GUEST EDITORIAL

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Recent Advancement on the Use of Global Navigation Satellite System-Based Positioning for Intelligent Transport Systems

The civil applications of geopositioning are undergoing exponential development. The latest market analysis for global navigation satellite systems (GNSSs) shows two major fields of application which share the majority of the market: intelligent transport systems (ITS), mainly in the road ITS domain, and location-based services, accessible on smartphones and tablets.

The modernization of GPS and Russia's GLONASS system and the development of Galileo and BeiDou are proceeding at a fast pace, introducing improved potential capabilities and higher performance levels for satellite-based positioning, and leading to new architectures for positioning and new strategies for positioning by means of other sensors. GNSSs are considered the superior system to provide accurate and global position, velocity, and time.

However, GNSS technology has its limitations due to the physical principles governing satellite-based position determination, which highly depends on the conditions in which it is used. Therefore, to meet the requirements demanded by ITS services, more complex navigation units must be adopted with the aim to enhance the performance in terms of positioning accuracy, reliability, and continuity of the position. Coupling sensors that have complementary characteristics enhance the performance of the navigation system while simultaneously limiting the weaknesses of each individual sensor.

In addition to classical inertial measurement units (IMUs), such as accelerometers and gyroscopes of high and low grade, different types of sensors and signals are being considered, for example, magnetometers, barometers, lidar, cameras, mobile network signals, and signals of opportunity (SOPs). Such sensors and signals aim to complement GNSS performance. Such integrated navigation systems are the core element for autonomous mobility and, in general, for future connected vehicles.

Despite the fact that hybridization is still part of the core of the positioning architecture, the increased use of satellite-based positioning solutions, such as real-time kinematic (RTK) and precise point positioning, is also posing new challenges to the data fusion algorithms. Furthermore, the 5G communication infrastructure, defining vehicle-to-vehicle and vehicle-to-everything links and protocols, provides an effective networking infrastructure for collaborative and cooperative positioning.

Rail and maritime transportations applications are taking advantage of a widespread use of GNSSs, and advanced solutions for the integration with other navigation systems onboard trains and vessels are under study. Advanced solutions are being devised to increase the navigation accuracy as well as reliability and continuity in challenging environments.

This special issue on recent advancements on the use of GNSS-based positioning for ITSs collects several recent results on the use of GNSSs in ITS applications, exploiting the full potential of the new and modernized constellations. All of the articles were selected after at least a double round of high-quality review by relevant experts in the field, so they include relevant results for a wide range of applications.

The special issue includes 11 articles that span from applications to terrestrial navigation, inland waterways, and aeronautical topics, and they target some of the most relevant challenges currently open to exploit the benefits of GNSS for navigation in ITS applications.

Navigation in urban environments faces the limited visibility

of satellites and the harsh propagation environment generating multiple reflections of the satellite signals as well as fading and attenuations. On the applications side, high reliability and continuity of service is required. The articles included in this special issue present both the reviews and the last mile solutions for sensor integration targeting inertial navigation systems (INSs), lidar, digital maps, and SOPs, thus providing a fairly complete picture of different technological solutions. On the other hand, the critical aspect of granting reliability of the estimated solution by means of integrity evaluation and by exploiting the new features of modernized GNSSs is addressed as well. A second set of articles focuses on safety issues in other environments, discussing emerging technologies and solutions for safe navigation in scenarios other than the urban environment.

The issue begins with a review on the use of positioning sensors, such as GNSS, inertial, and visual sensors for autonomous navigation in the particularly challenging conditions of the Arctic. The authors of the article "Toward Autonomous Driving in Arctic Areas" also analyze multisensor fusing strategies and map-matching algorithms. The quality of the satellite positioning at these high latitudes, its lack of integrity, and the difficulties for proper imaging under poor light conditions and snowy scenes becomes critical to meet the necessary performance demands of autonomous driving. The main findings of this extensive review are that conventional fusion and map-matching approaches are unsuitable for the challenging conditions of the Arctic areas, while the combination of GNSS, INS, and optical sensors promises to be the best way forward.

Also addressing the issue of integrity provision in satellite navigation, "An Experimental Evaluation of Global Navigation Satellite System/Inertial Navigation System-Verification Strategies for Vehicular Applications" focuses on the detection of spoofing attacks against GNSS. The author introduces two techniques, magnitude verification and horizontal components, based on the comparison between uncoupled GNSS and INS data and discusses their challenges and limitations. The analysis after the experimental evaluation shows that integrated solutions are needed to remove outliers, detect zero-speed situations, and adapt properly to vehicle dynamics.

In case the integration with INS is not sufficient to reach the target performance, additional information coming from maps and SOPs can be exploited. In "Robust Vehicular Localization and Map Matching in Urban Environments Through IMU, GNSS, and Cellular Signals," an integration framework based on an extended Kalman filter (EKF) is proposed. It fuses pseudorange observables extracted from cellular SOPs, IMU measurements, and GNSS-derived position estimates (when available). One of the challenging aspects covered in the article is the unknown clocks of SOPs. To address this, the EKF is coupled with a closed-loop map-matching approach to estimate the vehicle's states as well as the difference between the vehicle-mounted receiver clock error states (bias and drift) and clock error states of each cellular SOP. The experimental cases presented show how this solution can be profitable 1) whenever GNSS signals are available, by reducing the vehicle's localization error; and 2) whenever GNSS signals are unavailable, by providing an accurate and stable navigation solution.

The integration with different types of sensors is addressed by two other articles included in this special issue. In "Object-Detection-Aided GNSS and Its Integration With Lidar in Highly Urbanized Areas," the authors also opted for a hybridized solution to support outlier rejection. In their proposal, a lidar point-cloud-based object detection runs in a fault detection and exclusion algorithm capable of removing outliers caused by multipath propagation and non-line-of-sight (NLOS) reception. Measurements from the satellites that are found to be in NLOS are removed from the final solution, thus improving the GNSS solution and its noise features, as demonstrated in the experiments performed by the authors in Hong Kong.

The benefits of vision sensors is discussed in "Vision-Enhanced Low-Cost Localization in Crowdsourced Maps," where an urban scenario with the typical visibility of a small number of visible GNSS satellites and the application of lane-level localization. The authors propose an integrated solution based on a monocular front-facing camera, a low-cost IMU, and a single-frequency GNSS receiver. The original contribution is due to the fact that the camera is not used for inferring the motion of the vehicle but rather for directly correcting the localization results under usage of map information obtained from different public sources.

"GNSS Integrity Monitoring Schemes for Terrestrial Applications in Harsh Signal Environments" addresses challenges in integrity monitoring in urban areas arising due to multipath and NLOS GNSS signal reception, which causes large errors, even up to hundreds of meters in the worst case. Existing integrity monitoring methods have been mainly developed for the aviation industry and, therefore, are not able to handle challenges arising from multipath and NLOS caused by obstacles in the vicinity of the receiver. The article proposes two novel approaches based on monitoring residuals from snapshot weighted least squares and innovations from sequential weighted EKF processing measurements from a low-cost GNSS receiver, which improves the navigation accuracy in urban environments.

Modernized GNSSs provide new features that, if properly exploited, allow for the improvement of the accuracy and precision of the estimated position. In "Analysis of High-Accuracy Satellite Messages for Road Applications" the authors address the problem with road applications getting high accuracy in a short time by means of a GNSS high-accuracy service. The article addresses the design challenges, from the formatting of the messages to the optimization

of the encoding and of the broadcasting. With a proper design, such a service can provide fast convergence and sufficient accuracy worldwide even in low-visibility environments.

Still addressing high-performance GNSS-only solutions, "Deep-Urban Unaided Precise Global Navigation Satellite System Vehicle Positioning" presents a study of vehicular carrier-phase differential GNSS positioning performance in a deep urban setting, without the assistance provided by additional complementary sensors. The system is composed of a densely spaced reference network, a software-defined GNSS receiver, and an RTK positioning engine. A performance sensitivity analysis reveals that navigation data wipeoff for fully-modulated GNSS signals and a dense reference network are key to high-performance urban RTK positioning.

In this special issue, we also address some specific case-studies which, due to the particular environment and scenario-dependent threats, require sophisticated technological solutions. The authors of "Enabling Assistance Functions for the Safe Navigation of Inland Waterways" discuss the development of a positioning, navigation, timing, and integrity method combining GNSS code and phase observations with differential correction data providing centimeter-level positioning accuracy and integrity with reduced solution convergence time. The article also presents a novel approach for the transmission of GNSS data using an automatic identification system combined with GSM protocol. The method enables challenging inland vessel operations, such as bridge collision warning and automatic guidance.

In the aviation sector, robustness must be guaranteed and the increased risk of malicious transmission of GNSS signals (known as spoofing) is one of the most relevant concerns. The article, "An Assessment of GPS Spoofing Detection Via Radio Power and Signal Quality Monitoring for Aviation Safety Operations," discusses two complementary spoofing detection techniques that are available on commercial GPS receivers and thus require no additional hardware to operate. The primary methodology for detection is using the combination of radio power monitoring metrics, levering both automatic gain control and carrier-to-noise density ratio measurements, along with multiple correlations for signal distortion to provide a best practice detection algorithm which is able to distinguish between interference and spoofing. The article first assesses nominal statistics for both metrics compiled from more than 250 h of nominal data collected from multiple wide-area augmentation system stations. This data are compared to previous collections to validate the thresholds and false alarms rates and establish a complete testing methodology. These tests and thresholds are then assessed with the Texas Spoofing Test Battery series of GPS spoofing data sets to confirm detection capabilities. Finally, these test and thresholds are applied to assess the GPS signal of six extended flights over the United States to assess the performance on an aircraft.

The final article, "A Framework for Robust Assimilation of Potentially Malign Third-Party Data, and Its Statistical Meaning," discusses the development of countermeasures against incorrect data, either due to faults in the sensors or GNSS spoofing that would make the ITS fragile. The article proposes two modifications of a particle filter for real-time rejection of potentially faulty measurements. The method is based on the Fisher and Neyman-Pearson statistical testing theories and follows such theories to arrive at different testing procedures when the engineer has a reliable model of faults and when he or she does not. The authors believe that the proposed techniques will help to bring priors obtained from the engineering discipline to the surge of big data and will, therefore, aid in introducing GNSS and other big data to ITS and other built-environment applications.

The guest editors would like to thank the authors, *IEEE Intelligent Transportation Systems Magazine's* Editor-in-Chief Ljubo Vlacic, and the reviewers for the time and efforts they have devoted to provide detailed comments which have contributed to significantly improving the quality of the accepted articles.

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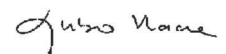
ITS

EDITOR'S COLUMN *(continued from page 4)*

This special issue of *IEEE Intelligent Transportation Systems Magazine* presents the state of the art in fusing one of the most common satellite navigation systems, global navigation satellite systems (GNSSs), with complementary positioning technologies, such as inertial navigation systems, optical sensing technologies, digital maps, cellular signals, and

so forth, to compensate localization errors. The articles deal with GNSS-assisted applications, from terrestrial navigation to inland waterways and aeronautical navigations, including the testing of a self-driving vehicle on Arctic roads during the Arctic winter and under heavy snow conditions.

I am sure you will enjoy reading each of these articles.

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ITS

PRESIDENT'S MESSAGE *(continued from page 5)*

- The IEEE International Conference on Mechatronic and Embedded Systems and Applications has been canceled.

In our uncertain postpandemic world, the public is concerned with large gatherings of people; therefore, virtual events will likely become the

norm. It is very important for the ITS Society to be able to offer top-notch online conferences. I would like to invite you to take part in the upcoming IEEE ITSC and IEEE IV events to share knowledge, learn from each other, expand your reach, and help make this new conference format

successful. We look forward to your participation and input.

Sincerely,

Wei-Bin Zhang
President, IEEE ITS Society

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