Detection of Steel Materials and Bolts from Point-Clouds of Power Transmission Pylon

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Abstract. Since power transmission pylons have long life cycles, they have to be repeatedly maintained by replacing deformed and corroded steel materials. In conventional maintenance, three or more workers have to climb on a pylon and measure the dimensions and bolt positions of damaged steel materials in order to manufacture replacement steel materials. However, such works are dangerous and costly. In this paper, we discuss methods for precisely calculating dimensions and bolt positions of steel materials using dense point-clouds captured by a terrestrial laser scanner. Since steel materials consist of planar surfaces, plane detection methods are useful for detecting steel materials. In our method, steel materials are detected by combining the RANSAC method, the thinning of planar regions, and the region growing method. We also propose a bolt detection method by fitting points to bolt shapes. We evaluated our method using actual point-clouds of a power transmission tower. We also evaluated the accuracy using sample steel materials. Our experimental results showed that our method achieved sufficiently good accuracy for practical use.

Keywords: point-clouds, pylon, terrestrial laser scanner.
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1 INTRODUCTION

Figure 1(a) shows a typical power transmission pylon, which is about 50m high. Since power transmission pylons have long life cycles, they have to be repeatedly maintained by replacing deformed and corroded steel materials. Pylons are manufactured by connecting a large number of steel materials with bolts. Therefore, for replacing steel materials, it is important to precisely measure the dimensions and bolt positions of damaged steel materials in order to manufacture replacement steels. In conventional maintenance work, three or more workers climb on a pylon and manually measure steel materials. Figure 1(b) shows conventional measurement work. However, measurement at high places are dangerous and costly, and the reliability of measurement depends on workers skills.

Terrestrial laser scanners (TLS) are promising for measuring steel materials safely, efficiently, and accurately without climbing on pylons. In this paper, we discuss methods for detecting steel materials and bolts from point-clouds and calculating their dimensions and positions. Figure 1(c) shows a laser scanner, FARO Focus 3D X330 placed on the ground. For measuring small bolts at distant positions from the ground, dense point-clouds are required. In our experiments, point-clouds of pylons were measured at the density of 20,000 x 10,000 points in a single laser scan.

Since steel materials of pylons consist of planar surfaces, plane detection methods are useful for detecting steel materials. Many plane detection methods have been developed based on the region growing or the RANSAC method. Tóvári et al. [12] extracted planes using region growing based on randomly selected seed regions. Nurunnabi et al. [9] used the seed point with the lowest curvature. Vieira et al. [13] segmented mesh models and selected inner points as seed regions avoiding sharp edges. Rabbani et al. [10] segmented points into smoothly connected surfaces using normals and connectivity of points. In RANSAC based approaches, Boulaassal et al. [1] extracted facade planes of buildings from TLS data using manually selected tolerances. Schnabel et al. [11] proposed an efficient RANSAC method by restricting regions of random sampling. Chida et al. [2] proposed box shape extraction by plane detection combining the RANSAC method and the region growth method.

Many methods have been also studied for extracting pipe structures from point-clouds. Kawashima et al. [4] and Masuda et al. [7] extracted pipe structures from a large-scale point-clouds using region growing. Lee et al. [5] calculated skeletons for detecting pipes. Lukacs et al. [6] proposed the least-squares method for precisely calculating spheres, cylinders and cones. Masuda et al. [8] calculated planes and cylinders by applying the RANSAC method to recursively subdivided regions.

To identify bolt positions on each steel material, it is necessary to determine the center positions of bolts and the boundaries of steel materials from a point-cloud. However, there are several problems in determining them precisely. In conventional plane detection methods, the quality of plane detection is sensitive to thresholds. According to the selection of thresholds, each steel material may be divided into multiple planes, or adjacent steel materials may be merged to a single plane, as shown in Figure 1(d). In measuring tall towers, the density and variation of point-clouds are largely different depending on the distances from the ground and the irradiation angles of laser beams. Therefore, it is required to adaptively select thresholds of plane detection. In addition, since pylons are constructed by bolting thin steel materials, small steps between bolted steel materials have to be detected using tight thresholds. On the other hand, since long steel materials are slightly bended, tight thresholds lead to dividing a steel material surface into multiple planes. It is required to develop methods for reliably separating thin steel materials from point-clouds.

Another problem is to accurately calculate bolt positions from partially captured points. Since the bolt head is a plane, bolts can be detected by detecting small planes above a steel material. However, points of the bolt head is only partially captured when the bolt is measured from the ground, as shown in Figure 1(e). Therefore, the center of measured points differs from the center of the bolt, as shown in Figure 1(f). It is necessary to estimate the true bolt position using partially captured points.

In this paper, we propose methods for detecting the boundaries of steel materials and the center positions of bolts. In our method, the pylon is measured only once using a laser scanner at the center on the ground. Since complete point-clouds of the pylon cannot be obtained due to occlusions, steel materials and bolts have to be extracted from incomplete point-clouds. To stably extract thin and deflected steel materials, we introduce a new method that calculates skeletons of steel materials and extract planar regions using adaptive thresholds. In addition, to calculating bolt positions precisely, we introduce a method to detect hexagon shapes from incomplete point-clouds, because the shapes of bolts are typically hexagons. In the following sections, firstly, we describe a method for stably separating steel materials using adaptive thresholds. Then we describe a method for calculating bolt positions. Finally, we evaluate our methods using point-clouds of power transmission pylons.

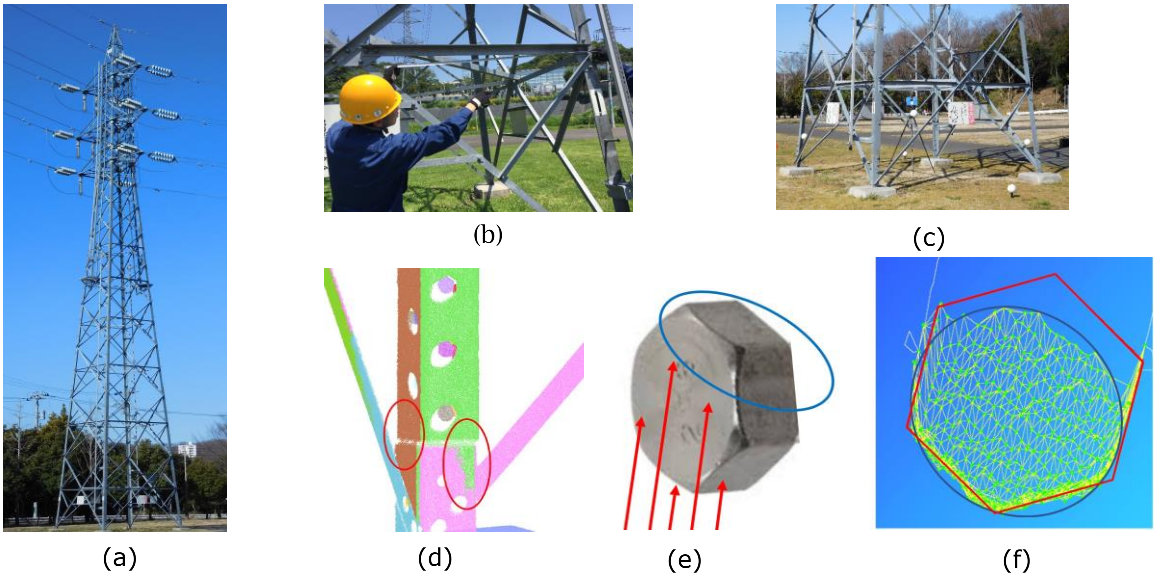


Figure 1: Power transmission pylon: (a) Steel Pylon, (b) Manual Measurement, (c) Laser Scanner on the Ground, (d) Detection of Planes, (e) Laser Scanning of Bolt, and (f) The Center Position of Bolt.

2 EXTRACTION OF STEEL MATERIALS

Although steel materials consist of planar surfaces, it is difficult to precisely separate each steel material in a point-cloud, as shown in Figure 1(d). Therefore, we extract each steel material through several processes. First, initial planar regions are detected using a conventional method. In the initial planar regions, separation of steel materials may be inappropriate. In the second stage, adjacent planes are merged when plane equations are similar, as shown in Figure 3, and bolting steel materials are merged into a single planar region. In the third stage, skeletons of each planar region are calculated, as shown in Figure 4(b). Since steel materials may be deformed in the long-length directions, each planar region is subdivided into small regions along the skeleton, as shown in Figure 4(c). Then the optimum seed point is selected on the skeleton, and planar regions are again calculated using the region growing method. Each steel material is obtained by connecting small planes, as shown in Figure 5.

2.1 Detection of Initial Planes

Efficient surface detection methods have been proposed for from large-scale point-clouds [7],[11]. In this paper, we use the method proposed by Masuda, et al. [7] for detecting initial planar regions. In this method, a point-cloud is mapped onto the 2D grid, as shown in Figure 2(b). The 2D grid is defined using the azimuth angle and elevation angle of laser beams in Figure 2(c). Planes are detected on the 2D grid. For improving performance, points are segmented into connected regions on the 2D grid, and planes are detected using the RANSAC method in each connected region. Each time a plane is detected, the connected region is further subdivided. Figure 2(d) shows detected planes.

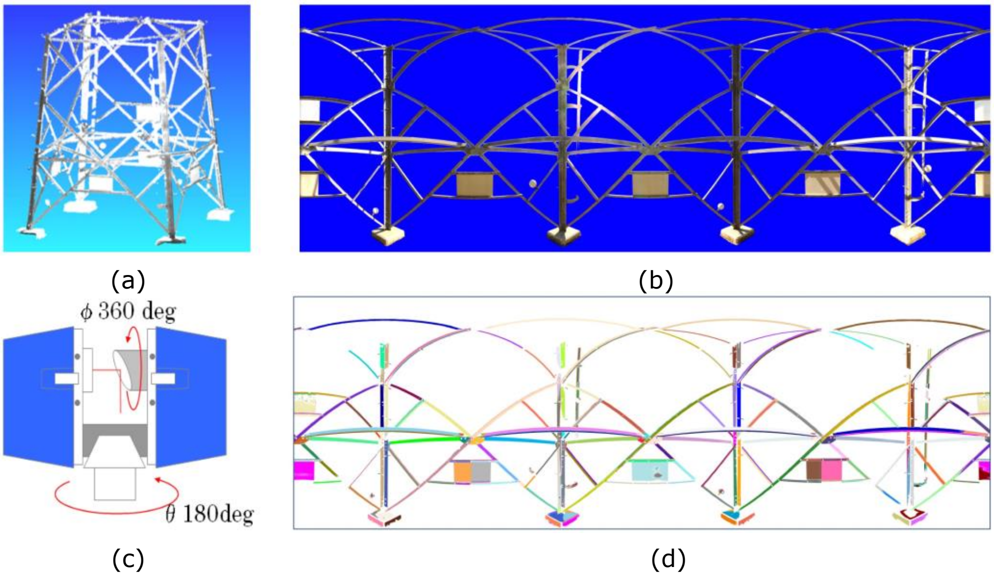


Figure 2: Plane detection using the RANSAC method: (a) Point-Cloud, (b) Direction of Laser Beam, (c) Mapping Points on the 2D Grid, (d) Detection of Planes on the 2D Grid

The RANSAC method is sensitive to thresholds that determine whether points are on the plane. Therefore, plane detection often results in over or under segmentation, as shown in Figure 3(a). First, over segmentation cases are removed by merging adjacent planes. Adjacent planes are merged when they have similar plane equations. Then bolting steel materials are merged into a single planar region, as shown in Figure 3(b). In the case of Figure 2(d), 734 planes are reduced to 66 merged planes.

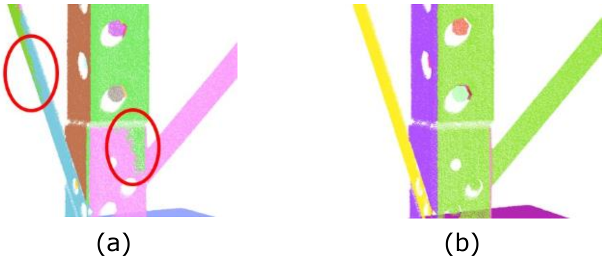


Figure 3: Merging adjacent planes: (a) Incorrectly Segmented Planes, and (b) Merged Planes.

2.2 Extraction of Skeletal Lines

In the next step, merged planes are divided into each steel material surface. First, each merged plane is segmented into elongated regions. Points on a merged plane are projected onto the 2D grid defined by the azimuth and elevation angles. Then the projected region on the 2D grid is regarded as a binary image, and the thinning operation is applied to the region, as shown in Figure 4(a). In this process, bolt holes are detected and filled before applying the thinning operation. We used the thinning operation proposed by Hilditch [3].

Next, straight lines are detected from the thinned points. Since the projection on the 2D grid does not preserve the linearity of shapes, the thinned points are again projected on a plane in 3D space and straight lines are detected using the RANSAC method, as shown in Figure 4(b). Then the merged plane is segmented into rectangle regions using straight lines.

When long steel materials are bending, each surface of steel materials may not be fitted to a single planar region. Therefore, the rectangle regions in Figure 4(b) are subdivided into overlapping small rectangle regions, as shown in Figure 4(c).

Planar regions are detected in each small rectangle region. Since steel materials are connected with bolts, small steps between bolted steel materials have to be identified. In our method, planes are detected by the region growing method using adaptively selected seed points. In the region growing method, the seed region has to be carefully selected so that points near steps, bolts and boundaries are not included. Therefore, we select candidates of seed points on the straight lines generated by thinned points, as shown in Figure 4(c). Then a plane is fitted to neighbors of each candidate seed point and the residual is calculated. The seed point with the smallest residual is selected in each rectangle region. The threshold of plane detection is determined based on the smallest residual.

Since adjacent rectangle regions are defined to have common points, detected planar regions are overlapping if they are the same plane. Therefore, overlapping planes are detected and they are merged as a planar surface of a steel material. Figure 5 shows detected planes, which correctly represent boundaries of steel materials.

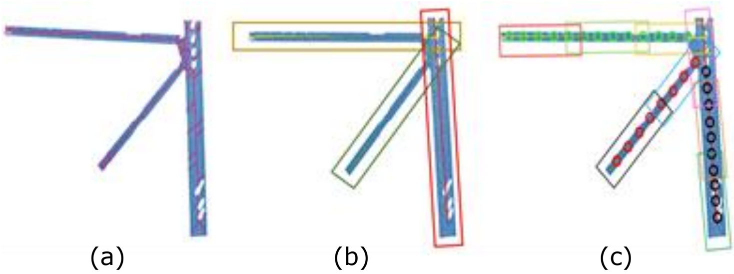


Figure 4: Calculation of skeletons: (a) Skeletons of a planar Region, (b) Center Lines, and (c) Regions along the Center Lines.

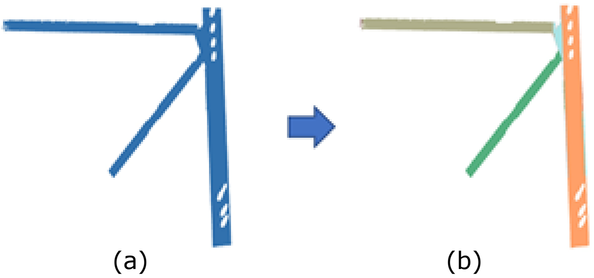


Figure 5: Segmented surfaces of steel materials: (a) Merged Plane, and (b) Detected Planes.

3 EXTRACTION OF BOLTS

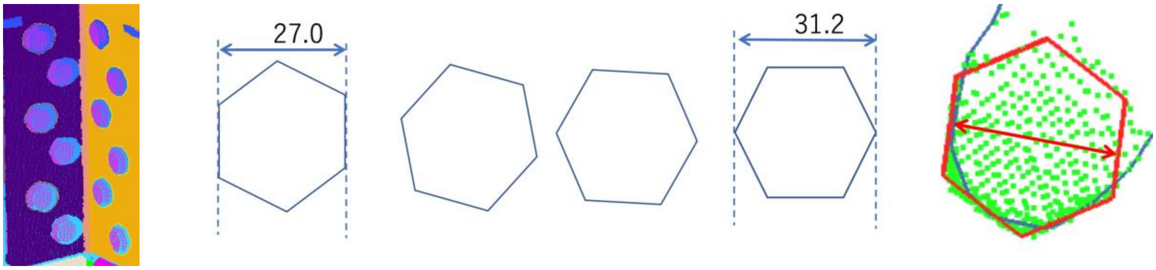
In plane detection, small planes of bolt heads are also detected, as shown in Figure 6(a). However, since these planes are extracted only partially due to occlusion, the center of measured points differs from the center of the bolt. In this section, we consider a method for estimating the bolt center from partially measured points.

First, candidate bolt planes are selected. A plane is regarded as a candidate of a bolt head only when the plane size is equal or less than possible bolt diameters and a large parallel plane of a steel material exists under the bolt head plane. Then points between the bolt head plane and the steel material plane are regarded as bolt points. Figure 6(a) shows bolt points with magenta color.

Since the shape of a bolt is a hexagon, the width of a bolt varies depending on the rotation angle of the bolt, as shown in Figure 6(b). For precisely calculating the diameters of bolts, the rotation angles of bolts have to be identified. In our method, the bolt size and position are estimated by fitting a hexagon to bolt points, as shown in Figure 6(c).

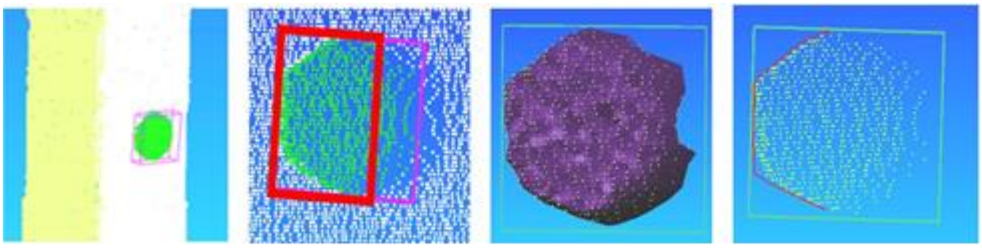
Figure 7 shows the process of hexagon fitting. First, a cuboid is generated so that bolt points are included, as shown in Figure 7(a). The orientation of the cuboid is specified so that two face of the cuboid is parallel to the steel material plane, and the laser beam intersects with other two faces as perpendicular as possible. Since points on the scanner side are densely measured without occlusion, a hexagon is fitted only to bolt points on the scanner side, as shown in Figure 7(b). For detecting the boundary of the bolt, bolt points are projected on a plane and triangulated using the Delaunay triangulation, as shown in Figure 7(c). A hexagon is fitted to the boundary points on the scanner side, as shown in Figure 7(d).

Since bolt sizes are standardized, several standard values close to the width of bolt points are selected. When a standard size is selected, the hexagon is placed near the center position of the cuboid. Then the number of boundary points on the hexagon is counted while slightly changing the positions and rotation angles of the hexagon. The position and rotation angle with the largest number of boundary points is selected as the bolt position. When there are multiple possible standard sizes, all hexagons are fitted to boundary points and the bolt size with the largest number of boundary points is selected. Figure 8 shows detected bolts.



(a) (b) (c)

Figure 6: Bolt points: (a) Bolt Points, (b) Bolt Widths depending on rotation Angles, and (c) Calculation of Bolt Position by fitting a Hexagon.



(a) (b) (c) (c)

Figure 7: Process of hexagon fitting: (a) Cuboid for Bolt Points, (b) Points on the Scanner Side, and (c) Triangulation of Bolt Points, and (d) Boundary Points on the Scanner Side.

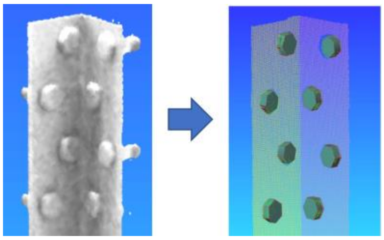


Figure 8: Detected bolts.

4 EXPERIMENTAL RESULTS

We detected steel materials and bolts from a point-cloud of an actual power transmission pylon. The pylon was measured at an angle interval of $\pi \times 10^{-4}$ radian. The number of measurements in a single laser scanning was 20,000 $\times$ 10,000.

Figure 9 shows detected steel materials using our method. Our method could successfully detect boundaries of most steel materials from merged planes unless steel materials were occluded. However, there were a few failure cases. When thin plates are bolted to steel materials, as shown in Figure 10, the boundaries of steel materials could not be detected, because the skeletons of the planar region could not be correctly obtained. In such cases, exceptional handling will be required.

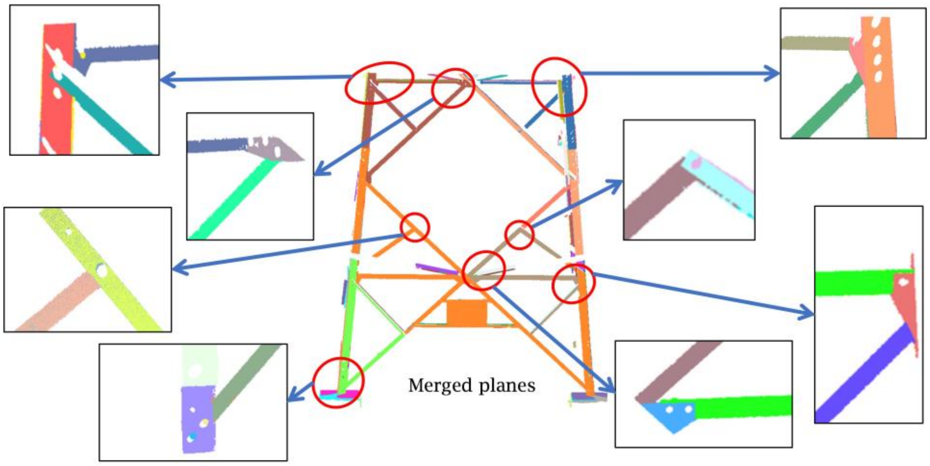


Figure 9: Segmented surfaces from merged planes.

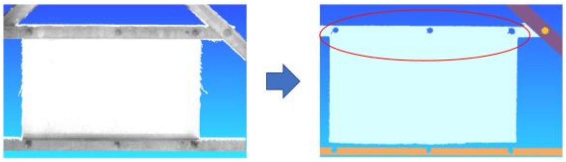


Figure 10: Failure case in steel material detection.

Figure 11 shows detected bolts using our method. In this example, 202 bolts could be successfully detected. However, 4 bolts could not be detected. There are two reasons for failure cases. One reason is that the angle between laser beams and bolt head planes are so small that ghost points were generated, as shown in Figure 12(a-b). In such cases, bolt equations of head planes tend to be incorrectly calculated. Another reason is that the bolt is located very close to a steel material surface, as shown in Figure 12 (c). In such cases, hexagon fitting may be failed because the boundary of bolts cannot be extracted.

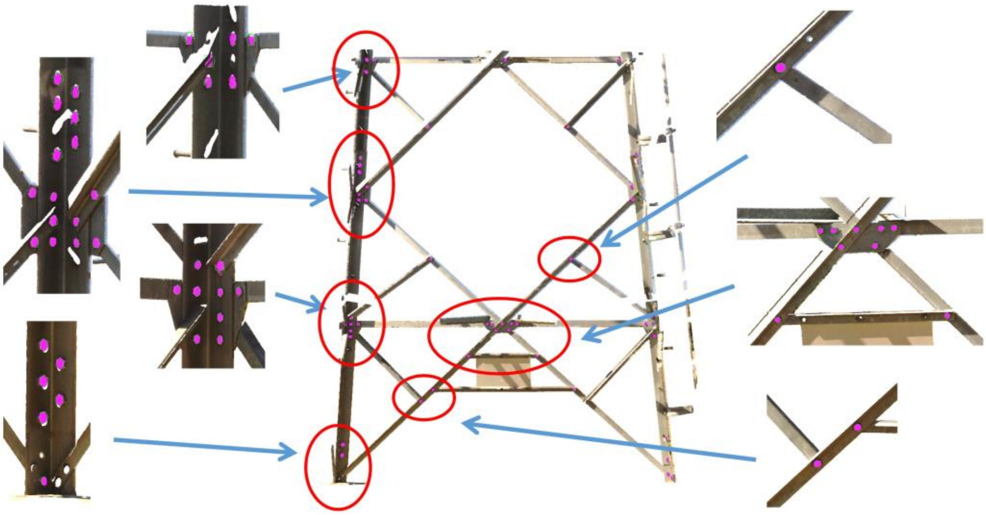
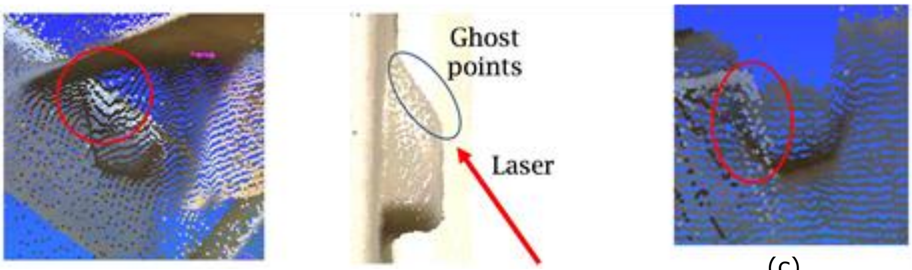


Figure 11: Detected bolts.



(a) (b) (c)

Figure 12: Failure cases in bolt detection: (a) Ghost Points of Bolt Head Surface, (b) The Reason why Ghost Points are generated, and (c) Bolt close to other Surface.

We also evaluated precision of bolt centers and steel material boundaries calculated from point-clouds. Since it is difficult for us to manually measure actual power transmission towers, we used sample steel materials with bolts provided by a power company. We placed two steel materials on the floor, as shown in Figure 13(a), and measured point-clouds of the steel materials. The distance between steel materials and the TLS was about 5m. Then the distances between bolts and steel material surfaces were calculated, as shown in Figure 13(b). We also manually measured centers of the hole on steel materials using vernier calipers. Since it is difficult to precisely measure bolt centers using vernier calipers, we measured distances *s* and *D* of holes, as shown in Figure 13(c) and calculated (s+D/2) instead of directly measuring *d*.

For comparison, we calculated bolt positions using the maximum width of bolt points, as shown in Figure 13(d). In this method, bolt points are projected on a plane, and the widths of points are calculated in various directions. This is because the bolt width varies depending on the rotation angle. When the maximum width is obtained, the center of the circle is determined so that the most points are included in the circle. The circle center is regarded as the bolt position.

The results are shown in Table 1. In this evaluation, the hexagon fitting method achieved excellent results, and was much better than the maximum width method. The results shows that our method can be used for practical use.

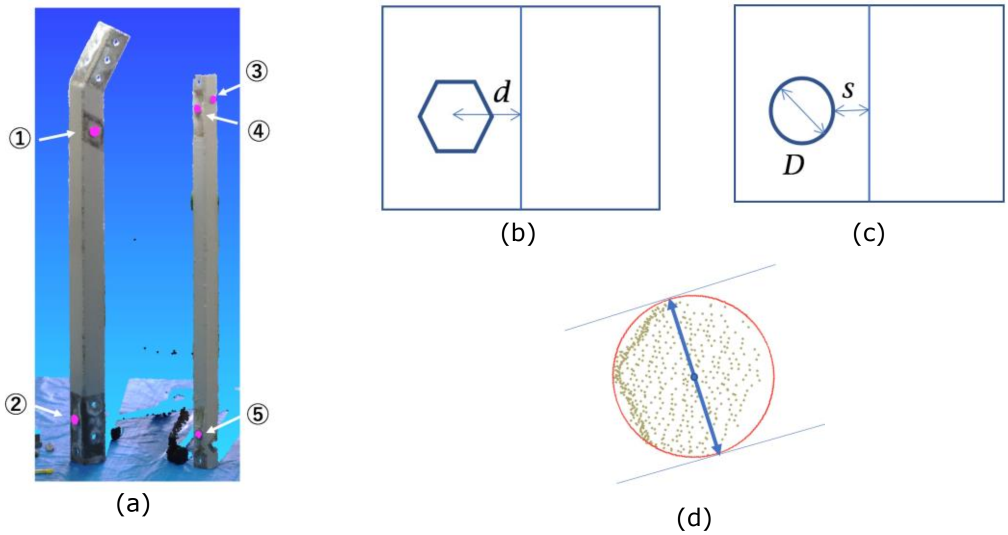


Figure 13: Experiment: (a) Steel Materials and Bolts, (b) Distance evaluated using Point-Cloud, (c) Manual Measurement using Vernier Calipers, and (d) Calculation of Bolt Position using the maximum Width.

Bolt	*Measured by vernier calipers*	*Maximum width method*		*Hexagonal fitting method*	
		Calculated value	*Difference*	*Calculated value*	*Difference*
1	45.5 mm	46.8 mm	1.3 mm	45.0 mm	0.5 mm
2	44.2 mm	42.9 mm	1.3 mm	44.6 mm	0.4 mm
3	38.9 mm	37.8 mm	1.1 mm	38.8 mm	0.1 mm
4	30.6 mm	32.5 mm	1.9 mm	30.5 mm	0.1 mm
5	30.6 mm	30.5 mm	0.1 mm	30.4 mm	0.2 mm
Average	-	-	1.1 mm	-	0.3 mm

Table 1: Experimental results.

5 CONCLUSION

In this paper, we proposed methods for stably detect planar surfaces of steel materials by combining the RANSAC method, seed point selection by thinning, and the region growing method. Experimental results showed that our method could segment planar regions stably and precisely.

We also proposed the bolt detection method using hexagonal fitting. In our experiments, we compared our method with manual measurement and the maximum width method. The experimental results showed that our method achieved excellent detection rates and accuracy.

In future work, we would like to investigate methods for evaluating the reliability of results, because the accuracy depends on measurement conditions. In this research, we did not discuss methods for evaluating deterioration of steel materials. We would like to investigate methods to automatically detect damaged steel materials by using point-clouds and digital images. In addition, in this research, we could not compare our results with the data measured by the inspectors on the pylon. We would like to evaluate the preciseness, reliability, and performance of our method as compared to measurements by skilled inspectors.

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