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EXTRACTION OF SURFACES USING SECTION CURVES FOR ENGINEERING PLANTS

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ABSTRACT

For simulating renovation of industrial facilities, 3D models are very useful. However, it is time-consuming to create 3D models. The terrestrial laser scanner is effective for easily capturing 3D data of large-scale facilities. So far, many researchers have proposed methods for reconstructing pipe structures in industrial plants using point-clouds. In those methods, planes and cylinders are extracted from point-clouds, but they are not enough for creating various types of equipment. Especially, in manufacturing plants for liquids and gases, rotating surfaces and generalized cylinders are typically used as well as planes and cylinders. In this paper, this paper proposes methods for extracting rotating surfaces and generalized cylinders from noisy and incomplete point-clouds. Since the section shapes of rotating surfaces and generalized cylinders are approximately ellipses, this method detects elliptic section shapes from point-clouds. Then rotating surfaces and generalized cylinders are reconstructed by extracting the center curves and section circles. Then the authors combine this method with general-purpose voxel-based shape reconstruction methods. Since this method is robust to missing points caused by occlusion, the quality of shape reconstruction can be improved even if points are partly missing due to occlusion.

1. INTRODUCTION

When industrial facilities are renovated, simulation using 3D models is very useful for realizing efficient operations without reworking. However, creation of faithful 3D models requires a lot of labor and time, because it is necessary to precisely measure shapes of facilities and create 3D models consisting of many surface patches.

In recent years, the terrestrial laser scanner (TLS) is used for measuring three-dimensional data of industrial facilities as point-clouds. As shown in Figure 1, TLS irradiates laser beams to objects while rotating the mirror in the vertical direction and the horizontal direction. 3D coordinates of objects are calculated using the direction and the round-trip time of the laser beam. The state-of-the-art TLS can capture 1 million points per second in the range of 100 m to 300 m. Point-clouds are effective for creating 3D models because three-dimensional data of large structures can be acquired precisely and quickly by using point-clouds.

However, it is difficult to acquire complete point-clouds of large structures because measurable positions in engineering plants are limited. To capture complete point-clouds of a large-scale facility, it is necessary to disassemble the facility or built footholds. However, in most cases, it is required to reconstruct 3D models from incomplete point-clouds, in which points are missing because of occlusion. Therefore, it is strongly required to estimate missing parts.

Generally, it is almost impossible to precisely restore missing regions where points are captured. However, the authors observe that the equipment in engineering plants is composed of planar surfaces and rotationally symmetrical shapes in many cases. Therefore, in terms of engineering plants, many missing regions could be reconstructed by detecting planes and rotationally symmetrical shapes [1-3].

So far, many general-purpose shape reconstruction methods have been proposed [4,5]. These methods can generate mesh

Figure 1. Terrestrial laser scanner

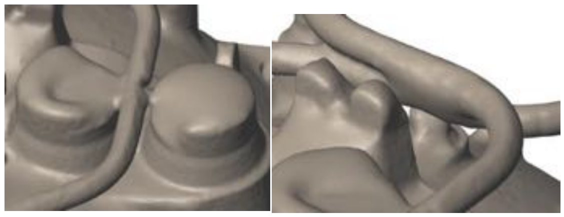
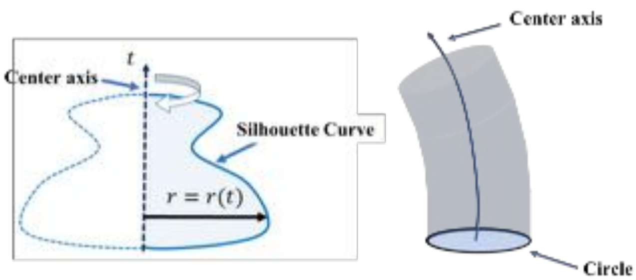


Figure 2. Wrong shapes generated from point-cloud



(a) Rotational surface (b) Generalized cylinder

Figure 3. Surfaces commonly used in engineering plants

models from point-clouds, but they tend to output impractical shapes when points are partly missing. For example, the Poisson surface reconstruction (PSR) produces faithful 3D shapes when points are completely and densely obtained [6]. However, as shown in Figure 2, PSR produces unacceptable shapes from the engineering point of view if points are partly missing.

In shape reconstruction for engineering plants, planes and cylinders have been extracted from point-clouds for reconstructing pipe structures [7-15]. These methods extract planes and cylinders from incomplete point-clouds and estimate shapes of pipe structures. However, they can be applied only to pipe structures.

In engineering plants, rotationally symmetric surfaces are often used to handle liquids and gases. In most cases, their section shapes are circles. Two types of surfaces are typically used, as shown Figure 3. On one type of surface, the center axis is the straight line. The authors call such surfaces as the rotational surface. On the other type of surface, the center axis is a smooth curve. The authors call such surfaces as the generalized cylinder. In both cases, the section shape is a circle if the surface is sliced by a plane perpendicular to the center axis.

In this paper, the authors discuss methods for extracting rotating surfaces and generalized cylinder surfaces from incomplete and noisy point-clouds. As shown in Figure 3, the rotation surface is defined as a shape generated by rotating a silhouette curve around the center line. The generalized cylinder is defined as a shape generated by sweeping a circle along the curve of the center axis.

Since the rotational surfaces and the generalized cylinders have high degree-of-freedom, it is difficult to extract them as implicit surfaces [16]. Therefore, the authors extract them as a set of section circles that are aligned along the center axis. Since

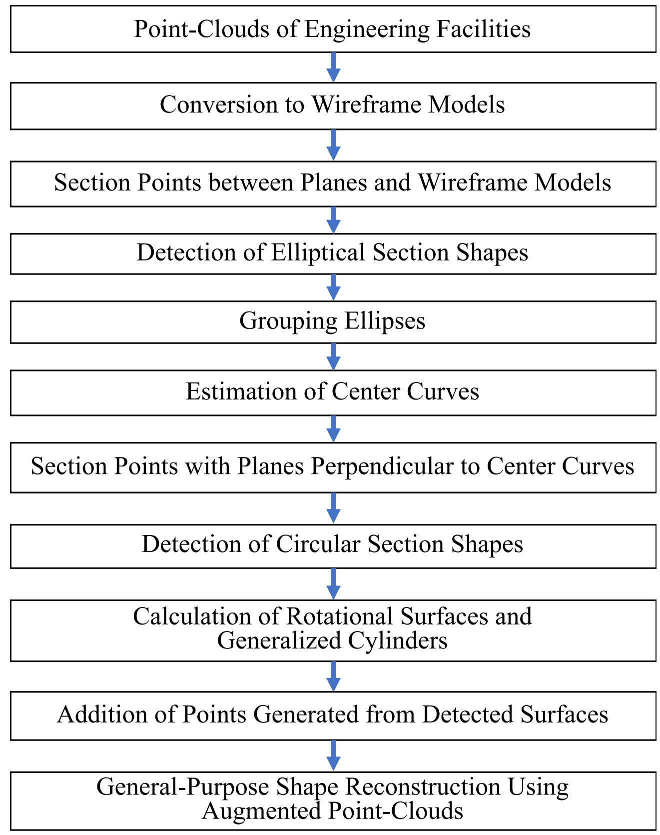


Figure 4. Process of shape reconstruction

this method detects 1D curves on the section plane instead of non-linear implicit surface detection, rotation surfaces and generalized cylinder surfaces can be stably extracted from incomplete point-clouds.

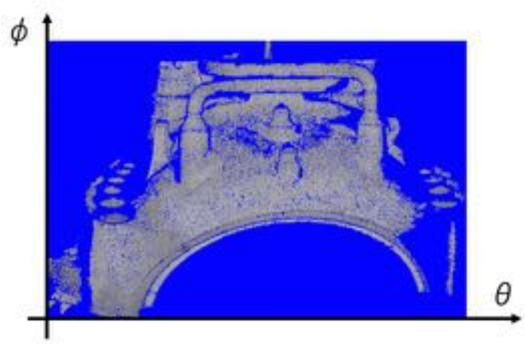
When rotational surfaces and generalized-cylinders are detected, points on the surfaces are added to the original point-clouds. Then a general-purpose shape reconstruction method, such as PSR, is applied to the augmented point-clouds.

In the following sections, the overview of this method is described. In Section 3, the authors explain methods for extracting elliptic section shapes and estimating the center axis of the surface. In Section 4, the authors describe methods for extracting the rotational surfaces and the generalized cylinders. Then in Section 5, the authors describe shape reconstruction based on augmented point-clouds and experimental results. In Section 6, the authors conclude the paper.

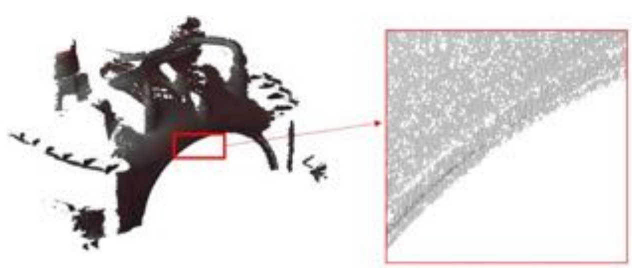
2. OVERVIEW

In this research, rotational surfaces and generalized cylinders are detected from point-clouds captured using a terrestrial laser scanner. We suppose all measured points are given as $\mathbf{P} = \{\mathbf{p}_k\}$ $(k \in \Lambda)$. A rotational surface R_i is defined as $R_i(\mathbf{P}_i; l_i, s_i)$, where l_i is the center line, s_i is the silhouette curve, and $\mathbf{P}_i$ is a subset of $\mathbf{P}$ on the rotational surface. A generalized cylinder G_j is defined as $G_j(\mathbf{P}_j; c_i, r_i)$, where c_i

Figure 5. Point-clouds of a turbine



(a) Points mapped on the angle space



(b) Wireframe model

Figure 6. Generation of wireframe model

is the center curve, r_i is the radius. Our goal is to find all surfaces $\{R_i(\mathbf{P}_i; l_i, s_i)\}$ and $\{G_j(\mathbf{P}_j; c_i, r_i)\}$ in $\mathbf{P}$ by obtaining the parameters and points $\{\mathbf{P}_i\}$ and $\{\mathbf{P}_j\}$.

The process of the proposed method is shown in Figure 4. In this method, section shapes are extracted from point-clouds, and rotational surfaces and generalized cylinders are reconstructed using section shapes.

Figure 5 shows point-clouds captured from a turbine in a thermal power plant. To avoid occlusion as much as possible, point-clouds were measured from 12 positions. These point-clouds are merged after being transformed using registration matrices. In these point-clouds, points are partly missing especially in the area between pipes and also the upper area of the turbine, because the laser beams could not reach these areas. In this paper, the authors consider methods for recovering missing points by extracting rotational surfaces and generalized cylinders.

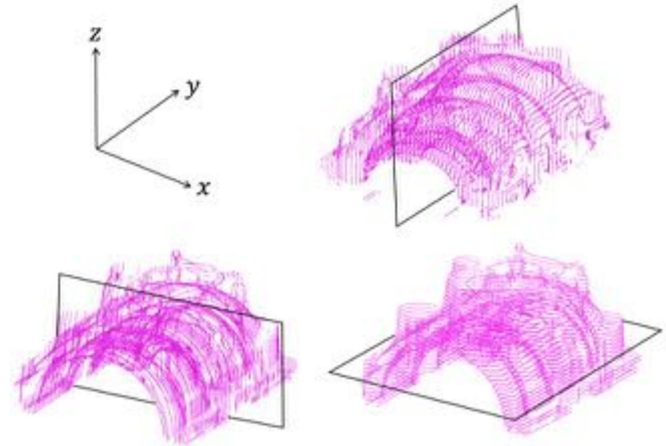


Figure 7. Section points with planes

In the process of this method, point-clouds are converted to wireframe models by connecting neighbor points. Then the wireframe models are sliced using planes perpendicular to one of x, y, and z axes. The section shape of the rotational shape or and the generalized cylinder is a circle if the surface is sliced using a plane perpendicular to the center axis, but the center axis of the surface is unknown. Therefore, the authors slice wireframe models in three directions, and search ellipses from section points.

A set of ellipses is detected that are nearly parallel and close in center positions. The center axis can be estimated as a straight line or a smooth curve that passes through the center points of ellipses. If the center axis is a straight line, the surface is regarded as a rotation surface. Otherwise, an ellipse set is regarded as a generalized cylinder surface.

Then wireframe models are sliced again using planes perpendicular to the center axis, and circles are searched from section points. Rotational surfaces and generalized cylinders can be generated by connecting circles. When surfaces are generated, points on the surfaces are calculated and added to the original point-clouds. Finally, the 3D model is generated using the general-purpose shape reconstruction method using the augmented point-clouds. In this paper, the authors apply PSR as the general-purpose method.

In experimental result section, the CPU time of calculation and the accuracy of surfaces generated in this method are evaluated.

3. EXTRACTION OF SECTION SHAPES

In this section, the method of section shape extraction is supposed. First of this paper, section shape extraction is necessary for extraction of rotational surfaces and generalized cylinder surfaces. Rotational surfaces and generalized cylinder surfaces are expressed as the continuous of some circles. Therefore, the purpose is extracting circles from sections acquired by cutting point-clouds with equally spaced planes. However, if the normal of cutting planes is inclined from the center line of rotational shapes or generalized cylinders, circle fitting become unstable. Therefore, ellipse fitting is used instead of circle fitting in this paper.

3.1 Generation of wireframe model

In the example data, point-clouds were measured from multiple positions as shown in Figure 5, and each point-cloud was separately maintained in a file using the PTX format, which describes coordinates on the scanner-centered coordinate system and a registration matrix.

As shown in Figure 1, the terrestrial laser scanner captures points while moving the laser beam along the altitude and azimuth angles. Therefore, points can be mapped on the angle space in a lattice manner, as shown in Figure 6(a). Then a point-cloud can be easily converted to a wireframe model by connecting adjacent points on the angle space, as shown in Figure 6(b).

Each wireframe model is transformed using the registration matrix and used for calculating intersection points with section planes.

3.2 Calculation of elliptical sections

Section planes are generated in the direction perpendicular to one of x, y, and z axis at equal intervals, and intersection points are calculated between wireframe models and section planes. Figure 7 shows intersection points. Although the center axis of the rotational surface is unknown, the section shape on at least one of three perpendicular planes becomes approximately an ellipse if the surface is a rotational surface or a generalized cylinder.

Intersection points are segmented on the section plane so that neighbor points belong to the same group. Neighbor point search can be realized using octrees, kd-trees, or Delaunay triangulation.

Then an ellipse is fitted to intersection points in the same group. We simply represent an ellipse as:

$$f(x, y) = a_1x^2 + a_2y^2 + a_3xy + a_4x + a_5y + 1 = 0,$$

and calculated the equation using the least-squares method. The ellipse is regarded as the section shape if the following two conditions are satisfied.

(1) The ellipse is divided into small arcs with the same central angle, and the number of points on each arc is counted. If the total angle of the arcs in which points exist is larger than the threshold value, the ellipse is a candidate section shape.
(2) If the ratio of the major radius to the minor radius of the ellipse is smaller than the threshold value, the ellipse is a candidate section shape.

Figure 8 shows ellipses detected from intersection points.

3.3 Grouping elliptic section shapes

The centers of elliptic section shapes are aligned on a straight line or a smooth curve if the section shapes are generated from a rotation surface or a generalized cylinder. Therefore, the authors detect a sequence of ellipses which are nearly parallel and close to each other. If the number of ellipses is larger than a threshold, they are regarded as a candidate of a rotational surface or a generalized cylinder.

Figure 8. Elliptic section shapes

(a) Groups of ellipses

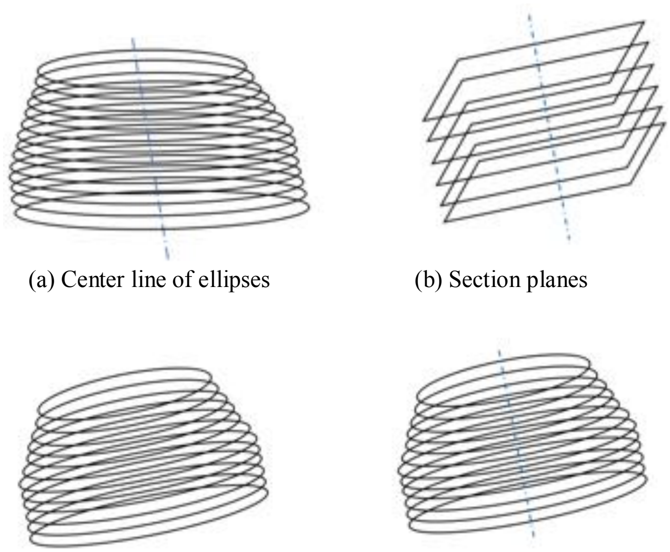
(b) Merging ellipse groups

Figure 9. Grouping elliptic section shapes

Then the principal component analysis is applied to the centers of ellipses. If the ratio between the first eigenvalue and the second eigenvalue is greater than a threshold value, the center axis is considered to be a straight line and the surface is a rotational surface. Otherwise the group of ellipses is regarded as a generalized cylinder surface. Figure 9(a) shows ellipse groups in different colors.

When the center axis of a generalized cylinder is sharply curved, it may be divided to two or more groups of ellipses. In such cases, ellipse groups are merged if the end points of ellipse groups are close to each other. In Figure 9(b), several ellipse groups are merged, and two long generalized cylinders are generated.

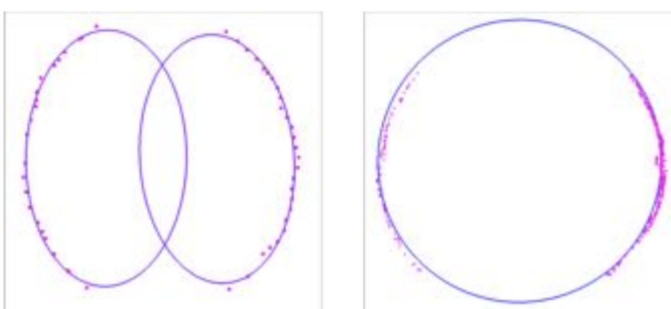
4. EXTRACTION OF ROTATIONAL SURFACES AND GENERALIZED CYLINDERS



(a) Center line of ellipses (b) Section planes

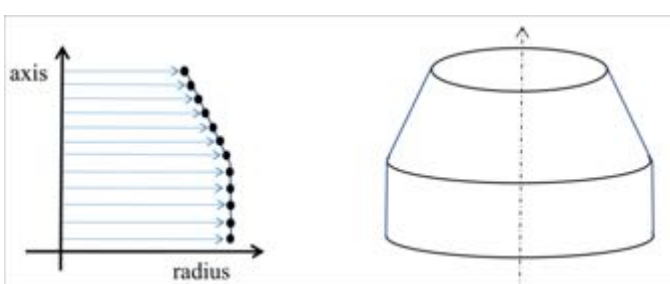
(c) Circle fitting (d) Updated center line

Figure 10. Calculation of the center line



(a) Wrong ellipse fitting (b) Circle fitting

Figure 11. Recalculation of section shapes



(a) Silhouette curve (b) Rotation surface

Figure 12. Calculation of silhouette curve

4.1 Rotational surface

The rotation surface is generated by rotating a silhouette curve by a certain angle around the center axis. The rotational surface is determined by the silhouette curve, the center axis, and the rotation angle.

The center axis can be estimated by fitting a straight line to the center points of ellipses, as shown in Figure 10(a). In this method, the straight line is extracted using the RANSAC method, and then it is updated by applying the least-squares method to the points near the line obtained by the RANSAC method.

However, it is unstable to detect ellipses if points on a surface is partly missing due to occlusion. For example, as shown in Figure 11, a section shape may be divided to multiple ellipses when points on the ellipse are partly missing as shown in Figure11(a). However, circle fitting can precisely detect section shapes even in these cases as shown in Figure11(b).

In order to extract rotational surfaces stably and precisely, wireframe models are sliced again using planes perpendicular to the center axis shown in Figure10(a). By slicing wireframe models with planes shown in Figure10(b), section points are acquired. Then a circle is fitted to section points on each section plane as shown in Figure10(c), because the section shape becomes a circle if the rotational surface is sliced by a plane perpendicular to the center axis. Since circle fitting is more stable than ellipse fitting, rotational surfaces can be calculated more stably and accurately. Then the center axis is updated using the centers of detected circles as shown in Figure10(d).

A rotation surface is reconstructed by rotating a silhouette curve around a center axis. The silhouette curve can be

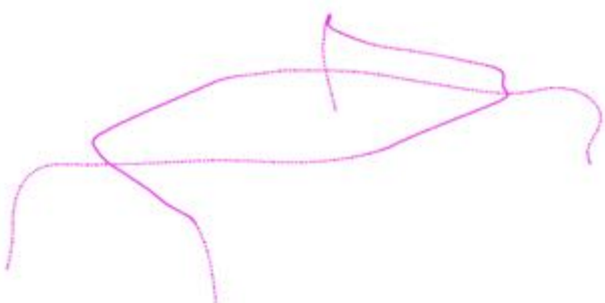
Figure 13. Perspective and top views of point-clouds

calculated by mapping each circle on the radius-axis plane, as shown in Figure 12(a). When the center line and the silhouette curve are obtained, the rotational surface can be reconstructed by rotating the silhouette curve around the center line as shown in Figure 12(b). The rotation angle is determined by examining the range where the point exists on the rotation surface.

4.2 Generalized cylinder

Figure 13 shows point-clouds of generalized cylinders. Points are missing especially at top and bottom sides of the pipes.

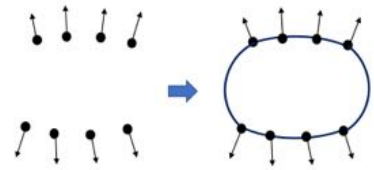
(a) Circles along the center curve



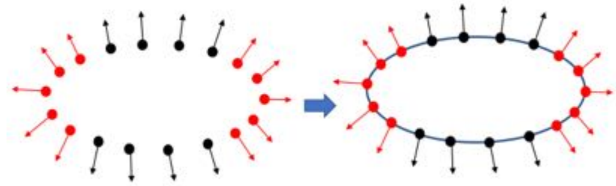
(b) The center axis of a generalized cylinder

(c) Reconstructed surface

Figure 14. Generation of a generalized cylinder

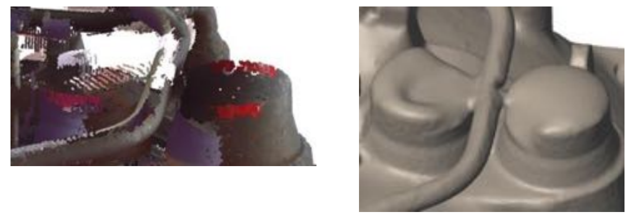


(a) Shape reconstruction from incomplete point-cloud

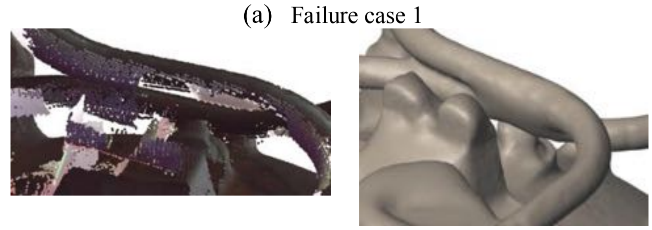


(b) Missing points are restored using engineering knowledge

Figure 15. Shape reconstruction



(a) Failure case 1



(b) Failure case 2

Figure 16. Incorrect shape reconstruction

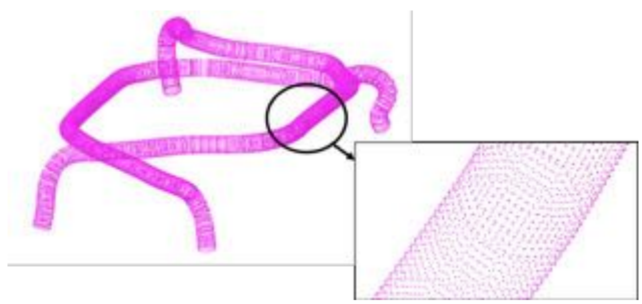
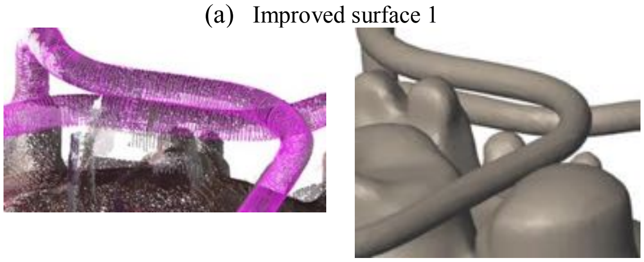


Figure 17. Generation of additional points

In this method, the center curve of a generalized cylinder is estimated using the centers of ellipses shown in Figure 9(b).

Then wireframe models are sliced again planes perpendicular to the center curve. In the case of generalized cylinders, the normal vector of each section plane is calculated according to the position on the center curve. Then intersection points are calculated between wireframe models and section planes, and circles are fitted to intersection points. Figure 14(a) shows detected circles.

(a) Improved surface 1



(b) Improved surface 2

Figure 18. Improved shape reconstruction

Figure 19. Shape reconstruction from augmented point-cloud

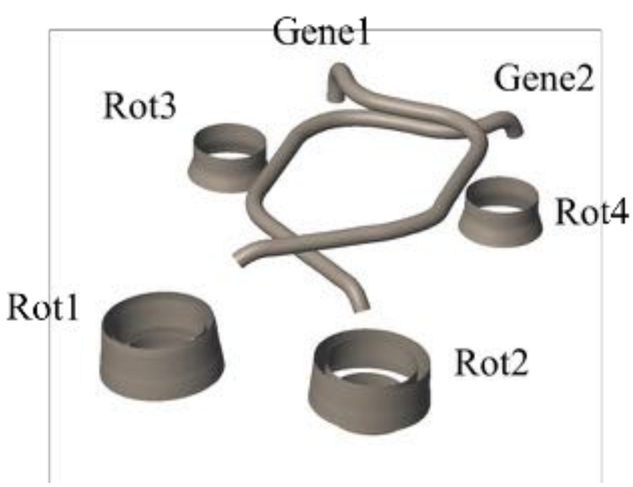


Figure 20. Generated rotational surfaces and generalized cylinder surfaces

Figure21. Superimposition of points and generated surfaces (Red shows surfaces. Yellow ellipses show the cause parts of errors.)

The center curve is also updated by connecting the center points of circles. Since the center curve is noisy, the low-pass filter is applied to remove noise [17]. Figure 14(b) shows the smoothed center axis generated from circles. The radius of the generalized cylinder is determined using the radii of circles.

Figure 14(c) shows the surface generated using the center axis and the radii.

5. SHAPE RECONSTRUCTION USING AUGMENTED POINT-CLOUDS

General-purpose shape reconstruction tools are powerful if complete and dense point-clouds are obtained. However, they often produce unacceptable shapes if points are partly missing. In this paper, the authors consider PSR as a general-purpose shape reconstruction method, because PSR can handle large-scale point-clouds in an out-of-core manner. PSR reconstructs 3D mesh models from points with normal vectors, as shown in Figure 15. This method is affected by missing points as shown in Figure15(a). Therefore, it is necessary to restore the missing parts of point-clouds. In general cases, it is almost impossible to precisely restore missing parts, if the missing parts can be estimated using the engineering knowledge, as shown in red points in Figure 15(b), the surface can be precisely reconstructed. The method in this paper restores missing points by supposing that many surfaces consist of rotationally symmetric surfaces in engineering plants.

Figure 16 shows shapes generated from incomplete point-clouds using PSR. In both cases, there are no points between closely placed components. Generated shapes are not acceptable from an engineering point of view.

Since this method extracts rotational surfaces and generalized cylinders, points can be restored using the detected surfaces. Since section shapes of the rotational surface and the generalized cylinder are circles, the coordinates and normal vectors on the surface are calculated using circles, as shown in Figure 17. Then points on surfaces are added to the original point-cloud, and PSR is applied to the augmented point-cloud.

Figure 18 shows that generated surfaces are improved compared to the cases in Figure 16.

Figure 19 shows the reconstructed shape generated from the augmented point-cloud. In this model, rotational surfaces and generalized cylinders are recovered.

6. EXPERIMENTAL RESULT

The authors evaluated the CPU time and the surface accuracy of rotational surfaces and generalized cylinder surfaces using point-clouds shown in Figure 5. This example consists of 12 point-clouds, and the number of points is 15,577,873. The CPU time was measured on a desktop PC with 4.00 GHz Intel Core i7 and 64.0 GB RAM. Section planes were generated at the interval of 1cm. The number of section planes were 729. In this evaluation, the CPU time was 237.5 sec.

The accuracy of generated surfaces shown in Figure.20 was evaluated by calculating the standard deviation of distances between surfaces and points. The accuracy of rotational surfaces is shown in Table1. Table2 shows the accuracy of generalized cylinder surfaces. Since typical accuracy requirements of plant modeling are 6 mm, the experimental results are sufficient for practical use. However, the errors are relatively larger compared to ones of typical reverse engineering of mechanical parts. This is mainly because the precision of terrestrial laser scanners is limited and the registration errors for large objects are relatively large.

Table1 Accuracy of rotational surfaces generation

Rot1	Rot2	Rot3	Rot4
3.9 mm	4.1 mm	4.1 mm	1.6 mm

Table2 Accuracy of generalized cylinders

Gene1	Gene2
3.9 mm	5.4 mm

7. CONCLUSION

In this paper, the authors proposed a method for extracting rotation surfaces and generalized cylinder surfaces from noisy and incomplete point-clouds captured by a TLS. In this method, point-clouds are converted into wireframe models, and calculated intersection points with section planes, which were placed at the interval of 1cm. Then ellipses from intersection points on each section plane are detected. Rotational surfaces and generalized cylinders were detected by grouping ellipses. Then the surfaces are updated by slicing wireframe models using planes perpendicular to the center axes and extracting circles. In addition, missing points were recovered using detected surfaces, and applied a general-purpose shape reconstruction method. The authors showed that shapes could be adequately reconstructed by adding missing points on rotational surfaces and generalized cylinders.

In future work, the authors would like to develop methods for extracting other types of surfaces and form-features using section shapes. The authors also would like to implement this method in an out-of-core manner so that huge point-clouds can be processed.

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