MODEL-BASED POINT CLOUD RECONSTRUCTION OF EXCAVATION SITE FOR BURIED PIPE MANAGEMENT

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ABSTRACT: Construction space modeling is required for automated operation of construction vehicles, construction management, and safety management. Construction sites are constantly changing during drilling work. Thus, a base map of the construction site should be updated using point clouds acquired through several steps in construction work. Particularly, multiple buried objects such as underground pipes should be measured in construction work because buried objects are difficult to measure with 3D scanners after such work is complete. Moreover, it is better to visualize buried objects with software products such as virtual reality and augmented reality to avoid accidental destruction because of excavation work using construction vehicles such as backhoes. Therefore, 3D measurement and modeling of buried objects are significant in construction work. In this study, we proposed a rapid 3D measurement and modeling of underground objects in construction work. First, we estimate the central axis of point clouds for the 3D modeling of buried pipes. Second, the 3D pipe model was fit to acquired point clouds. Buried pipes can be represented as known geometry models because of products provided based on industrial standards. Thus, the 3D model fitting approach was applied using a pipe model prepared in advance. Then, after 3D model fitting, the depths of buried pipes from ground surfaces were calculated using the estimated axis and point clouds of ground surfaces. We conducted an experiment on 3D measurement based on point cloud acquisition with SfM/MVS and 3D laser scanner during electric line pipe installation work. We also experimented on the 3D modeling of pipes using point clouds acquired with a handheld camera and 3D laser scanner to reconstruct 3D shapes and positions of pipes at a construction site.

1. INTRODUCTION

In building information modeling/ construction information modeling (BIM/CIM), 3D modeling of the construction site is necessary for the coordination of automated operations of construction vehicles, construction management, and analysis, and the use of point clouds is expected to be very useful for understanding the current status. Construction sites are constantly changing during drilling work. Thus, it is necessary to link real-time point cloud measurements from construction equipment to point cloud acquisition with off-line processing (base map point cloud), which is used as a base map. The base map point cloud represents the static and visible area of the construction space, which can be acquired with a 3D laser scanner, handheld LiDAR, UAV-SfM, or UAV-LiDAR. By acquiring this base map point cloud not only before and after, but also during construction, it is possible to grasp the detailed position and shape of underground buried objects, which are managed by point and line data. However, the acquired point cloud cannot reproduce the entire space, as it contains noise and missing regions because of obstacles.

2. METHODOLOGY

There are many studies on modeling and object recognition of cylinders and cylindrical shapes, including underground pipes-which are the subject of this study-plant facilities (Kazuaki et al., 2014a), modeling of indoor pipes, and utility and other poles on roads (S. I. El-Halawany et al., 2011b). In research on the modeling of cylinders and cylindrical shapes, RGB-D cameras equipped with a distance sensor that can acquire depth images in addition to color images (Hiroki et al., 2015c) and 3D laser scanners are often used to acquire point clouds. By contrast, when images from point cloud acquisition with structure from motion/ multi view stereo (SfM/MVS) (Benjamin et al., 2020d) using handheld cameras are used as input data, the modeling process of cylindrical and cylindrical shapes becomes unstable because of the large amount of spike noise and missing regions. The proposed method to solve this problem is shown in Figure 1.

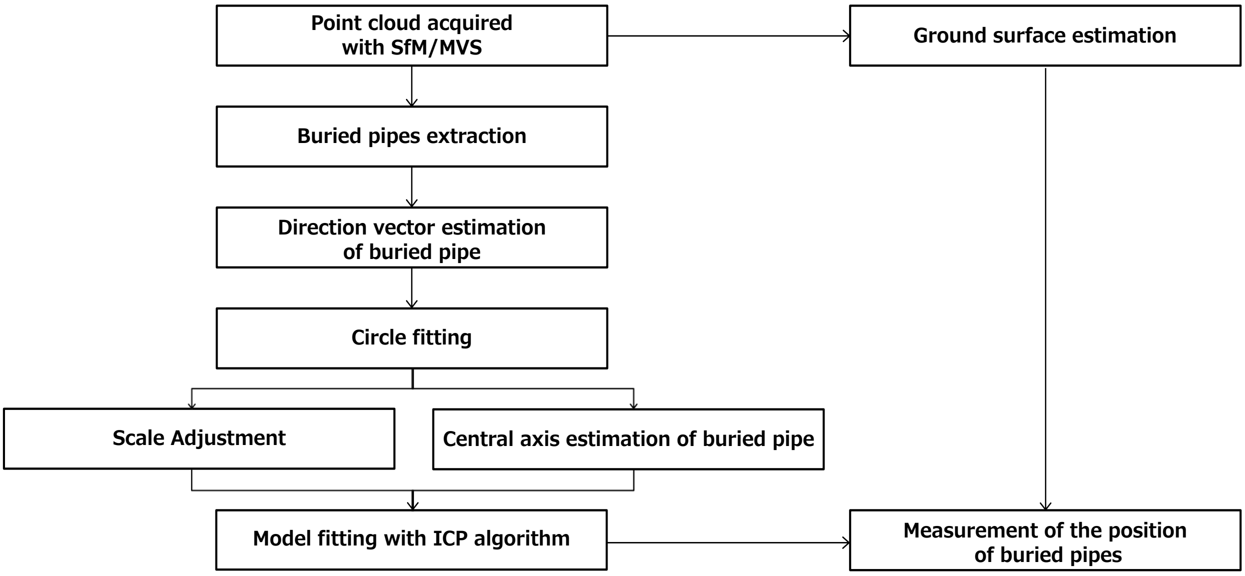


Figure 1. Proposed method

2.1 Modeling of buried pipes

The buried pipe to be modeled is an industrial product for which standards are defined. Therefore, the modeling of the buried pipe adopts a model fitting methodology that uses the pipe model prepared in advance. First, we classify the buried pipe and the ground objects other than the buried pipe by using the color information on the colored point cloud, which is the input data, and extract the point cloud of the entire buried pipe (Figure 2). Next, the longitudinal direction of the excavation site is defined as the X-axis, the transverse direction is defined as the Y-axis, and the height direction is defined as the Z-axis, and the point clouds of the buried pipe are projected onto the XY and XZ planes, respectively. Then, using the projected area of the point cloud in the XY and XZ planes, the neighboring point clouds are selected for each pipe model. The direction vector of the central axis of the buried pipe is estimated from the selected point clouds, and the point cloud of the whole buried pipe is divided into each buried pipe (Figure 3). Model fitting is applied to each of the divided buried pipes. The model fitting is performed by aligning the central axis of the pipe model with the central axis of each buried pipe, which is generated by fitting a circle of input points. In this study, the input point clouds are point cloud acquisition with SfM/MVS and a 3D laser scanner. Model fitting is performed for each input point cloud. Point cloud acquisition with a 3D laser scanner is processed except for the scale adjustment. The radius of the circle estimated during the circle fitting of each point cloud is compared and evaluated.

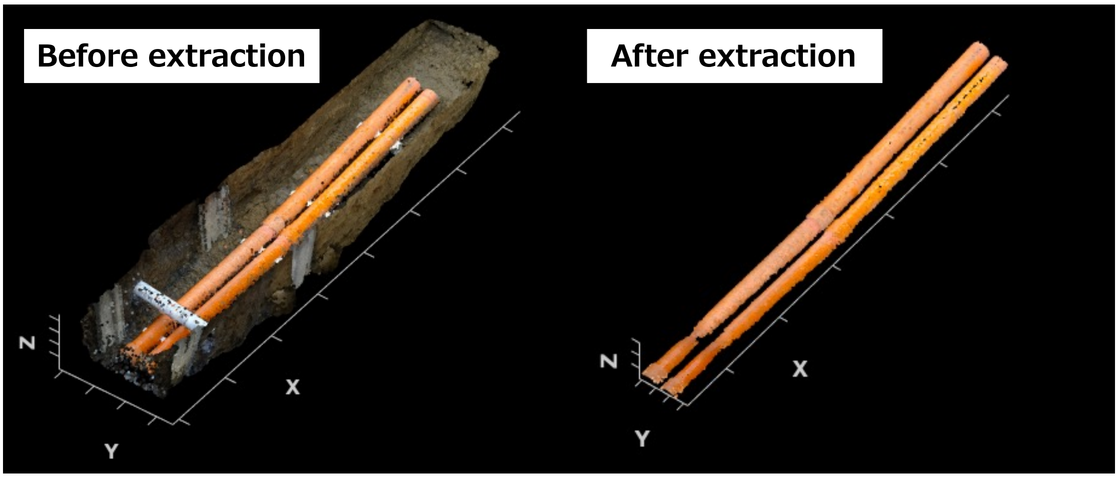


Figure 2. Pipe extraction

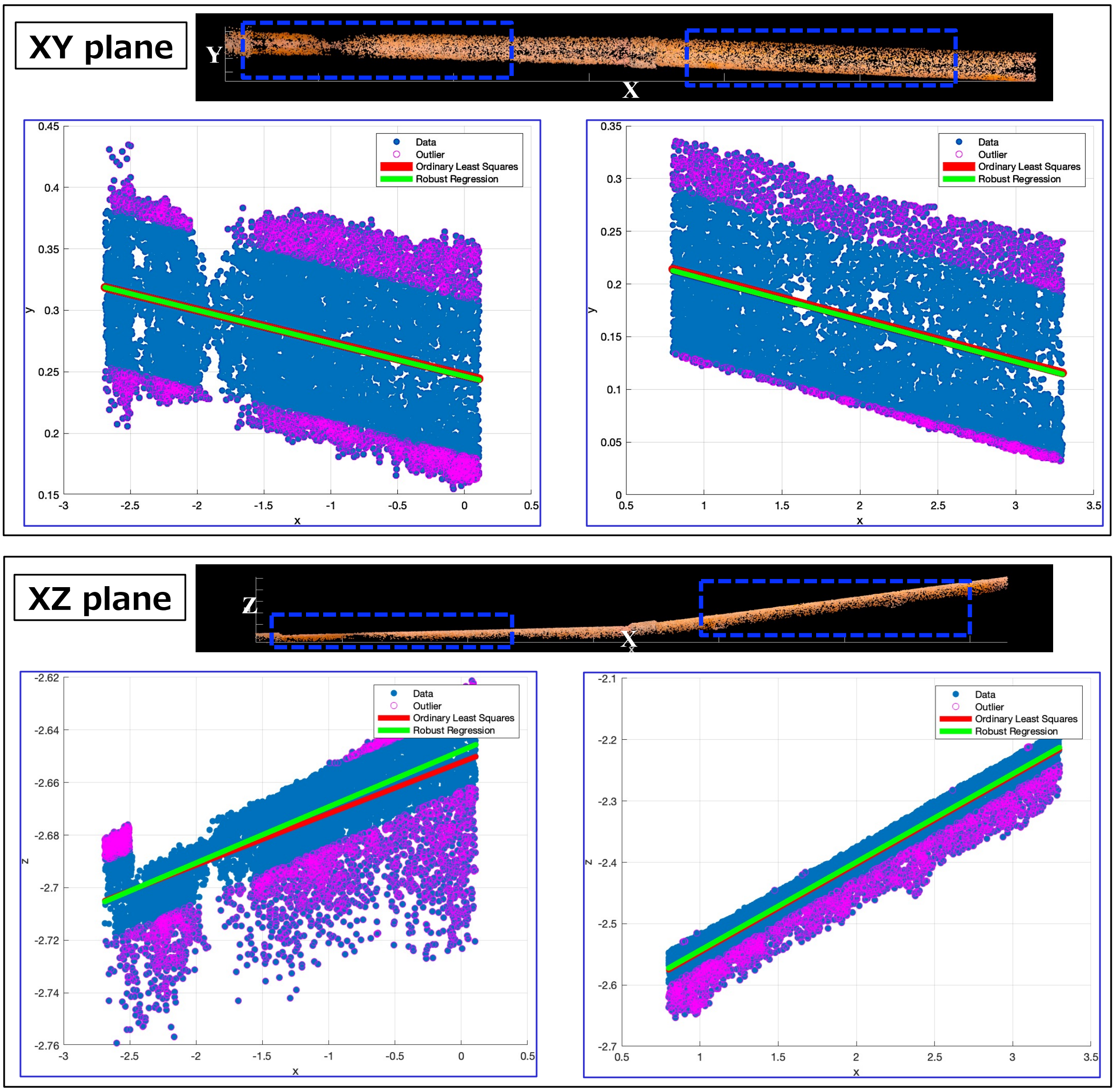


Figure 3. Estimation of the pipe direction vector

2.2 Generating the central axis of a pipe

For a pipe model with known shape and dimensions, point clouds are assigned to the central axis at equal intervals in advance. Each buried pipe in the input point cloud is also assigned a point cloud at the coordinates of the center of the circle estimated at the same interval, and the central axis is generated. First, the point cloud of the buried pipe is cut at equal intervals, and the circle is fitted to each cut surface to estimate the center coordinates. Next, the central axis is generated by connecting the center points of the circle estimated on each cut plane. Because the center of the circle cannot be estimated accurately at points where the point cloud is sparse, the central axis is corrected. Random sample consensus (RANSAC) is then used to estimate the center axis without the effect of outliers (Figure 4).

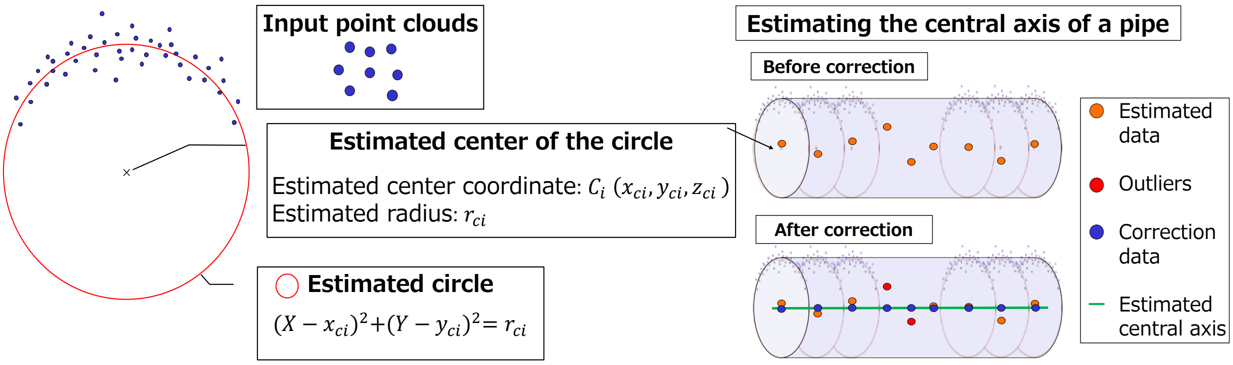


Figure 4. Estimation of the central axis

2.3 Scale adjustment

Since point cloud acquisition with SfM/MVS is different from the actual scale, it is necessary to adjust the scale. We adjust the scale by mapping the radius of the pipe model, whose shape and dimensions are known, to the radius of the pipe estimated in the point cloud. The center coordinates C_i of the i-th circle estimated on the point cloud are set to (x_{ci}, y_{ci}, z_{ci}), the radius is r_{ci}, and the radius of the pipe model is r_m. The scale S_i calculated using the i-th radius can be expressed as in Equation (1).

$$S_i = r_m / r_{ci} \qquad (1)$$

After adjusting the scale for all parameters $S_1 \sim S_n$, the root mean square error (RMSE) of the residual between the radius of the pipe model is calculated and the radius of the pipe is estimated in the point cloud. Scale parameter S_i that minimizes the RMSE is determined.

2.4 Model fitting

For model fitting, we use the iterative closest point (ICP) (Helmut et al., 2004e) algorithm, which is a method of aligning point clouds. The model fitting is performed by aligning the point cloud that constitutes the central axis of the pipe model (Figure 5), which has been created in advance, to the point cloud that constitutes the central axis generated by fitting the circles of each buried pipe in the input point cloud (Figure 6). The rotational matrix R_{ICP} and the translational matrix T_{ICP} are calculated, and the model fitting is performed using a three-dimensional rigid transformation. The relationship between the input point cloud $ptCloud_{In}$ and the 3D model point cloud $ptCloud_{Out}$ can be expressed as in Equation (2).

$$ptCloud_{In} = ptCloud_{Model} \cdot R_{ICP} + T_{ICP} \qquad (2)$$

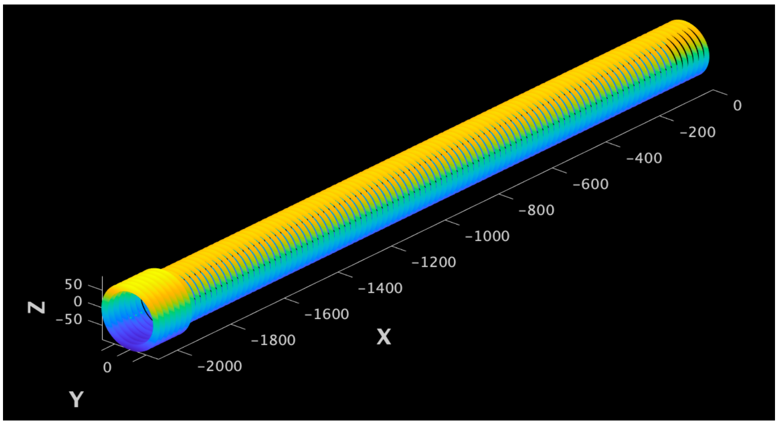


Figure 5. Fitting model

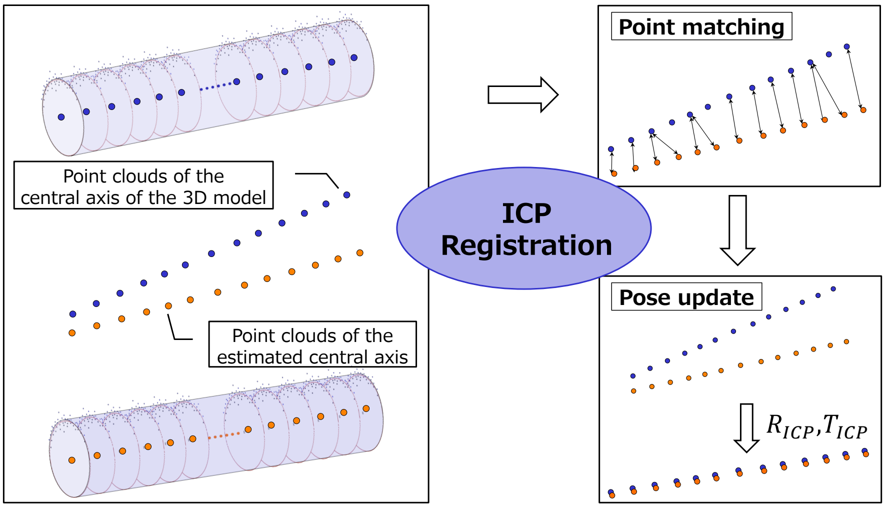


Figure 6. Fitting model

2.5 Measurement of the position of buried pipes

In this study, the position of the buried pipe is defined as the height from the ground surface to the central axis of the pipe (Figure 7). First, we estimate the plane using RANSAC for a set of points that are assumed to exist on the ground surface. The general equation of the plane can be expressed as in Equation (3). Let $P(x_{pn}, y_{pn}, z_{pn})$ be any point on the plane that satisfies Equation (3).

$$ax + by + cz + d = 0 \qquad (3)$$

The coordinates of the central axis of the buried pipe $C_i(x_{ci}, y_{ci}, z_{ci})$ are known by model fitting. Therefore, the distance D_i from the i-th point of the central axis of the buried pipe to the plane can be expressed as in Equation (4).

$$D_i = |z_{pn} - z_{ci}| \qquad (4)$$
$$z_{pn} = (ax_{ci} + by_{ci} + d)/(-c)$$

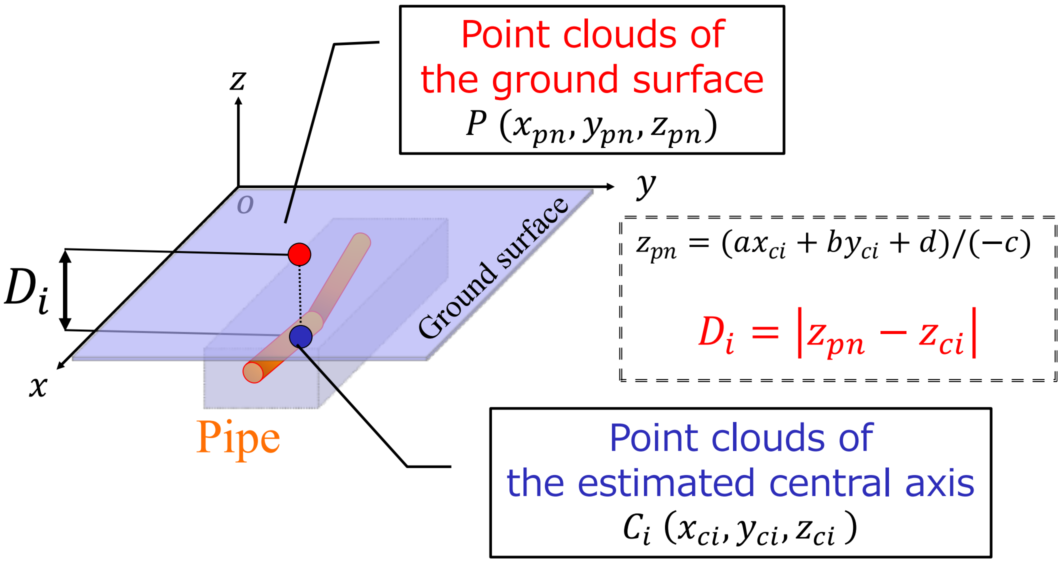


Figure 7. Measurement of the position of buried pipes

3. EXPERIMENTS

We conducted an experiment on 3D measurement based on point cloud acquisition with SfM/MVS and 3D laser scanner during electric line pipe installation work. The point cloud acquisition with SfM/MVS was obtained from 420 images taken by a handheld digital camera (Figure 8) and used as input data (Figure 9). COLMAP was used to generate the point cloud. The geometry information of the PFP shown in Figure 10 (pipe length including socket section: 2,080 [mm] outer diameter: 150 [mm]) was used to create the pipe model for model fitting. As parameters for model fitting, the pipe cutting interval was set to 20 [mm] and the number of cross-sectional points was set to 104. In addition, we conducted the same experiment on 3D measurement to the acquired point cloud with a 3D laser scanner for the same measurement target (Figure 11).

Digital camera

DSC-HX60V (SONY)

Number of pixels (effective): 20.4MP
Sensor type: 1/2.3" type (7.82mm) Exmor R™ CMOS sensor
Focal Length: f=4.3-129mm
GPS: ✓

Figure 8. Specifications of DSC-HX60V (SONY)

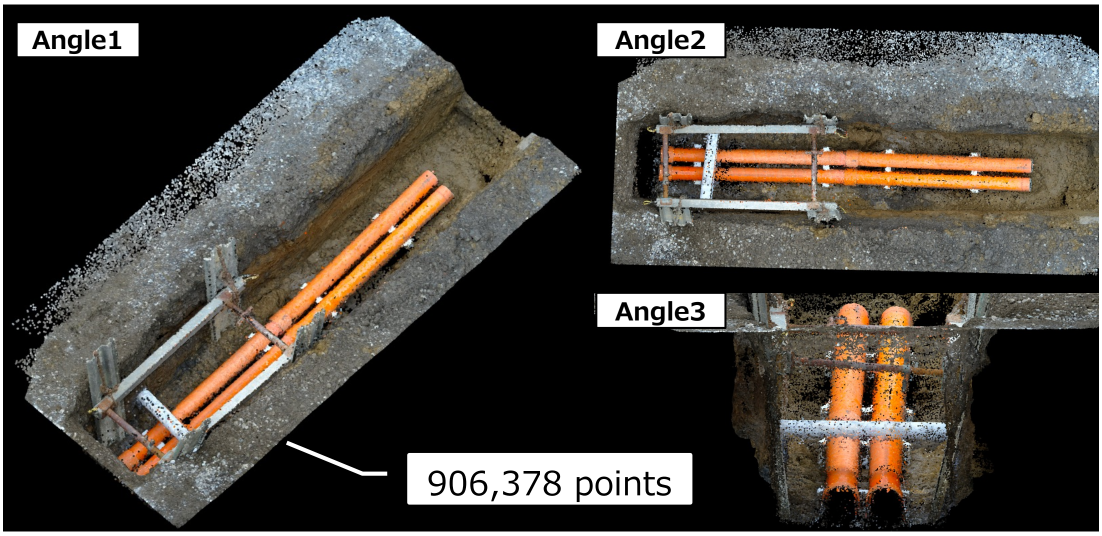
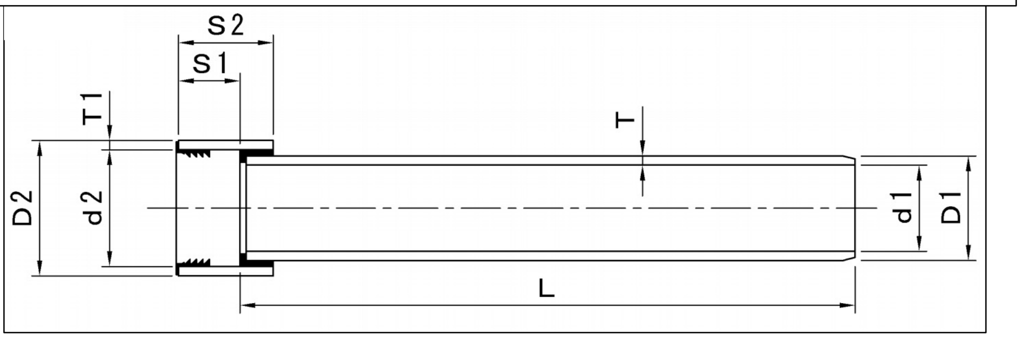


Figure 9. Input point clouds acquisition with SfM/MVS

PFP (Polyester Concrete Fiberglass Reinforced Plastic Pipe)



Pipe body section [mm]			
Inner diameter d1	Pipe thickness T	Outer diameter D1	Pipe length L
130	10	150	2,000

Socket section[mm]				
Inner diameter d2	Pipe thickness T1	Outer diameter D2	Socket section length S1	Socket section length S2
160	10	180	80	130

Figure 10. Specifications of PFP

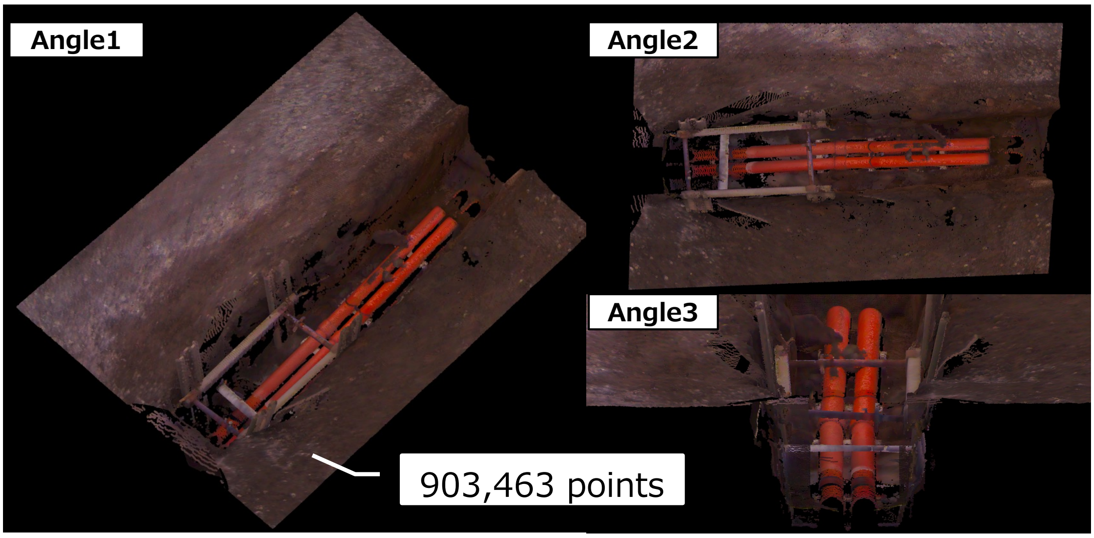


Figure 11. Input point clouds acquisition with a 3D laser scanner

4. RESULTS

4.1 Results of fitting the pipe model

The results of the model fitting of the four PFP are shown in Figure 12 and Figure 13. The processing time was 13.5 seconds (Intel Core i5, 1.4 GHz, MATLAB). The RMSE results of the residuals between the true value of the estimated radius of the buried pipe in the point cloud acquisition with SfM/MVS and 3D laser scanner are shown in Table 1. The RMSE of the Euclidean distance between the point clouds is 22.7 [mm] when the point cloud acquisition with SfM/MVS and 3D laser scanner in the excavation site are aligned.

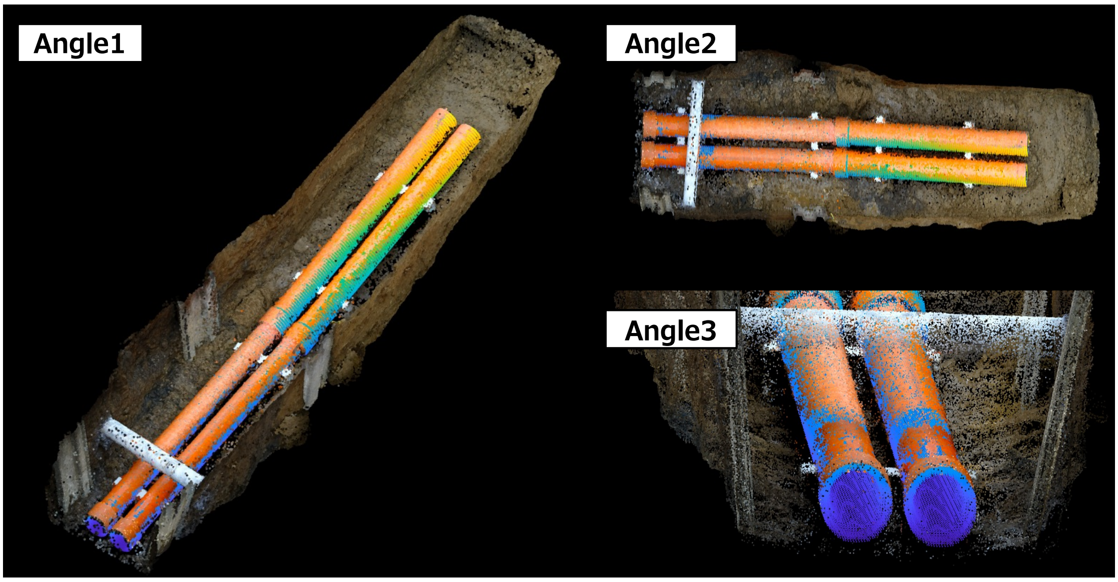


Figure 12. Results of the model fitting (point cloud acquisition with SfM/MVS)

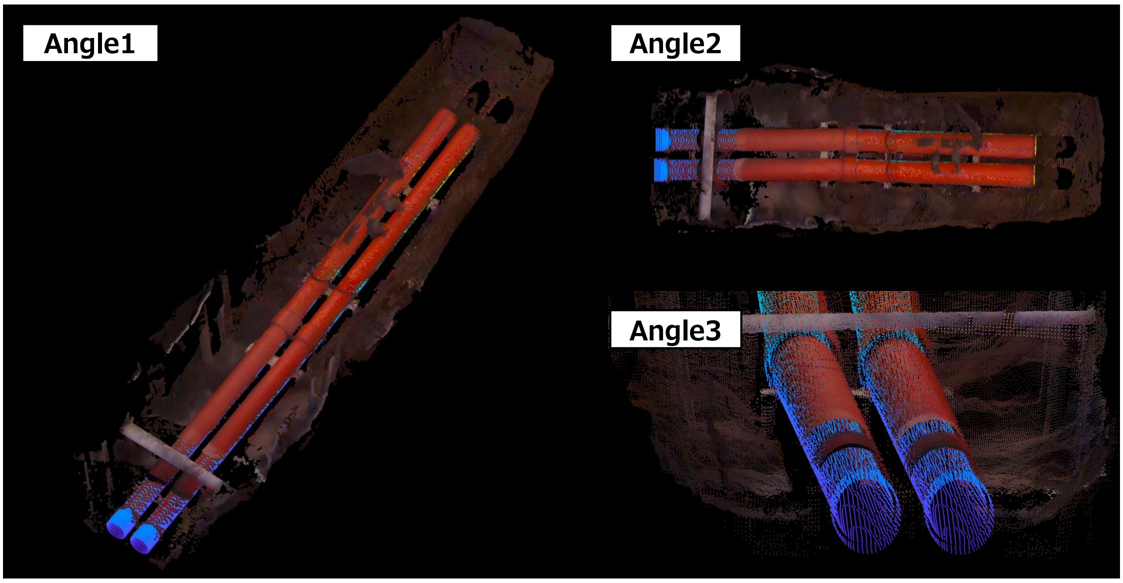


Figure 13. Results of the model fitting (point cloud acquisition with a 3D laser scanner)

Table 1. Results of the model fitting

	RMSE of estimated radius [mm]	
	Point cloud acquisition with SfM/MVS	Point cloud acquisition with 3D Laser Scanner
Pipe1	4.85	1.66
Pipe2	1.05	2.17
Pipe3	3.59	1.24
Pipe4	2.14	2.24

4.2 Results of measuring the position of buried pipes

Table 2 and Table 3 show the results of measurement of the position of the buried pipes. The distance from the ground surface was calculated at the central axis of each of the four pipes from the endpoint of the pipe body (1st), the center point of the pipe (52nd), and the endpoint of the socket (104th). The processing time was 15.4 seconds (Intel Core i5, 1.4 GHz, MATLAB). The RMSEs of the residuals of the points of the corresponding central axes in the point cloud acquisition with SfM/MVS and 3D laser scanner are shown in Table 4.

Table 2. Distance from the ground surface to the central axis of the pipe
(point cloud acquisition with SfM/MVS)

Distance from the ground surface to the central axis of the pipe [mm] : Point cloud acquisition with SfM/MVS			
	Endpoint of pipe body section	Center point of pipe	Endpoint of socket section
Pipe1	884	917	949
Pipe2	583	736	881
Pipe3	893	926	957
Pipe4	596	748	892

Table 3. Distance from the ground surface to the central axis of the pipe
(point cloud acquisition with 3D laser scanner)

Distance from the ground surface to the central axis of the pipe [mm] : Point cloud acquisition with 3D Laser Scanner			
	Endpoint of pipe body section	Center point of pipe	Endpoint of socket section
Pipe1	879	913	940
Pipe2	574	729	876
Pipe3	889	920	950
Pipe4	591	743	886

Table 4. Comparison of RMSEs of buried pipe position

Comparison of RMSEs of buried pipe position [mm] : Point cloud acquisition with SfM/MVS and 3D Laser Scanner			
Pipe1	Pipe2	Pipe3	Pipe4
4.81	6.72	5.82	5.69

5. CONCLUSION

In this study, we conducted 3D modeling and accuracy evaluation of an excavation site using point cloud acquisition with SfM/MVS and a 3D laser scanner for buried pipe installation It is confirmed that both point cloud acquisition with SfM/MVS and a 3D laser scanner can be used for modeling of buried pipe by model fitting based on the estimation of the central axis of the pipe. It is also confirmed that the accuracy of the proposed method is comparable to that of the point cloud acquisition with a 3D laser scanner, even if point cloud acquisition with SfM/MVS contains a large amount of noise. The registration of the model using a GNSS survey can be applied to determine the buried position (horizontal position), although it depends on the positioning accuracy of a GNSS survey. To measure the buried position (height), it is confirmed that the distance from the ground surface can be calculated using the central axis of the pipe generated during the modeling. Accurate measurement of the position (height) of the buried pipe, which will not be visible after backfilling, will enable advanced automation of re-excavation. For future research, experiments in larger-scale environment are necessary to confirm that the accuracy of the proposed method does not depend on scale.

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