

Editorial

High-Precision and High-Reliability Positioning, Navigation, and Timing: Opportunities and Challenges

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Abstract: The research scope of the papers published in this Special Issue mainly focuses on high-precision and high-reliability positioning, navigation, and timing (PNT) with Global Navigation Satellite System (GNSS) or multi-source sensors, resilient PNT with GNSSs or multi-source sensors in challenging environments, integrated PNT with GNSSs and multi-sensor systems, applications of PNT with GNSSs or multi-source sensors, etc.

Keywords: PNT; GNSS; multi-sensor system; challenging environment; applications of GNSSs and multi-sensor systems

1. Introduction

Global Navigation Satellite Systems (GNSSs) provide high-precision positioning, navigation, and timing (PNT) capabilities in open areas and have gained widespread use in various fields, including high-precision monitoring and intelligent transportation [1]. However, their performance is hindered in challenging environments where signals are susceptible to reflection, refraction, diffraction, and blockage by buildings [2–4]. These factors can degrade signal quality, leading to inconsistent or disrupted PNT with GNSSs. Fortunately, certain sensors complement GNSSs, and thus multi-source sensors, including the inertial measurement unit (IMU), light detection and ranging (LiDAR), and vision and odometer sensors, are extensively explored and employed, particularly in autonomous driving and ground unmanned vehicles [5–8]. Simultaneous Localization and Mapping (SLAM) stands out as a notable application of multi-source sensor fusion, attracting significant attention due to its high robustness and accuracy [9,10]. The diversification of GNSS constellations, multi-source sensors, and observation environments put forward higher requirements for technology and algorithms to maintain high-precision and high-reliability PNT services [11]. Advanced algorithms serve as the key to solving practical application issues related to GNSSs and multi-source sensors, thereby expanding their scope of applications.

This Special Issue aimed to present studies covering improved methods and the latest challenges in PNT, especially in challenging environments, covering a wide range of research investigations and practical applications. Both theoretical and applied research contributions in GNSSs and multi-source sensor fusion technologies in all disciplines were considered. Topics may cover anything from high-precision and high-reliability PNT with GNSS or multi-source sensors, resilient PNT with GNSS or multi-source sensors in challenging environments, integrated PNT with GNSS and multi-sensor systems, and applications of PNT with GNSS or multi-source sensors. Therefore, new algorithms for high-precision positioning and navigation, fusion of multi-sensor systems, software development



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for data collection, integration, and processing, and their applications in various fields are all included.

2. Overview of Contributions

This section provides a synthesis of the key findings and contributions from each paper published in the Special Issue “High-Precision and High-Reliability Positioning, Navigation, and Timing: Opportunities and Challenges”. Here, we examine each contribution to highlight its significance in advancing methodologies, addressing current challenges, and enhancing the overall understanding of PNT in diverse environments.

Dai et al. (contribution 1) proposed a structural health monitoring (SHM) scheme where an inertial measurement unit (IMU) and multi-antenna GNSS were tightly integrated. The phase centers of multiple GNSS antennas were transformed into the IMU center, which increased the observation redundancy and strengthened the positioning model. To evaluate the performance of the tight integration of an IMU and multiple GNSS antennas, high-rate vibrational signals were simulated using a shaking table (i.e., vibrational test platform), and the errors of horizontal displacements of different positioning schemes were analyzed using recordings of a high-precision ranging laser as the reference. The results demonstrated that applying triple-antenna GNSS/IMU integration for measuring the displacements can achieve an accuracy of 2.6 mm, which was about 33.0% and 30.3% superior to the accuracy achieved by the conventional single-antenna GNSS-only and GNSS/IMU solutions, respectively.

Zhang et al. (contribution 2) proposed an improved Carrier Smoothing Code (CSC) algorithm by considering Satellite-induced Code Bias (SICB) for Geostationary Orbit (GEO), Inclined Geosynchronous Orbit (IGSO), and Medium Earth Orbit (MEO) satellites in BeiDou Navigation Satellite System (BDS) constellations. The correction model of SICB for IGSO/MEO satellites was established by using a 0.1-degree interval piecewise weighted least squares Third-Order Curve Fitting Method (TOCFM). The Variational Mode Decomposition combined with Wavelet Transform (VMD-WT) was proposed to establish the correction model of SICB for the GEO satellite. To verify the proposed method, the SICB model was established by collecting 30 Multi-GNSS Experiment (MGEX) BDS stations in different seasons of the year, in which the BDS data of ALIC, KRGG, KOUR, GCGO, GAMG, and SGOC stations were selected for 11 consecutive days to verify the effectiveness of the algorithm. The results showed that there was obvious SICB in the BDS-2 Multipath (MP) combination, but the SICB in the BDS-3 MP was smaller and could be ignored. Compared with the modeling in the references, TOCFM was more suitable for IGSO/MEO SICB modeling, especially for the SICB correction at low elevation angles. After the VMD-WT correction, the root mean square error (RMSE) of SICB of B1I, B2I, and B3I in GEO satellites was reduced by 53.35%, 63.50%, and 64.71%, respectively. Moreover, Zhang et al. [2] carried out Ionosphere-Free Single Point Positioning (IF SPP), Ionosphere-Free CSC SPP (IF CSC SPP), CSC single point positioning with the IGSO/MEO SICB correction based on the TOCFA method (IGSO/MEO SICB CSC), and CSC single point positioning with the IGSO/MEO/GEO SICB correction based on VMD-WT and TOCFA (IGSO/MEO/GEO SICB CSC), respectively. Compared to IF SPP, after the IGSO/MEO/GEO SICB correction, the overall improvement was about 10%, and positioning improved significantly.

Guo et al. (contribution 3) designed and implemented a satellite-ground microwave time-frequency comparison system and method based on a three-frequency mode in response to the requirements for assessing the long-term stability of high-precision space atomic clocks. Ground-based experimental results demonstrated that the equipment layer could achieve a satellite-ground time comparison accuracy better than 0.4 ps (RMS), with the equipment delay stability (ADEV) for all three frequencies being better than 8×10^{-18} at 86,400. The authors constructed a satellite-ground time-frequency comparison simulation and verification platform by using the ground-based experimental results. This platform realized ultra-high-precision satellite-ground time-frequency comparison based on the China Space Station. After correcting various transmission delay errors, the satellite-

ground time comparison achieved an accuracy better than 0.8 ps and an ADEV better than 2×10^{-17} at 86,400 s (i.e., 24 h). This validation of the novel satellite–ground time–frequency comparison system and method, capable of achieving a stability of 10^{-17} order, was not only a significant contribution to the field of space time–frequency systems but also paved the way for future advancements and applications in space science exploration.

Cai et al. (contribution 4) proposed a low-cost and robust multi-sensor data fusion scheme for heterogeneous multi-robot collaborative navigation in indoor environments, which integrated data from IMUs, laser rangefinders and cameras, among others, into heterogeneous multi-robot navigation to address the challenge in the multi-robot collaborative systems. Based on Discrete Kalman Filter (DKF) and Extended Kalman Filter (EKF) principles, a three-step joint filtering model was used to improve the state estimation, and the visual data were processed using the YOLO deep learning target detection algorithm before updating the integrated filter. The proposed integration was tested at multiple levels in an open indoor environment following various formation paths. The results showed that the three-dimensional root mean square error (RMSE) of indoor cooperative localization was 11.3 mm, the maximum error was less than 21.4 mm, and the motion error in occluded environments was suppressed. The proposed fusion scheme was able to satisfy the localization accuracy requirements for efficient and coordinated motion of autonomous mobile robots.

Sun et al. (contribution 5) considered the code multipath to be influenced not only by the elevation and azimuth angle of certain stations to satellites but also to be related to satellite characteristics such as nadir angle. Hence, azimuth angle, elevation angle, nadir angle, and carrier-to-noise power density ratio were taken as multiple indicators to characterize the multipath significantly. Then, the authors proposed an Attention-based Convolutional Long Short-Term Memory (AT-Conv-LSTM) that fully exploited the spatiotemporal correlations of multipaths derived from multiple indicators. The main processing procedures using AT-Conv-LSTM were given. Finally, the AT-Conv-LSTM was applied to a station for 16 consecutive days to verify the multipath mitigation effectiveness. Compared with sidereal filtering, multipath hemispherical map (MHM), and trend-surface analysis-based MHM, the experimental results showed that using AT-Conv-LSTM could decrease the root mean square error and mean absolute error values of the multipath error by more than 60% and 13%, respectively. The proposed method could correct the code multipath to the centimeter level, which was one order of magnitude lower than the uncorrected code multipath. Therefore, the proposed AT-Conv-LSTM network could be used as a powerful alternative tool to realize multipath reduction and will be of broad practical value in the fields of standard and high-precision positioning services.

Yu et al. (contribution 6) presented a novel RGB-D dynamic Simultaneous Localization and Mapping (SLAM) method that improved the precision, stability, and efficiency of localization while relying on lightweight deep learning in a dynamic environment compared to the traditional static feature-based visual SLAM algorithm. Based on ORB-SLAM3, the GCNv2-tiny network instead of the ORB method improved the reliability of feature extraction and matching and the accuracy of position estimation; then, the semantic segmentation thread employed the lightweight YOLOv5s object detection algorithm based on the GSConv network combined with a depth image to determine potentially dynamic regions of the image. Finally, to guarantee that the static feature points are used for position estimation, dynamic probability is employed to determine the true dynamic feature points based on the optical flow, semantic labels, and the state in the last frame. The authors have performed experiments on the TUM datasets to verify the feasibility of the algorithm. Compared with the classical dynamic visual SLAM algorithm, the experimental results demonstrated that the absolute trajectory error was significantly reduced in dynamic environments and that the computing efficiency was improved by 31.54% compared with the real-time dynamic visual SLAM algorithm with close accuracy, demonstrating the superiority of DLD-SLAM in accuracy, stability, and efficiency.

Quan et al. (contribution 7) proposed a robust method based on factor graphs to improve the performance of integrated navigation systems. The authors proposed a detection method based on multi-conditional analysis to determine whether the GNSS was anomalous or not. Moreover, the optimal weight of GNSS measurement was estimated under anomalous conditions to mitigate the impact of GNSS outliers. The proposed method is evaluated through real-world road tests, and the results showed that the positioning accuracy of the proposed method was improved by more than 60% and the missed alarm rate was reduced by 80% compared with the traditional algorithms.

Li et al. (contribution 8) proposed a stationary detection method based on the fast Fourier transform (FFT) for a stopped land vehicle with an idling engine. An urban vehicular navigation experiment was conducted with the authors' GNSS/IMU integration platform. Three stops for 10 to 20 min were set to analyze, generate, and evaluate the FFT-based stationary detection method. The FFT spectra showed clearly idling vibrational peaks during the three stop periods. Through the comparison of FFT spectral features with decelerating and accelerating periods, the amplitudes of vibrational peaks were put forward as the key factors of stationary detection. For consecutive stationary detection in the GNSS/IMU integration process, a three-second sliding window with a one-second updating rate of the FFT was applied to check the amplitudes of the peaks. For the assessment of the proposed stationary detection method, GNSS observations were removed to simulate outages during three stop periods, and the proposed detection method was conducted together with the ZVU. The results showed that the proposed method achieved a 99.7% correct detection rate, and the divergence of the positioning error constrained via the ZVU was within 2 cm for the experimental stop periods, which indicated the effectiveness of the proposed method.

Wang et al. (contribution 9) investigated the feasibility of extracting ionospheric observables from the multi-GNSS single-frequency (SF) UU-PPP to reduce the cost of ionospheric modeling. Meanwhile, the between-satellite single-differenced (SD) method was applied to remove the effects of the receiver differential code bias (DCB) with short-term time-varying characteristics in regional ionospheric modeling. With the introduction of the proposed SD ionospheric model into the multi-GNSS kinematic RT SF-PPP, the initialization speed of vertical positioning errors can be improved by 21.3% in comparison with the GRAPHIC (GRoup And PHase Ionospheric Correction) SF-PPP model. After reinitialization, both horizontal and vertical positioning errors of the SD ionospheric-constrained (IC) SF-PPP can be maintained within 0.2 m. This proved that the proposed SDIC SF-PPP model could enhance the continuity and stability of kinematic positioning in the case of some GNSS signals missing or blocked. Compared with the GRAPHIC SF-PPP, the horizontal positioning accuracy of the SDIC SF-PPP in kinematic mode can be improved by 37.9%, but its vertical positioning accuracy may be decreased. Overall, the 3D positioning accuracy of the SD ionospheric-constrained RT SF-PPP can be better than 0.3 m.

Pang et al. (contribution 10) introduced a cost-effective Simultaneous Localization and Mapping (SLAM) system design that maintains high performance while significantly reducing costs. First, the authors developed a robust robotic platform based on a traditional four-wheeled vehicle structure, enhancing flexibility and load capacity. Then, they adapted the SLAM algorithm using the LiDAR-inertial odometry framework coupled with the Fast Iterative Closest Point (ICP) algorithm to balance accuracy and real-time performance. Finally, they integrated the 3D multi-goal Rapidly exploring Random Tree (RRT) algorithm with Nonlinear Model Predictive Control (NMPC) for autonomous exploration in complex environments. Comprehensive experimental results confirmed the system's capability for real-time, autonomous navigation and mapping in intricate indoor settings, rivaling more expensive SLAM systems in accuracy and efficiency at a lower cost.

Zhang et al. (contribution 11) presented a Sage-Husa Kalman filter where the noise uncertainty of strong motion acceleration was adaptively estimated to integrate GNSSs and strong motion acceleration for obtaining the displacement series. The performance of the proposed method was validated by a shake table simulation experiment and the

GNSS/strong motion co-located stations collected during the 2023 Mw 7.8 and Mw 7.6 earthquake doublet in southeast Turkey. The experimental results showed that the proposed method enhanced adaptability to the variation in strong motion accelerometer noise levels and improved the precision of the integrated displacement series. The displacement derived from the proposed method was up to 28% more accurate than that from the Kalman filter in the shake table test, and the correlation coefficient with respect to the references arrived at 0.99. The application to the earthquake event showed that the proposed method can capture seismic waveforms at a promotion of 46% and 23% in the horizontal and vertical directions, respectively, compared with the results of the Kalman filter.

Tian et al. (contribution 12) conducted a systematic and comprehensive evaluation of signal characteristics for BDS-3, BDS-2, GPS, and Galileo regarding carrier-to-noise ratio (C/N₀), code noise, and multipath in the contribution using the data of the globally distributed MGEX stations. First, a comprehensive signal quality assessment method for BDS/Galileo/GPS satellites and signals was proposed, including C/N₀ modeling and MP modeling. For BDS, the BDS-3 satellites apparently have higher signal power than the BDS-2 satellites at the same frequency, such as B1I and B3I, and the B2a signal of BDS-3 was superior to other signals with a signal power that was comparable with the superior Galileo E5 and GPS L5 signals. Among all the signals, the observation accuracy of E5 was the highest regardless of receiver type, and the next highest was BDS-3 B2a and GPS L5. Due to not being affected by the systematic code errors of BDS-2, the observations of BDS-3 satellites contained smaller multipath errors than those of BDS-2 satellites. As for the multipath suppression performance, the BDS-3 B2a signal, GPS L5, and Galileo E5 and E5b performed better than the other signals, which may be related to their wide signal bandwidths.

Mu et al. (contribution 13) proposed a cruise speed model based on the self-attention mechanism for speed estimation in Autonomous Underwater Vehicle (AUV) navigation systems. By utilizing variables such as acceleration, angle, angular velocity, and propeller speed as inputs, the self-attention mechanism was constructed using Long Short-Term Memory (LSTM) for handling the above information, enhancing the model's accuracy during persistent bottom-track velocity failures. Additionally, this study introduced the water-track velocity information to enhance the generalization capability of the network and improved its speed estimation accuracy. The sea trial experiment results indicated that compared to traditional methods, this model demonstrated higher accuracy and reliability with both position error and velocity error analysis when the used Pathfinder DVL fails, providing an effective solution for AUV combined navigation systems.

Gong et al. (contribution 14) proposed a new unified positioning algorithm using multi-sensor time difference in arrival (TDOA) and frequency difference in arrival (FDOA) measurements without prior target source information. The method represented the position of the target source using MPR and described the localization problem as a weighted least squares (WLS) problem with two constraints. The authors first obtained the initial estimates by WLS without considering the constraints and then investigated a two-step error correction method based on the constraints. The first step corrected the initial estimate using the Taylor series expansion technique, and the second step corrected the DOA estimate in the previous step using the direct error compensation technique based on the properties of the second constraint. Simulation experiments showed that the method was effective for the unified positioning of moving targets and could achieve the Cramer–Rao lower bound (CRLB).

Liu et al. (contribution 15) proposed a new method to locate UAVs via shape and spatial relationship matching (SSRM) of buildings in urban scenes as an alternative to UAV localization via image matching to address the challenge of capturing the unique characteristics of buildings due to their high density and similarity in shape within urban environments. SSRM first extracted individual buildings from UAV images using the SOLOv2 instance segmentation algorithm. Then, these individual buildings were subsequently matched with vector e-map data (stored in .shp format) based on their shape and

spatial relationship to determine their actual latitude and longitude. Control points were generated according to the matched buildings, and finally, the UAV position was determined. SSRM can efficiently realize high-precision UAV localization in urban scenes. Under the verification of actual data, SSRM achieved localization errors of 7.38 m and 11.92 m in downtown and suburban areas, respectively, with better localization performance than the radiation-variation insensitive feature transform (RIFT), channel features of the oriented gradient (CFOG), and SSM algorithms. Moreover, the SSRM algorithm exhibited a smaller localization error in areas with higher building density.

Li et al. (contribution 16) developed a dual-media stereovision measurement simulation model and conducted comprehensive simulation experiments to analyze the impact of refraction-parameter deviations on measurements in underwater structure visual navigation. The results indicated that to achieve high-precision underwater measurement outcomes, the calibration method for refraction parameters, the distribution of the targets in the field of view, and the distance of the target from the camera must all be meticulously designed. These findings provided guidance for the construction of underwater stereo-vision measurement systems, the calibration of refraction parameters, underwater experiments, and practical applications.

3. Conclusions and Future Directions

The contributions to this Special Issue highlight significant advancements in high-precision and high-reliability PNT technologies. These advancements pave the way for more reliable, accurate, and versatile PNT solutions across various applications, from structural health monitoring to autonomous navigation systems. Key takeaways include:

- (1) Integration of multiple sensors and data fusion techniques greatly enhances PNT accuracy and reliability, particularly in challenging environments.
- (2) Machine learning and deep learning approaches show promise in improving GNSS signal processing, multipath mitigation, and SLAM algorithms.
- (3) Innovative algorithms for error correction and adaptive filtering demonstrate substantial improvements in positioning accuracy across various applications.
- (4) The BeiDou Navigation Satellite System (BDS) continues to evolve, with BDS-3 showing improved performance over BDS-2 in many aspects.

As the field continues to evolve, interdisciplinary approaches combining advances in sensor technology, signal processing, artificial intelligence (AI), and application-specific knowledge will likely play a crucial role in driving innovation in PNT systems. Therefore, based on the findings published in this Special Issue, future research directions in PNT may include:

- (1) Further development of robust multi-sensor fusion algorithms for seamless indoor–outdoor navigation.
- (2) Exploration of advanced AI techniques for real-time signal processing and error mitigation in GNSSs and other positioning systems.
- (3) Investigation of novel approaches for PNT in emerging fields such as autonomous vehicles, UAVs, and underwater navigation.
- (4) Continued improvement of GNSS performance, particularly in challenging urban and indoor environments.

These future directions aim to address the ongoing challenges in PNT technologies while pushing the boundaries of accuracy, reliability, and applicability across various domains.

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