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POSITIONING AND TRAJECTORY INTERPOLATION USING SLAM AND PPP-RTK FOR RIVER MAPPING

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ABSTRACT: The autonomous boat can be used to improve traffic and infrastructure maintenance. Conventional autonomous boats depend on global navigation satellite systems to estimate self-position data. Thus, in urban rivers, autonomous boats are difficult to use because urban rivers are densely surrounded by structures such as bridges, buildings, and metropolitan highways. Although beacon installation is one of the popular techniques for location estimation in non-satellite positioning environments, transmitters as positioning infrastructure are not easy to be installed in wide areas. Therefore, we focus on simultaneous localization and mapping using LiDAR (LiDAR-SLAM). We developed a methodology to integrate LiDAR-SLAM and precise point positioning (PPP)-RTK to achieve indoor-outdoor seamless positioning on river mapping. Although SLAM is a popular methodology for automatic robot operation, conventional SLAM fails point cloud integration and self-position estimation because few geometrical features exist around rivers. Thus, our approach uses PPP-RTK using the quasi-zenith satellite system (QZSS) to assist LiDAR-SLAM. Through an experiment on a laser measurement for 3D mapping of urban rivers, we confirm that our methodology can improve point cloud acquisition for river mapping in dense urban areas.

1. INTRODUCTION

The use of autonomous boats in urban rivers has the potential to improve water transportation infrastructure. Moreover, autonomous boats can be used for daily maintenance and management of river infrastructures such as bridges and revetments. However, in the current state, no base map for autonomous boats exists in Tokyo's urban rivers. Moreover, although conventional autonomous boats depend on global navigation satellite systems (GNSS) to estimate self-position data, the performance of GNSS positioning is insufficient for autonomous boats in dense urban areas. Therefore, we focused on a methodology of indoor-outdoor seamless positioning by combining LiDAR-based simultaneous localization and mapping (LiDAR-SLAM) and GNSS positioning. The SLAM is a process technique to estimate self-location and maps (point clouds) simultaneously without GNSS positioning. Although the SLAM cannot obtain absolute coordinate values, precise local position and dense point clouds can be obtained. We also focused on the centimeter level augmentation service (CLAS) based on the precise point positioning real-time kinematic (PPP-RTK) positioning to improve the performance of GNSS positioning. The CLAS is a technique to provide higher accurate single-point positioning using the L6 signal as rectification information is transmitted from the quasi-zenith satellite system (QZSS) called MICHIBIKI. Although the service range is limited to the vicinity of Japan, positioning accuracy is improved as well as RTK-GNSS positioning without wireless communication using mobile devices. In indoor-outdoor seamless positioning for autonomous boats, we developed a methodology of positioning mode selection among SLAM and PPP-RTK with linear interpolation-based processing for lacking GNSS positioning areas. Through laser measurement experiments using a boat, we clarify that our methodology can generate point clouds in urban rivers.

2. METHODOLOGY

Our methodology consists of data synchronization, positioning mode selection and mapping (point cloud integration) (Figure 1). First, position and attitude data are obtained in both indoor and outdoor environments. PPP-RTK positioning is applied to the positioning in outdoor environments, and self-position estimation with LiDAR-SLAM is applied to the positioning in indoor environments. The PPP-RTK does not require the installation of a reference point, thus, the efficiency of positioning work is improved. The obtained PPP-RTK data are converted from WGS84 coordinate systems to local coordinate systems to integrate with position data estimated from LiDAR -SLAM. In data acquisition, horizontal and diagonal LiDARs are used to acquire point clouds for SLAM processing. The horizontal LiDAR is mainly used for horizontal position estimation and horizontal section maps. The diagonal LiDAR is mainly used for rolling angle rectification and dense point cloud acquisition of building walls, bridges, and revetments. Next, in the positioning mode selection, input position data are selected from PPP-RTK and SLAM results. We focus on the status of PPP-RTK positioning, such as FIX, FLOAT, GNSS locked, and no signals. When the FIX positioning solution is obtained, the estimated position is used as the sensor position. Alternatively, when the other status is obtained, the estimated position from SLAM processing is used as sensor position data. Then, the estimated position is rectified with an error adjustment using the start and end points of SLAM processing to integrate with acquired PPP-RTK positioning data. In the LiDAR-SLAM, a scan matching algorithm is applied to estimate the rotation and translation parameters of LiDAR, based on point cloud matching using overlapped temporal laser scanning data.

Before the SLAM processing, point clouds around the boat are deleted, and several scanning lines are selected to improve the performance of SLAM processing. Moreover, although an iterative closest point algorithm can be used for scan matching processing, we apply a normal distribution transform (NDT) algorithm as scan matching processing to improve the stability of SLAM processing. Then, in rivers of non-GNSS sections, because the SLAM processing tends to be unstable, the trajectory for initial positions for the SLAM in non-GNSS sections is estimated with linear interpolation using PPP-RTK position data at the edge points of each GNSS positioning section. Finally, the boat trajectory and integrated point clouds are estimated using PPP-RTK position data and SLAM processing results in indoor and outdoor environments.

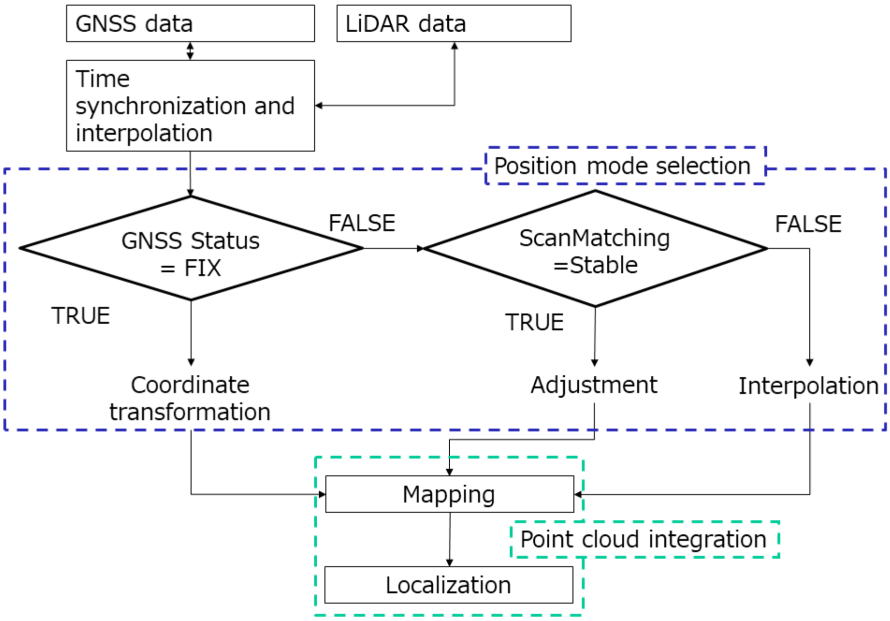

Figure 1. Proposed methodology

3. EXPERIMENTS ENVIRONMENT

The Kanda and Nihon-bashi Rivers were used as the test sections of our study areas (Figure 2). The measured route consists of discontinuous open-sky sections (Kanda River) and continuous non-GNSS sections (Nihon-bashi River). On two days (May 14, 2021 and December 3, 2021), we conducted experiments on 3D measurement. We installed two types of LiDAR (VLP-16 and VLP-32C, Velodyne), RTK-GNSS receiver (F9P, u-blox), and PPP-RTK (AsteRx4, CORE) on a quick-charging plug-in electric boat “Raicho I” (Figure 3). The VLP-32C was installed at a horizontal position, and the VLP16 was installed at a diagonal position (lower-forward with 35 degree tilt angles). LiDAR and positioning data were recorded on a laptop PC and processed using MATLAB (Intel Core-i9, 3.5 GHz). We also connected GPS antennas to each LiDAR for timing. Then, all sensors were synchronized using GPS clock data.

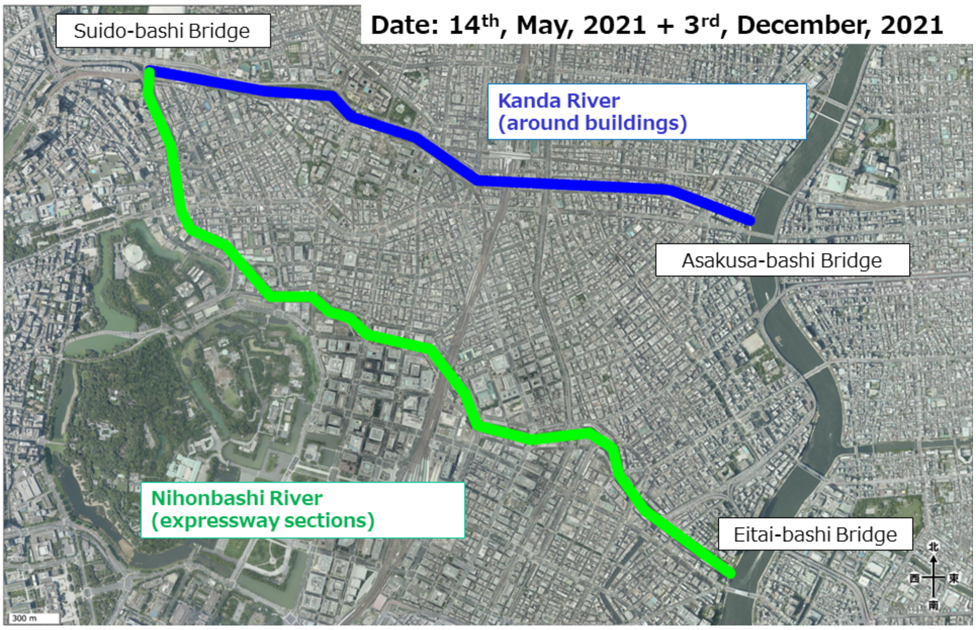

Figure 2. Study area

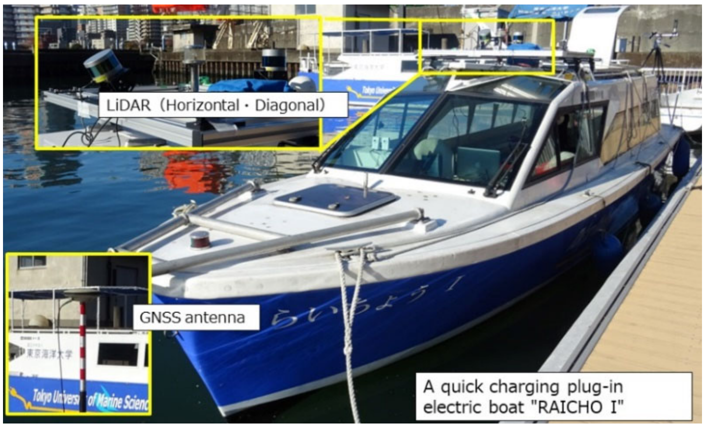

Figure 3. Platform and measurement devices

4. RESULTS

We obtained 38,640 epochs in GNSS positioning. First, we extracted position data with FIX solution to evaluate the relative accuracy of PPP-RTK positioning, as shown in Table 1. We used RTK-GNSS positioning data as reference data. Second, we evaluated a ratio of FIX in GNSS positioning. In the Kanda River, we confirmed that the FIX positioning solutions were obtained in open-sky areas. On the other hand, the FIX positioning solutions were not obtained in all sections of the Nihon-bashi River (Figure 4).

Table 1. PPP-RTK positioning result

The number of positioning points	38,640
Positioning accuracy (FIXED)	0.05-0.10m (horizontal direction)

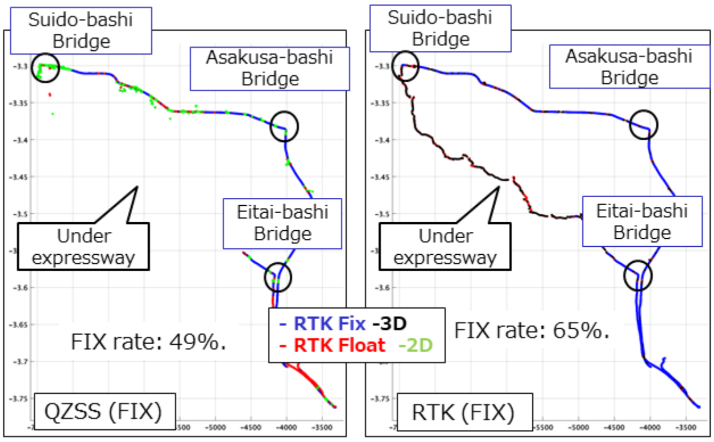

Figure 4. Overall results of GNSS positioning

The results of the LiDAR-SLAM processing without GNSS positioning data are shown in Table 2 and Figure 5. We confirmed that the results for the Nihon-bashi River represented the actual boat behavior. On the other hand, in the results for the Kanda River, position estimation results differed from the actual boat behavior because of degeneracy problems that occurred in the SLAM processing. We confirmed that SLAM processing tended to be unstable around monotonous shapes of straight revetments and wide piers under bridges.

Table 2. LiDAR processing data

LiDAR	VLP-16	VLP-32C
The number of frames	40700 frames	37000 frames
Date	14th,May,2021	3rd,December,2021
Start point	Asakusa-bashi Bridge	Eitai-bashi Bridge
Selected measurement range	10-70 m	10-70 m
File size	6.7 GB	12.3 GB
The number of scanning lines	3 (horizontal)	3 (horizontal)
Integration accuracy	2cm（under the expressway）/scan	2.5cm（under the expressway）/scan
Processing time	904.2 s	1777.2 s

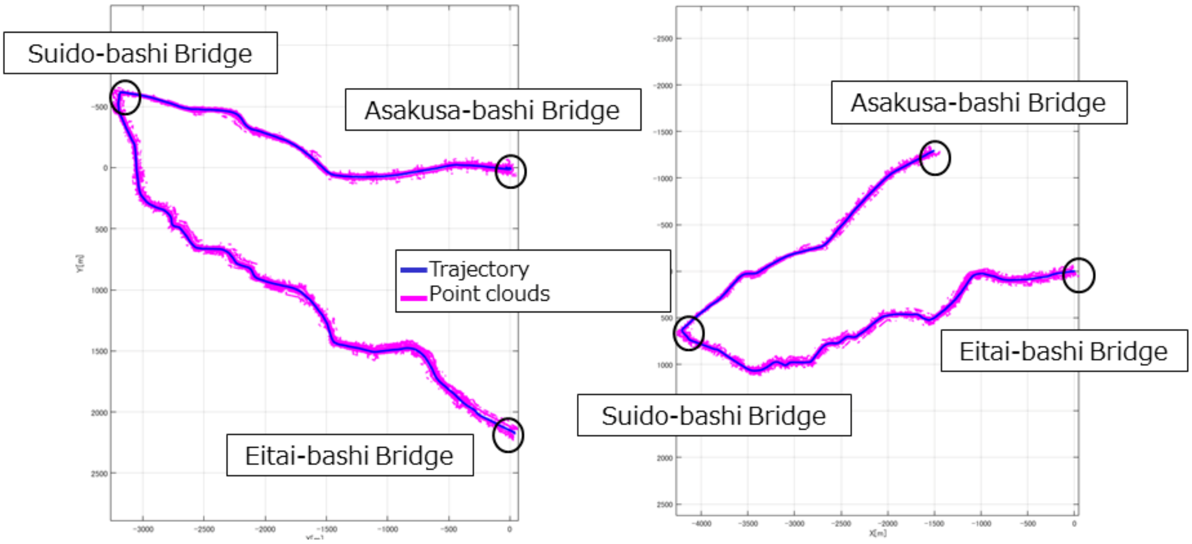

Figure 5. Integrated point clouds (left: result using VLP-16; right: result using VLP-32C)

Moreover, we interpolated PPP-RTK data to reconstruct position data of all positions in the Kanda River. Lacked GNSS points were interpolated using the closest GNSS points with the FIX solution. Figure 6 shows point clouds integrated horizontal LiDAR data with interpolated GNSS positioning data from the Asakusa-bashi Bridge to the Suido-bashi Bridge.

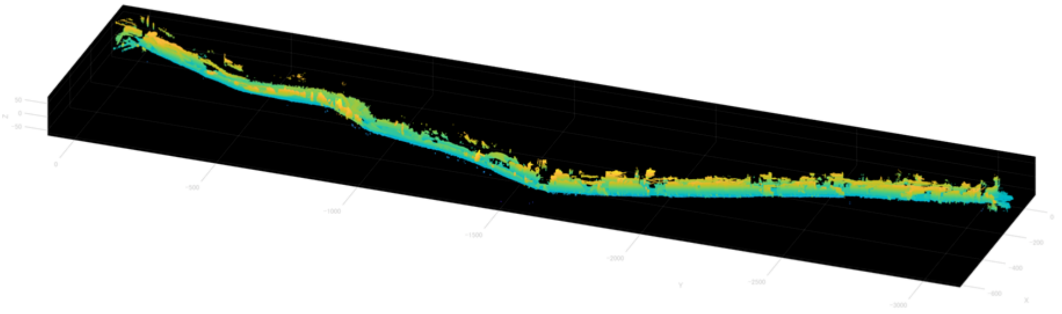

Figure 6. Integrated point clouds (Kanda River)

5. DISCUSSION

We confirmed that PPP-RTK positioning was available in open-sky areas in the Kanda River. Moreover, SLAM processing was stable around the Asakusa Bridge area because of rich geometrical features for scan matching, such as complex-shaped buildings and houseboats anchored in the river. In addition, we confirmed that miss-FIX lacked positioning data in some sections of the open-sky environments because of multipath problems. In particular, the estimated trajectory between the Suido-bashi and Hijiri-bashi Bridges did not match the actual trajectory (Figure 7) because position estimation failure in SLAM called degeneration problems occurs in the section that had monotonous geometrical shapes. When the LiDAR data from two frames are successfully matched, corresponding scores such as the distances among matched points are high. However, in the geometrical monotonous section, even if position estimation failed, the LiDAR data are matched with high-matching scores.

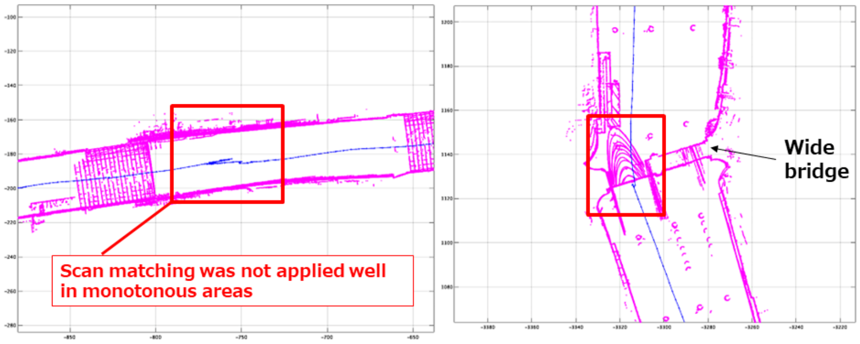

Figure 7. Degeneration problem in SLAM

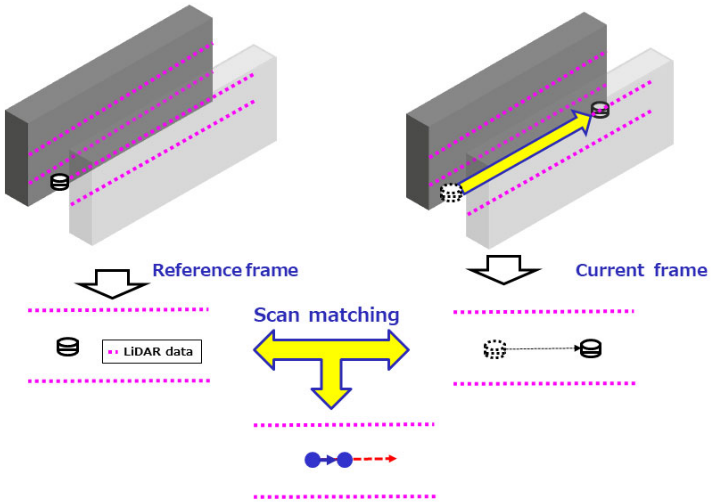

Figure 8. Factors of failures in SLAM processing

Although position data with FIX positioning solutions were not obtained along the Nihon-bashi River because the upward visibility was obstructed by expressways, SLAM was successfully processed because of many geometrical features, such as piers and structures of the metropolitan expressway, as shown in Figure 9. Although accumulated errors exist, the scan matching accuracy was several centimeters in the Nihon-bashi River.

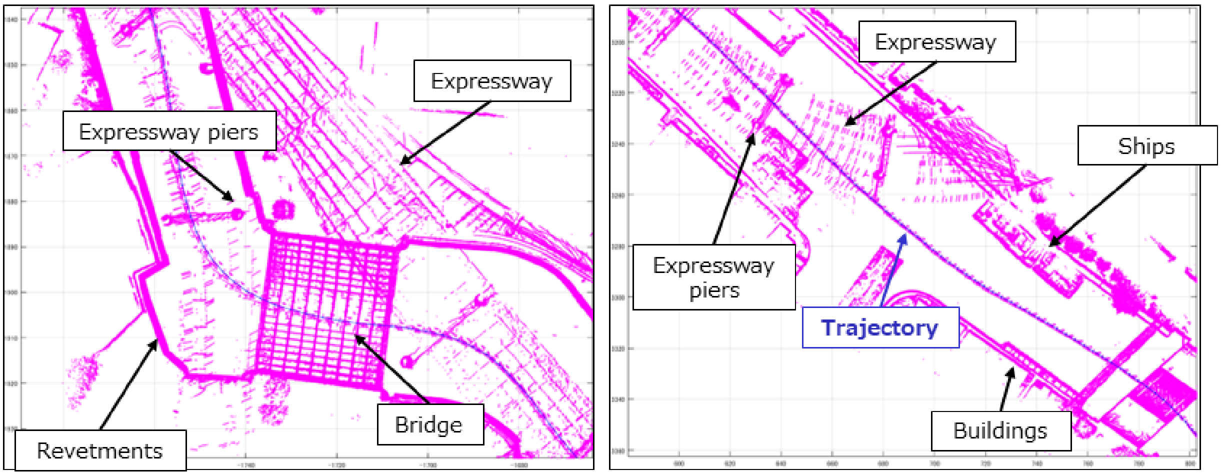

Figure 9. SLAM processing result (point cloud integration and position estimation)

In the Kanda River, such as sections under bridges from the Hijiri-bashi Bridge to the Mansei-bashi Bridge, we confirmed that linear interpolation of position data was sufficient for the initial position data estimation in SLAM at each short section of missing PPP-RTK data. However, in cases of long non-GNSS sections, the position interpolation approach was insufficient for SLAM processing because the estimated position data were a low representation of trajectory. Therefore, position data estimation will require auxiliary data, such as magnetic heading data and the boat's motor rotation data. In the quantitative evaluation of indoor-outdoor seamless positioning, total stations or terrestrial laser scanning data obtained from ground points can be used for the evaluation of trajectory estimation and point cloud generation results. However, in urban rivers, installations of total station and terrestrial LiDAR are difficult; thus, a quantitative accuracy evaluation methodology should be developed. Alternatively, in this research, visible and qualitative evaluations were conducted using existing building maps and photos of bridges and buildings to inspect results on the representation of estimated trajectory and integrated point clouds, as shown in Figure 10.

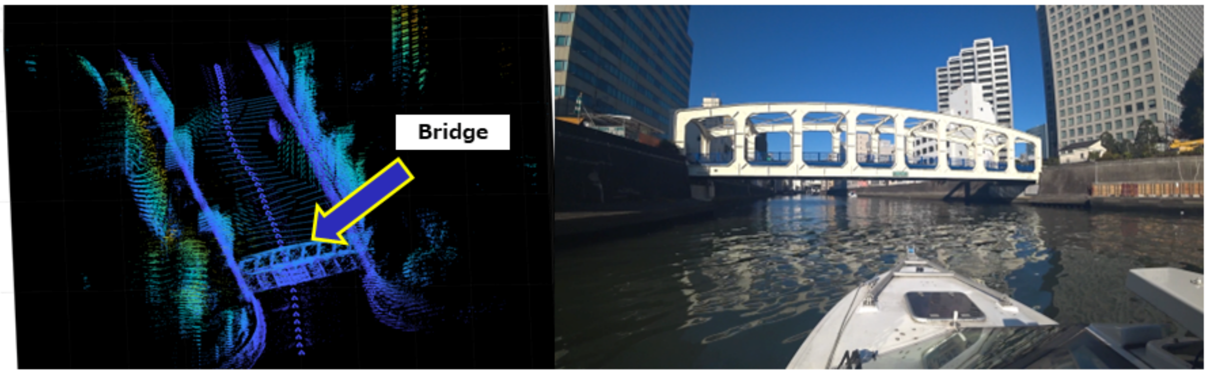

Figure 10. Qualitative evaluation result (left: point clouds; right: photo)

In our future works, we will use oblique LiDAR to rectify the rotation data of LiDAR. We will also use an omnidirectional camera to generate colored point clouds.

6. CONCLUSION

In this study, we proposed a methodology to integrate LiDAR-SLAM and PPP-RTK positioning to achieve an indoor-outdoor seamless positioning for 3D mapping of urban river spaces. Through laser measurement experiments in urban rivers, we confirmed that the proposed methodology can generate point clouds and estimate position data using a multilayer laser scanner and PPP-RTK receiver in both open-sky areas and non-GNSS areas with automated positioning mode selection.

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