STRATEGY ON HIGH-DEFINITION POINT CLOUD MAP CREATION FOR AUTONOMOUS DRIVING IN HIGHWAY ENVIRONMENTS

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KEY WORDS: High-Definition Map Creation, Multi-Sensor Fusion, Mobile Mapping System, Autonomous Driving, Navigation Estimation.

ABSTRACT:

In recent years, a lot of researchers have been trying the development of efficient ways to create HD maps with centimeter-level precision. Mobile mapping system (MMS) produce 3D HD point cloud map of the surrounding by integrating navigation (i.e., direct georeferencing or DG process) and high-resolution imaging sensor data. Unfortunately, in partially environments, the provided accuracy of the GNSS system degrades dramatically. In order to constraint the drift and correct the georeferenced point cloud map, ground control points (GCPs) are placed along the road. Moreover, there are approaches which use laser-based point cloud registration techniques to construct the point cloud map. However, all promising mapping techniques which currently use the laser as the core sensor for mapping the high-definition point cloud map may not be promised to construct the point cloud map in partially or unfriendly environments. As a literature review and result, a suitable approach for creating the promising point cloud map is to combine the INS/GNSS navigation solution, LiDAR matching techniques, and GCPs. Thus, this study introduces the HD point cloud map generation method that can potentially help researchers create personalized and globalized HD point cloud maps and develop new HD point cloud map generation methodologies.

1. INTRODUCTION

A high-definition (HD) map provides detailed environmental information and gives driving instructions to the autonomous driving (AD) vehicles (Bao et al., 2023). HD map helps localization, detecting and planning of AD vehicles in combination with inertial measurement unit (IMU), global navigation satellite system (GNSS), and (LiDAR). With the remarkable improvements in sensor technologies and data processing methods in recent year, HD map for AD vehicles have been well-known for their high precision than a traditional map. In recent years, a lot of researchers have been trying the development of efficient ways to create HD maps with centimeter-level precision. Mobile mapping system (MMS) produce 3D HD point cloud map of the surrounding by integrating navigation (i.e., direct georeferencing or DG process) and high-resolution imaging sensor data (Ilci and Toth, 2020). Unfortunately, in partially or GNSS-challenging environments, the provided accuracy of the GNSS system degrades dramatically. In order to constraint the drift and correct the georeferenced point cloud map, ground control points (GCPs) are placed at 2 to 4 points within 1 km along the road (Tsushima et al., 2020). For this case, the surveyed accuracy of GCP plays an important role. Moreover, there are approaches which use laser-based point cloud registration techniques, such as normal distribution transform (NDT) to construct the point cloud map (Kato et al., 2015; Jeong et al., 2022). However, all promising mapping techniques which currently use the laser as the core sensor for mapping the high-definition point cloud map may not be promised to construct the point cloud map in partially or unfriendly environments (Bao et al., 2023). As a literature review, a suitable approach for creating the promising point cloud map is to combine the INS/GNSS navigation solution, LiDAR matching techniques (e.g., NDT, iterative closest point or ICP), and GCPs. Thus, this study introduces the HD point cloud map generation method that can potentially help researchers create personalized and globalized HD point cloud maps and develop new HD point cloud map generation methodologies. Moreover, point cloud pre-processing algorithms (i.e., point cloud un-distortion and moving objects removal) also introduce to ensure the actual and usable measurements of point cloud for point cloud map generation.

The contributions of this study are as follow:

1. Point cloud un-distortion with INS/GNSS navigation solutions-assisted approach;
2. Moving objects removal (MOR) with road lane parameters-assisted approach;
3. Alternative ground control points (GCPs) sources for HD point cloud map correction;
4. Precise HD point cloud map for AD applications in highway scenario.

The rest of this study is organized as follows. Section II presents the high-definition point cloud map generation workflow; data collection, point cloud pre-processing, point cloud map generation, and point cloud map correction. Section III describes experiment setups. Section IV presents the results and discussion. Finally, the conclusion is presented in Section V.

2. HIGH-DEFINITION POINT CLOUD MAP GENERATION WORKFLOW

In this study, we mainly focus on generating high-definition point cloud map for autonomous driving applications in highway scenario. As shown in Figure 1, the process contains data collection, point cloud pre-processing, point cloud map generation, and point cloud map correction.

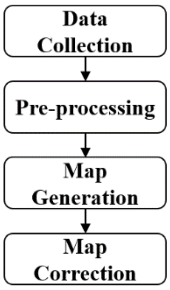


Figure 1. Workflow of HD point cloud map generation.

2.1 Data Collection

This is the first step in creating HD point cloud map. In this study, data collection is done using a mobile mapping system (MMS). As shown in Figure 2, our MMS is a mobile vehicle attached with mapping and navigation sensors, including IMU, GNSS and LiDAR, to collect geospatial data. The collected data contains 3D real-world data, including INS/GNSS navigation solutions, and 3D point clouds.

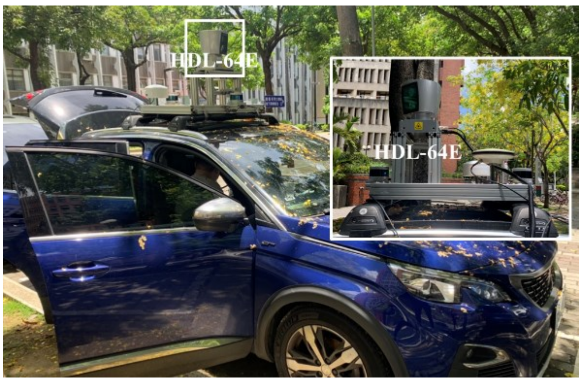


Figure 2. Mobile mapping system (MMS).

2.2 Point Cloud Pre-processing

At the data collection stage, the vehicle runs at a high speed of 70-90 km/h and takes 360-degree LiDAR scans in an interval of every 2.5 m in this highway environment. Inevitably, LiDAR scan of point cloud would be affected with the motion distortion and contaminated with the unwanted object points (e.g., moving objects). Therefore, LiDAR point cloud need to be properly pre-processed before passing raw LiDAR data through further mapping steps. In this study, we introduce our developed algorithms for un-distorting LiDAR scan of point cloud and removing the moving objects (e.g., moving cars and trucks).

2.2.1 Point Cloud Un-distortion: Mounting the LiDAR on a moving platform will change distances to objects in the scene during scanning, resulting in a distorted point cloud (Mounier et al., 2023). As shown in Figure 3, the raw point cloud differs from the actual because LiDAR measurements are referred to the sensor frame's first position at the start of the scan. With aiding of an accurate position and orientation system (POS) from tightly coupled (TC) INS/GNSS navigation solution and geometric relationship of navigation sensors, an undistorted point cloud can be timely compensated and precisely performed. The major difference of undistorting point cloud in this study compared to previously proposed methods is that the accuracy of POS. Instead of using the predicted POS from LiDAR-SLAM or filtered POS from Kalman filtering (KF)-based method, in this study we utilized the smoothed POS from tightly coupled INS/GNSS integration system which is much more precise and accurate POS.

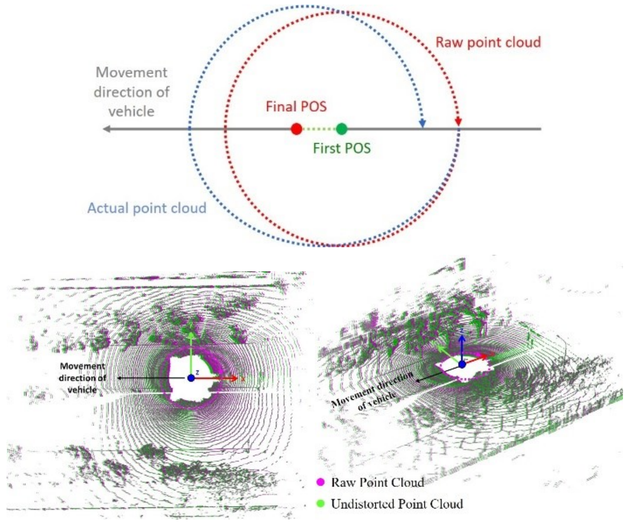
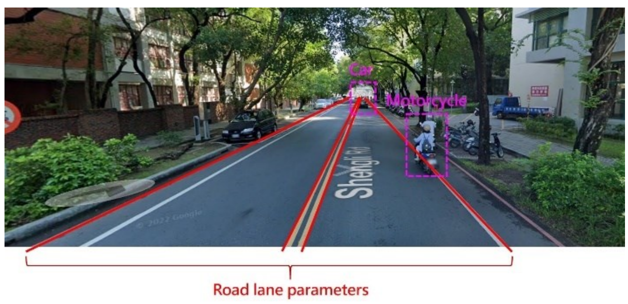


Figure 3. Effect of motion distortion on LiDAR scan.

2.2.2 Moving Object Removal (MOR): To detect and exclude moving object out of LiDAR point cloud on the road, we proposed the road lane boundary-assisted MOR approach instead of using recent deep learning-based dynamic removal as demonstrated in Figure 4. The basic concept of removing those moving objects is that all above the ground plane within road lane are considered as unwanted or moving objects and need to be removed before further processing steps.



(a) Road lane boundary-assisted MOR algorithm

This contribution has been peer-reviewed.
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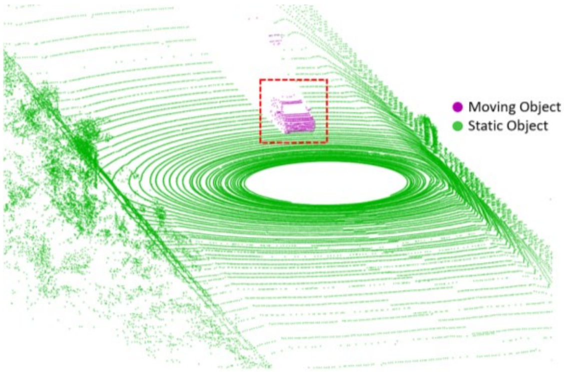

(b) Unwanted or moving object (e.g., car) vs static objects in highway environment

Figure 4. Road lane parameters-assisted moving objects removal.

2.3 Point Cloud Map Generation

Generally, point cloud map generation techniques can be classified into online and offline. In this study, the map is created offline after data collection and pre-processing steps. Figure 5 shows the detailed flowchart of the proposed mapping process in this study. In summary, after the LiDAR scan of point cloud is pre-processed, a direct geo-referenced (DG) point cloud is obtained to construct the point cloud map. Regarding the vehicle runs at a high speed of 70-90 km/h, it is difficult to continually obtain and promise an accuracy of navigation solution from INS/GNSS integration system at long distances and challenging environment like highway. On the other hand, there are approaches which use laser-based sensors to construct the point cloud map using point cloud registration techniques. However, all promising mapping techniques which currently use the laser as the major or core sensor for mapping the high-definition point cloud map may not be able or promised to construct the point cloud map at featureless or unfriendly environments. Hence, a suitable approach for creating the point cloud map is to combine the INS/GNSS navigation solution and LiDAR matching techniques (e.g., normal distribution transform). The main idea of utilizing LiDAR matching is to refining an accuracy of navigation estimation obtained from INS/GNSS system in some circumstances. In order to detect and isolate the registration failure, accuracy assessment is also implemented in this mapping process.

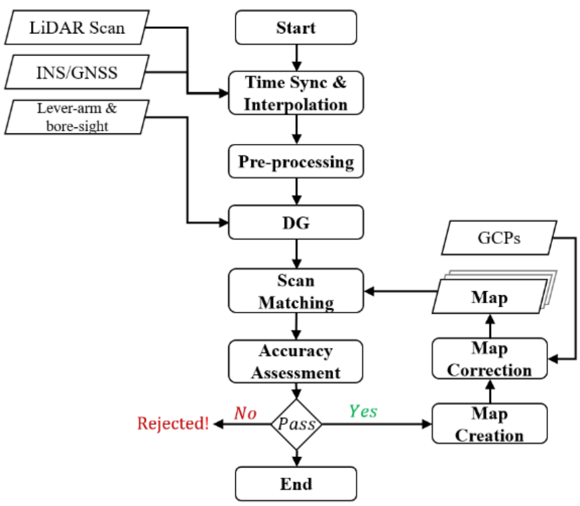

Figure 5. Proposed strategy on HD point cloud map creation.

2.3.1 Direct Geo-referencing (DG): Figure 6 depicts the geometric relationship of navigation sensors we assembled on a land-based mobile mapping system (MMS). With aiding of an integrated INS/GNSS navigation solution in Cartesian mapping frame (*m*-frame), the direct geo-referencing of LiDAR measurements at epoch time (*t*) on a land vehicular platform can be expressed as follows:

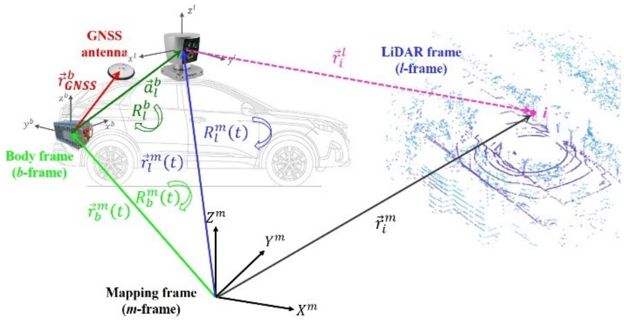

Figure 6. Direct geo-reference (DG) for LiDAR measurements.

$$r_i^m = (r_b^m)_t + (R_b^m)_t(R_l^b \cdot r_i^l + a_l^b) \quad (1)$$

where r_i^m = transformed coordinates of *i-th* point in *m*-frame
$(r_b^m)_t$, $(R_b^m)_t$ = translation vector and rotation matrix in *b*-frame with respect to *m*-frame
a_l^b, R_l^b = translation vector (lever-arms) and rotation matrix (bore-sight) of *l*-frame with respect to *b*-frame
r_i^l = local coordinates of *i-th* point in *l*-frame

2.3.2 LiDAR Scan Matching: There are numerous LiDAR scan matching techniques have been recently proposed over the past decades. However, the normal distribution transform (NDT) scan matching technique seems to provide more robust and accurate pose estimate among other techniques particularly the iterative closest point (ICP) variants (Magnusson, 2009). As of these benefits, NDT has been chosen to be our LiDAR scan matcher in this study. Figure 7 demonstrates the result of INS/GNSS-aided NDT scan matching in highway environment.

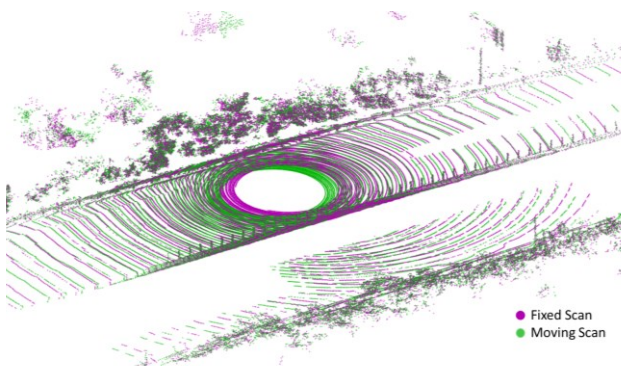

Figure 7. NDT scan matching result in highway environment.

2.4 Point Cloud Map Correction

To establish an accurate HD point cloud map for further steps in HD map production (e.g., vector map generation), correction step of point cloud map needs to be considered. In this study, ground control points (GCPs) for the 3D point cloud data are collected and placed at 4 points within 1 km along the road. The accuracy of GCPs are less than 7 cm and 10 cm in horizontal and vertical components, respectively.

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3. EXPERIMENT

To verify the proposed strategy on HD point cloud map creation, highway environment is intentionally considered in this study. An environment was a highway road section under open-sky and high speed of vehicles, where feature points could not be sufficiently used for the LiDAR-registered POS estimation in most areas. The following section describes the equipment used and the experimental area in detail.

3.1 Equipment Description

To establish a reliable INS/GNSS navigation solutions for HD point cloud map creation, the Inertial Explorer (IE) Version 8.9 software program (NovAtel, Calgary, Alberta, Canada), which is a commercial INS/GNSS software program was used. The navigation solution (i.e., POS) included a navigation-grade IMU (iNAV-RQH), a GNSS receiver, and an antenna (PwrPak7). The POS was post-processed using the TC scheme with the forward and backward smoothing process. The IMU specifications are presented in Table 1. A Velodyne sensor (HDL-64E S3) was used for our LiDAR mapping. The specifications of the HDL-64E S3 sensor are presented in Table 2. Figure 8 illustrates our experimental car in this study.

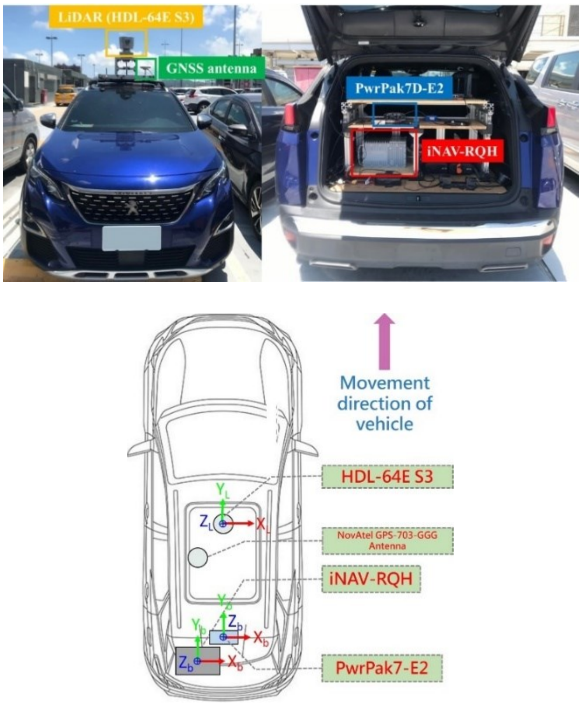


Figure 8. Experimental platform.

	Accelerometer	Gyroscope
Bias Instability	$< 15\ \mu g$	$< 0.002°/\ hr$
Random Walk Noise	$8\ \mu g\ /\ \sqrt{Hz}$	$0.0018°/\ \sqrt{hr}$

Table 1. Specifications of IMU (iNAV-RQH).

Specifications	HDL-64E S3
Max. Measurement Range (m)	120
Accuracy (cm)	±2.0
Field of View:	
- Vertical	+2.0° to -24.9°
- Horizontal	360°
Angular Resolution:	
- Vertical	0.4°
- Horizontal/Azimuth	0.08° to 0.35°

Table 2. Specifications of LiDAR (HDL-64E S3).

3.2 Scenario Description

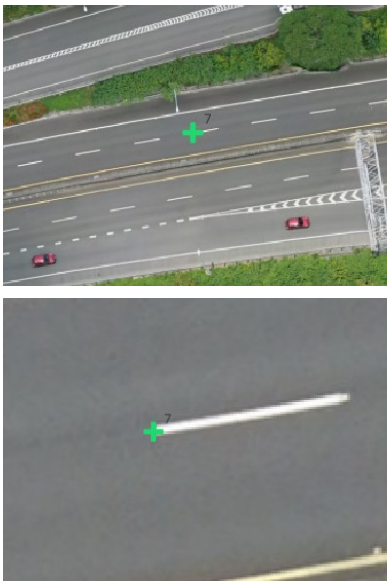
As presented in Figure 9, a highway environment under open-sky was selected to evaluate the influence of speedy movement of vehicle on the proposed method. The movement direction of vehicle was travelled from East-to-West. The traveling distance in this scenario was approximately 6 km. Regarding the sufficient appearance of point cloud was limited, the LiDAR-based pose estimation may have been negatively affected by the sparsity of point clouds.

Figure 9. Experimental environment.

3.3 GCP Description

Although GNSS coordinates could be obtained in the highway environment (open-sky), maintaining a high POS accuracy for direct geo-referenced point cloud map creation was difficult with the high speed of vehicle used and other conditions involved. Correction of point cloud map is needed. However, regarding the limitation of physically establishing GCPs on site and highway regulations such as costs and safety concerns, alternative GCP sources could be considered. The unmanned aerial vehicle (UAV)-assisted GCPs was introduced in this study as shown in Figure 10.

(a) UAV photogrammetric map with selected GCPs (green points)



(b) Enlarged view of establishing GCP on the road's center line

Figure 10. Establishing UAV-assisted GCPs in this study

4. RESULTS AND DISCUSSION

The experimental results obtained in the highway scenario is presented in this section. The main aim of this study was to evaluate point density, effect of motion distortion compensation, MOR, and map correction.

4.1 Point Cloud Density

According to the criteria of the manual of public survey in Japan, the minimum point cloud density is defined as 400 pts/m^2 or more are required (Tsushima et al., 2020). Figure 11 illustrates that the appearance of our point cloud density for large-scale HD map is roughly 800 pts/m^2 (only a single leg from East-to-West direction). However, in order to obtain more accurate data in the process of 3D plotting and other HD map generation's purposes, the point density is preferably 1,000 pts/m^2 or more.

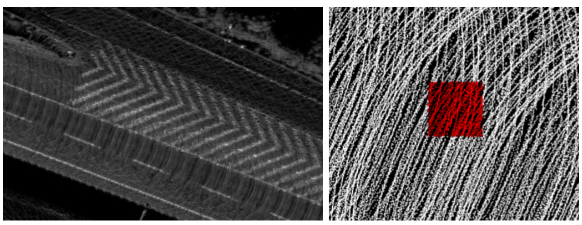
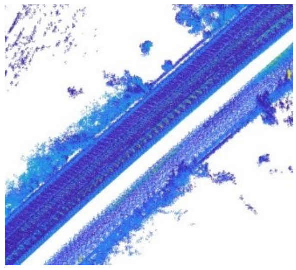


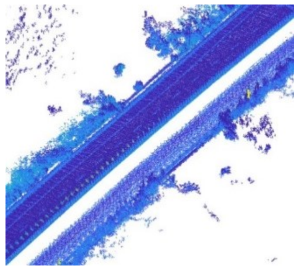
Figure 11. Verification of point cloud density in highway.

4.2 Effect of MOR

As shown in Figure 12, proposed MOR algorithm greatly provides more clearer point cloud data. However, some noisy or moving object points are still remained, due to the poorly defined road lane parameters and limitation of MOR algorithm in some areas. Thus, manual manner of MOR is still needed afterward.



(a) Before MOR



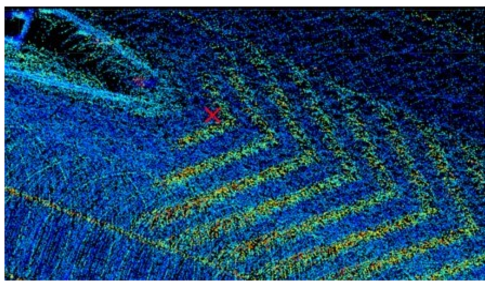
(b) After MOR

Figure 12. Effect of MOR algorithm

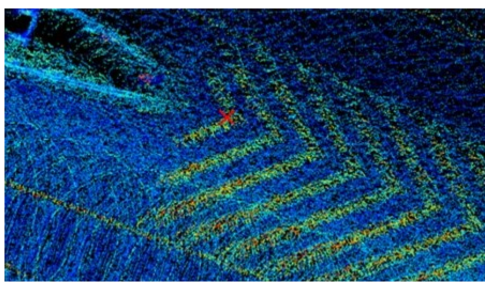
4.3 Effect of Map Correction

Figure 13 illustrates the created point cloud map (before correction) and corrected point cloud map (after correction). To obtain transformation parameters (i.e., scale factor, translation vector and rotation matrix), at least 4 corresponding points between GCPs (indicated by red cross) and point cloud features (road markers) are utilized for each strip map (~1 km). As presented in Figure 13(a), the created map exhibited 3D positioning differences of less than 0.40 m compared with GCPs. The maximum positioning difference was noted in the easterly direction (i.e., movement direction of vehicle or along-track direction), followed by the north and height directions, respectively. The root mean square errors (RMSE) of the positioning differences in the east, north, and height direction were approximately 0.396, 0.236, and 0.043 m, respectively. Obviously, no significant offset problem was noted in the height information obtained with the created map and the TC-INS/GNSS integration scheme seems to provide the underestimated position in the along-track direction (Srinara et al., 2022).

As displayed in Figure 13(b), after map correction, the corrected map exhibited 3D positioning differences of less than 0.10 m. While the corrected HD point cloud map is depicted in Figure 14 and Figure 15.



(a) Before correction



(b) After correction

Figure 13. Map correction

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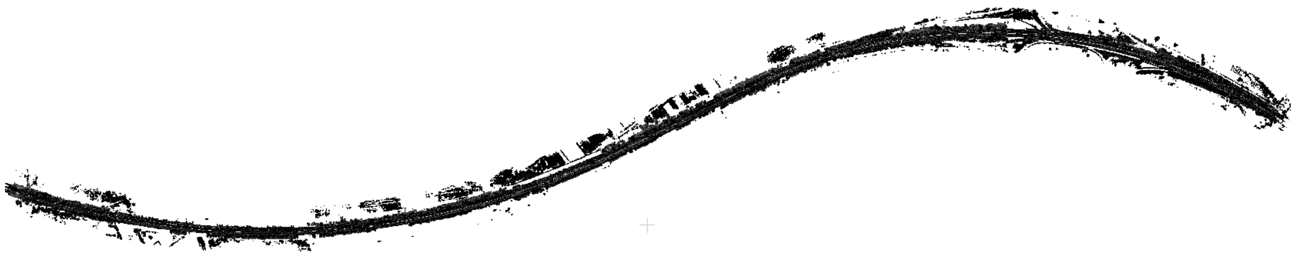
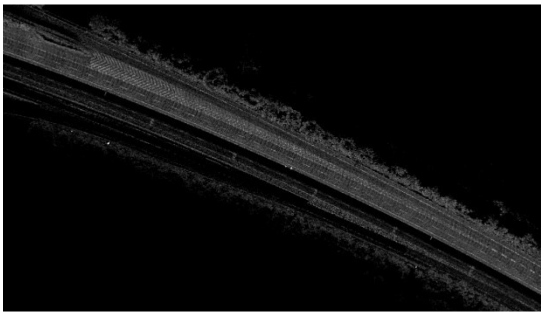


Figure 14. HD point cloud map after map correction

(a) 2D UAV photogrammetric map



(b) Enlarged view of 3D LiDAR point cloud map

Figure 15. Comparison of 2D UAV photogrammetric map and 3D LiDAR point cloud map

5. CONCLUSIONS

This study proposes a strategy on HD point cloud map creation for autonomous driving in highway environment. As a result, a suitable approach for creating the promising point cloud map is to combine the INS/GNSS navigation solution, LiDAR matching techniques, and GCPs. In summary, the proposed strategy outperforms standalone or conventional methods, particularly in terms of map accuracy. The high accuracy of the corrected HD point cloud map of less than 0.10 m can be obtained. The proposed strategy structure is suitable for researchers to potentially create their personalized and globalized HD point cloud maps. Moreover, point cloud information is critical to the 3D plotting, vectorization and other HD map production, thus, effect of motion distortion and moving object removal need to be improved. However, in the future, the proposed method and system should be tested in various other scenarios. Future studies can establish a full-HD point cloud map creation to obtain more reliable 3D information for achieving a high-performance level in fully autonomous driving.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by the Ministry of Interior (MOI) in Taiwan. We also thank the editor and anonymous reviewers for their constructive comments on this paper.

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