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Article

Conceptual Issues Regarding the Development of Underground Railway Laser Scanning Systems

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Abstract: Mobile Laser Scanning (MLS) systems are widely applied for spatial data collection and support applications in many aspects. In recent years, MLS technology had been introduced to railway applications and greatly enhanced the spatial detail and efficiency when compared to traditional approaches. However, the advance of MLS technology is not completely applied to railway environment. Typical MLS systems rely on integrated navigation through the use of Inertial Navigation Systems (INS) and Global Navigation Satellite Systems (GNSS) for geo-referencing, while operation under long-term GNSS outages or even GNSS-free environments, such as underground railway or long tunnels, remains a challenging issue due to the degraded operation of standalone inertial navigation. Commercial MLS systems usually employ high performance inertial measurement units (IMU) and various strategies to manage GNSS outages, but GNSS components are still necessary prior to and after experiencing the loss of GNSS signals. To tackle the problem of permanent GNSS outages, alternative methods are introduced to replace the GNSS and so allow the use of MLS systems in GNSS-free underground railway environments. Such approaches encourage the MLS systems to be developed into the Underground Railway Laser Scanning (URLS) systems, which may provide several alternative operational functions for the management of underground railway operation.

Keywords: mobile laser scanning; underground railway; GNSS outage

1. Introduction

Mobile Laser Scanning (MLS) systems have been developed as rigorous solutions for dynamic spatial data acquisition. In general, MLS systems employ laser profilers, digital frame cameras, and other devices for measurements. The measurements are georeferenced by time-tagged trajectory which is maintained by a Position and Orientation System (POS). Nowadays, commercial MLS systems can be extensively used for engineering topographic surveys, as-built surveys, structures and clearance surveys, deformation surveys, environmental surveys, or urban modeling. The fundamentals of MLS technology have been reviewed in detail [1–3]. MLS systems are also widely applied to railways for rail track surveys, clearance measurements, infrastructure reconstruction and tunnel mapping [4–7]. However, such applications predominantly rely on a POS for navigation, and thus geo-reference performance is diminished with Global Navigation Satellite System (GNSS) outages. Since the systems depend on GNSS conditions, additional control surveys and post-process adjustments are usually necessary to achieve required accuracy. The usability and practicability of applications are limited. Some system configurations have been simplified and decomposed into subsystems and are capable of non-rigorous online applications in railways without inertial navigation [8,9], but the functions are restricted by the system design. To enhance the system performance in underground railways, available information and infrastructure in railway systems are alternatives to replace GNSS components. For example, overhead power lines and gantries, track configuration and alignment data, route assignment information, control and signaling systems, tunnel structures, and platforms can be employed. Furthermore, the development of continuous operation will expand the extent of system applications. This study firstly reviews current solutions for managing GNSS outages and then presents alternative solutions to be incorporated into an integrated Underground Railway Laser Scanning (URLS) system for use in GNSS-free environments. Secondly, the scope of development and application of continuous URLS systems are discussed along with the benefits such a technology would bring to the management of underground railway assets.

2. Solutions for Bridging GNSS Outages

In recent years, some commercial MLS systems such as Optech's Lynx Mobile Mapper, IGI's RailMapper, and Riegl's VMX-450-Rail, have been adapted for railway applications through the use of high-end POS architectures and sophisticated data processing techniques to minimize the negative impact of GNSS outages on data accuracy. These approaches are outlined in the following section. While such systems are appropriate for aboveground railways where GNSS outages may last for certain periods of time, a totally GNSS-free environment exists in underground railway systems. Consequently, alternative solutions are required to replace the GNSS component and are outlined in Section 2.2.

2.1. Current Strategies to GNSS Outages

The majority of land-based MLS systems employ a POS for the estimation of navigation trajectory. Some existing strategies such as various POS architectures, smoothing algorithms, velocity updates, landmark updates, photogrammetric bridging and system simplification are currently adopted to maintain system performance during GNSS outages, which are summarized here.

2.1.1. POS Architecture

There are various ways the Inertial Navigation System (INS) and GNSS may be coupled when forming a POS, with three of them being: loosely coupled, tightly coupled and deeply coupled. Tightly coupled integration is employed by the majority for commercial navigation systems, due to its advantage of utilizing the measurements from less than a sufficient number of satellites for GNSS positioning [1,10]. Nevertheless, the coupling configuration has no effect on the system performance under total GNSS outages. For a totally GNSS-free environment, the architecture should be redesigned to replace the GNSS by coupling the INS with other sources of positioning information.

2.1.2. Optimal Smoothing Algorithm

An optimal smoothing algorithm, such as forward-backward smoothing, or Rauch-Tung-Striebel Smoothing [11], is a post-processing technique adopted by most commercial MLS systems to bridge GNSS outages and reset the INS by combining and smoothing the forward and backward propagation [12–14]. With proper system initialization and finalization with GNSS positioning, centimeter to sub-decimeter level accuracy can be achieved for long periods of GNSS outages by combining other methods [15]. However, undetected errors would still be accumulated during GNSS outages and cannot solve the standalone INS problem independently, especially for a MLS system with a low cost IMU.

2.1.3. Velocity Updates

In addition to the POS architecture, a wheel-mounted Distance Measuring Indicator (DMI) is commonly employed for independent velocity measurements [2], which supports accurate velocity update or Zero Velocity Update (ZUPT) through the INS/GNSS processor. It can be applied in any GNSS conditions, but is important to control the integration drift of the INS during GNSS outages. For specific MLS applications, alternative instruments or techniques are used for the velocity update. While it controls position and velocity drifts, absolute position errors and attitude errors cannot be reset. In railway environments, velocity update is one of the fundamental approaches for positioning the vehicle along the track.

2.1.4. Landmark Updates

To control position errors, Landmark Updates (LMU) are commonly applied to support the MLS navigation by correcting the vehicle position with measurements to landmarks or control features [14,16,17]. This approach is usually implemented with photogrammetric or laser scanning measurements and serves as intermittent Coordinate Updates (CUPT) to maintain accuracy during GNSS outages. The solution is usually post-processed and its accuracy depends on control surveys, MLS system measurements, and the available intervals of control features. Results have shown that the overall accuracy is significantly improved to centimeter level accuracy with 25 m control interval by using commercial MLS systems [15,16].

2.1.5. Photogrammetric Bridging

Photogrammetric bridging is a solution without the need of additional control surveys for landmarks, which is applied to bridge the GNSS outages through relative orientation of image pairs [18–20]. Under normal conditions, INS/GNSS is used for navigation updates and determining the camera Exterior Orientation Parameters (EOP) through the Kalman filter. During GNSS outages, photogrammetric adjustment is capable of updating the EOPs through the relative orientation of stereo-overlapped images for INS error estimation. A similar approach using video imagery is also a common solution for some MLS systems [21,22]. In general, photogrammetric bridging cannot maintain long term accuracy, while its performance is limited by environmental conditions, such as illumination and operation speed. Nevertheless, these criteria are significantly deficient inside railway tunnels.

2.1.6. Simplified Mobile Profile Scanning

For some applications, the MLS systems are decomposed into subsystems and employed for tunnel profile scanning in railway [8,9]. The simplified configuration does not rely on INS for geo-reference, but only reference to local system with respect to rail track. Such a simplified system is combined with railway localization and capable of real-time operation, which is used for monitoring the condition of railway infrastructure.

Although the profile scanning does not depend on GNSS condition and is able to work as a real-time solution, it is not a rigorous solution and is limited to certain purposes. The orientation of the scanning unit is limited in vertical direction to minimize the errors due to reference uncertainty, but attitude variation and train body motion are ignored.

2.2. Alternative Approaches for URLS Systems

The majority of current strategies are implemented with the presence of intermittent GNSS outages. Their performance depends on the duration of GNSS outages, and the quality of the IMU and auxiliary measurement devices. None of them is capable of compensating for the total loss of GNSS data. Instead, alternative methods for GNSS substitution are introduced for the development of URLS. To achieve consistent and reliable performance, the GNSS component has to be replaced by the rail track and other alternatives. This section outlines various possible approaches to the development of GNSS-free URLS systems.

2.2.1. Localized Tunnel Projection

For local referencing, tunnel geometry serves as a nominal constraint for adjusting the navigation trajectory and the mapping data [23]. Since the INS usually maintains short-term precision (depending on the IMU's quality), the relative precision within a segment of point cloud data is sufficient to describe the mapped object. Point cloud segmentation provides independent trajectory adjustment with respect to the tunnel geometry and the entire tunnel is divided into sections for storage and analysis.

The tunnel projection simplifies the adjustment and the representation of measurement results. It is designed for tunnel surveys and works in GNSS-free railways, but does not provide geo-referenced solutions, and absolute accuracy of measurement is not maintained.

2.2.2. Rail-Bound Navigation

Train positioning in a railway system relies on the alignment of the rail, which serves as a continuous control feature for CUPT and substitutes the GNSS component. Since the train movement is pre-defined and bounded by the rail track, the train position tracking is reduced to one-dimensional distance with respect to rail alignment data. The position and orientation of a train is approximately defined through a reference axle if the axle's chainage is accurately determined, as illustrated in Figure 1.

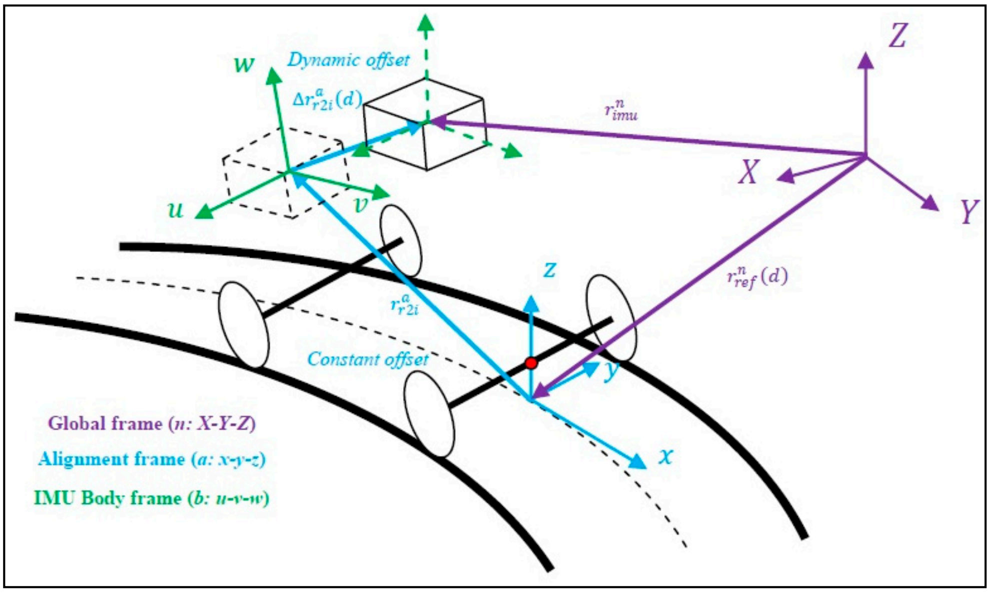

Figure 1. Configuration of Rail-bounded Navigation.

Unfortunately, a train car is not a rigid body and the motion of the reference axle varies with the upper car body where the MLS system components are typically attached, meaning that direct employment of track alignment would introduce additional position errors. Relative motions between the axle and train body are potentially caused by various issues, such as train acceleration, centrifugal force, passenger movements, vibration at track junctions, and rail defects, *etc.* The problem of relative motion between the reference axle and MLS system mount is described by Equation (1). The nominal three-dimensional offset between MLS body center and the reference axle $\mathbf{r}^a_{r2i}$ in alignment frame is calibrated and constant. The dynamic correction $\Delta\mathbf{r}^a_{r2i}(d)$ between MLS estimated position $\mathbf{r}^n_{imu}$ and track alignment estimated position $\mathbf{r}^n_{ref}(d)$ is recorded for updates and adjustment in repeated operations. It is smoothed or modeled by a polynomial with respect to alignment chainage, or recorded at nominal intervals.

$$\mathbf{r}^n_{imu} = \mathbf{r}^n_{ref}(d) + \mathbf{C}^n_a(d)\left(\mathbf{r}^a_{r2i} + \Delta\mathbf{r}^a_{r2i}(d)\right) \quad (1)$$

where $\mathbf{r}^n_{imu}$ is the estimated position of IMU center, $\mathbf{r}^n_{ref}(d)$ is the position of axle from reference alignment, $\mathbf{C}^n_a(d)$ is a horizontal rotation from alignment frame (a) to navigation frame (n), $\mathbf{r}^a_{r2i}$ and $\Delta\mathbf{r}^n_{r2i}(d)$ are the nominal offset and dynamic offset measured in alignment frame, and d is the reference distance which refers to sectional chainage.

2.2.3. Dual-IMU Architecture

In addition to rail-bound navigation, the errors caused by inaccurate track geometry data or inconsistent offsets between repeating runs limit the system performance. This problem is resolved by a dual-IMU architecture using an additional IMU on the reference axle. The processing strategy for this architecture is summarized in Figure 2. The reference IMU processor handles the alignment data and velocity updates, which supports the main processor independently.

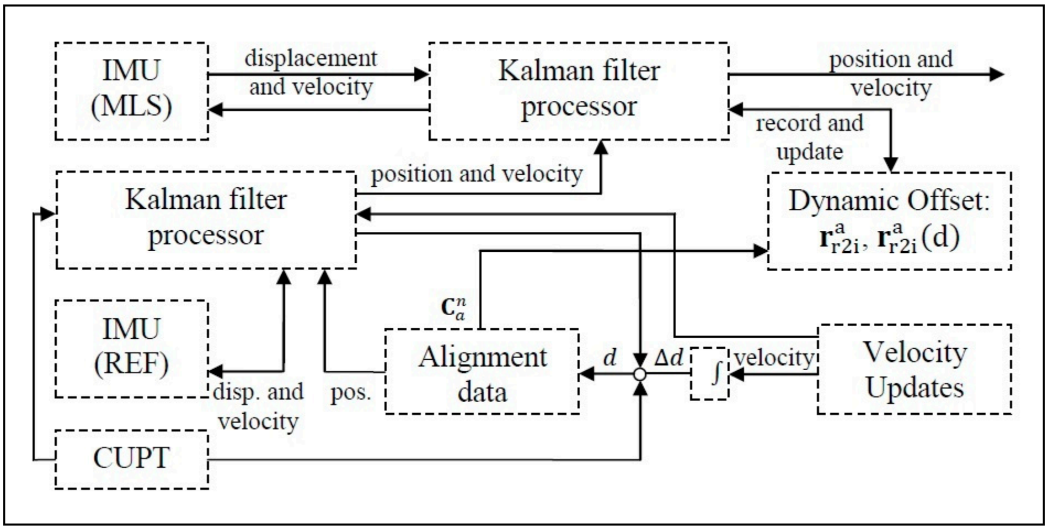

Figure 2. Dual-IMU Architecture.

Although the rail track and alignment data are refined by the additional reference IMU, the train motions caused by various effects of train axle compensators are uncertain. The consistency of navigation accuracy is limited. In addition to attitude and lateral position control from track alignment, the position and velocity errors along the rail track is still uncertain.

2.2.4. Velocity Updates

As mentioned in the previous section, Velocity Updates or ZUPT are important to control the velocity errors of inertial navigation. If the MLS is operated during normal train service, ZUPT can be implemented at stations or temporary stopping before the junctions. It is easily implemented through Kalman filter processors without any requirement of additional equipment for intermittent updates.

For normal trains, tachometers are usually installed for speed measurement and support train-borne positioning (linear distance) through the cumulative distance integrated from speed. Other techniques, such as transponder/balise [24], Doppler RADAR [25], eddy current sensing [26], or inertial measurement are possible methods fulfilling the positioning accuracy for current train operation. Numerous techniques and sensors are applicable for speed measurements with corresponding levels of precision. Simple averaging/weighted averaging, consensus sensing, or Kalman filtering are the possible approaches for the sensor fusion [27].

In addition to the sensor fusion, the patterns of operation speed are applicable for velocity estimation. For normal train service, the acceleration and deceleration of trains are usually gradual to maintain passengers' comfort and operational safety. The navigation control is supported by the knowledge of train speed behavior through its modeling.

2.2.5. Coordinate Updates

To control the growth of position errors, CUPT is implemented by external position information independent of the INS estimation. For general MLS systems, GNSS positioning provides continuous CUPT, which has to be substituted by alternative methods for operation in a GNSS-free environment.

In underground railways, intermittent CUPT is available when the train is approaching a stop at a certain location to allow accurate positioning in the direction of the rail alignment. Since the railway systems follow a regular operation pattern, the temporary stopping positions are approximately known, such as rail junctions and stations. Strips of reflectors can be installed at the stopping zones and are scanned in high-density point clouds when the train decelerates. The scanned targets serve for CUPT and align for point cloud registration. Since the scanned details increase at a lower train speed, a potential improvement in positioning accuracy is expected. In addition, other static positioning methods are also applicable to reset position errors during the stop. The level of position accuracy can reach centimeter level or better depending on accuracy of control information and the choices of alternative methods. Besides static positioning methods, unique vibration patterns from inertial measurements created by junctions and track joints are identifiable from the post-processed trajectory and recorded with position.

To maintain the continuous system performance, CUPT implementation by continuous LiDAR measurement is an alternative. In the railway environment, rail track is the essential feature, which is continuously measurable for URLS. From the scanning data, the two rail tracks are extracted and compared with estimated parameters from reference alignment, such as position of center line, alignment orientation, gradient, super-elevation and rail track offsets. As illustrated in Figure 3, the mismatched position and attitude errors perpendicular to the track alignment are detectable, but errors in the alignment direction are not.

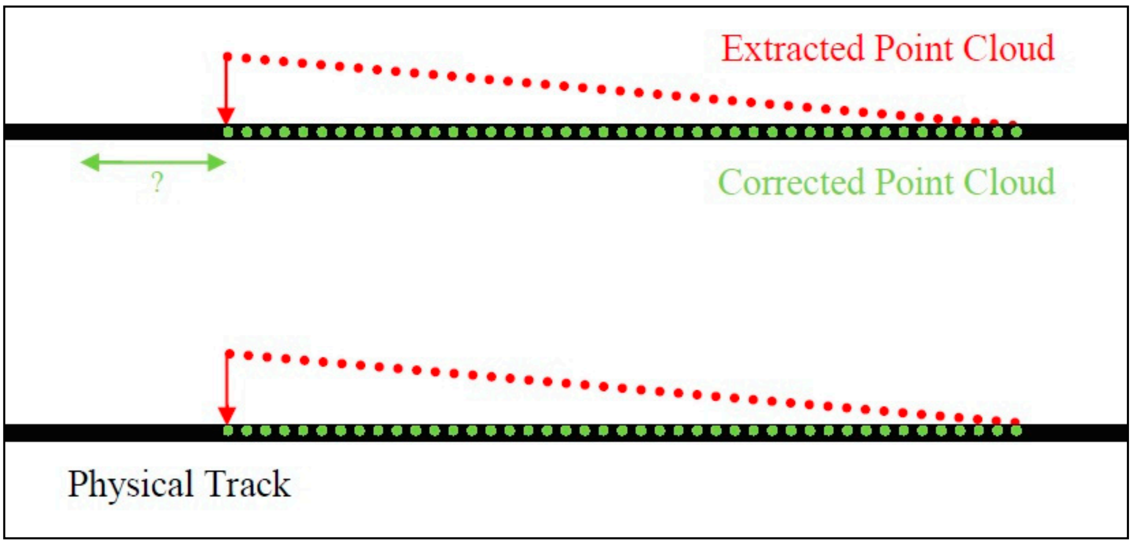

Figure 3. Position Control from LiDAR Data.

A railway's infrastructure, such as railway station platform, trackside instrument or tunnel surface, is stable to be the reference landmark. Certain configuration of laser profilers further improves the results by inter-matching the LiDAR data within a single run as shown in Figure 4. After the first pass, features are extracted from scanning data and act as control features. The features are identified and matched with measurements in repeated runs for semi-continuous CUPT. However, conventional processing approach may not be suitable for on-the-fly operation.

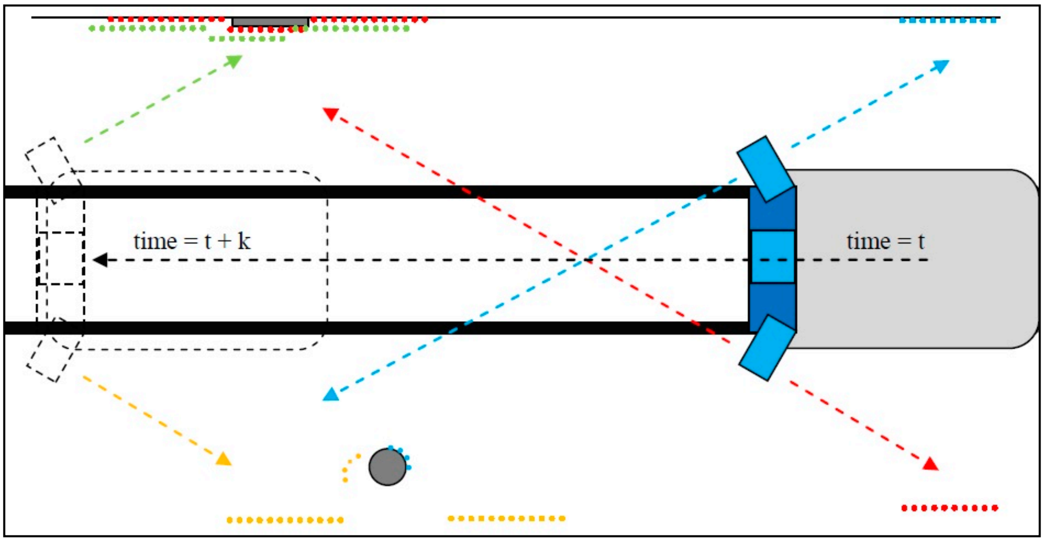

Figure 4. Inter-matching of LiDAR Data.

Simultaneous Localization and Mapping (SLAM) is a technique conventionally applied to robotic or autonomous vehicle systems for real-time applications, which aims at mapping the environment and localizing itself within the map simultaneously. It replaces the CUPT and enhances localization and orientation through the mapping data for MLS systems. The implementation of SLAM is currently emerging and intensively researched [28–31], while the point cloud quality is optimized through Iterative Closest Point-type (ICP) algorithms as illustrated in Figure 4 [30,31].

The SLAM algorithm is an ideal GNSS-free approach for URLS, which can better integrate the navigation estimation and spatial data measurements. The major difficulty of using SLAM in underground railway tunnels is lack of loop closure within a single journey, and so the navigation trajectory strongly relies on inertial navigation quality or pre-surveyed landmarks. As mentioned in previous paragraphs, the rail track can be used as the necessary landmarks. Other unique and identifiable infrastructures are also applicable in the SLAM process.

2.3. Integrated Approach for URLS

To develop the URLS system, rail track geometry and the train movement estimation are the main issues for navigation control. Although there are various shortcomings for individual approaches, the potential performance of the system would be further enhanced through their integration.

The integrated approach is simplified and illustrated in Figure 5. Independent fusion and adjustment for various sources of velocity measurements (1) serves for precise chainage estimation and velocity updates of INS. The correction from designed alignment data to physical track alignment is estimated through rail-bound navigation approach (2). The refined alignment describes the rail track orientation and position, and is utilized for continuous CUPT through laser scanning measurements or implemented through SLAM (3). Supplementary intermittent CUPT can be implemented through landmarks or vibration patterns from inertial measurements (4), while any stationary positioning method (5) is also integrated to the processor for accuracy enhancement. However, the fundamental architecture for URLS process involves various sub-systems, which may be too complex for real-time operation.

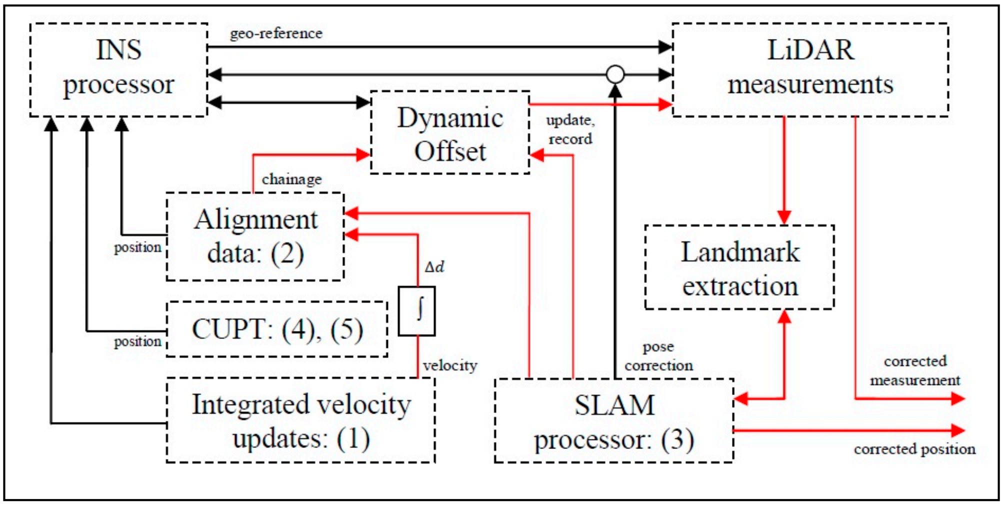

Figure 5. Simplified Architecture for URLS.

To enhance the real-time availability, the configuration of an URLS system can be decomposed and simplified by dropping and replacing the inertial navigation by alternative components. Low cost Mobile Mapping solution has demonstrated the quality of simplified direct geo-reference solution by single frequency GNSS receiver, one axis gyroscope and odometer [32]. To simplify the URLS configuration, the positioning and orientation tracking is replaced by the rail-bound navigation with integrated velocity updates. The simplified approach is represented in Figure 5 by the processing paths depicted in red.

3. Potential Development and Applications

The previous sections outline various approaches to replacing the GNSS component in an Underground Railway Laser Scanning system. Apart from the intrinsic use of an URLS system in recording the rail system in point cloud form, such a system has the potential to enhance underground railway operations in other ways. Some of them are introduced in the following sections.

3.1. Real-Time or Near Real-Time Monitoring

After the establishment of railway point cloud database, the URLS has the potential to maintain its functions without relying on inertial navigation as mentioned. The rail tracks and/or the over-head power cables are the continuous features to assist the preliminary trajectory recovery in alignment frame and maintain the relative accuracy of point cloud data. Hence, the tunnel conditions such as the main structure and the existence of unexpected objects are immediately inspected before post-processing. The SLAM-based approach solely requires the laser scanning devices and velocity information such that continuous tunnel monitoring and train positioning are conducted in real-time and refined by sectional key point registration with a database. The point cloud data can be directly transmitted to a control center for post-processing and structural analysis, or temporarily stored on board for real-time visualization and condition monitoring.

In addition to the existing tunnel monitoring systems, a URLS can open up an integrated solution for mapping and monitoring most of the underground infrastructure by a single measurement system, such as tunnel structure, rail track, overhead cable, point machine, wayside equipment, *etc.* It may replace part of the existing monitoring systems, or extend and visualize different monitoring results. Moreover, URLS would provide a dynamic solution for improving the availability and the flexibility of railway monitoring.

3.2. Train-Borne Hazard Detection

Different methods for train-borne obstacle detection have been extensively studied in computer vision or related aspects [33–36]. In addition, research has illustrated the efficiency of train collision detection using the MLS technique [37], which is a more comprehensive and multi-purpose solution. Collision detection is not the only function of URLS, nevertheless, the conditions of different sections of the railway tunnel are simultaneously monitored by any train equipped with URLS systems; the risk of collision with trackside objects or equipment damages would be better assessed through their use. URLS systems provide an alternative to achieve a higher level of service reliability and safety through risk management and hazard detection in railway operation.

3.3. Train Localization

The method for train localization is a critical issue for safety and train regulation in railway systems. Traditional methods usually rely on trackside equipment for back-up solutions that are costly to install and maintain. Modern signaling systems requires dynamic train positioning to facilitate the efficiency with moving block signaling control, which is implemented by train-borne localization methods or train detection with loops.

A real-time URLS solution is an alternative to current train localization methods, which supports the train positioning with surrounding spatial measurements. Such a characteristic is particularly useful when the railway signaling system has failed. It can aid the train to localize itself for system initialization. In the meantime, URLS systems have the function of train detection to prevent rear-end collision under a diminished mode of train operation.

3.4. Train Control Automation

The train control and signaling system is a vital and key component to modern railway systems, which provides the fundamental signaling, control and protection to trains and interface to the supervision of train network for safety and efficiency. Advanced Train Control System (ATCS), Chinese Train Control System (CTCS) or European Train Control System (ETCS) are the examples of national standards designed to unify the safety systems for railways. The standards are usually specified at different levels according to the integrity of train control and supervision.

For underground railways, the degree of automation is a critical issue to railway operation, since the operation safety, line capacity and service stability have to be maximized by rigorous train control and supervision. URLS systems support the automatic train control by detection and identification of obstacles, which makes it possible to support driverless train operation or unattended train operation.

4. Conclusions

In this study, the concept of a GNSS-free URLS system that aims at replacing GNSS components and integrating the MLS and underground railway systems was introduced. Current strategies for GNSS outages were briefly reviewed and modified for the GNSS substitution. In order to minimize the deficiencies, an integrated approach is suggested for the configuration of URLS, which is possible to be simplified into real-time approach without inertial measurements. It is believed that the URLS solution would enhance the safety and management of underground railway systems with applications such as the improvement of monitoring systems, assisting train automation, and in safety enhancement. In addition, URLS can act as an example for the further development of self-contained GNSS-free MLS systems in general.

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Author Contributions

The first author is the main author of the article and was responsible for much of the conceptualization presented. The second author clarified the direction of the research, prompted discussion on the concepts, and provided editorial assistance. The third author contributed to the development of the system architectures.

Conflicts of Interest

The authors declare no conflict of interest.

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