal, IMU data and Camera data within a unified ultra-tightly coupled integration framework. The MEMS IMU and camera data are integrated using a Multi-state Constrained Kalman Filter (MSCKF), which is used to estimate the dynamic stresses caused by the receiver motion and then used to assist the GNSS PLLs. It significantly reduces the residual dynamic stress compared with using a standalone IMU or camera. Furthermore, a multi-channel cooperative tracking loop is proposed to eliminate the impact of oscillator instability. Consequently, the local PLL can substantially extend the coherent integration time, resulting in continuous and accurate carrier phase tracking in harsh environments

characterized by signal attenuation, intermittency, and severe multipath effects, such as dense tree canopies. Finally, a sky-pointing fisheye camera is used to produce the satellite blockage mask, which can identify and eliminated the NLOS effects radically at the GNSS baseband signal processing level, improving the availability of GNSS carrier phase observations in urban canyon environment.

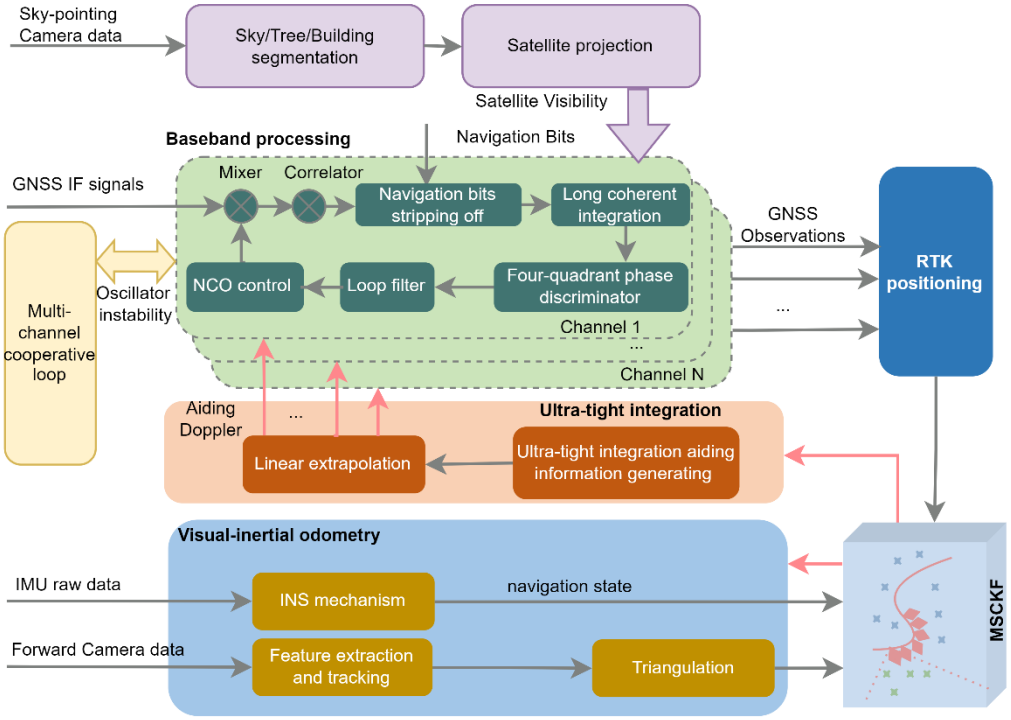


Fig. 1 Overall diagram of the proposed GNSS/INS/Vision ultra-tight integration system

The main contributions of this paper are as follows:

1. A long coherent integration architecture with a multichannel cooperative loop is proposed, which addresses the difficulty of tracking carrier phases when GNSS signals are attenuated, and the phase-locked loop (PLL) is simultaneously constrained by receiver clock errors and strong thermal noise. Since the receiver clock errors have the same impact on different baseband processing channels, a multichannel cooperative loop is designed to track the clock errors using correlation results from multiple local PLLs. The estimated clock error is then used to assist local PLLs in performing long coherent integration carrier phase tracking. Subsequently, The transfer function of LCI tracking loops is established in s-domain, and the tracking error models induced by thermal noise and Allan deviation oscillator phase noise are derived in z-domain. Static field test results demonstrate that the proposed method enables ultra-long coherent integration time of up to 3 seconds, achieving continuous and precise tracking of extremely weak carrier phase signals (as low as 5dB-Hz), with a 20dB improvement in tracking sensitivity compared to conventional PLLs.

2. A multi-sensor ultra-tight integration method, which uses a visual-inertial odometry (VIO) to assist GNSS baseband processing, is proposed to address the degradation of tracking accuracy caused by dynamic stresses (induced by the relative motion between the receiver and satellite) when GNSS signals are weakened in dynamic environments. First, a Multi-state

Constrained Kalman Filter (MSCKF) is used for the fusion of RTK positioning, MEMS IMU, and forward monocular camera at the data processing level. Subsequently, the multi-sensor sensed dynamics is utilized to assist carrier phase tracking loops and realizes extended coherent integration periods, thus achieving multi-sensor fusion at the signal processing level. A tracking error model for the multi-sensor assisted carrier phase tracking is established, and the performance of the VIO-assisted-PLLs in extending the coherent integration period under dynamic conditions is analyzed. Dynamic field test results show that the VIO can support a maximum coherent integration time of 800ms, which is twice as long as the integration duration with pure inertial assistance, significantly improving the accuracy and continuity of carrier phase tracking in GNSS signal-degraded environments, such as dense tree canopies.

3. A carrier phase tracking method aided by a sky-pointing fish-eye camera is proposed to mitigate frequent loss or false lock issues of GNSS PLLs under dynamic conditions involving signal attenuation, obstruction, and reflection. First, a multi-sensor-assisted open-loop prediction strategy for carrier phase tracking is introduced, which predicts the carrier NCO control information during signal outages. A closed-loop convergence algorithm based on FFT-based frequency discrimination is also developed to enable rapid and accurate carrier re-locking upon signal recovery. Next, a sky-pointing fish-eye camera is integrated into the system, and a deep learning-based semantic segmentation network is employed to classify the scene into sky, foliage, and building regions, which is used to determine the visibility of GNSS signals by projecting the satellite positions onto the segmentation output pictures. Based on the satellite visibility and loop signal indicators, an adaptive open/closed-loop tracking scheme is designed. Experimental results in harsh environments demonstrate that, compared to conventional PLLs, the proposed method enables continuous and precise carrier phase tracking under tree canopies and effectively avoids erroneous tracking of non-line-of-sight (NLOS) signals reflected from buildings, significantly improving carrier phase availability.

4. In order to realize dynamic high-precision positioning in harsh environments, a GNSS/INS/Vision ultra-tightly coupled integration system was developed and extensively tested using a wheeled robot platform. The system consists of a multi-sensor data fusion subsystem and a GNSS subsystem, responsible for high-level navigation data fusion and low-level signal processing fusion, respectively. Comprehensive tests were conducted on the wheeled robot to evaluate the system's performance. Tests conducted in tree-canopy-covered environments show that due to the poor carrier phase availability, conventional multi-sensor data fusion yields only meter-level positioning accuracy. In contrast, the proposed ultra-tight integration system achieves robust and continuous carrier phase tracking, enabling consistent and reliable centimeter-level positioning. Further tests in complex scenarios involving both tree canopies and buildings demonstrate that the ultra-tight integration system significantly enhances carrier phase tracking accuracy and continuity in harsh environments, thus achieving continuous and robust sub-decimeter-level positioning, promoting the development of multi-sensor integrated positioning technologies for GNSS-degraded scenarios.

The doctoral research was carried out by Xin Feng in GNSS Research Center, Wuhan University. His doctoral advisors were Prof. Jingnan Liu (Member of Chinese Academy of

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