Title:
Shape Reconstruction of Structural Members of Steel Tower Considering Symmetrical Relationships

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Keywords:
Point-Clouds, Shape Reconstruction, Pylon, Terrestrial Laser Scanner, Point Processing

DOI: 10.14733/cadconfP.2022.204-208

Introduction:
With the recent advances in laser scanning technology, many methods have been proposed for shape reconstruction from point clouds. If complete point clouds can be obtained, these methods can be used to create realistic 3D models from point clouds. However, it is difficult for large-scale structures to obtain complete point clouds without missing points. In order to obtain complete point clouds of large-scale structures, it is necessary to capture point clouds using UAVs or perform dangerous measurements on scaffolds. Such work requires a lot of time and money.

In many cases, standard steel members are used in large-scale structures such as infrastructure facilities. Furthermore, these members are assembled symmetrically using regular connection methods due to manufacturing and construction reasons.

In this study, we discuss a shape reconstruction method considering relationships among the members of power transmission towers. As shown in Fig. 1(a), typical power transmission towers in Japan are made of angle steel, which consists of orthogonal planes. Fig. 1(b) shows six types of steel members: (1) main members, which are used for four legs that support the structure; (2)(3) diagonal and horizontal members, which support main members; (4)(5) diagonal and horizontal members, which support steel members in (1)-(3); and (6) opposite-side members, which support the inside strength of the tower. Each steel member is bolted to each other.

In our previous work [2], we proposed a method for detecting steel members and bolts of steel towers and reconstructing their 3D models from point clouds captured by a terrestrial laser scanner (TLS) on the ground. However, it is very difficult to reconstruct all structural members and bolts from incomplete point clouds, which lead to loss of detail, missing portions, and incorrect shape reconstruction.

In this research, we discuss a method for reliably reconstructing 3D models of structural members of steel towers by considering positional relationships among steel members.

Fig. 1: Members of steel tower: (a) Angle steel and (b) Classification of steel members.

Segmentation of Point-Clouds:
The shape of a power transmission tower is a square pyramid. The main body of the power transmission tower is supported by four legs, each of which consists of main members bolted together.
First, the four legs are detected from a point cloud, and then the point cloud is subdivided into points on the four faces of the square pyramid and points the inside the square pyramid.

Fig. 2 shows a process for detecting four legs from a point cloud. Fig. 2 (a) shows a point cloud of a power transmission tower. In our method, a point cloud is mapped on a 2D lattice using the azimuth and elevation angles of the laser beam, and planar regions are detected on the 2D lattice using the method proposed by Masuda et al. [1]. Fig. 2(b) shows detected planes from the point cloud. To detect angle steels, adjacent orthogonal planes are selected and their intersection lines are calculated, as shown in Fig. 2(c). The intersection lines are candidates of the main axes of angle steels. Since the main members of a tower are nearly vertical, nearly vertical intersection lines are selected and those on the same line are grouped together, as shown in Fig. 2(d). Then, sufficiently long line groups are selected and they are regarded as four legs of the tower, which are shown in red in Fig. 2(e).

The four legs are regarded as edges of the square pyramid. We refer to the four faces of the square pyramid as the main planes of the steel tower. Then, points on each main plane are detected by selecting points whose distance from each main plane is within a threshold. Points that are not included in any main plane are classified as inner points of the steel tower. Fig. 2(f) shows the points on four main planes and the points inside the tower in different colors.

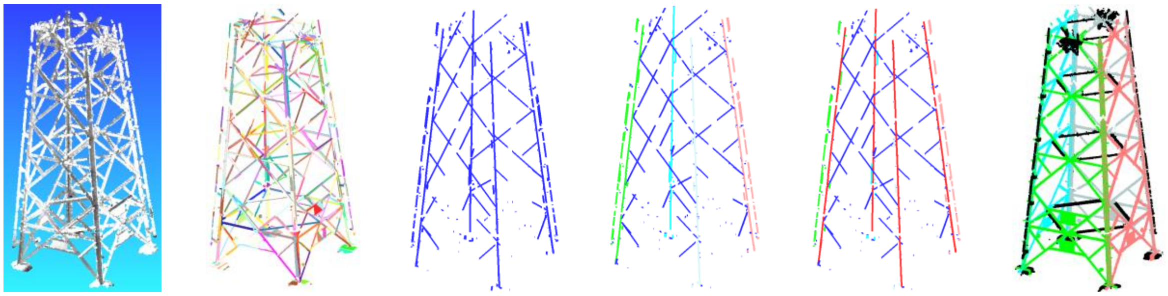

Fig. 2: Process of segmentation: (a) Point-clouds, (b) Detected planes, (c) Intersection lines, (d) Groups of vertical lines, (e) Four legs consisting of main members, and (f) Points segmented into five groups.

Detection and Completion of Main Axis Segments:
The main axes of angle steels are detected from each of five-point groups. Fig. 3 shows a process to detect angle steels on each main plane. The intersection lines of adjacent orthogonal planes shown in Fig. 3 (a)(b) are used to detect angle steels. The length of the intersection line is less than a threshold, it is removed as noise. Then, intersection lines are classified into vertical, horizontal, and diagonal ones. The vertical line segments are those whose angle with the z-axis is less than the threshold, and the horizontal line segments are those whose angle with the xy-plane is less than the threshold. The other line segments are classified into diagonal ones.

All line segments are projected onto each main plane. If two-line segments are on the same line and have close endpoints, they are merged into a single line segment. Fig. 3 (b) shows the projected line segments. Angle steels are detected on the 2D plane.

The main members are extracted from the vertical line segments. The main axes of connected main members can be obtained as a long line consisting of the highest and lowest endpoints of vertical line segments on the same line, as shown in Fig. 3(c). The connected main members are subdivided by detecting bolts. This method will be described later.

After connected main members are detected, the endpoints of diagonal line segments are extended to the closer main axes of the main members, as shown in Fig. 3(d). As shown in Fig. 1, the diagonal member and the diagonal support member are connected to one or two main members, respectively. Therefore, if a diagonal line segment is connected to two main members, it is regarded as a diagonal member. If it is connected to one main member, it is regarded as a diagonal support member.

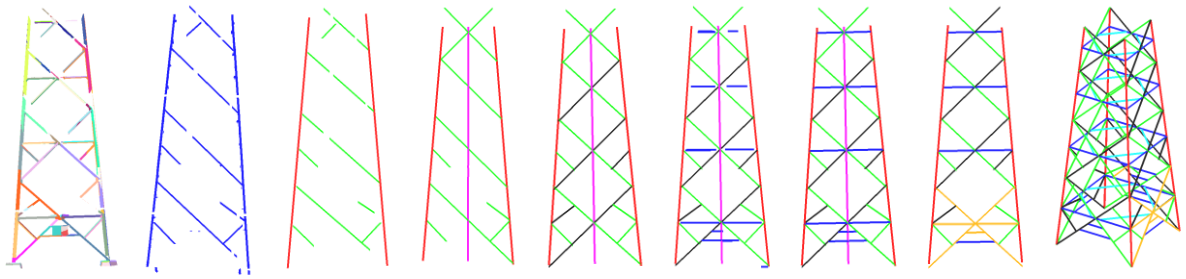

Fig. 3: Steel members on the main plane: (a) Planes, (b) Intersection lines between orthogonal planes, (c) Corrected main members, (d) Unified line segments and the symmetry axis, (e) Members added using linear symmetry, (f) Horizontal members, (g) Compensated members, (h) Members compensated from other main plane, and (i) Detected members including opposite-side members.

However, in Fig. 3(d), many steel members are not be detected, because two orthogonal faces of each angle steel may not be visible from the laser scanner on the ground, and the intersection lines cannot be obtained. To compensate missing steel members, we assume that (1) the structure of members is linear symmetric in each main plane, and (2) the structure of members is the same on each main plane.

The symmetry axis can be calculated using the main axes of main members, as shown in pink in Fig. 3 (d). If there is no symmetrical line segment with respect to the symmetry axis, a line segment is added to the symmetrical position. The added line segment is then extended to neighbor steel members. If there are a pair of symmetrical line segments, their endpoints are corrected to symmetrical positions. Fig. 3 (e) shows the complemented members in black.

Steel members are also complemented so that the structures on the four main planes of the square pyramid become the same. In the example of Fig. 3, some diagonal members and diagonal support members were copied onto other main planes.

For most horizontal members, since only one face of each angle steel is visible to the laser scanner, the intersection lines cannot be obtained. In such cases, each member is calculated using only one face of the angle steel. When a plane has no adjacent orthogonal plane, the main axis direction is estimated using principal component analysis (PCA). If the direction is nearly horizontal, it is regarded as a candidate of a horizontal member, as shown in blue in Fig. 3(f). Then, the horizontal line segment is extended to adjacent members. If the horizontal line segments connect to diagonal members or main members, they are regarded as horizontal members or horizontal support members. Fig. 3(g) shows the detected horizontal members and horizontal support members. By comparing horizontal members on the four main planes, and missing members are copied from other main planes. In Fig. 3(h), compensated horizontal members are shown in yellow.

The opposite-side member connects two horizontal members on adjacent main planes, as shown in Fig. 1. The opposite-side members are detected from the inner points. Since two orthogonal faces of the opposite-side member are not visible from the laser scanner in most cases, the direction of the main axis is calculated by applying PCA to points on a single face. Then, the line segment is extended to neighbor horizontal members. If the line segment does not connect horizontal members, it is discarded. The detected opposite-side members are corrected to symmetrical positions. Fig. 3(i) shows all detected steel members including opposite-side members.

Detection of Bolts Considering Joint Relationships:

For the maintenance of steel towers, deteriorated members are replaced to new members, which have bolt holes at the same positions. Since bolt holes on steel members of existing towers are occluded, it is required to measure bolt head positions. Yoshiuchi et al. [2] proposed a method for detecting bolts from point clouds. In this method, hexagonal planar regions are detected from point clouds, and if they are on larger planes of steel members and match the standard bolt size, they are regarded as bolt heads that join steel members. However, this method did not take into account the relationship between the bolt and the steel members. Therefore, a lot of inconsistent bolts could not be eliminated. In this research, we consider how each bolt joins steel members to reconstruct the shapes of steel members with bolt holes at correct positions.

In the previous section, steel members are detected from point clouds. We also detect bolt candidates by using the method proposed by Yoshiuchi et al. [2]. Then, we classify the types of bolts according to the number of steel members to be joined, as shown in Fig. 4(a).

For bolts on only one member, the type is further classified into two cases. One is the case where the bolt joins two main members of the leg of the tower. In this case, the position of the bolt is a clue to divide the tower leg into each main member. The other is the case where steel members are bolted with an auxiliary plate for fixing multiple steel members, as shown in Fig. 4(b). For power transmission towers in Japan, auxiliary plates with the same shape are used depending on the way steel members are combined. Therefore, we prepare template 3D models of auxiliary plates including bolt holes.

To determine the types of bolts, the intersection points among the main axes of steel members are calculated. If a bolt is located near the intersection point, it is associated with two or more steel members. If the bolt is located near only one member, the bolt is associated with the member. If there are no main axes near the bolt, the bolt is discarded as false detection.

If a bolt is on only one steel member, an auxiliary plate may exist, as shown in Fig. 4(b). If the bolt positions match all of the bolt holes of a template auxiliary plate, we consider that an auxiliary plate exists to fix steel members. Then, the bolts are associated with the auxiliary plate and the joined steel members. If a bolt is associated with only one steel member and not with either the main member or auxiliary plate, it is regarded as false detection.

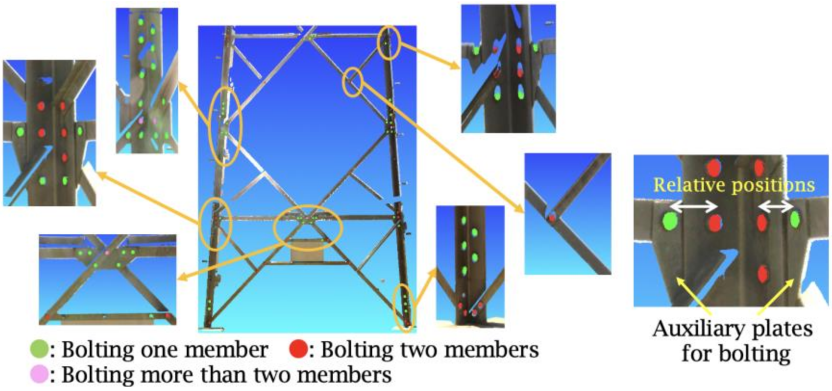

Fig. 4: Detected Bolts: (a) Joint types of bolts, and (b) Auxiliary plates for bolting.

<u>3D Models of steel members:</u>
Steel members of the tower are angle steels shown in Fig. 5(a). The shapes of angle steels can be determined by the width and the length. The possible widths are specified by the industrial standards. We calculate the width of each steel member using point clouds, and select the closest width value from the industrial standards.

In the calculation of the width of each member, the points of the member are subdivided into equal intervals along the main axis, and the maximum distance between the points and the main axis is calculated at each interval. The width is considered to be the median of maximum distances except the intervals on other members or auxiliary plates.

The length of each member is determined so that it does not intersect with other members. In the construction of steel towers, there is a design rule regarding the distances between the steel end and the nearest bolt position, shown in Fig. 5(b). In our example towers, it was about 2 cm. If the steel end is occluded by other members, the length of the member is determined using the bolt positions according to the design rule.

In Fig. 3, the main members and the horizontal members are obtained as joined long lines. Each member is extracted by subdividing bolt positions. If a bolt is associated only with a main or horizontal member, the bolt is considered to be joining two members of the same type. Then, the long line is subdivided into multiple main axes of steel members.

The 3D model of each steel member is generated by fitting an angle steel model to the main axis. Fig. 4(c)-(f) show the results of 3D models of the tower generated using different heights of the point clouds. As the height from the ground increases, the point density decreases, and less steel members can be detected from point clouds. By complementing steel members using symmetrical relationships, steel members could be reconstructed to sufficient heights.

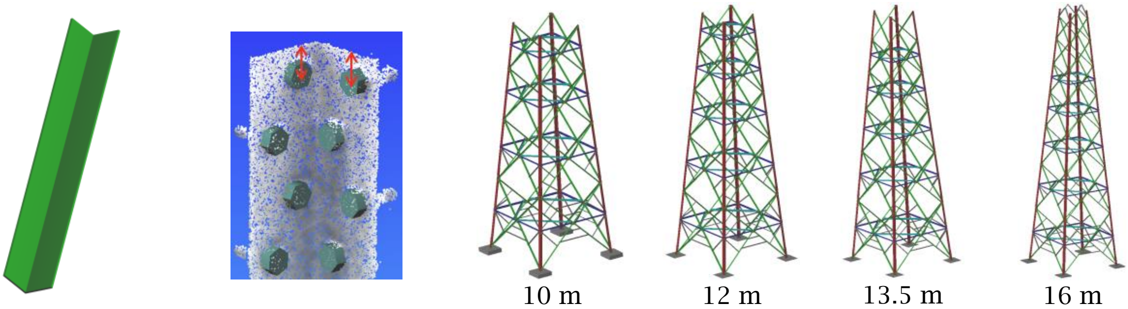

Fig. 5: Fitting 3D Models: (a) 3D shape of angle steel, (b) Distance from the edge, and (c)-(f) The results of shape reconstruction up to different heights.

Experimental Results:

We evaluated the proposed method using a point cloud of a power transmission tower with a height of about 27m. The laser scanner was Faro Focus 3D X330, and the number of points was approximately 170 million. Fig. 6 shows results of the shape reconstruction up to a height of about 10 m. The result shows that our method could successfully reconstruct each steel member including bolts and auxiliary plates with semantic attributes.

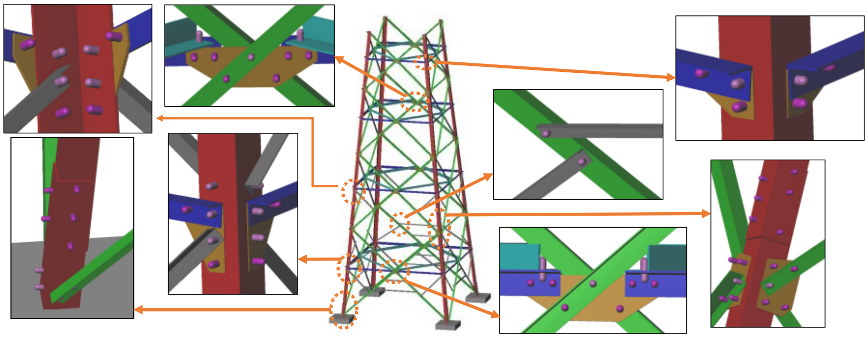

Fig. 6: Reconstruction of steel members, bolts, and auxiliary plates of the steel tower.

Conclusion:

In this paper, we proposed a shape reconstruction method considering the structural symmetry and joint relationships of bolts. In the evaluation of the proposed method, we successfully extracted and reconstructed the 3D models of each steel, bolt, and auxiliary plate of the power transmission tower.

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