様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）On Multilevel Road Mapping for Autonomous Vehicles: A Study to Generate Accurate 2.5D LIDAR Maps Using Graph SLAM in Challenging Environments

研究課題名（英文）On Multilevel Road Mapping for Autonomous Vehicles: A Study to Generate Accurate 2.5D LIDAR Maps Using Graph SLAM in Challenging Environments

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　3,500,000円

研究成果の概要（和文）：1年目は主に困難な環境での正確な 2.5D マップの生成に取り組みましたが、2 年目は多層道路構造に対処して、階層化された道路コンテキストをグローバル座標系で正確に位置合わせすることが目標でした。したがって、標高画像はマッピング システムに統合され、路面画像の高度値を示しています。ループ クロージャ モジュールは、標高情報に基づいて道路層を自動的に検出して区別するように変更されました。したがって、XY 平面で路面画像の位置を最適化し、検出されたループ クロージャでの標高エラーを最小限に抑えて、XY 平面と Z 平面でのグローバル マップの一貫性と一貫性を確保するためのコスト関数が開発されました

研究成果の学術的意義や社会的意義
The proposed mapping system outperformed an accurate GNSS-RTK systems to generate precise 2.5D maps in challenging multilevel environments such as Bejoji and Ohashi junctions and accurately combine maps that collected by different agents to increase the safety and accuracy of autonomous driving

研究成果の概要（英文）：Generating precise 2.5D maps in challenging environments was mainly addressed in the first year whereas dealing with multilevel road structures to precisely aligning the layered road context in the global coordinate system was the goal in the second year. Thus, the elevation images have been integrated into the mapping system to indicate the altitudinal values the road surface images. The loop closure module has been modified to detect and distinguish the road layers based on the elevation information automatically. Accordingly, the cost-function was developed to optimize the positions of the road surface images in the XY plane and then minimize the elevation errors at the detected loop-closures and ensure the global map consistency and coherency in XY and Z planes. The cost function has then been modified to combine maps in terms of updating the road surface representation, expanding the encoded areas and adjusting the map global position for precise localization in the real world.

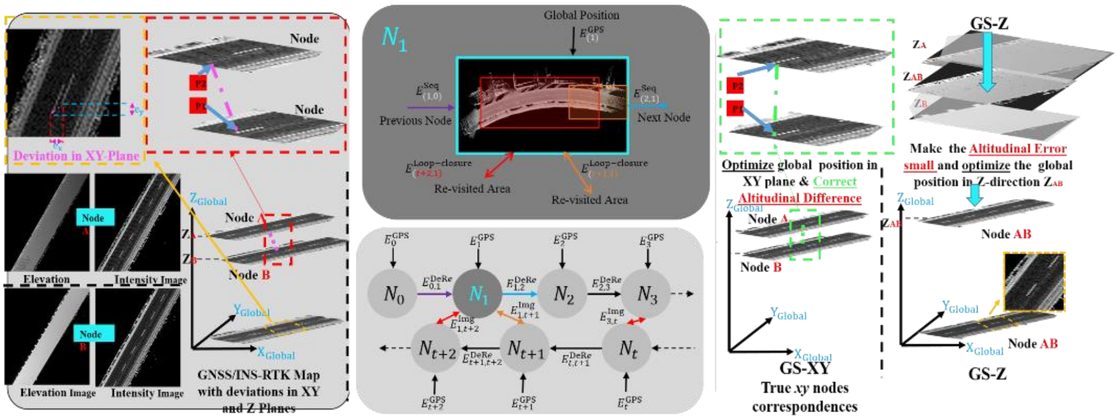
研究分野： Autonomous Vehicles

キーワード： Graph SLAM　Autonomous Vehicles　Mapping Systems　LIDAR

１．研究開始当初の背景

Generating accurate LIDAR maps in the XY and Z planes is very important to bring autonomous vehicles into reality and marketplace. The controlling maps must be very accurate in terms of positioning the roads with respect to the real world and encoding the corresponding environments in high definition level. SLAM technology is a very promising concept to increase the map accuracy. However, integrating such technique to the mapping module is very difficult and challenging in order to obtain reliable results. The researchers are usually try to apply SLAM and generate the full map in XY and Z directions at once. This is a wrong tactic because of including the altitudinal and high environmental features. This increases the data size and decreases the effciency of applying any matching algorithm between the point-clouds to recover the relative-position errors. This is because of that the open-sky areas such as wide road segments, highways and roads between cities are featureless environments in the Z direction. In addition, the high environmental features in the urban areas may affect the matching techniques because of encoding temporarily stopped vehicles and preventing the encoding of the true static features. For example, a row of cars stopped at a traffic signal and encoded in the first visit/scan of the environment by the robotic vehicle during the map-data collection. The robotic vehicle visits the area second time and may either encode different pattern of the car distribution or the true static environmental features because of green-on period. In the both cases, matching each one to first scan point-clouds will lead to wrong results because of the huge change in representing the same environment. Therefore, researchers try to compensate the 3D relative-position in XYZ plane at once.

２．研究の目的

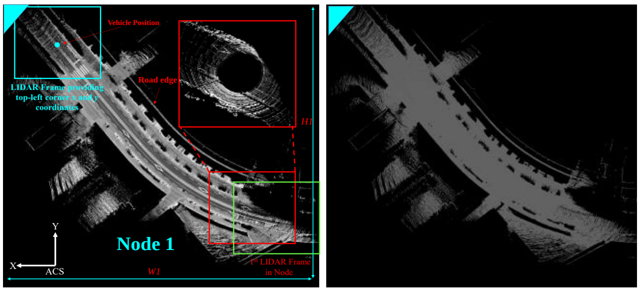


D: Map Distortions in XYZ using Satellite Positioning System (GNSS/INS-RTK)　　E: Designed SLAM Concept in Intensity Image Domain　　F: Applying SLAM in XY Plane and then in Z Plane

We broke down the problem of applying Graph SLAM into two phases. First is to apply GS in the XY-plane using only the road-surface landmarks. This is because of that these landmarks are fixed and less subject to change than the altitudinal/high features. By doing so, the same road segments (that encoded by many visits of the same area) at each loop-closure event are brought to the same area in the XY-plane with compensating the xy-relative-position (eliminating the ghosting effect) and publishing the map in the real world accurately with compensating the global errors. Accordingly, the correspondences in XY-plane can be determined accurately and compensating the z-relative errors can be achieved by applying Graph-SLAM in Z-plane to make the relative-errors as small as possible.

３．研究の方法

Maps are divided into two maps: intensity and elevation. The intensity map is used to represent the road surface in XY-plane whereas the elevation map represents the corresponding altitudinal value of each point in the road surface map in the Absolut coordinate system.

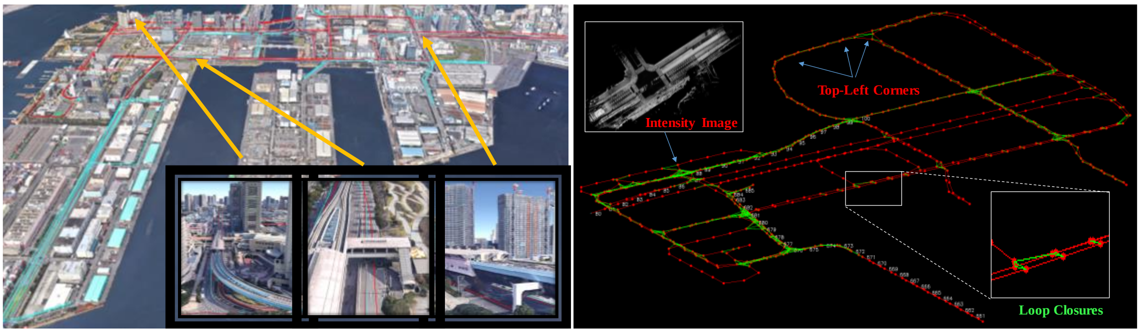


To create intensity map, the road surface should be the dominant stationary component to compensate the relative-position errors in XY-plane. One may claim that the road surface may not well painted in some segments. Therefore, the point-cloud is cut at height of 30cm to encode road-surface and the surrounding environments in a 2D image called “*LIDAR intensity-frame*”. This value is chosen to encode curbs, road edges and lower parts of trees, traffic signals, poles, barriers and traffic lights. The altitudinal values of the cut features are simultaneously encoded in individual image/matrix called *LIDAR elevation frame*.

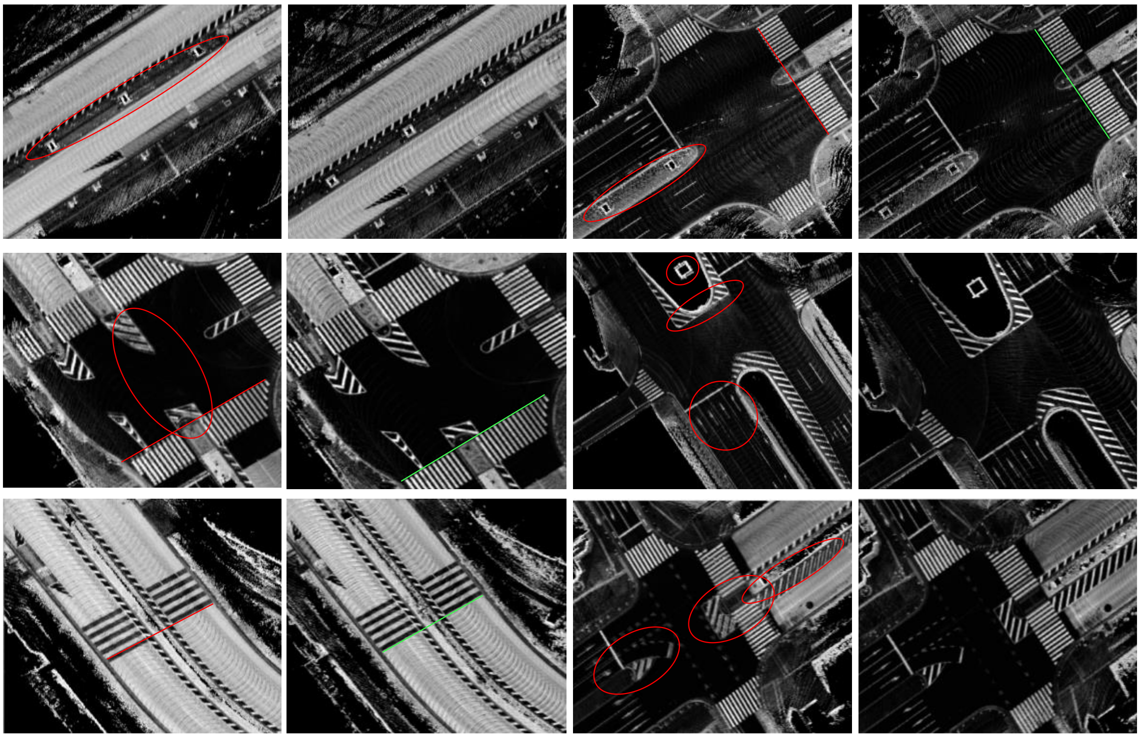
In order to solve the problem of LIDAR sparsity and compensate the relative-position errors, a node strategy is invented. The road is divided into nodes and each node represents an environment area in the real-world. The size of the area depends on the vehicle trajectory and the free space of hitting the LIDAR laser beams. A 2D cut LIDAR point-cloud is converted into a grayscale image with fixed width *w* and height *h* called *LIDAR-frame*. The frames are accumulated in an intensity image, *road-surface*, based on Dead-Reckoning (DR) position estimation. DR is used to preserve smooth measurements of vehicle XY positions inside the nodes and avoid local jumps of GPS signals. As DR accuracy is proportional to the initial position, DR is initialized with GPS position at the beginning of each node (1st LIDAR-frame). The elevation values of the encoded pixels in the intensity image are simultaneously assigned according to the same distribution pattern to a new image (float matrix) called *elevation-image*.

A node must be identified in ASC in order to generate the entire map after applying GS. According to the accurate-node strategy, the top-left corner of each node can be considered as a signature. The xy coordinates of the top-left corner are obtained by the minimum/maximum vehicle positions in x/y directions inside the node and with respect to *w* and *h*. For identification in Z-direction, the average altitudinal value in the corresponding elevation-image is calculated. These accumulation, identification and arrangement procedures are concluded in a term called *Accurate-Node Strategy*. Thus, each node is guaranteed to represent a smooth change of the vehicle position in XY and Z planes and encode very smooth illustration of the road surface context without local deviation or drifting. Similarly, the elevation image is also guaranteed to represent the road slope in Z direction smoothly and sufficiently. In addition, the sparsity of the LIDAR has been converted into a dense representation of a considerable wide area of the road by accumulating point clouds continuously. This wide area enables to apply high-level image processing techniques to conduct matching between the nodes’ intensity-images and significantly compensate the relative-position errors in the XY-plane.

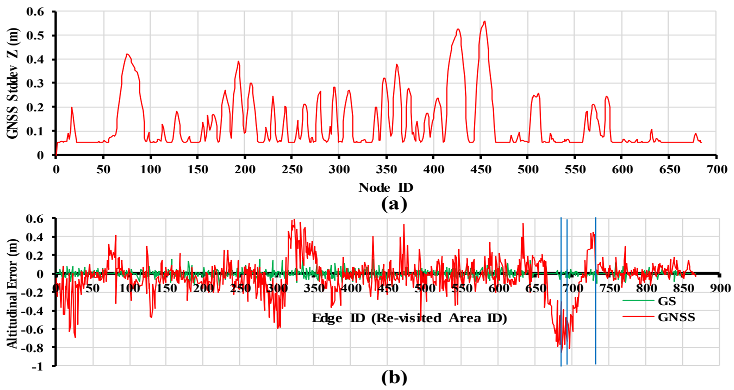
４．研究成果



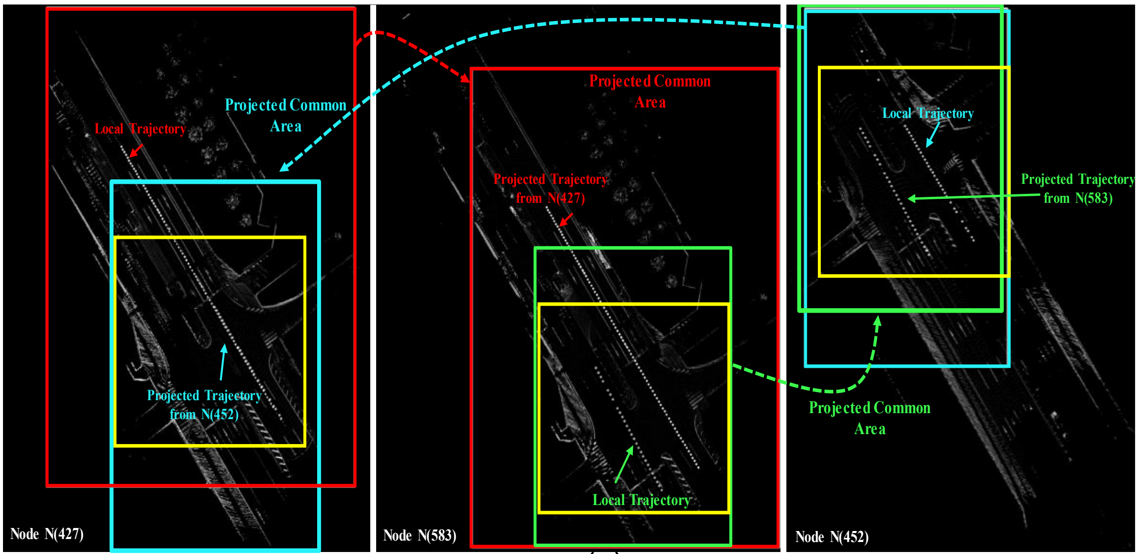
As maps are the main pillar to enable safe autonomous driving, the system has **outperformed expensive and accurate (GIR) systems** to **generate precise maps in Odaiba where there are high buildings, dense trees and the road is covered by a tram railway**. This leads to massively and continuously obstruct and deflect the satellite signals. In addition, we drove in different directions and visited many areas multiple times as demonstrated in the above figure (green links). Accordingly, the GIR map was not accurate in XY plane including misalignments between road shoulders, distortions in landmarks and ghosting in lane lines. The GS-XY has been applied to correct these errors and recover the consistency and coherency of the road representation using intensity road images as demonstrated in the below figure where the first and third columns refer to GIR map and the second and forth show the generated map by the proposed system.



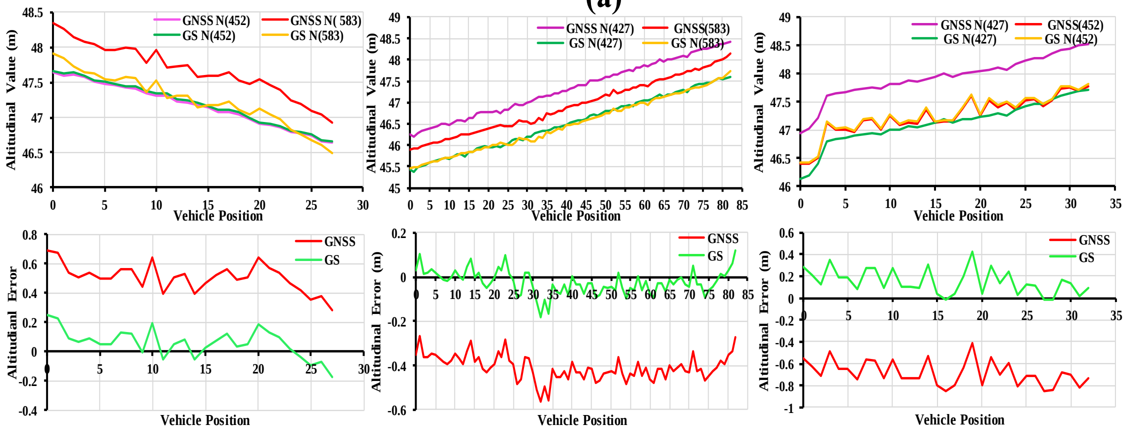
After applying GS-XY, the elevation errors at the revisited areas can be mesured accuretly because of recovering the releative errors between nodes in the XY plane. Thus, the same influnce of this critical environemnt can be issummed in the Z direction where the elevation map of GIR has showed considerable altitudinale errors in the revisited areas as illustrated by the GIR low accuracy in Z direction (a) and the coresponding elevation errors using the red



profile in (b). GS-Z has been applied to optimize the node position in the Z direction and manimize the elevation error as indicated by the green profile in (b) where the average elevation error has become less than 5cm. As an edgeID in (b) represents a loop-closure between two nodes and these nodes may share different areas with other nodes in the map, we particularly analyze a case-study of nodes 427, 452 and 583 as shown in the below figure (a). The relationships are encoded in edges of 686, 688 and 726 and correspond to nodes 427-452, 427-583 and 452-583, respectively. The common areas between the nodes are highlighted by the rectangles in the below figure (a) and the local and projected vehicle trajectories are illustrated as well. The altitudinal values of the marked pixels are obtained from GNSS and GS elevation-maps as shown in below figure (b). It can be observed that the GNSS profiles among the three graphs have a considerable and different distances in Z-direction. This indicates the altitudinal relative-position errors as well as the global position errors of the map in ACS. The corresponding GS profiles are perfectly aligned to make the relative error as small as possible and bring the common areas in the loop-closure events into the same Z-level in ACS.



(a)



(b)

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　3件）

１．著者名 Aldibaja Mohammad、Yanase Ryo、Suganuma Naoki	４．巻 24
２．論文標題 Waypoint Transfer Module between Autonomous Driving Maps Based on LiDAR Directional Sub-Images	５．発行年 2024年
３．雑誌名 Sensors	６．最初と最後の頁 875～875
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/s24030875	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Mohammad Aldibaja and Noaki Suganuma and Reo Yanase	４．巻 14
２．論文標題 2.5D Layered Sub-Image LIDAR Maps for Autonomous Driving in Multilevel Environments	５．発行年 2022年
３．雑誌名 Sensor (Remote Sensing)	６．最初と最後の頁 1-18
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/rs14225847	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Mohammad Aldibaja and Noaki Suganuma, Keisuke Yoneda and Reo Yanase	４．巻 14
２．論文標題 Challenging Environments for Precise Mapping Using GNSS/INS-RTK Systems: Reasons and Analysis	５．発行年 2022年
３．雑誌名 Sensor (Remote Sensing)	６．最初と最後の頁 1-19
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/rs14164058	査読の有無 有
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〔学会発表〕　計2件（うち招待講演　2件／うち国際学会　2件）

１．発表者名 Mohammad Aldibaja, Reo Yanase and Naoki Suganuma
２．発表標題 On Mapping in Multilayer Environments: A Robust Graph-SLAM Approach Using LIDAR Intensity and Elevation Data
３．学会等名 The 25th IEEE International Conference on Intelligent Transportation Systems (IEEE ITSC 2022)（招待講演）（国際学会）
４．発表年 2022年

１．発表者名 Mohammad Aldibaja, Naoki Suganuma, Reo Yanase
２．発表標題 On LIDAR Map Combination: A Graph Slam Module to Generate Accurate and Largescale Maps for Autonomous Driving
３．学会等名 2022 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)（招待講演）（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関