www.cadanda.com Computer-Aided Design AND APPLICATIONS

Shape Reconstruction of Structural Members of Steel Tower Considering Symmetrical Relationships

Kota Kawasaki[1] and Hiroshi Masuda[2]

[1]The University of Electro-communications, kota.kawasaki@uec.ac.jp
[2] The University of Electro-communications, h.masuda@uec.ac.jp

Corresponding author: Hiroshi Masuda, h.masuda@uec.ac.jp

Abstract. 3D models of large-scale structures are useful to support maintenance tasks, such as fabrication of replacement members, structural analysis, and process simulation. However, 3D models or reliable drawings for old structures do not often exist. In such cases, shape reconstruction from point clouds is very useful. This paper discusses methods for detecting steel members from point clouds of power transmission towers, and creating the 3D assembly models in which steel members are joined with bolts. Since many steel members are partly occluded by other members, it is difficult to reliably create their 3D models. Therefore, 3D models are reconstructed by using prior knowledge regarding typical structures, symmetry assumptions, and joining conditions among components. In our method, steel members are extracted from point clouds, and undetected ones are estimated using the symmetry assumptions. Bolts are also detected from point clouds, and they are used for assembling steel members. Finally, a complete assembly model of a steel tower is reconstructed. We evaluated our methods using actual point clouds of different power transmission towers. Our experimental results showed that our method could reliably reconstruct 3D models of steel members and assembly models of steel towers.

Keywords: Point-Clouds, Shape Reconstruction, Pylon, Terrestrial Laser Scanner, Point Processing.
DOI: https://doi.org/10.14733/cadaps.2023.814-825

1 INTRODUCTION

Since large-scale structures have very long lifecycles, they have to be regularly inspected and renovated by replacing deteriorated members. 3D models are very useful to support maintenance tasks, such as fabrication of replacement members, structural analysis, and simulation of renovation process. For old large-scale structures, however, 3D models or reliable drawings do not often exist. In such cases, it is an effective solution to generate 3D models from point clouds captured using terrestrial laser scanners (TLS).

With the recent advances in laser scanning technology, dense point clouds can be obtained from large-scale facilities in a short time. So far, many shape reconstruction methods from point clouds have been proposed [3], [6]. If dense point clouds with few missing points can be obtained, these methods can create realistic 3D models. However, it is not easy to acquire point clouds without missing points for large-scale structures. In order to obtain complete point clouds of large-scale structures, it is necessary to use UAVs or take dangerous measurements on scaffolds. The measurement by UAVs has accuracy problem, and the measurement on scaffolds is time-consuming, costly, and often impractical. It is desirable to develop shape reconstruction methods from incomplete point clouds of large-scale structures.

For reconstructing object shapes from incomplete point clouds, it is useful to use prior knowledge about target objects. Vanegas et al. [12] reconstructed 3D shapes of buildings based on the Manhattan-World assumption that many components of the building should be arranged in three mutually orthogonal directions. This assumption can also be applied to modeling in industrial plants [11]. Zheng et al. [15] used repeatability and self-similarity to reconstruct building facades. Repeatability can also be used for generating 3D models of guardrails [9]. Furthermore, various types of symmetries in objects have been used in shape modeling [4],[10]. For modeling components of pipelines in industrial plants, rules for connecting components were used to create 3D models [5], [7].

In this paper, we discuss shape reconstruction of power transmission towers from point clouds. So far, several methods have been studied for reconstructing 3D models of power transmission towers. Power transmission towers have certain geometrical patterns based on industrial standards established in each country. Guo et al. [2] reconstructed 3D shapes of power transmission towers based on a model-driven approach using a predefined model library. The tower structure can be segmented into sub-structures by considering similarity and functionality. For segmented structures, the data-driven method has been studied for extracting surfaces and lines that characterize the structures [1], and the model-driven method has been studied for estimating parameters for towers [13]. Hybrid approaches combining these two strategies have also been proposed [16]. However, these methods focused on reconstructing only the main structure of the tower, and did not extract each member of the tower.

Maintenance of steel towers involves replacing deteriorated members with new members that have bolt holes at the same locations. For this purpose, it is important to detect bolt positions on each steel member. In our previous work [14], we proposed a method to detect steel members and bolts from point clouds acquired by a TLS placed on the ground. However, since complete point cloud of the steel tower could not be obtained due to occlusions, many steel materials were missing partly or entirely. In addition, it was difficult to stably detect small steps in steel members joined by the bolts for detecting each steel member. Therefore, the assembly model of the steel tower could not be reconstructed.

This paper proposes a method for detecting each steel member of a power transmission tower from point clouds, reconstructing 3D models of steel members, and assembling the 3D models to the steel tower. Although it is generally difficult to create a complete assembly model from incomplete point clouds, we create assembly models by using prior knowledge regarding typical tower structures, symmetry assumptions, and joining conditions between steel members.

Typical Japanese power transmission towers consist of angle steels, each of which consists of two orthogonal planes, as shown in Figure 1(a). Steel members of each tower can be categorized into six types. Figure 1(b) shows the six types, which are (1) main members used for the four legs that support the tower structure; (2) (3) diagonal and horizontal members that support the main members; (4) (5) diagonal and horizontal support members that support the members in (1) through (3); and (6) opposite-side members that support the internal structure of the tower. Each steel member is bolted together and arranged symmetrically considering strength and center of gravity.

Our method extracts six types of steel members from point clouds. First, planar surfaces are extracted from point clouds, and then, steel members and bolts are detected [8], [14]. Undetected or partly missing steel members are recovered by considering the symmetry of the steel tower. The symmetry assumption is also used for recovering missing bolts or to remove incorrectly detected bolts. In addition, the bolt positions are used to separate individual angle steels even if the small steps between bolted steel members cannot be detected. In some cases, angle steels are indirectly joined using auxiliary planes. In our method, auxiliary plates are estimated using the template patterns of bolt positions. Finally, 3D models of steel members and bolts are reconstructed, and a complete assembly model of a steel tower is reconstructed.

In the next section, we discuss methods for detecting steel members by considering the symmetry of steel towers. In Section 3, we discuss methods for detecting bolts and assembling steel members by the bolts. In Section 4, we describe experimental results, and finally, we conclude our research.

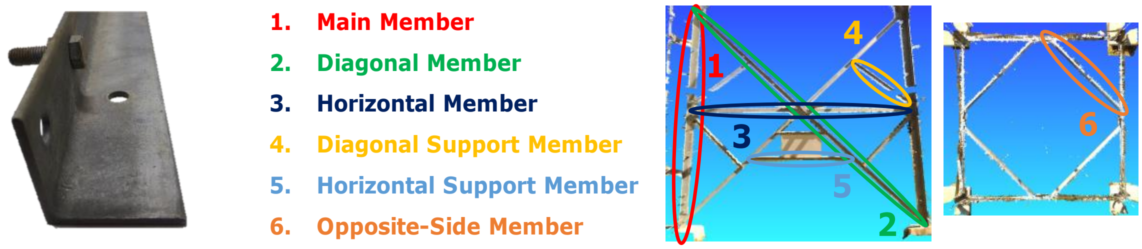

Figure 1: Members of steel tower: (a) Angle steel and (b) Classification of steel members.

2 DETECTON OF STEEL MEMBERS

2.1 Segmentation of Point-Clouds

The main body of the steel tower is supported by four legs, each of which consists of main members bolted together. The four legs can be regarded as edges of a square pyramid, as shown in Figure 2. Most steel members exist on the four faces of the pyramid. In the interior of the pyramid, internal steel members are placed between the four faces. In our method, the four legs are first detected from the point cloud to identify the pyramid shape, and then the point cloud is subdivided into the points on the four faces and the points inside the square pyramid.

Figure 2 shows a process for detecting the four legs and subdividing points. Figure 2(a) shows a point cloud of a power transmission tower captured by a TLS. In our method, planar regions are detected using the method proposed by Masuda et al. [8]. This method is suitable for detecting planes from a large-scale point cloud. In this method, a point cloud is mapped on a 2D lattice using the azimuth and elevation angles of the laser beam, and planes are detected on the 2D lattice. Figure 2(b) shows detected planes from the point cloud.

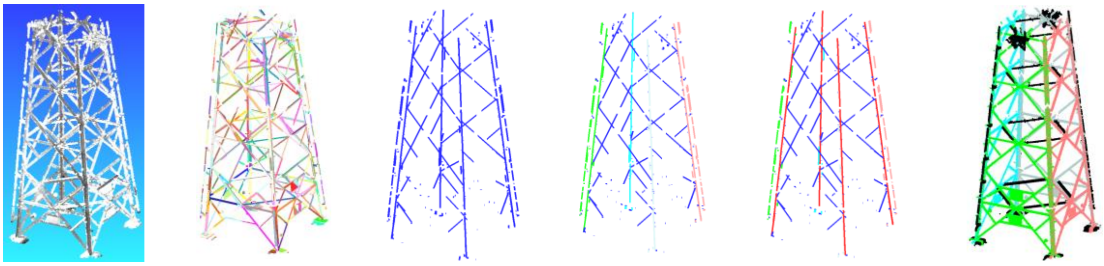

Figure 2: Process of segmentation: (a) Point-clouds, (b) Detected planes, (c) Intersection lines, (d) Groups of vertical lines, (e) Four legs consisting of main members, and (f) Points segmented into five groups.

To detect angle steels, nearly orthogonal adjacent planes are detected, and their intersection lines are calculated as the main axes of angle steels, as shown in Figure 2(c). The length of each angle steel is initially set as the common part of the two planes, and is corrected later when the steel members are assembled. To detect the four legs, nearly vertical lines are selected and those on the same line are grouped, as shown in Figure 2(d). Then, sufficiently long line groups are regarded as four legs of the tower, as shown in red in Figure 2(e).

The obtained four legs are regarded as edges of a square pyramid. The four faces of the square pyramid are referred to as the main planes of the steel tower. Then, points close to each main plane are selected as points on the main plane. Points that are not included in any main plane are classified as the inner points of the steel tower. As a result, the point cloud is classified into five groups: the four main planes and the interior. Figure 2(f) shows the five groups of points in different colors.

2.2 Detection of Steel Members

Steel members are detected from each of the five-point groups. Figure 3 shows the detection process for steel members. Steel members on the main plane and those inside the tower are detected separately. In our method, the symmetry on each main plane and the symmetry between main planes are considered to recover missing steel members. Steel members at symmetrical positions are automatically recovered if at least one steel member can be detected.

2.2.1 Steel Members on the Main Plane

The main axis of each angle steel can be calculated as the intersection line of two orthogonal planes. Figure 3(a) shows planes detected on one of the four main planes, and Figure 3(b) shows the intersection lines between two orthogonal planes. Then, intersection lines are classified into vertical, horizontal, and diagonal line segments according to the directions of lines. The vertical line segments are those whose angle with the z-axis is less than a threshold. The horizontal line segments are those whose angle with the XY-plane is less than a threshold. The other line segments are classified into diagonal ones. All line segments are projected onto each main plane.

In Figure 3(b), some line segments are partly missing due to occlusion. In such cases, if two lines are on the same line and have close endpoints, they are merged into a single line segment. By connecting lines, the four legs of the tower are obtained as long straight lines, as shown in red in Figure 3(c).

Each diagonal members are bolted with one or two main members for supporting the main members. Therefore, the endpoints of diagonal line segments are extended to the main members, as shown in Figure 3(d). In this process, the endpoints are not extended across the centerline. As shown in Figure 1(b), while the line segment of diagonal members connects to two main members, the line segment of diagonal support members connects to one main member. Therefore, each diagonal member can be classified into the diagonal member or the diagonal support member.

In Figure 3(b), many diagonal steel members are entirely missing. This is because one face of the angle steel could not be visible from the laser scanner on the ground, and the intersection line of two orthogonal faces cannot be obtained. To recover missing steel members, we introduce symmetry assumptions that (1) steel members are symmetric about the center line in each main plane, and (2) steel members are assembled in the same way on each main plane. Therefore, missing steel members are added if there are line segments at the symmetric positions. Then, the endpoints of added steel members are extended to the main members. Figure 3(e) shows the recovered steel members according to the assumption (1) in black. Diagonal steel members are also complemented so that the same steel members exist on each of the four main planes. Figure 3(h) shows the recovered diagonal steel members according to the assumption (2) in yellow.

In some cases, one face of angle steel is not visible at all symmetric positions. In Figure 3(e), most of the horizontal members are missing due to this reason. In such cases, the axis of each steel member is estimated from only one face using principal component analysis (PCA). The axis direction is calculated from points on one visible face as the principal component direction with the largest eigenvalue. Then, a rectangle with two edges parallel to the axis direction and enclosing the points is created. Since the face not visible from the ground is the upper face of the steel member, the upper of the two parallel rectangle edges is considered to be the axis of the steel member. If the direction of the estimated line segments is nearly horizontal, it is a candidate for a horizontal member, as shown in blue in Figure 3(f). Then, line segments on the same line are grouped and the endpoints of the line segments are extended to the main members. If a horizontal line segment intersects the diagonal members, it is regarded as a horizontal member. Otherwise, it is regarded as a horizontal support member. Figure 3(g) shows detected horizontal members and horizontal support members. Horizontal steel members are also complemented according to the assumption (2), as shown in yellow in Figure 3(h).

2.2.2 Steel Members inside the Steel Tower

The opposite-side member connects to two horizontal steel members on two different main planes and supports the internal structure of the tower, as shown in Figure 1(b). As with other steel members, the axis is calculated from one or two planes. If the axis direction is nearly horizontal, it is regarded as an opposite-side member. Their line segments are extended to neighboring horizontal members. If the line segment cannot be connected to horizontal steel members, it is discarded. The four opposite-side members are symmetrical on the horizontal cross-section, as shown in Figure 1(b). Therefore, if opposite-side members are missing, the missing ones are recovered at the symmetric positions. Figure 3(i) shows all detected steel members including opposite-side members.

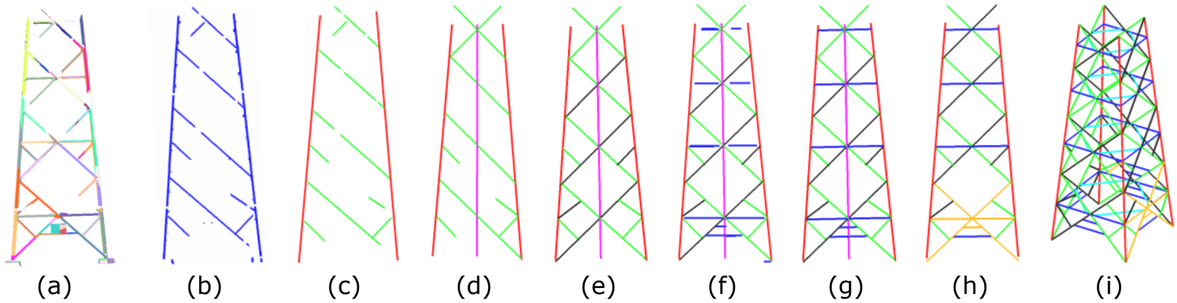

Figure 3: Steel members on the main plane: (a) Planes, (b) Intersection lines between orthogonal planes, (c) Main members (red), (d) Corrected line segments (green) and the symmetry axis (pink), (e) Members added using linear symmetry (black), (f) Steel members calculated from one face (blue), (g) Compensated horizontal members (blue), (h) Members compensated from other main planes (yellow), and (i) All detected steel members.

2.3 Dimensional Calculation for Steel Members

The shape of angle steel can be determined by the width and the length. The possible widths are determined by industrial standards. In our method, the width of each steel member is calculated using point clouds and the closest value in industrial standards is selected as the width. Figure 4(a) shows the 3D model of an angle steel with the calculated width. The position of each 3D model is determined by fitting the 3D model to the axis of each detected steel member, as shown in Figure 4(b) and (c).

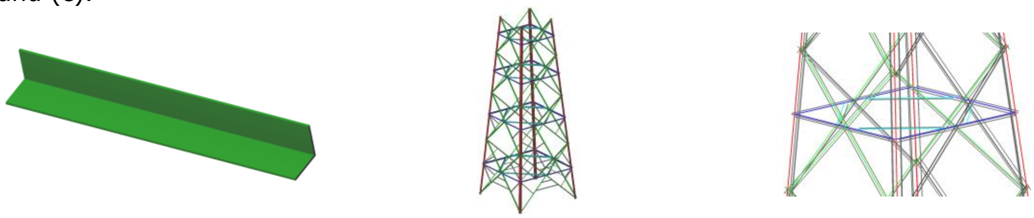

Figure 4: Fitting 3D models: (a) 3D shape of angle steel, (b) 3D models of steel members, and (c) Close-up.

3 RECONSTRUCTION OF ASSEMBLY MODEL USING OF JOINT RELATIONSHIPS

The previous section described methods for detecting steel members from a point cloud. In this section, we discuss a method for detecting bolt positions and assembling steel members. In addition, the lengths of steel members are correcting using bolt positions. Our method for bolt detection is based on the method proposed by Yoshiuchi et al. [14], but we recover missing bolts using the symmetry assumptions.

3.1 Detection of Bolts

First, bolt candidates are detected using the method proposed by Yoshiuchi et al. [14]. This method detects bolt head planes that satisfy conditions: (1) sufficiently close to a steel member, (2) parallel to a steel member plane, and (3) consistent with the standard bolt sizes. If the shape of a detected plane fits to a hexagonal shape of a standard bolt, it is regarded as a bolt head. The center position of the bolt is obtained as the center of the hexagon.

Each detected bolt is associated with one or more steel members. The intersection points among the line segments of steel members are calculated, and a bolt close to each intersection point is associated with the steel members. If a bolt is associated with no intersection points, it is associated with only one member closest to the bolt.

In the upper part of the tower, it is difficult to detect bolts due to low point density. Therefore, bolts in the upper part are recovered using bolts detected in the lower part. As shown in Figure 3, the same combination of steel members appears repeatedly in a steel tower. Therefore, we assume that if the combination of steel members is the same, the bolt pattern is also the same. By using this assumption, missing bolts are recovered at the corresponding positions.

3.2 Correction Using Relationships between Steel Member and Bolt

We classify the bolt types according to the number of steel members to be joined, as shown in Figure 5(a). When a bolt is only on one steel member, there are two possible cases. One is the case where the bolt joins two main members. The other is the case where steel members are bolted with an auxiliary plate for fixing multiple steel members, as shown in Figure 5(b).

Since bolt positions are calculated using a relatively small number of points, the bolt positions may not be accurate. Therefore, the bolt positions are corrected so that the relative positions on associated steel members are consistent, as shown in Figure 6. For recovered bolts, the bolt positions

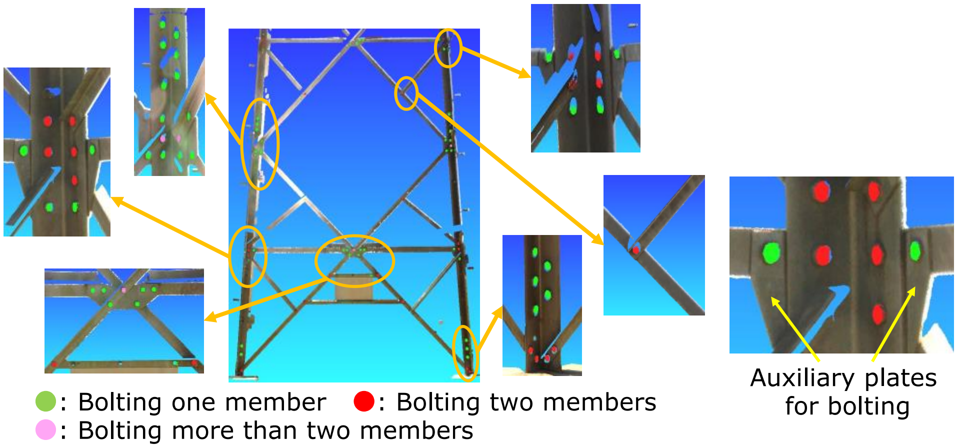

Figure 5: Detected bolts: (a) Joint types of bolts, and (b) Auxiliary plates for bolting.

are determined by assuming that the relative positions on the steel members are the same as the bolts in the symmetrical positions.

When a bolt is on only one steel member, an auxiliary plate may exist, as shown in Figure 5(b). In our observation, the same types of auxiliary plates are used for many steel towers. Therefore, we prepare templates of auxiliary plates, each of which defines the bolt positions and the combination of steel members. Figure 7 shows templates of auxiliary plates for typical steel towers. When detected bolt positions and steel members match one of template auxiliary plates, the auxiliary plate is added for assembling the steel members. Then, some steel members are subdivided according to the template combination, such as horizontal members in Figure 7(e).

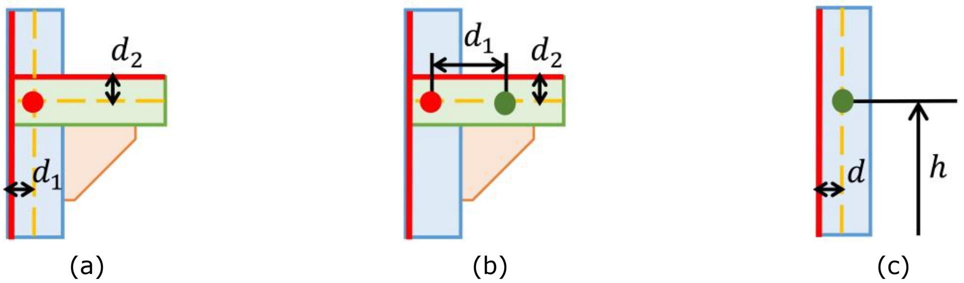

Figure 6: Calculation of bolt center position: (a) Bolting two members, (b) Bolting one member, and (c) Bolting main member.

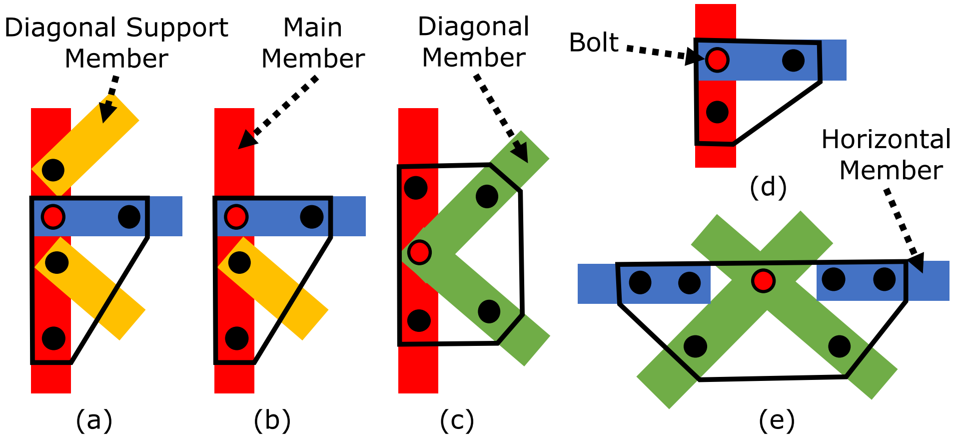

Figure 7: Templates of auxiliary plates.

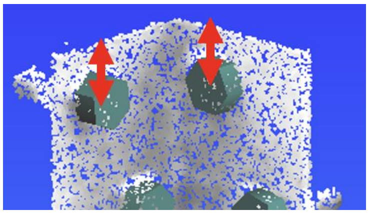

Figure 8: Design rules for steel members and bolts.

When the endpoints of steel members are occluded by other steel members, it is necessary to estimate the endpoint locations so that steel members do not intersect each other. To solve this problem, we use a design rule for the construction of power transmission towers. For strength reasons, there is a recommended minimum distance from the steel member end to the bolt, as shown in Figure 8. In our method, the endpoints of occluded steel members are determined using this minimum distance from the calculated bolt positions.

4 EXPERIMENTAL RESULTS

We evaluated the proposed method using point clouds of three different power transmission towers. One is a typical transmission power with a height of about 27 m. The second is a larger tower with a height of about 48 m. The third is a very old tower, with a different structure, about 22 m heigh and slightly tilted. Point clouds were captured using Faro Focus 3D X330 on the ground in the center of the tower. The number of points was approximately 170 million for each tower.

First, the proposed method was applied to a typical power transmission tower, which was located in the area controlled by an electric company. Figure 9 shows the results of the shape reconstruction up to a height of about 10 m. All steel members could be successfully extracted, and they were correctly assembled. In this model, there are auxiliary 72 plates and 504 bolts. Table 1 shows the numbers of detected steel members. There was no false detection. The bolts connecting steel members could also be successfully reconstructed without false detection.

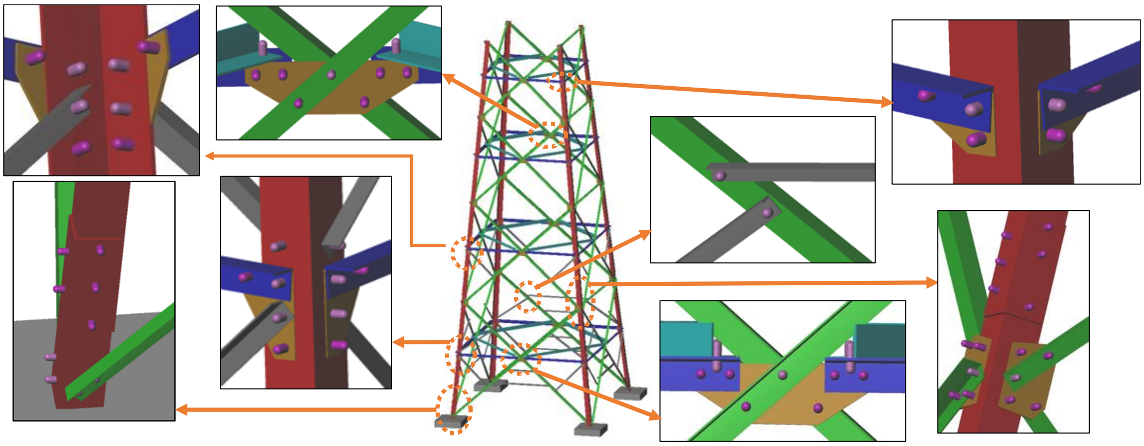

Figure 9: Reconstruction of a typical steel tower up to a height of about 10 m.

Classification of member	*Quantity*	*Detected*	*Rate*	*False*
Diagonal member	32	32	100.0 %	0
Horizontal member	32	32	100.0 %	0
Diagonal support member	24	24	100.0 %	0
Horizontal support member	10	10	100.0 %	0
Opposite-side member	16	16	100.0 %	0

Table 1: Steel members detected from the typical steel tower.

In the upper part of the tower, steel members could not be stably detected due to low point density. In our method, undetected steel members are recovered using symmetry assumptions. To evaluate the robustness of our method, we applied the method to point clouds up to 12 m, 13.5 m, and 16 m. As shown in Figure 10(a)-(c), the proposed method could successfully reconstruct 3D models in the upper part of the tower, where a point cloud of steel members and bolts could not be sufficiently acquired. At all heights, auxiliary plates were successfully created using templates and the joint relationships, and steel members were correctly joined by the auxiliary plates.

In the 12 m height case, all 306 undetected bolts were recovered, and a total of 604 bolts were reconstructed. In the case of 13.5 m height, all 289 undetected bolts were recovered, and a total of 648 bolts were reconstructed. However, in this case, in our visual inspection of the resulting 3D model, the bolts and the steel members intersected at high locations, as shown in Figure 10(b) (d). This is because the relative positions of bolts were differed at high positions. In the 16 m height case, 346 undetected bolts were recovered, and a total of 680 bolts were reconstructed. However, the combination of steel members in Figure 10(e) was different in the high positions, and therefore, they could not be corrected using steel members in the lower part.

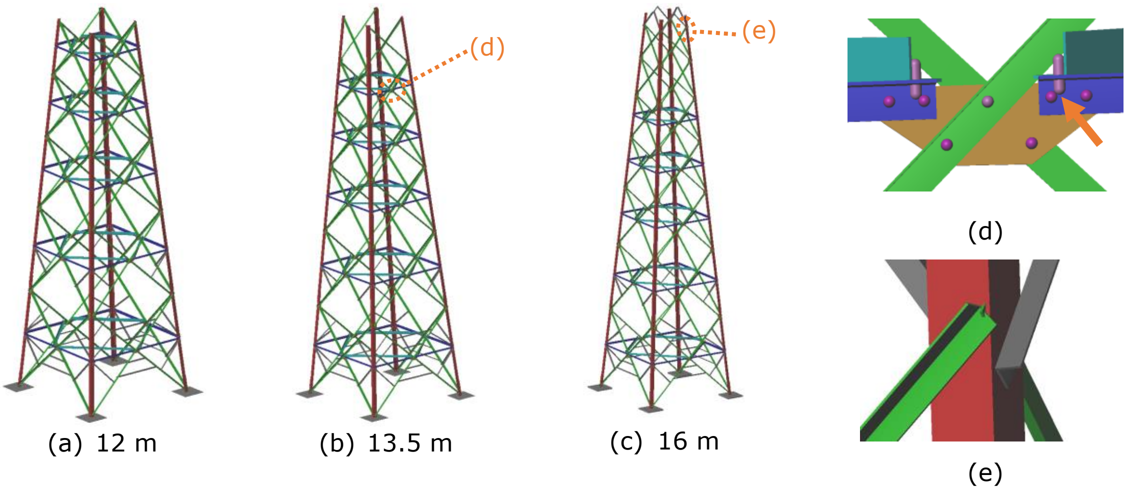

Figure 10: Reconstruction of a typical steel tower up to different heights: (a) 12 m height, (b) 13.5 m height, (c) 16 m height, (d) Incorrect bolt positions, and (e) Incorrectly joined members.

The second example was a large steel tower with a more complex structure and a height of about 48 m. The structure of this tower is different from the typical tower. The point cloud was used up to a height of 15 m. Figure 11 (a) shows the created assembly model of the tower. Our method could detect 95% of steel members, as shown in Table 2. Seven horizontal support members could not be reconstructed. The assembly model contains 12 auxiliary plates and 520 bolts. Detected steel members were correctly assembled except four positions. Figure 11(b) shows incorrectly joined steel members. This is because the combination of those steel members did not exist in the lower part of the tower, and bolts could not be detected in the high positions due to low point density. In addition, at a height of 9.5 m, four auxiliary plates were missing because their shape was not included in the templates of auxiliary plates.

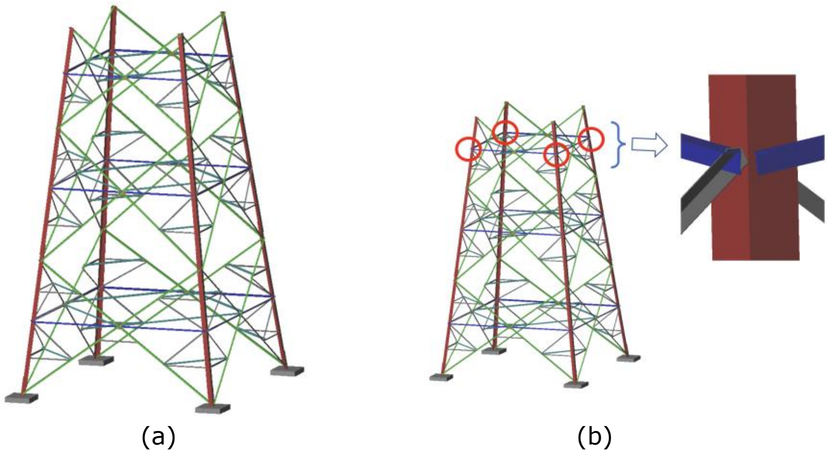

Figure 11: Reconstruction of a large steel tower: (a)Created assembly model, and (b)Incorrectly joined members due to undetected bolts.

Classification of member	*Quantity*	*Detected*	*Rate*	*False*
Diagonal member	24	24	100.0 %	0
Horizontal member	24	24	100.0 %	0
Diagonal support member	40	40	100.0 %	0
Horizontal support member	48	41	85.4 %	0
Opposite-side member	32	32	100.0 %	0

Table 2: Steel members detected from the large steel tower.

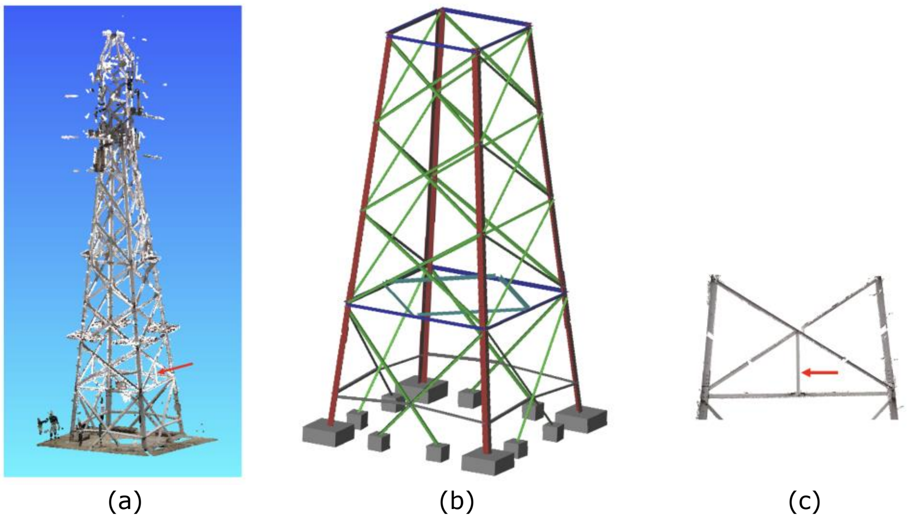

Figure 12: Reconstruction of an old steel tower: (a) Point cloud of the old tower, (b) Reconstructed assembly model, and (c) Unsupported steel member.

Classification of member	*Quantity*	*Detected*	*Rate*	*False*
Diagonal member	32	32	100.0 %	0
Horizontal member	8	8	100.0 %	0
Diagonal support member	8	8	100.0 %	0
Horizontal support member	0	0	-	0
Opposite-side member	4	4	100.0 %	0
*Vertical support member	4	0	0.0 %	0

Table 3: Steel members detected from the old steel tower.

The third example is an old steel tower, about 22 m high, built about 80 years ago. This tower is leaning and the bottom part is buried underground due to ground subsidence. The point cloud was used up to a height of about 10 m. Figure 12 shows the reconstructed assembly model of the old tower. In this case, all standard steel members in Figure 1 could be correctly detected, as shown in Table 3. However, this tower contained vertical support members that are not found in newer steel towers and are not classified in Figure 1(b). Our method could not reconstruct such unsupported steel members.

From these three evaluations, we conclude that our method is able to extract steel members and create assembly models of steel towers correctly except some special cases. Limitations of our method are that steel members joined differently in symmetrical positions may not be correctly recovered and that unsupported steel members and auxiliary plates cannot be reconstructed.

5 CONCLUSION

In this paper, we proposed a shape reconstruction method using prior knowledge regarding the tower structures, the structural symmetry, and joint relationships among steel members. In our method, steel members and bolts are detected from point clouds, and the assembly model of the tower is reconstructed using the joint relationships among steel members and bolts. Undetected steel members and bolts are recovered using the symmetry assumptions. In addition, auxiliary plates for bolting more than two steel members are detected using the templates. Our experimental results showed that our method could reconstruct adequate assembly models of towers except some special cases.

We consider that our method could be applied to other structures consisting of steel members other than steel towers, such as bridges. In future work, we would like to evaluate our method using many types of structures and investigate rules for assembling components. Currently, prior knowledge for shape reconstruction is specific to the object class, but we would like to investigate methods for generalize knowledge for many large-scale structures.

Kota Kawasaki, https://orcid.org/0000-0001-5188-158X
Hiroshi Masuda, https://orcid.org/0000-0001-9521-6418

REFERENCES

[1] Chen, S.; Wang, C.; Dai, H.; Zhang H.; Pan, F.; Xi, X.; Yan, Y.; Wang P.; Yang, X.; Zhu, X.; Aben, A.: Power Pylon Reconstruction Based on Abstract Template Structures Using Airborne LiDAR Data, Remote Sensing, 11(13), 2019, 1579. https://doi.org/10.3390/rs11131579

[2] Guo, B.; Huang, X.; Li, Q.; Zhang, F.; Zhu, J.; Wang, C.: A Stochastic Geometry Method for Pylon Reconstruction from Airborne LiDAR Data, Remote Sensing, 8(3), 2016, 243. https://doi.org/10.3390/rs8030243

[3] Hoppe, H.; DeRose, T.; Duchampy, T.; McDonaldz, j.; Stuetzl, W.: Surface Reconstruction from Unorganized Points, ACM SIGGRAPH Computer Graphics, 26(2), 1992, 71–78. https://doi.org/10.1145/142920.134011

[4] Jiang, N.; Tan, P.; Cheong, L.-F.: Symmetric architecture modeling with a single image, ACM Transactions on Graphics, 28(5), 2009, 1–8. https://doi.org/10.1145/1618452.1618459

[5] Kawashima, K.; Kanai, S.; Date, H.: As-built modeling of piping system from terrestrial laser-scanned point clouds using normal-based region growing, Journal of Computational Design and Engineering, 1(1), 2014, 13-26. https://doi.org/10.7315/JCDE.2014.002

[6] Kazhdan, M.; Bolitho, M.; Hoppe, H.: Poisson Surface Reconstruction, Eurographics Symposium on Geometry Processing, 2006, 61-70. http://dx.doi.org/10.2312/SGP/SGP06/061-070

[7] Lee, J.; Kim, C.; Son, H.; Kim, C.: Skeleton-based 3D reconstruction of as-built pipelines from laser-scanned data, ASCE International Conference on Computing in Civil Engineering, 2012, 245. http://dx.doi.org/10.1061/9780784412343.0031

[8] Masuda, H.; Niwa, T.; Tanaka, I.; Matsuoka, R.: Reconstruction of Polygonal Faces from Large-Scale Point-Clouds of Engineering Plants, Computer-Aided Design and Applications, 12(5), 2015, 555-563. http://dx.doi.org/10.1080/16864360.2015.1014733

[9] Matsumoto, H.; Mori, Y.; Masuda, H.: Extraction and Shape Reconstruction of Guardrails using Mobile Mapping Data, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W13, 2019, 1061–1068. https://doi.org/10.5194/isprs-archives-XLII-2-W13-1061-2019

[10] Mitra, N.J.; Pauly, M.; Wand, M.; Ceyla, D.: Symmetry in 3D Geometry: Extraction and Applications, Computer Graphics Forum, 32(6), 2013, 1–23. https://doi.org/10.1111/cgf.12010

[11] Mizoguchi, T.; Kuma, T.; Kobayashi, Y.; Shirai, K.: Manhattan-World Assumption for As-Built Modeling Industrial Plant, Key Engineering Materials, 523-524, 2012, 350-355. https://doi.org/10.4028/www.scientific.net/KEM.523-524.350

[12] Vanegas, C.A.; Aliaga, D.G.; Benes, B.: Automatic Extraction of Manhattan-World Building Masses from 3D Laser Range Scans, IEEE Transactions on Visualization and Computer Graphics, 18(10), 2012, 1627-1637. https://doi.org/10.1109/TVCG.2012.30

[13] Wang, H.; Hu, T.; Wang, Z.; Kang, Z.; Akwensi, P.H.; Yang, J.: Reconstruction of Power Pylons From LiDAR Point Clouds Based on Structural Segmentation and Parameter Estimation, IEEE Geoscience and Remote Sensing Letters, 19, 2020. 10.1109/LGRS.2020.3026691

[14] Yoshiuchi, I.; Shinozaki, Y.; Masuda, H.: Detection of Steel Materials and Bolts from Point-Clouds of Power Transmission Pylon, Computer-Aided Design and Applications, 17(3), 2020, 575-584. https://doi.org/10.14733/cadaps.2020.575-584

[15] Zheng, Q.; Sharf, A.; Wan, G.; Li, Y.; Mitra, N.J.; Cohen-Or, D.; Chen, B.: Non-local scan consolidation for 3D urban scenes, ACM Transactions on Graphics, 29(4), 2010, 1–9. https://doi.org/10.1145/1778765.1778831

[16] Zhou, R.; Jiang, W.; Huang, W.; Xu, B.; Jiang, S.: A Heuristic Method for Power Pylon Reconstruction from Airborne LiDAR Data, Remote Sensing, 9(11), 2017, 1172. https://doi.org/10.3390/rs9111172