3D MODELING OF OUTDOOR SCENES BY INTEGRATING STOP-AND-GO AND CONTINUOUS SCANNING OF RANGEFINDER

Toshihiro ASAI[†], Masayuki KANBARA[†], Naokazu YOKOYA[†]

[†]Graduate School of Information Science, Nara Institute of Science and Technology, 8916-5 Takayama, Ikoma, Nara, Japan.
{toshih-a,kanbara,yokoya}@is.naist.jp

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ABSTRACT:

This paper describes a 3D modeling method for wide outdoor environments by integrating stop-and-go and continuous scanning of laser rangefinder. First, range images of an outdoor scene are measured by stop-and-go scanning by using omnidirectional laser rangefinder, and the 3D surface model is generated. Next, to recover the parts that are not measured in the stop-and-go scanning mode due to occlusion, we measure the outdoor scene in the continuous scanning mode where the laser rangefinder line-scans the scene under movement is employed. In the continuous scanning mode, the position and orientation of the rangefinder is acquired by a hybrid sensor which consists of GPS (Global Positioning System) and INS (Inertial Navigation System). Finally, multiple range data acquired in two scanning modes are integrated by registering overlapped parts of range data.

1 INTRODUCTION

3D models of outdoor environments can be used in a number of applications such as landscape simulation, human navigation and virtual walk-through. However, such 3D models are often made manually with high costs, so recently automatic 3D modeling methods have been widely investigated; for example, 3D shape estimation from an image sequence (1)-(5) and 3D measurement by a laser rangefinder (6)-(9). The merit of the former is that the method can reconstruct a 3D model with only a camera. However, since it is difficult for vision-based methods to reconstruct a 3D model with high accuracy, the approaches are not suitable for 3D modeling of wide area outdoor environments. On the other hand, the latter can widely measure the shape of object with high accuracy. Thus it is useful for wide area outdoor environments. Two scanning methods of rangefinder have been proposed:

- Stop-and-go scanning (7)-(9),
- Continuous scanning (10)-(11).

The stop-and-go scanning method measures environments at a number of fixed positions. In order to generate 3D models of environments, range data acquired at multiple points should be registered. In most conventional methods for registration of multiple range data, the ICP algorithm (12) is often used. In the method, the distance between corresponding points in paired range data is defined as a registration error, and a transformation matrix is calculated so that the error is minimized. Therefore, to apply the ICP algorithm, it is necessary for a pair of range data to include overlapped regions. Since outdoor environments are complex, many occlusions occur and also there are some objects which cannot be measured by the rangefinder stably. In order to solve this problem, Gunadi et al. (13) have registered local range data acquired on the ground into a global range data acquired from the sky.

In the stop-and-go scanning, it takes a long time for data acquisition of wide outdoor environments without lacking portions caused by occlusion. This method measures the real environments by a moving sensor system mounted a car or an airplane etc. This method can measure wide area scenes efficiently.However, to generate a 3D model from acquired range data, the positions and orientations of rangefinder are needed. The accuracy of generated model depends on the accuracy of estimated positions and orientations of rangefinder during measurement. One of the continuous scanning methods used a GPS (Global Positioning System) and an INS (Inertial Navigation System) sensor to acquire position and orientation of rangefinder (10), this method can acquire the position and orientation stably. However, a GPS is influenced by the reflection of radio wave by the buildings, and an INS sensor can not acquire data with sufficient accuracy for 3D modeling by an accumulative error, when the sensor is used for a long time.

As another method, Früh et al. (11) have acquired range data by using a line scanner which scans the scene horizontally, and the position and orientation are estimated by matching horizontal scan data. They have carried out 3D modeling of an urban site with a texture by using the method. This method estimates the current position and orientation of rangefinder from the difference between previous and current scanning results. For that reason, an error is accumulated. Moreover, when the current scan line can not match previous one because of the influence of objects which are not measured stably or the shake of sensor system, the position and orientation can not be estimated.

This paper proposes a 3D modeling method which is based on integrating the data acquired by stop-and-go and continuous scanning for reduction of non-measured portions. First, outdoor environments are measured at multiple points by stop-and-go scanning using an omnidirectional laser rangefinder, and a 3D surface model is generated. Then, the portions, defined as non-measured portions, which are not measured by stop-and-go scanning are measured by continuous scanning. In order to register multiple range data of wide area acquired by stop-and-go scanning stably, only planar surfaces that are extracted from the range data are used for registration process, because typical outdoor environments contain many plane regions such as walls and roads. Multiple range data are simultaneously registered by the improved ICP algorithm using detected plane portions. In registration process, the position and orientation, which are acquired by RTK-GPS and INS sensor, are used as initial values of sensor position and orientation of range data for registration by the ICP algorithm.

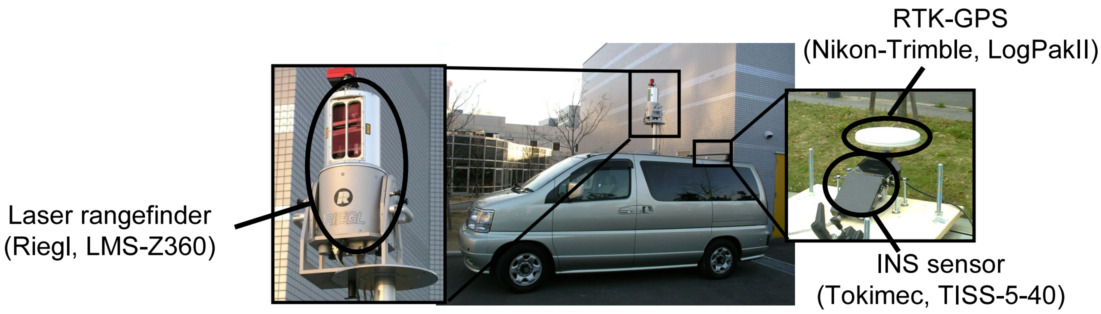


Figure 1: Sensor system mounted on a vehicle.

Table 1: Specification of LMS-Z360

measurable angle	horizontal: 360° vertical: -50°∼40°
measurable range	1m∼200m
measurement accuracy	±12mm
minimum step angle	0.01°
maximum resolution	horizontal: 0.0025° vertical: 0.002°
measurement rate per line	20Hz

The 3D surface model is generated by polygonizing the registered range data. The non-measured portions exist sparsely in the environments measured by stop-and-go scanning mode at multiple points. Therefore, the proposed method attempts to reduce the non-measured portions and time for measurement of environments by continuous scanning mode using a line scanner. Moreover, the positions and orientations of rangefinder during measurement are optimized by registering the range data acquired in the continuous scanning mode into the 3D surface model acquired in the stop-and-go scanning mode.

This paper is structured as follow. Section 2 briefly describes the sensor system used in this study. Section 3 explains the registration of omnidirectional range data acquired at multiple positions. Section 4 describes the method for integrating the data which are acquired by stop-and-go and continuous scanning. In Section 5, experimental results are described. Finally, Section 6 gives summary and future work.

2 SENSOR SYSTEM

This section describes the sensor system. Fig. 1 illustrates the sensor system mounted on a vehicle. In the proposed method, the position and orientation of sensor system are fixed during acquisition of data. The system equips the omnidirectional laser rangefinder (Riegl, LMS-Z360), RTK-GPS (Nikon-Trimble, LogPakII), and INS sensor (Tokimec, TISS-5-40). The system is used in both stop-and-go and continuous scanning modes.

Omnidirectional Rangefinder

The specification of the rangefinder is shown in Table 1. Angle and resolution of measured range data can be determined by user. This rangefinder can measure environments omnidirectionally by illuminating a laser beam radially. The rangefinder takes at least 45 seconds for omnidirectional measurement. The rangefinder is used as an omnidirectional rangefinder in the stop-and-go scanning mode and is used as a line scanner in the continuous scanning mode.

RTK-GPS and INS sensor

RTK-GPS and INS sensor are used to measure the position and orientation of sensor system, respectively. In general, a yaw value

Table 2: Specifications of hybrid sensor (measurement rate : 50Hz)

(a) Accuracy of position.

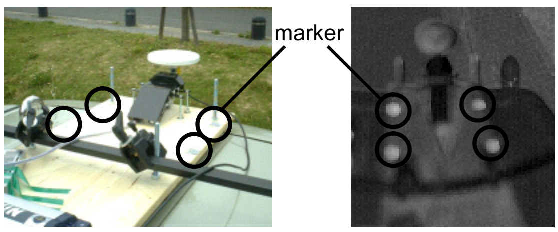
latitude	±3.0cm
longitude	±3.0cm
altitude	±4.0cm

(b) Accuracy of orientation.

yaw	±2°
roll	±0.5°
pitch	±0.5°

measured by the INS sensor includes an accumulative error. The INS sensor is interlocked with RTK-GPS in order to correct the accumulative error by measuring the direction of movement calculated by GPS data during movement. This hybrid sensor can acquire the position and orientation with high accuracy by compensating the low measurement rate of RTK-GPS and accumulative error of INS sensor. The specification of hybrid sensor is shown in Table 2.

The transformation matrix between rangefinder and INS sensor can be estimated by measuring more than three markers whose positions in the INS sensor coordinate system are known. The markers are placed at positions which can be measured by the rangefinder as shown in Fig. 2(a). The transformation is estimated by measuring the positions of markers with respect to the rangefinder as shown in Fig. 2(b).



(a) Layout of markers (b) Laser intensity of markers

Figure 2: Alignment of rangefinder and INS sensor coordinate systems.

3 GENERATION OF 3D SURFACE MODEL BY STOP-AND-GO SCANNING

A surface model of environment is generated by registering multiple omnidirectional range data (14). All the range data are registered to the GPS coordinate system. Since the position and orientation acquired by the sensors include some errors, they are used as initial values in registration and should be optimized. The ICP algorithm (12) is often used for registration of multiple range images. In the conventional ICP algorithm, the distance between corresponding points in paired range data is defined as a registration error, and the transformation matrix is calculated so that the error is minimized. The present rangefinder measures the distance by rotating the laser scan, thus the spatial density of data points depends on the distance; that is, close objects are measured densely and far objects are measured sparsely. In registering range data obtained at different positions, this causes the problem that multiple points may correspond to a single point. The solution tends to fall into a local minimum, because the correspondences between points are discrete and do not include the surface information about an object (16). The proposed method first detects plane regions from all the range data, and then determines point-to-plane correspondences. Finally, the transformation matrix of range data is calculated by overlapping the corresponding planes.

3.1 Simultaneous Registration of Multiple Omnidirectional Range Data

Multiple range data are registered by overlapping the corresponding planes among range data. For this purpose as a pre-processing, planar regions in range data are detected and the normal vectors at the measured points in planar regions are calculated, and then the plane in one data is matched with planar points in other data. Multiple range data are simultaneously registered for optimization of transformation matrices. The position and orientation acquired by RTK-GPS and INS sensor are used as an initial value in the optimization. The flowchart of the registration is shown in Fig. 3 and the detail of each process is described in the following.

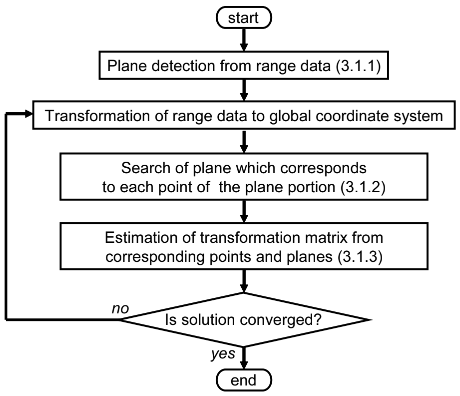


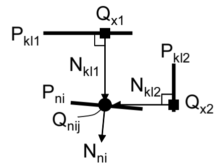
Figure 3: Procedure of registring range data

3.1.1 Plane Detection from Range Data

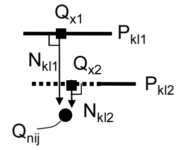
Planar regions are detected from range data by local plane fitting. We employ the renormalization method (15) for planar region detection and the quadtree segmentation recursively. The whole range image is taken as an initial region. The distances between estimated plane and points in the region are calculated and when at least one distance is bigger than a threshold, the region is split. On the other hand, when all the distances are smaller than the threshold, the region is defined as a plane portion. The points which are not defined as a plane portion are not used for registration process.

3.1.2 Search of Corresponding Plane

The plane corresponding to the plane of a certain range data is looked for from another range data. The plane correspondence is described below. Let RD_n be range data n $(n = 1, \cdots, N)$, P_{ni} be a planar region in RD_n $(i = 1, \cdots, I)$ and Q_{nij} be a point in the plane P_{ni} $(j = 1, \cdots, J)$. The normal vector of P_{ni} is denoted by N_{ni}. A plane corresponding to the point Q_{nij} is searched from range data other than the range data n. A plane P_{kl} corresponding to the point Q_{nij} is selected so that $|\overline{Q_{nij}Q_x}|$, which means the distance between Q_{nij} and Q_x, is minimized. Note that P_{kl} and Q_{nij} satisfy two conditions shown in Fig. 4: the inner product of N_{kl} and N_{ni} is below a threshold (Fig. 4(a)) and a point Q_x where the vector N_{kl} passing through point Q_{nij} intersects the plane P_{kl} exists (Fig. 4(b)). P_{kl1} is chosen as the plane which corresponds to Q_{nij} in both Fig. 4(a) and (b).



(a) Selection by threshold of an inner product.



(b) Selection by existence of an intersection.

Figure 4: Selection of corresponding plane.

3.1.3 Estimation of position and orientation of range data

The sensor position of range data is estimated from the distances between points in a plane and the corresponding planes and the sensor orientation of range data is estimated from the inner products of normal vectors of corresponding points and planes. Let T_n and R_n be sensor position and orientation of range data n $(n = 1, \cdots, N)$, respectively.

step 1. The orientations R_n are estimated by maximizing the correlation C_N defined as the sum of inner products of normal vectors of a point Q_u and the plane P_{Qu} which is corresponding Q_u $(u = 1, \cdots, U)$, where U represents the number of pairs of corresponding point and plane.

$$C_N = \sum_{u=0}^{U} (R_{Q_u} N_{Q_u}) \cdot (R_{P_{Qu}} N_{P_{Qu}}) \rightarrow max, \qquad (1)$$

where N_{Q_u} and $N_{P_{Qu}}$ are the normal vectors of Q_u and P_{Qu} respectively.

step 2. The positions T_n are estimated by minimizing the error E_T which is defined as the sum of distances between corresponding point and plane as follows.

$$E_T = \sum_{u}^{U} distance(Q'_u, P'_{Qu}) \rightarrow min, \qquad (2)$$

where Q'_u and P'_{Qu} are Q_u and P_{Qu} after transformation by (R_{Q_u}, T_{Q_u}) and $(R_{P_{Qu}}, T_{P_{Qu}})$, and the orientations estimated in step 1 are fixed.

The corresponding plane is searched again after the step 2 and the process is iterated until the solution is converged. Downhill simplex method in multidimensions (17), which does not need the derivatives, is used for the optimization.

3.2 Polygonization of Range Data

A polygonal representation is generated from each range data by connecting four corners of each region defined as a plane portion in the plane detection process in order to reduce the number of polygons. In a non-plane portion, a polygon is generated by connecting adjoining pixels which are neighbors of pixels and one of diagonal neighbors of pixels. A range data partially overlaps other range data. The quantity of data is reduced by removing redundant polygons at overlapping regions. Polygons are generated from range data in order of input. The generated polygons which correspond to the vertices of the generating polygon with the method described in Section 3.1.2. are searched. When distances between vertices and intersection Q_x are less than a threshold, the polygon is deleted as a redundant one as shown in Fig. 5. Note that only the polygon defined as a plane portion is deleted to maintain the quality of model and to reduce the amount of data.

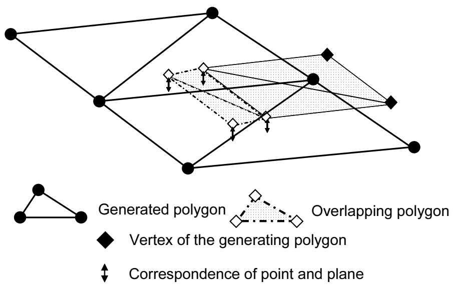


Figure 5: Deletion of overlapping areas.

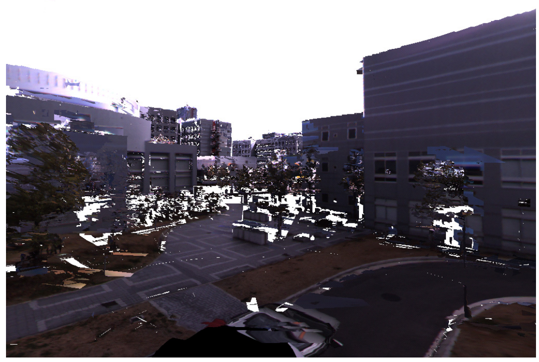


Figure 6: Non-measured portions of generared 3D model

4 INTEGRATION OF STOP-AND-GO AND CONTINUOUS SCANNING

This section describes the method for integrating the range data which are acquired by stop-and-go and continuous scanning. 3D surface model which is generated from the data acquired by stop-and-go scanning has non-measured portions as shown in Fig. 6 (white portions). The non-measured portions exist sparsely in the environments measure by stop-and-go scanning mode at multiple points using an omnidirectional rangefinder. Therefore, the proposed method attempts to reduce the non-measured portions and time for measurement of environments by continuous scanning mode using a line scanner. The positions and orientations of rangefinder during movement are measured by the hybrid sensor which consists of a RTK-GPS and an INS sensor. The positions and orientations of rangefinder during measurement are optimized by registering the range data acquired in continuous scanning mode into the generated model from stop-and-go scanning.

In continuous scanning, the positions and orientations of rangefinder are continuously measured by the hybrid sensor. Since the accuracy of GPS is dependent on the state of an electric wave, it is difficult to maintain the high accuracy. Therefore, positions and orientations acquired by the hybrid sensor are used as initial values for registration and are optimized by registering continuous scanning data with the model generated in Section 3. In the case of registration process for the data acquired in the stop-and-go scanning mode, in order to exclude complex objects such as trees, plane portions are detected from range data and only the plane parts are used for registration. For the same reason in continuous scanning, straight lines are detected from each scan line of range data, and only the straight line parts are used for registration. Procedure of registration is shown in the following.

1. Straight lines are detected from each scan line of range data by straight line fitting by downhill simplex method in multidimensions (17).

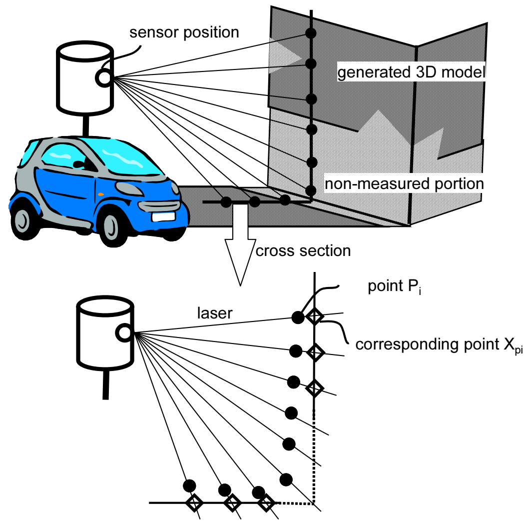


Figure 7: Search of the corresponding point. (The case which take up a certain scan line.)

2. The point corresponding each point $\mathbf{P}_i (i = 1, \cdots, I)$ is searched from generated 3D surface model as shown in Fig. 7. The point corresponding to $\mathbf{P}_i$ is defined as $\mathbf{X}_{Pi}$ which is intersection of the laser beam on $\mathbf{P}_i$ and the generated model.

3. The transformation matrices $\mathbf{M}_{Pi}$ are estimated by minimizing the error which defined as the sum of distances between corresponding points as follows.

$$E = \sum_{i=1}^{I} \left| \overline{(\mathbf{M}_{Pi}\mathbf{P}_i)\mathbf{X}_{Pi}} \right| \rightarrow min.$$

4. If the solution does not converge, return to 2.

5 EXPERIMENTS

We have carried out experiments of registration of range 3D modeling by integrating the data acquired in the stop-and-go and continuous scanning modes. In stop-and-go scanning, the omnidirectional range images are acquired at 68 points in our campus (about 250m × 300m). Since the proposed registration method requires overlapping portions among range data in stop-and-go scanning, we have acquired the omnidirectional range data approximately at 30m interval. The resolution of each omnidirectional range image is 1024×512. A cluster system consisting of 24 PCs (CPU: Pentium4 1.7GHz, Memory: 1024MB) is used for finding corresponding planes, and a single PC (CPU: Pentium4 1.8GHz, Memory: 2048MB) is used for registration of multiple omnidirectional range data. The time required for registration is about 7 days. The generated 3D surface model from the data by stop-and-go scanning is shown in Fig. 8. From Fig. 8 we confirm that the generated model has no large distortion.

In a preliminary experiment of continuous scanning, the data acquisition area and the path of sensor system for measurement of the non-measured portions are determined manually. The data are integrated by registering the range data acquired by continuous scanning into the generated 3D surface model. The 3D surface model is generated from the 3 range data acquired by stop-and-go scanning. In continuous scanning, the rangefinder by which the direction was fixed is used as a line scanner for acquisition of data, and range data of 1000 lines are acquired in the 70m path. The range image acquired by continuous scanning is shown in Fig. 9. The sensor system has been already aligned among sensor coordinate systems and timing of data acquisition. The 3D

Figure 9: Range data acquired by continuous scanning.

surface model used for the experiments is shown Fig. 10(a), and the range data acquired by continuous scanning is shown 10(b). It is assumed that the range data of one scan line is acquired at the same position and orientation, and the sensor motion are optimized on the condition that the position and orientation between sequential scan lines vary smoothly. The results of registration are shown in Fig. 11. Although the model registered by only the positions and orientations which are acquired by hybrid sensor includes distortion in some parts in Fig. 10(b), from Fig. 11 we confirm that the registered data is revised correctly.

6 CONCLUSION

This paper has proposed a 3D modeling method which integrates the data acquired in stop-and-go and continuous scanning modes using a rangefinder for the reduction of non-measured portions. In stop-and-go scanning, a 3D model is generated from omnidirectional range images acquired at multiple positions. We have confirmed that the model has no large distortion. However, we can observe many small data lacking portions mainly caused by occlusions in the generated model. The data lacking portions are measured by continuous scanning. In a preliminary experiment of continuous scanning, the data acquisition area and the path of sensor system for measurement of the non-measured portions are determined manually. The data are integrated by registering the data acquired by continuous scanning using a line scanner to the model generated from the data by stop-and-go scanning. We have confirmed that the non-measured positions are reduced by registering the data acquired by stop-and-go and continuous scanning.

We are planning to control the direction of rangefinder for measurement of non-measured portions by storing the generated model in a measurement system and automatically detecting the non-measured portions.

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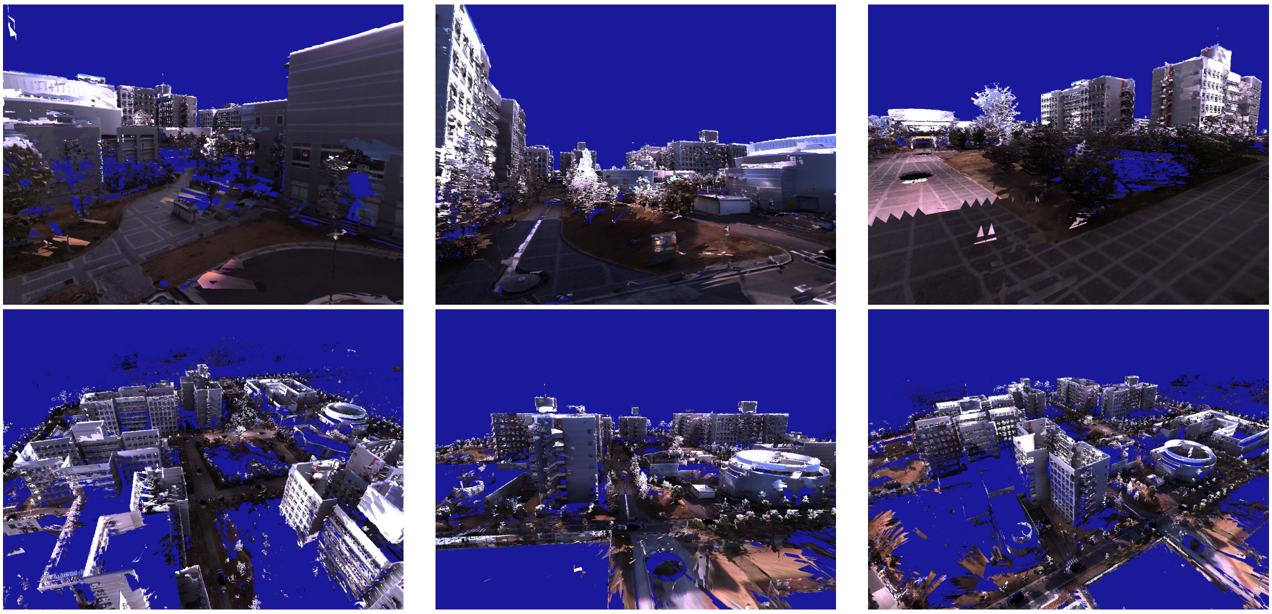
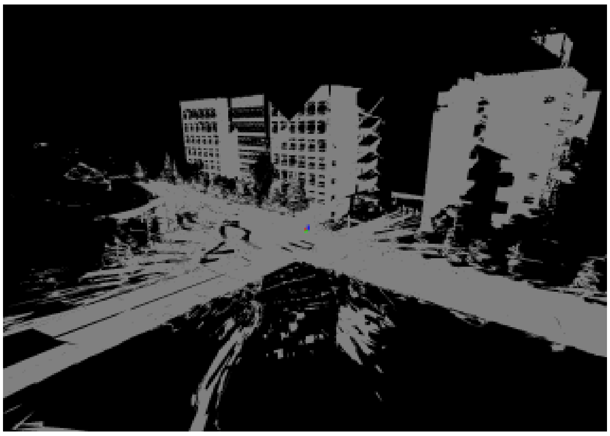
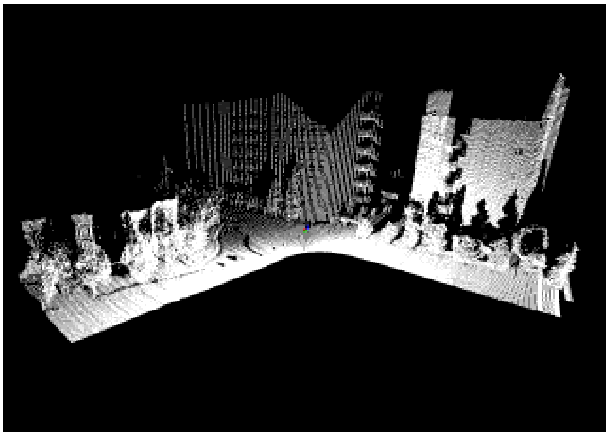


Figure 8: Gennerated 3D model with texture from the data which are acquired by stop-and-go scanning.



(a) Generated 3D model from the data acquiring by stop-and-go scanning.



(b) Data acquiring by continuous scanning.

Figure 10: Acquired model data.

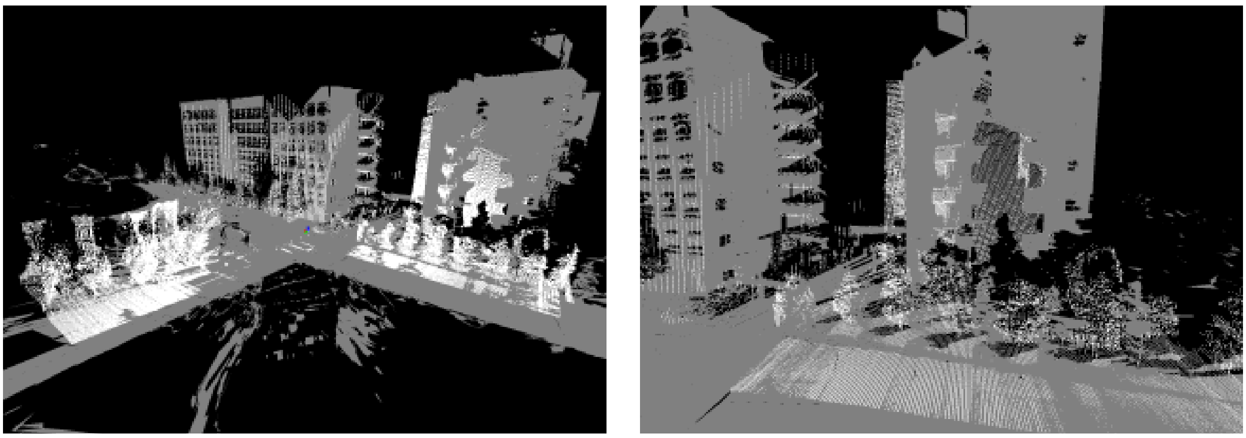


Figure 11: Integration results of stop-and-go (gray) and continuous (white) scanning.