様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　５ 年　 ６ 月 ２０ 日現在

機関番号：１３３０１
研究種目：若手研究
研究期間：2020～2022
課題番号：２０Ｋ１９８９３

研究課題名（和文）A Study on Generating Accurate and Largescale LIDAR Maps Based on Graph-Slam Technology for Autonomous Vehicles

研究課題名（英文）A Study on Generating Accurate and Largescale LIDAR Maps Based on Graph-Slam Technology for Autonomous Vehicles

研究代表者
Ａｌｄｉｂａｊａ　Ｍｏｈａｍｍａｄ（ALDIBAJA, Mohammad）

金沢大学・高度モビリティ研究所・特任助教

研究者番号：１０８６８２１９

交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：このプロジェクトの目標は、科学的かつ実用的に達成され、非常にインパクトのある素晴らしい結果を得ることができました。 従来の3次元点群領域での手法に代わり、画像領域で動作する独自のGraph-SLAMフレームワークを設計・実装しました。その結果、長いトンネル、高い建物、密集した木々、地下道、橋などの困難な環境において、正確な地図を生成するために、正確で高価なGNSS/INS-RTKシステムを凌駕しました。 したがって、マッピングモジュールは、XY平面で正確な地図を生成し、グローバル座標系で路面をコヒーレント表現して新しいエリアを含む地図を自動的に拡張する、非常に堅牢なものとなりました。

研究成果の学術的意義や社会的意義
Precise Mapping of challenging environments is very important to commercialize autonomous vehicles and this research stands to safely conduct hand-free mapping with taking into account the driving scenarios, traffic flows, road topological representations and sensor configurations.

研究成果の概要（英文）：We are glad to report that the goal of the project has been achieved scientifically and practically with very impactful and impressive results. We analyzed the reasons of generating low quality maps using GNSS/INS-RTK systems and studied the influences on the localization accuracy during autonomous driving. A unique Graph-SLAM framework has been designed and implemented to operate in the image domain instead of the conventional methods in the 3D point cloud domain. The obtained results have outperformed accurate/expensive GNSS/INS-RTK systems to generate accurate maps in challenging environments such as long tunnels, high buildings, dense trees, underpasses, bridges and so on. Accordingly, the mapping module has become very robust to generate accurate maps for autonomous vehicles regardless of the complexity of the road structure in the XY plane as well as extend the map automatically to contain new areas with coherent representation of the road surface in the global coordinate system.

研究分野：Autonomous Vehicles

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

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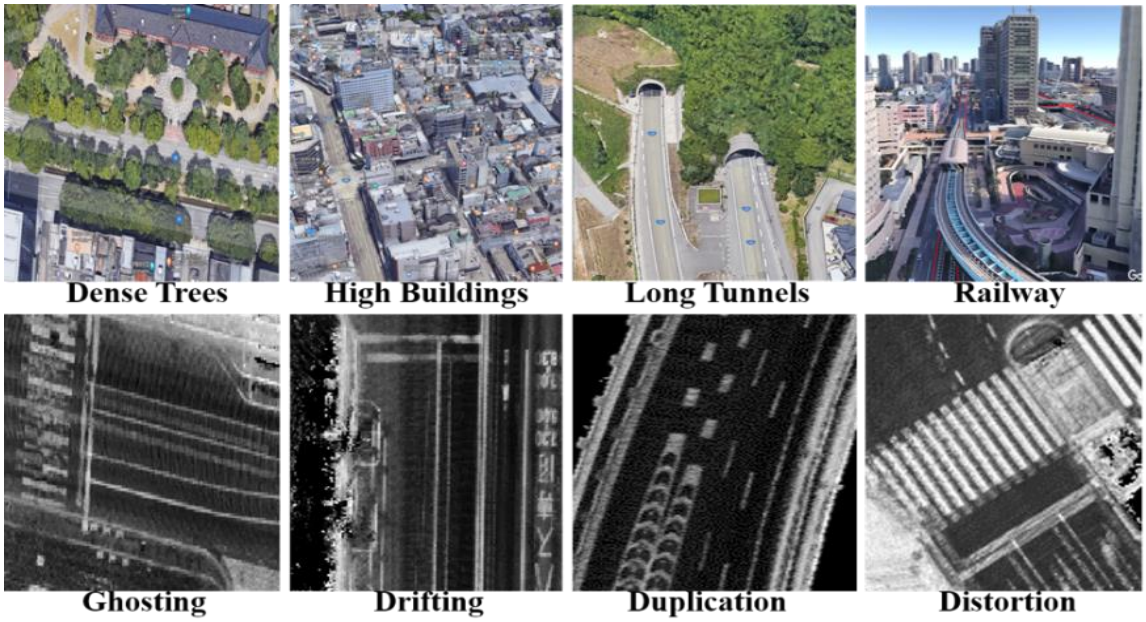
様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Mapping system is a very critical pillar to enable safe autonomous driving because of influencing the performance of the autopilot's modules such as localization and path planning. Most of mapping companies use **an accurate and expensive GNSS/INS-RTK (GIR) system** to precisely estimate the vehicle trajectories and then accumulate the sensory data accordingly to build the maps. 3D LIDAR point cloud based mapping systems are **conventional and relay on the shape and distribution** of the point clouds. However, they have **many problems** such as sparsity in representing environments and huge size of data as well as the difficulties to implement and integrate robust technologies to improve the map accuracy such as Simultaneous Localization and Mapping (**SLAM**). In addition, GIR systems doesn't estimate the vehicle trajectories **precisely** in **challenging environments such as long tunnels, dense trees, high buildings, underpasses and bridges.** This leads to produce ghostings, duplications, distortionss and drifting in representing environments and landmarks as shown in the below figure. Accordingly, autonomous driving cannot be conducted using these damaged maps because of the high potential to localize vehicles wrongly in the real world and lead to traffic accidents. Therefore, robust SLAM technologies **should be integrated** into the mapping module to generate **accurate** maps **regardless the complexity of road structures.**

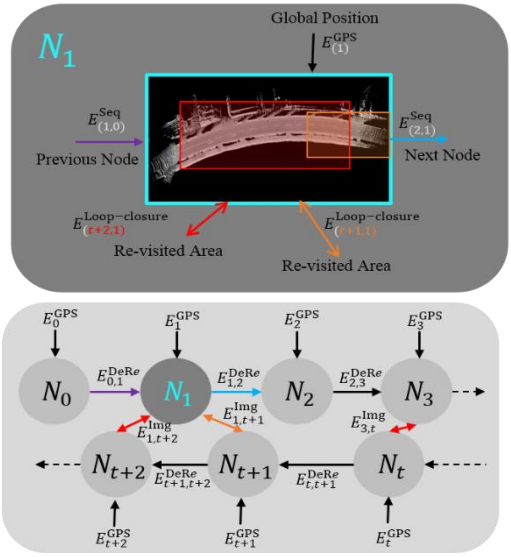


２．研究の目的

Accurate maps must be generated to control vehicles during the autonomous driving. The projected aimed to propose a **mass-production** framework to **generate largescale LIDAR maps** in size of **cities and prefectures**. Such a demand **is challenging and unique in Japan as well as in the autonomous vehicle research field globally**. Thus, the proposal investigated the following problems:

1. Generating **road surface** maps based on **Graph Slam** technology.
2. Enhancing the **relative-position** of the map data in **re-visited areas** in environments of **long tunnels** and **roads covered by dense trees and high buildings**.
3. Increasing the **global position accuracy** of the maps in critical environments such as **multilayer roads and bridges.**
4. **Combining map data** that collected on different **dates** by different **vehicles** to generate **largescale maps**.

３．研究の方法



I **invented a new SLAM strategy** to **generate accurate maps** in the image domain instead of the conventional SLAM methods in the 3D point cloud domain. **The core idea is to convert vehicle trajectories into grayscale road surface images**, identify these images in the global coordinate system, build a network to represent the relationships bet ween the images globally and then re-localize these images to recover the road **consistency** in the **XY** plane as demonstrated in the beside figure. **This imposed to redesign the entire steps of SLAM processes** but significantly facilitated to **robustly** achieve them compared to the conventional methods. For example, constituting relationships between images instead of vehicle trajectories, detecting revisited areas between images instead of vehicle positions, **accurate compensating of relative position errors in the XY plane using dense image matching techniques** instead of applying iterative registration techniques on sparse 3D point clouds, facilitating the design of the SLAM cost function to optimize the road consistency in the XY plane instead of the vehicle trajectory and finally, ensuring accurately calculation of the relative elevation error between consistent road images by SLAM in the XY plane to **optimize the road coherency in the Z plane** instead of optimizing the ***xyz*** vehicle trajectories **at ones** in the 3D point cloud domain.

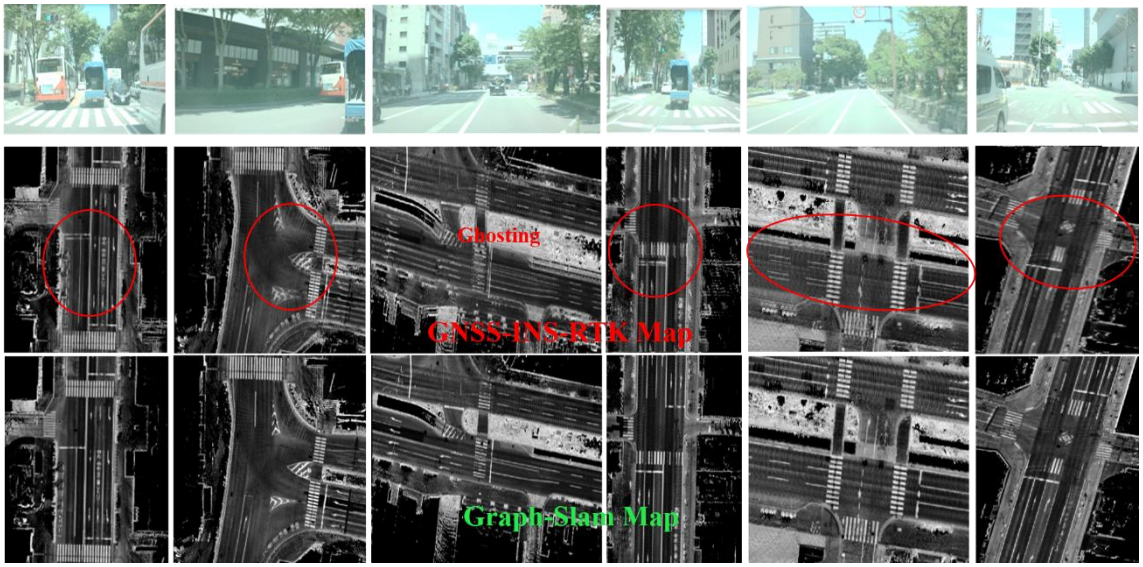
The **next stage** was **to address the challenge of accurately merging maps to generate largescale maps in the level of cities and prefectures**. The most important points were to determine the **global position** of the road in the common areas between maps, **propagate the local position improvement** in the common areas to the other road segments, **preserve the road consistency** in the combined map and estimate the **global position accuracy** of the combined map. This is because of the necessity to design the SLAM cost function **to (1) merge maps that are collected for the first time at once or (2) update a previously processed SLAM map with newly collected data**. By achieving these two formulas, the mapping modules can be proved to generate **accurate and largescale maps** in levels of cities and prefectures.

４．研究成果

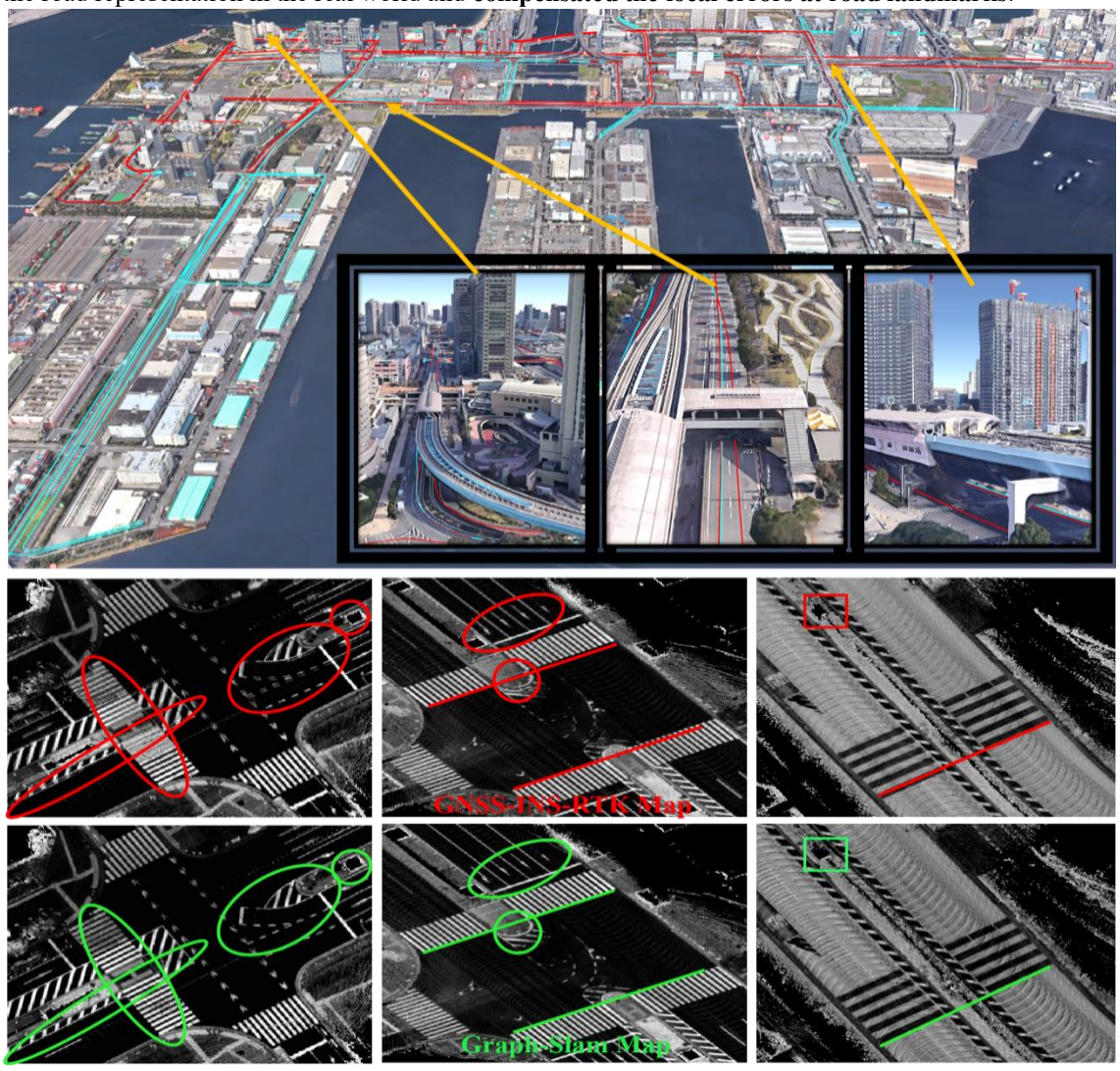
As maps are the main pillar to enable safe autonomous driving, the system has **outperformed expensive and accurate (GIR) systems** to **generate precise maps in different challenging environments** as follows:

A: Kanazawa Downtown: the downtown contains **high buildings** and **dense trees**. The roads have been scanned multiple times in different direction to collect data on the entire environments. Accordingly, the **GIR map was not accurate with containing ghosting effects at different areas**. The proposed system has **recovered** the road representation and generated an **accurate map**. The generated map has been then

used to **conduct very safe autonomous driving**.



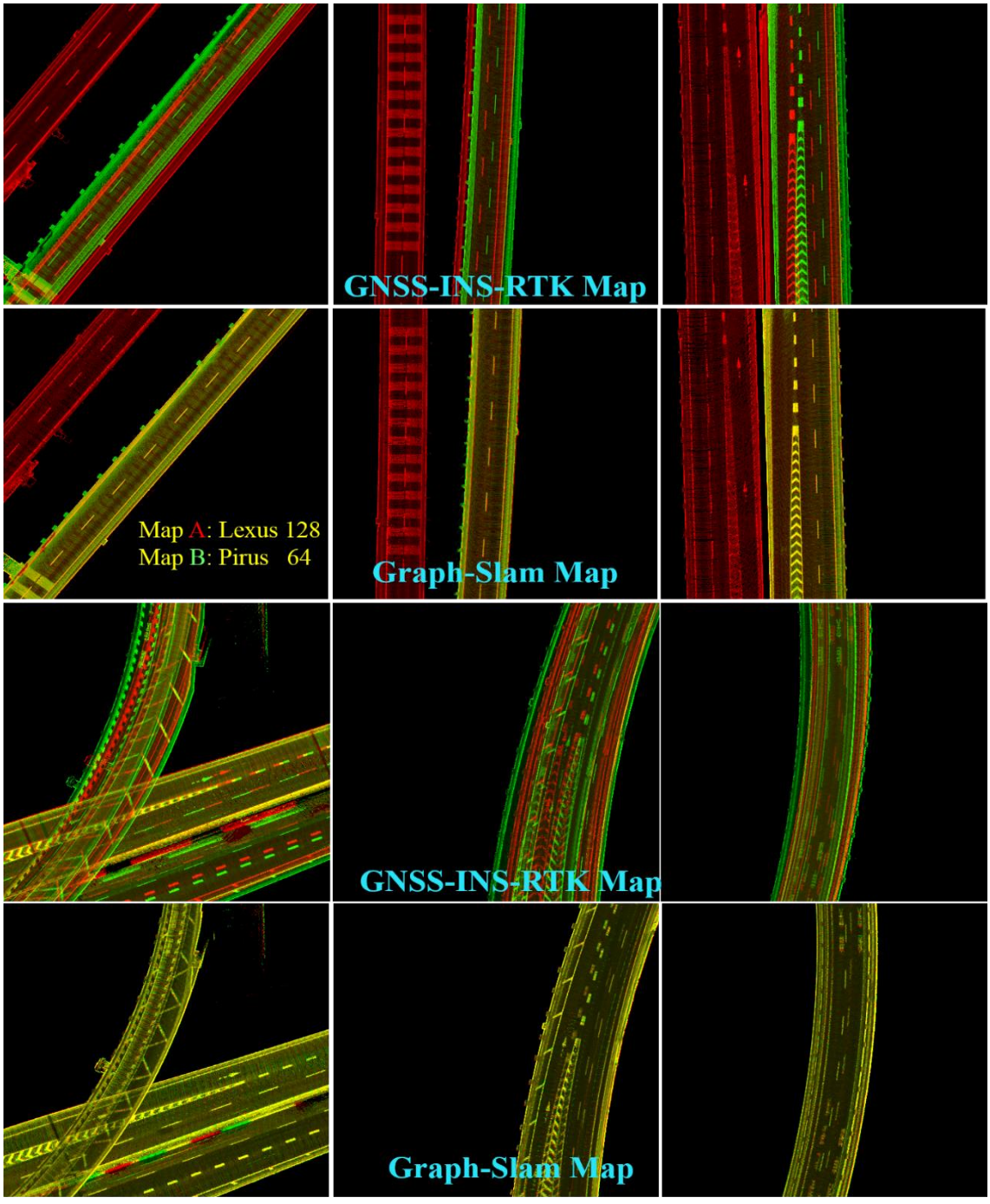
B: Odaiba: the Tokyo waterfront contains **high buildings, dense trees and is covered by a tram railway**. This leads to massively and continuously obstruct and deflect the satellite signals. Accordingly, the GIR map was not accurate and **the misalignment between road shoulders has been observed at different segments** as demonstrated in the below figure. The proposed system has recovered the **true alignment** of the road representation in the real world and **compensated the local errors at road landmarks**.



C: Yamate Tunnel: Yamate tunnel is the longest tunnel in the world. The two combination formulas to merege maps have been tested **by merging mapping data of Yamate tunnel (18 km underground with**

a maximum depth of 30m) that were collected with a two-year interval by **different** agents, starting/ending points, traffic conditions and driving scenarios. **It is almost impossible to obtain the same global accuracy by any GIR system in such challenging environments. Accordingly, the duplication of the road surface has been observed gradually and continuously along the entire map inside the tunnel.** In contrast, the proposed system **has provided a very precise, consistent and coherent combined map** with the total length of **235km as illustrated at different road segments in the below figure**.

As can be observed from the results, the proposed Graph SLAM framework has been proved to generate very accurate maps regardless the complexity of road structure in different challenging environments. Furthermore, the experimental results have verified the scalability and robustness of the proposed framework to combine maps precisely collected using different agents and sensor configuration. Accordingly, the proposed system reliably solves a very critical problem in levels 4 and 5 of autonomous driving and allows to conduct safe autonomous driving.



５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　2件）

１．著者名 Mohammad Aldibaja and Noaki Suganuma	４．巻 13
２．論文標題 Graph SLAM-Based 2.5D LIDAR Mapping Module for Autonomous Vehicles	５．発行年 2021年
３．雑誌名 Sensor (Remote Sensing)	６．最初と最後の頁 1-16
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/rs13245066	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
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

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４．発表年
2021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