# Urban River Modeling based on CityGML using Water-borne MMS Point Clouds

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***Abstract***

*CityGML is an open and internationally standardized data format for 3D city models that, describes the conceptual structure of geographic objects in XML format. One of the features of CityGML is a seamless scale representation to manage, small-scale and large-scale map data simultaneously, based on the concept of level of detail (LOD) for 3D objects. However, in the urban river space, the discussion on geographic object modeling has not been sufficient to represent 3D maps for navigation of autonomous boats. In addition, the current version of PLATEAU does not provide high-definition 3D map data of rivers because there are many technical issues such as occlusion, which can be observed by aerial photogrammetry, mobile mapping system survey, and terrestrial laser scanning. To promote more effective use of urban rivers, we focus on autonomous boat navigation technology. In the effective use of urban river space, new transportation services such as MaaS, which combines land and water transportation, have been designed and are expected to be used. To achieve autonomous boat navigation technology, precise GNSS/non-GNSS seamless positioning techniques, autonomous control technology, and 3D maps should be prepared. In this study, we developed a method for 3D modeling and attribute assignment of geographic features in urban river space through point cloud acquisition from water-borne MMS. Moreover, we discussed a description of 3D models based on CityGML, for autonomous boats in urban rivers. The first step is point cloud processing, which classifies the acquired water-borne MMS point cloud into geographic features. Next, voxelization, meshing, and 3D polygonization are applied to create a 3D model. Finally, the model is designed and described for the CityGML description. The Kandagawa and Nihonbashigawa rivers were selected for the experiment, and measurements were taken. The proposed method was investigated by acquiring point clouds based on mobile measurements using a small boat equipped with a LiDAR system. The 3D model and maps generated by our proposed method can contribute to autonomous boats and infrastructure management around rivers.*

*Keywords: Water-borne mobile mapping, CityGML, 3D modeling,*

## Introduction

Open data of 3D city models provided in CityGML format data, such as the project PLATEAU [1], are used for urban planning and disaster simulation. PLATEAU is a Japanese project launched by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in 2020, to develop a 3D city model of all of Japan for urban digital twin and DX of urban planning. CityGML is an international standardized data format for 3D city models developed by the Open Geospatial Consortium (OGC) [2], CityGML describes the conceptual structure of geographic features required to represent 3D city models in XML format. The main feature of CityGML is a seamless scale representation, of 3D objects for centralized management from small-scale to large-scale map data based on the concept of Level of Detail (LOD). However, in urban river spaces, the modeling of geographic objects in urban river spaces has not been sufficiently explored. Moreover, the current version of PLATEAU has not yet provided high-resolution 3D map data of rivers because many areas are not easily observed by aerial photogrammetry, mobile mapping system (MMS) surveying, or terrestrial laser surveying. Furthermore, we can focus on the effective use of urban rivers for new transportation services that combine land and water transportation, energy transportation using autonomous boats during disasters, the establishment of temporary high-speed communication hubs on the water, and the automation of infrastructure inspection around rivers, Autonomous boat navigation requires, not only high-precision positioning systems, autonomous control technologies, and precise 3D maps of rivers. In this study, we developed a method for 3D modeling and attribute assignment of geographic features in urban river space using point clouds acquired with a water-borne MMS. We also investigated a method for describing 3D objects around rivers based on CityGML.

## Literature Review

Existing studies include the use of 3D city models and extensions to CityGML. A study on extending the CityGML standard to underground spaces [3] suggests that the standard can be used for urban planning and various applications such as underground property management. Moreover, the application schema can handle data requirements related to legal boundaries in underground environments that cannot be handled by the standard schema. Thus, the relationships between legal and physical spaces underground are clarified and visualized in a 3D space. In our research, we aim to describe urban river environments in CityGML to promote the effective use of urban river spaces. In addition, we design a LOD design, of 3D models of geographic features in urban river environments.

We have developed a water-borne MMS using LiDAR mounted on a boat to acquire, registered point clouds [4]. The water-borne MMS consists of Centimeter-Level Augmentation Service (CLAS) and LiDAR, based on Simultaneous Localization and Mapping using LiDAR (LiDAR-SLAM). The urban river space is surrounded by buildings and bridges, 3D data acquisition is difficult due to the poor GNSS environments. Although we can acquire point clouds with a handheld SLAM-LiDAR without GNSS positioning, global coordinate values are needed for map management and boat navigation. Therefore, we also developed a system GNSS/non-GNSS seamless positioning methodology for the water-borne MMS to improve the positioning performance for 3D data acquisition.

In attribute data mapping to geographic features using point clouds with deep learning, there are many methods such as a new neural network called SCPNeT to perform semantic segmentation of point cloud data [5]. This methodology can be applied to dynamic objects in dense scenes. However, in urban river spaces, the preparation of training data for deep learning is a technical issue. Therefore, in this study, we classify geographic features based on conventional point cloud processing with a knowledge-based approach.

## Methodology

The proposed method is based on the use of a water-borne MMS that integrates the CLAS and SLAM [4]. We can also use a handheld LiDAR, to improve the generality of point cloud acquisition. Figure 1 shows the processing flow from point cloud acquisition to CityGML description. The proposed method is divided into three main processes. First, point cloud processing is performed to classify water-borne MMS point clouds according to geographic features. Next, a 3D model is generated by applying voxelization, meshing, and polygon data generation to assign attributes to the geographic features. Finally, the generated 3D model is converted to XML format based on CityGML.

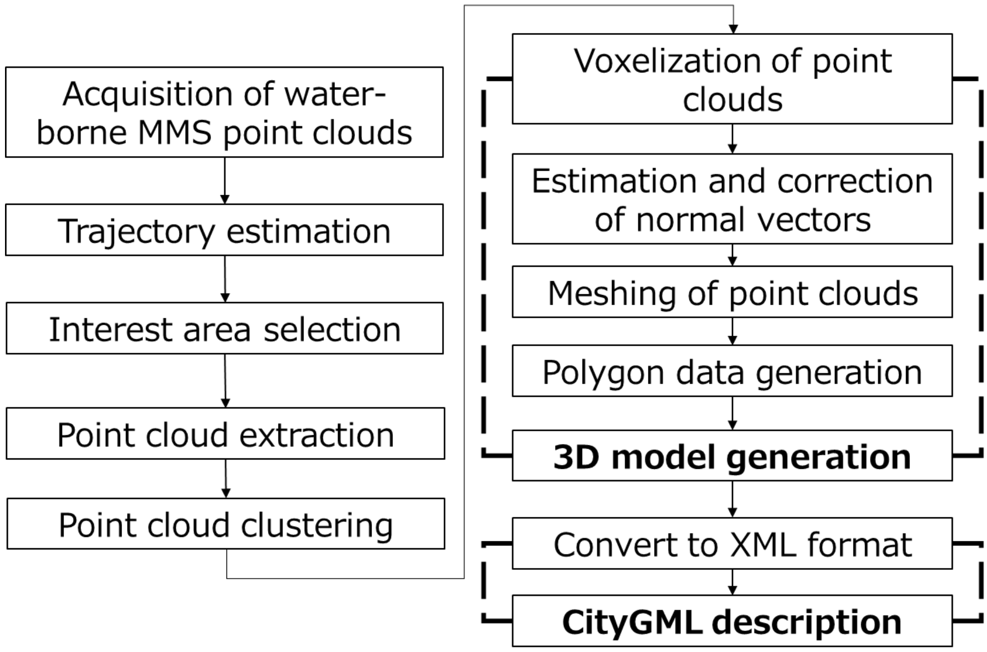


Figure 1: Processing Flow.

**a. Point cloud clustering:**

Point cloud clustering is used to classify geographic objects in urban river spaces. First, the region of interest is created in the point clouds. The threshold of the region size is set from the trajectory data to the landmarks. A neighborhood search is performed to extract the point clouds using a Kd tree-based search algorithm. Moreover, point cloud clustering is performed based on Euclidean distance. These processes are combined to group different geographic features into individual clusters by each geographic feature. In this study, revetments, bridges, buildings, and railroad bridges are extracted from the input point clouds.

**b. 3D model generation voxelization**

3D modeling methods are applied to the point cloud data classified for each object. First, voxelization is performed on the point clouds. Voxelization is the process of replacing the point cloud data with representative points of a 3D grid of arbitrary resolution, which allows discrete point cloud data to be used as a consistent format. Since the original point cloud data have high density, it requires a long processing time for 3D modeling. Therefore, voxelization is applied for efficient 3D modeling. Since the discrimination and reproducibility of geographic features depend on the resolution of the voxels, an appropriate threshold value should be set. If the resolution is too low, the boundaries of the geographic objects become unclear to interpret the details of the features. By contrast, if the resolution is too high, although the boundary may be clear, the data size becomes large and the processing efficiency decreases. Therefore, the optimal voxel size is required for feature extraction from point clouds.

**c. Mesh model generation**

First, the normal vectors of point clouds are estimated for mesh modeling. If there are incorrect normal vectors exist, an accurate 3D model cannot be generated because some mesh surfaces will be inconsistently flipped. Mesh data can be thought of as geometry data consisting of point clouds as vertices connected by edges and faces. Although dense point clouds can represent detailed shapes, the data volume of data increases due to the large number of vertices and edges. One approach to mesh modeling use, the ball pivot method is used to generate the model to triangulate a set of points by rolling a ball with a radius of r over point clouds. In this method, three sample points are first selected and the ball is placed tangent to these points to form a seed triangle. The ball is then rotated (pivoted) while touching two of the edges of the seed triangle until it touches another point. When the ball touches the new point, a new triangle is formed at the edge and at that point. By repeating this process, adjacent point clusters of points are meshed with triangles. This process continues until all reachable edges are covered, and if any areas remain uncovered, the other seed triangle is selected to perform the same process.

**d. Polygon model generation**

The geometry of the mesh model is simplified based on the attribute information of the geographic feature for polygon model generation. Since each triangle in the mesh model has no boundary information of features, the mesh model is simplified using a quadratic matrix of all vertices to merge inside vertices to generate a polygon model.

**e. CityGML description**

In the description of CityGML, a geographic model of river features is designed for boat navigation and mapping. For mapping, revetments, buildings, bridges, and vegetation are selected as the main geographic features (Figure 2). Revetments are structures that are unique to the river space and can be used to guide navigation to a destination. Moreover, knowing the width of the river can also be used as an indicator of whether boats can pass each other. Vegetation, including trees, may extend above the river, which is necessary to determine if the river is navigable. In the case of bridges, piers and railroad bridges can also be identified and classified. Other landmarks such as street lights and electric lines have also been identified.

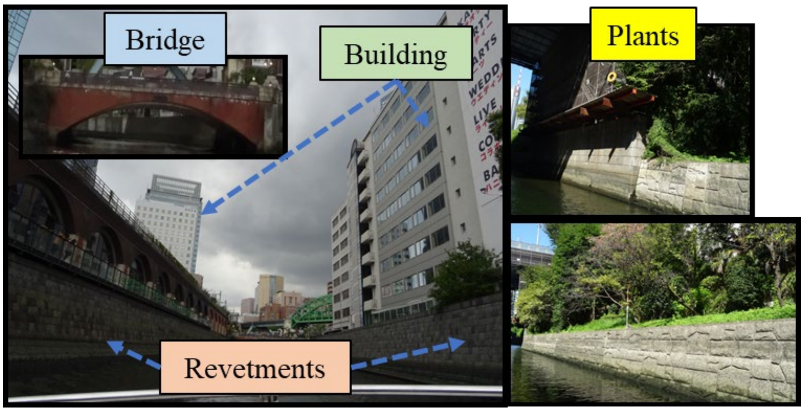


Figure 2: Model design in urban river space.

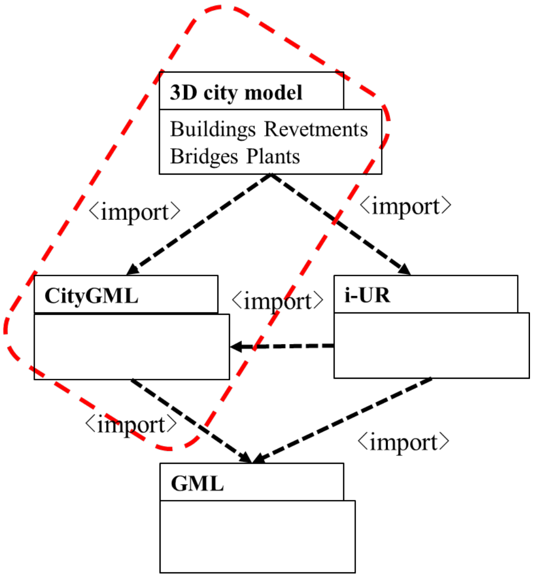


Figure 3: Schema in urban river space.

Figure 3 shows the applied schema in the 3D city model. A schema defines the structure of 3D city data and ensures data consistency and interoperability. An applied schema refers to a data model that is customized for a specific application. For example, PLATEAU consists of packages such as buildings, roads, topography, land use, urban planning, disaster risk, urban facilities, and vegetation. In this study, the urban river space is modeled with the composition of the packages indicated by the red dashed box.

**f. LOD design**

The difference in LOD represents not only the difference in appearance, but also the difference in the amount of information contained in the 3D model. The LOD design for buildings in the 3D city model has five levels, from LOD0 to LOD4. LOD0 is a geometric projection of the city object onto a plane; LOD1 is a simple 3D model such as a box model. LOD2 is a box model with additional shape information such as roofs; LOD3 is a more detailed model; and LOD4 is a model that includes indoor information. It can be used for various applications such as simulation and urban planning. We designed LOD for geographic features in urban river space. In this study, three levels of LOD from LOD0 to LOD2 were set due to the consequence between the collected data. The geographic features related to the spatial schema are revetments, bridges, buildings, and vegetation. The landforms that have different expressions from those of the buildings exist. The revetment is a flat surface in the acquired data, so it is represented as a point sequence in LOD0. Vegetation such as trees is difficult to represent in a simple model such as a box, so LOD1 is not set. In LOD0, the 3D point cloud is projected onto a horizontal plane and output in 2D for use in 2D maps. LOD1 is a polygon model with height added to the surface information. LOD2 is a mesh model to represent the detailed geometry of the landform. The following table shows the LOD design for landforms in the urban river space as shown in Table 1.

Table 1: LOD design for each object

| | LOD0 | LOD1 | LOD2 |
|---|---|---|---|
| Revetments | Continuous 2D points | Polygon model | Mesh model |
| Bridge | 2D point clouds | Polygon model | Mesh model |
| Building | 2D point clouds | Polygon model | Mesh model |
| Plants | 2D point clouds | — | Mesh model |

The relative relationships of the geographic features in the urban river space are shown in Figure 4. The extracted geo-attributes are categorized into navigation-related and non-navigation-related. Furthermore, with the adjacency relationship of landmarks, features can be managed based on the degree of impact on navigation.

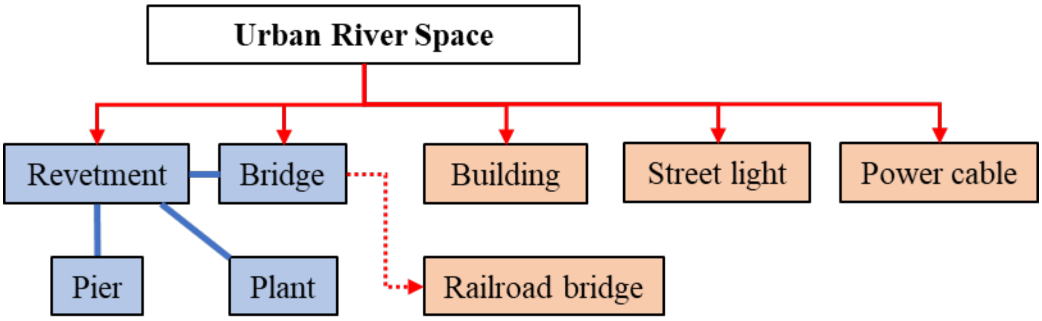


Figure 4: Relationships of river features (water-above objects).

**Experiment**

On October 13, 2023, water-borne measurements were conducted along the Nihonbashi and Kanda Rivers (Figure 5a). A battery-powered boat "Raicho I" (Figure 5b) was equipped with a GNSS antenna and receiver for centimeter-level augmentation services (CLAS) (AsteRx4 and mosaic-X5, Septentrio), and two LiDARs (VLP-32C and VLP-16, Velodyne) (Table 2). We also used a handheld SLAM-LiDAR (Hovermap STX, Emesent) for the additional measurements (Table 3). The boat was approximately 10 m long, which was suitable for narrow urban rivers due to its length of approximately 10 m. The boat also supported stable measurements because its battery propulsion reduced rocking and vibration.

The Nihonbashi River had many sections running under the Metropolitan Expressway running. On the other hand, the Kanda River had a good GNSS environment to receive stable CLAS signals. Among the measured sections, we focused on the Mansebashi - Hijiribashi section (Figure 5a), where there were many types of geographical features.

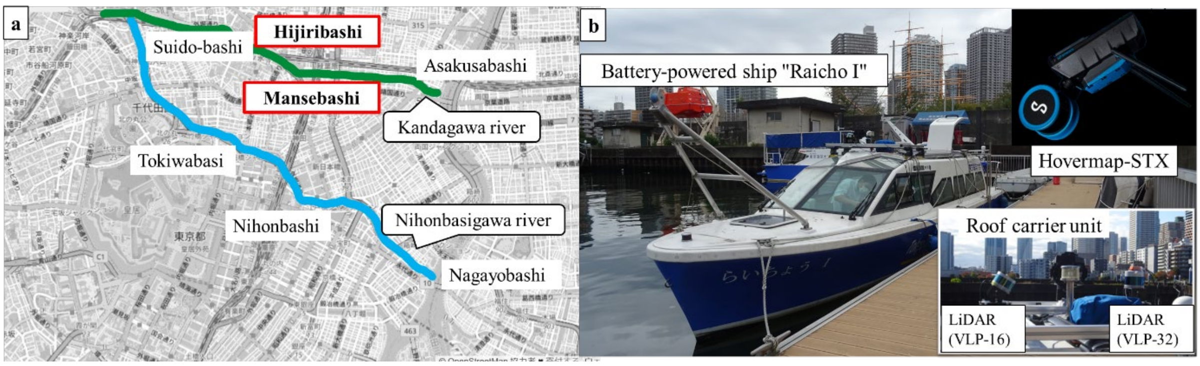


Figure 5: Experiment (left: experimental section, right: water-borne MMS).

Table 2: Specifications of the LiDAR (VLP-16).

| | |
|---|---|
| Weight | 830g |
| Sensor channels | 16 |
| Measurement range | 100m |
| Accuracy | Up to ±3cm (typical) |
| Vertical field of view | +15.0° to -15.0°( 30°) |
| Vertical angle resolution | 2.0° |
| Horizontal field of view | 360° |
| Horizontal angle resolution | 0.1° –0.4° |
| Sampling rate | 5 Hz – 20 Hz |

Table 3: Specifications of the LiDAR (Hovermap STX).

| | |
|---|---|
| Weight | 1.57kg |
| Sensor channels | 32 |
| Measurement range | 0.5m～300m |
| Mapping method | SLAM |
| Mapping accuracy | Outdoor environment ± 15mm<br>Indoor environment ±10mm<br>Short range ±5mm |
| Viewing angle | 360×290° |
| Data acquisition rate | 640,000（points/second） |
| Sampling rate | 5 Hz – 20 Hz |

**Results of point cloud processing**

Figure 6 shows the results after ground object classification and voxelization using point clouds. The color information indicates the type of estimated features. Red color indicates revetments, blue color indicates bridges, yellow color indicates railroad tracks, and green color indicates buildings. In object classification and voxelization, the voxel size should be determined for 3D model creation. If the voxel size is too large, the shape of the object cannot be distinguished when it is converted into a 3D model.

Some geographic features could not be extracted by neighborhood search using trajectory data. Simultaneous extraction was difficult for Hijiribashi and railway bridges with distinctive shapes. Automatic extraction was more difficult the further away from the trajectory data in the height direction. Only the trajectory data near the bridge was used for extraction by reapplying the nearest neighbor search. For the area near the railway bridge, trajectory data and height restrictions were set. Moreover, buildings that were mixed in the extraction were separated as segmentation noise.

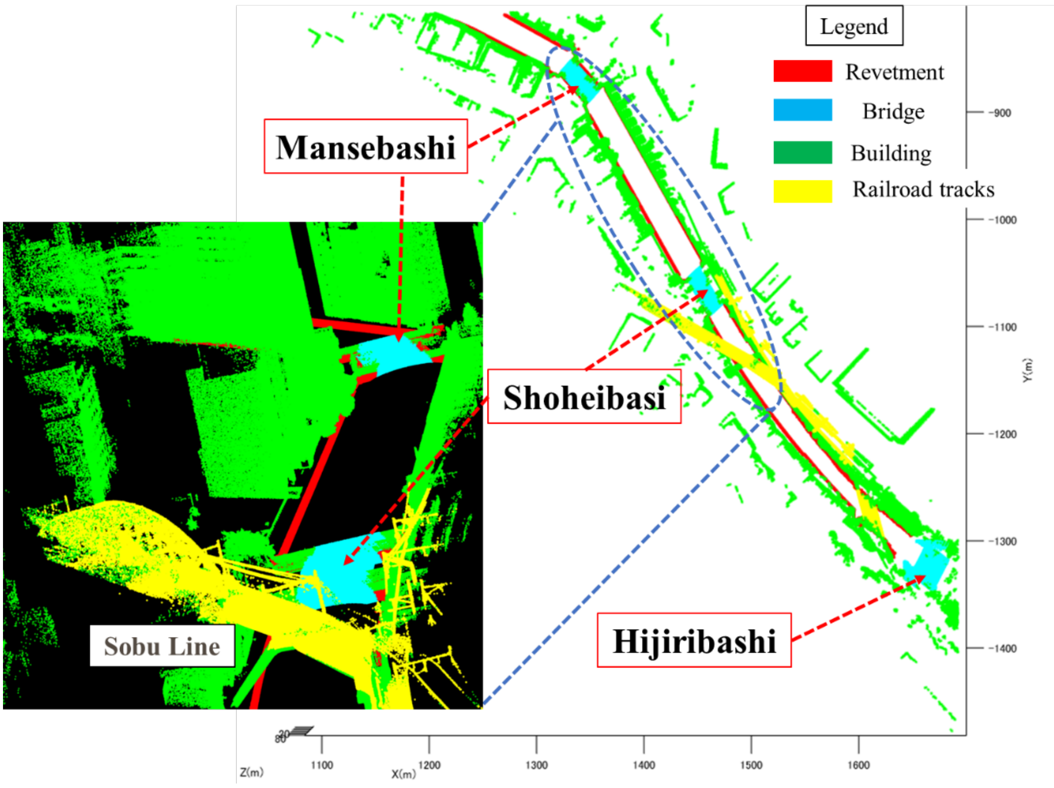


Figure 6: Processing result of point clouds.

**Results of 3D model generation**

The geometric information was simplified using mesh and polygon modeling. Figure 7 shows a visualization result color-coded by each attribute. Compared to the mesh model, the polygon model had fewer vertices and faces. However, the model contained many missing parts.

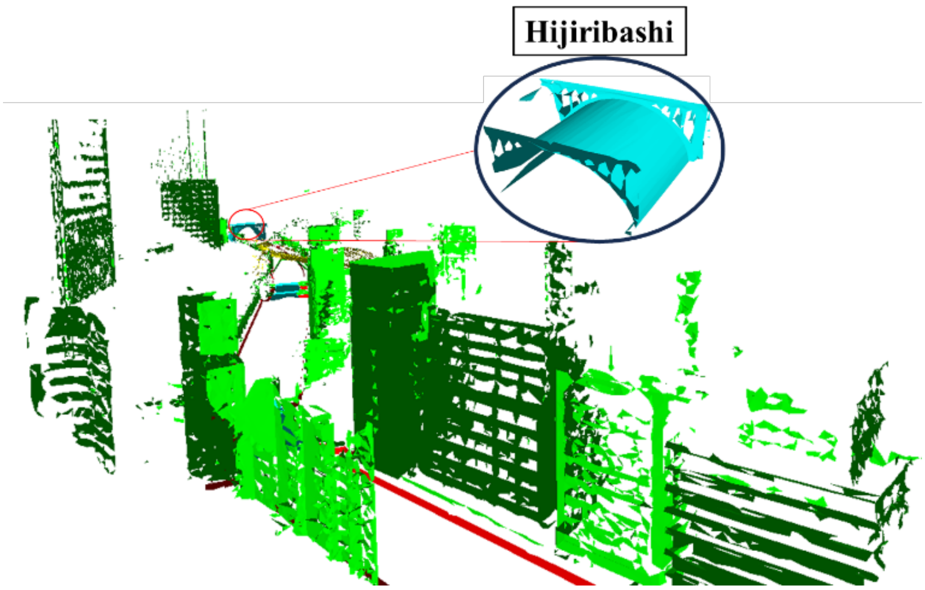


Figure 7: Surface model generation results.

**Discussion**

We confirmed that the geographic features in the urban river can be represented by the description of the boat water-borne MMS point clouds in the CityGML format. However, in the process of extracting geographic objects, some features such as bridges, buildings, and trees were not extracted, as shown in Figure 8. Although the center of the bridge was correctly identified, the ends near the revetments were incorrectly identified as revetments or buildings. We also confirmed that the overlapping parts between bridges and revetments were difficult to classify into them based on their relative distance from the boat, as bridge parts outside of the river were recognized as buildings. To identify geospatial features, classification should be based on a combination of knowledge of geospatial features, such as bridges associated with revetments, and relative distance and direction from the boat.

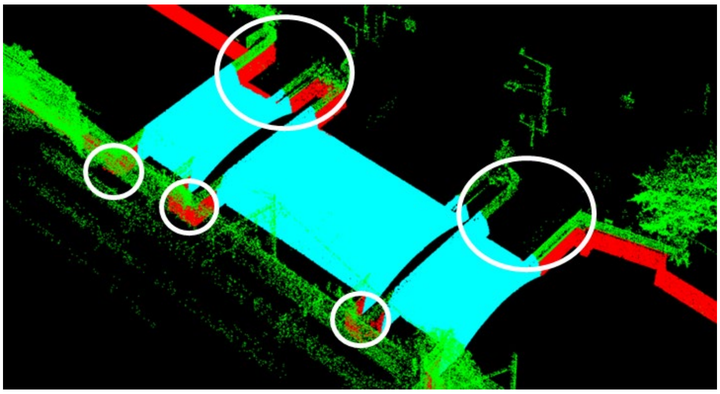

Figure 8: Example of a failed geo-extraction.

Although the railroad tracks were successfully extracted, not all of the electric lines were accurately extracted from the point clouds. Unlike buildings and bridges, the electric lines overlap with surrounding landmarks in many places and differ in height direction, making it difficult to accurately identify them based on the relative distance of the point clouds alone, and it is believed that they were incorrectly extracted. Therefore, it is necessary to set appropriate thresholds according to the characteristics of each object. In this study, vegetation was not accurately classified. Moreover, in the sections where revetments and vegetation were mixed, especially near the Hijiribashi Bridge, it was difficult to classify objects because the vegetation covered the revetments, as shown in Figure 9. While the surfaces of artificial structures such as revetments and bridges have uniform and dense point clouds, the surfaces of trees and vegetation have scattered and sparse point clouds.

Therefore, we can focus on the continuity of the point clouds to improve the classification. We can also focus on image-based segmentation to avoid the difficulty of point cloud classification for revetments covered with vegetation.

Figure 9: Area where vegetation covers the revetments (near Hijiribashi Bridge).

**Considerations for 3D model generation**

When buildings and other structures were partially covered by other geographic objects, the generated mesh model was insufficient. Moreover, not all sides of buildings can be reconstructed because only building facades were measured from the river. Therefore, object estimation of unobserved areas and additional data collection such as aerial photogrammetry are required for 3D modeling. In addition, we confirmed that the reproducibility of geographic features depends on the voxel resolution.

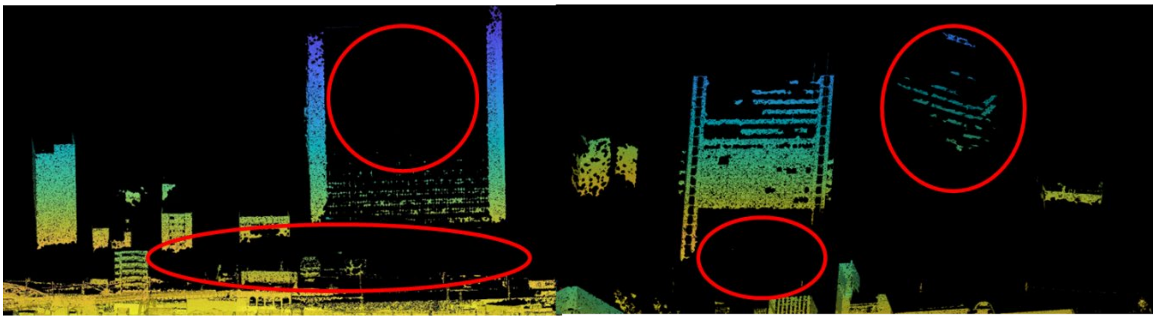

Figure 10: Areas where the 3D model is missing.

3D city models described by the CityGML format are increasingly being integrated with BIM and GIS using detailed 3D models with geospatial data to improve the performance of urban planning and architectural design (Zhu et al, 2021). In this research, we aim to integrate the generated 3D city models with GIS. Triangular meshes are inefficient in spatial search and analysis. Therefore, 3D model transformations from mesh models to polygon models are required for easier and more GIS-compatible data processing.

**Future Prospects**

When creating maps for boats, information about underwater obstacles, such as piers of the Metropolitan Expressway and rocks existing in the riverbed is necessary to consider the risk of stranding. It is difficult to accurately identify and avoid underwater obstacles using only visual observation from a boat. In addition, LiDAR cannot acquire underwater point cloud data. Therefore, we can focus on a multibeam sonar for depth survey as a future issue. Moreover, by incorporating tidal level change data, more precise maps can be produced for boats. Since there are sections of urban river space where navigation is restricted due to the influence of tidal levels, underwater data and surface data above the water should be integrated for safe and efficient navigation support.

**Conclusion**

In this study, we investigated the CityGML description of urban river environments through a 3D city model generation from water-borne MMS point clouds. From the experimental results, we confirmed that the proposed method can classify geographic features for 3D urban river model generation. For an appropriate LOD representation, it is necessary to model geographic features according to their reproducibility, rather than simply applying a mesh modeling of point clouds. In addition, the use of bathymetric data for modeling underwater objects is an issue to be addressed in the future, considering the avoidance of boat stranding.

**Acknowledgments**

This work was supported by JSPS KAKENHI Grant Number JP 24K07704.

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