

Research on a Method to Consider Inspection and Processing for Atypical Wood Members Using 3D Laser Scanning

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Abstract –

The purpose of this research is to use digital technology to streamline operations and improve construction when using non-uniform building materials with discrete and differing forms, such as those used in traditional wooden buildings. Taking irregular timber procurement as a model use case, we formulated a method of utilizing 3D scanning technology to facilitate inspection and processing considerations.

Keywords –

Traditional building; Wood; BIM; 3D laser scanner; Point cloud

1 Introduction

Recent years have seen the wider construction industry in Japan look to the use of cutting-edge technologies in construction work as a possible means of increasing productivity. For example, the Ministry of Land, Infrastructure, Transport and Tourism has begun a set of initiatives, called "i-Construction," to promote the use of digital technologies. At the same time, given the growing problem of the declining number of construction workers with advanced skills, new construction methods are needed to mitigate the loss of human resources and these advanced skills. Some examples exist of research into construction management or processing building materials method utilizing digital technology. One is a research project by Kano et al., who are exploring a method to automatically ascertain the progress of PCa projects using 3D laser scanners during the construction stages [1]. In terms of research into the machining of

building materials, Takabayashi et al. have reported on a method of generating machining paths for regular, uniform timber using robotic arms [2]. One of the key points proposed in these research projects is a technology to measure the shape of the PCa member and the lumber processed accurately. The authors have focused herein on digitizing material geometry accurately as one technical issue commonly found in the above research and other initiatives to refine craftsmanship and manufacturing through digital technology. Construction is the process of assembling building materials to match design information. By digitizing the shape of the building material accurately throughout each phase of the production process, this technique should allow for using complex simulations and automated control of machinery during subsequent construction steps.

The focus in this research is on renovation projects involving traditional wooden buildings as the most suitable use case. This is because the parts used are not mechanically machined such as those seen in industrial products, but those in which the processing steps must accommodate the unique geometry and form of each tree. Shrines, temples, castles and other ancient structures were built in Japan long ago, with many such traditional buildings remaining in existence and of high value today. While wooden buildings today generally use machined timber such as laminated wood and CLT, traditional Japanese wooden buildings tend to, for instance, employ a single timber log for columns or beams and exceptional skills are required throughout the entire production process, from procurement to processing and assembly.

Accordingly, we chose to treat the procurement phase, which marks the start of the manufacturing process, as a case study and propose a method to assist inspection work. This method employs 3D scanning technology to

digitize the timber geometry during the inspection phase. We also propose a method of converting the data into a lightweight and general-purpose format, reflecting the assumption that the shape data would be used when considering how to process the timber in subsequent work phases.

2 Current Workflow

We begin by enumerating some of the aspects of the procurement and processing process in traditional Japanese wooden building conservation and renovation projects.

In terms of the procurement process, the timber supply chain is very unique and since the timber used in traditional wooden structures is generally a single piece from a single tree, the materials involved tend to be large. Many of these pieces of timber are over 5m long and weigh upwards of 1 ton. Construction companies lack the commercial flow and know-how to purchase large pieces of timber within a short time, making it difficult for construction companies to purchase materials directly from timber owners. Consequently, construction companies must themselves purchase from specialist wood suppliers. The construction company communicates the design specifications to the suppliers and the suppliers collect pieces of timber that meet these specifications on the contractor's behalf. Timber obtained from the supplier in line with the above is generally rough, with only the bark removed and processed into square or round shapes. Since the cross-sectional dimension and curvature of this timber is unique in each case, construction companies inspect the merchandise at the warehouse to determine its fitness for a specific portion of the architectural design, ultimately purchasing only those pieces that pass this check. The current inspection covers points like shape, such as length and cross-sectional dimensions; aesthetics, such as color and scratches; and physical properties, such as Young's modulus. For shape inspections, 1:1 scale printed drawings are laid under the timber to check the size and the details are checked via tape measure, while aesthetic inspections are conducted visually by the design

supervisor. In many cases, special measuring instruments are used to ascertain the physical properties. In addition, the inspector also relies on visual particularities, such as the shape, knots, barks caught inside and rots to infer the internal condition of the wood and determine whether it is fit for use. Given the considerably advanced skills and timber processing experience this entails, construction companies sometimes assign carpenters to handle inspections. The construction company asks the carpenter to cut the timber down to match the desired dimensions and cut the surface to ensure a consistent cross-sectional shape. Any pieces that are intended to connect to other parts must be further processed in detail.

The process by which the shape of the timber changes is shown in Figure 1.

3 Creation of Inspection Assistance and Data Conversion Methods

Two methods, to facilitate inspection work and convert the data into a lightweight and general-purpose format are explained in detail.

3.1 Inspection Assistance Methods

The timber shape is digitized accurately in advance and automatically screened by the program, so the inspection itself takes place minimizing the number of people involved and with maximum accuracy. The technical requirements for implementing our proposed method are as follows:

3.1.1 Digitization of Timber Shapes

First, a 3D laser scanner is used to digitize the timber geometry accurately as shown in Figure 2. This is because it is a machine that can measure the shape of objects very precisely, rendering them as a collection of points with three-dimensional coordinates. Many commercially available products of this type can measure target objects up to ten meters away with error tolerance to within 2 to 3 mm, making it sufficiently accurate to facilitate timber inspection and processing. The data obtained is a collection of point data described by seven



Trees in the forest



Timbers after felling



Timber at inspection



Timber after processing

Figure 1. Process by which the shape of a timber changes

text strings: three-dimensional coordinates (x, y, z), laser reflection (intensity) and color information (R, G, B). This is generally referred to as a point cloud. Next, two data processing schemes are implemented to generalize the point cloud data and perform registration such that it is converted into a general-purpose format for editing by common programs using most commercially available software.

3.1.2 Automation Program for Inspections

Next, we developed a new program used to automate the inspection of timber geometry. To replace conventional inspection work with programmatic processing, the main functions required are: (1) automatic generation of the required dimensions, (2) superimposition (overlying) of design blueprints. We developed a program to meet the following requirements to utilize timber point cloud data for the purposes described above:

- a) Ability to read point cloud data
- b) Point cloud data display function

Most pass/fail criteria are expressed numerically, such as dimensions and the position of the dimensions to be measured is determined in a horizontal or vertical projection plane relative to the timber. We opted to display the point cloud data in three two-dimensional perspectives, rather than three-dimensional views, namely: plan, elevation and cross-section.

- c) Automatic sorting and alignment of point cloud data

The timber orientation is crucial. Cross-sectional cut surfaces, which always includes two sections, are referred to as the "koguchi," or cut end, with the root side referred to as the "motokuchi," and the other, the "suekuchi." A lot of pine timber is bent as a characteristic of the material and when using wood, the curvature generally faces upward, as a building material to the extent possible the area closest to the "motokuchi". Accordingly, the location of the "motokuchi," "suekuchi," and bend must be determined, even when measuring the dimensions. The program we developed is designed to automatically arrange the timber rendering in the above desired orientation when importing the cloud point data. This process involves first generating a 3D

bounding box for the cloud point data and arranging it on the plan view such that the long side of this rectangular solid is horizontal. Next, we compare the two point cloud sections closest to the two faces on the short side and determine that the larger and smaller areas correspond to the "motokuchi" and "suekuchi" respectively, arranging them such that the "motokuchi" is on the right side in the plan view. Finally, all point clouds in the bounding box are compared to the point clouds for the cut ends and the point clouds in the bounding box are positioned so as to appear higher up in the plan view.

- d) Automatic display of dimension lines and figures

We referred to the inspection sheets used in actual inspections and discussions with designers, contractors and shrine carpenters, to indicate which dimensions should be used to determine a pass or fail. We used this insight to develop the program such that it automatically generates the exterior dimensions and those implicated in downstream processing, to facilitate timber inspection. The processing dimensions indicate where the timber (in its raw state during inspection) should be cut to obtain the desired piece. This cutting process is referred to as "kidori." The bend is a key criterion during assembly and calculated based on the shape obtained after the "kidori" process. When viewing the external timber lines in a plan view, the two long sides form the arcs of a curved line and represent the "mukuri," calculated as the largest vertical distance from the straight line obtained by connecting both ends. The names and dimensions of each part of the timber are shown in Figure 3.

- Outer dimensions of the timber: width and height of both cut ends, length of timber

- Timber dimensions: length from the "motokuchi" and "suekuchi" sides to the location of the "kidori," length of timber after "kidori" cutting (design length), camber value after "kidori," and the width and height of both cut ends after "kidori"

- e) Overlaid display of blueprint data

For items for which determining the dimensional values is difficult, the system superimposes the cloud point data with cross-sectional lines from the blueprint when displayed in plan view and these cross-sectional lines indicate the sections on which other cut materials



Figure 2. 3D laser scanner

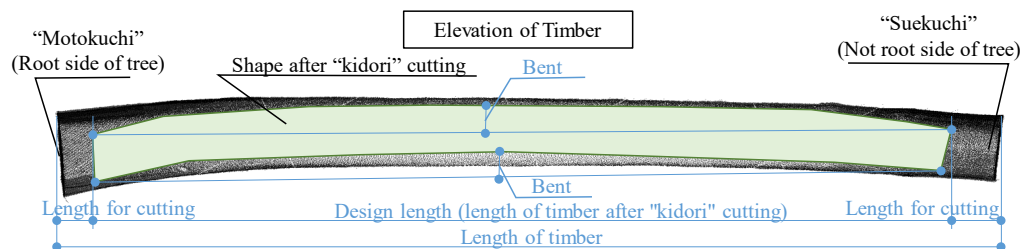


Figure 3. Names and dimensions of each part in timber

intersect. Given that timber does not comprise perfectly straight lines or curves, it must be checked prior to assembly to verify whether it will properly intersect and connect with other pieces.

3.2 Data Compaction and Generalization Method for 3D Scan Data

We propose a method of converting point cloud data into a lightweight, general-purpose format such that the geometry data of the timber obtained in Section 3.1 can continue to be used in subsequent processes.

We focused on using this solution in the context of considering how to process wood after it is procured. This process presumes the use of the tool to simulate, using a CAD program, how timber would be processed and machined for subsequent use. The cloud point data is converted into a more lightweight polygon mesh.

To that end, we employed both the following algorithms to convert the data to meet those requirements:

3.2.1 Culling Point Clouds Using Octrees

When generating polygon mesh data from point cloud data, we first mechanically generate triangles using the point clouds as vertices. Therefore, creating lightweight polygon mesh data requires culling points to a more even approximation. However, point cloud data is a collection of points measured by laser radially around a 3D laser scanner, which means even the same piece of timber can exhibit considerable variation in point density depending on the scan location. Accordingly, an even thinning method using octrees is used to simplify the non-uniform point cloud data. Octrees are a representational method of dividing a target space evenly on a grid; we believed that leaving single point data within the cells of a subdivided space would help us obtain evenly culled

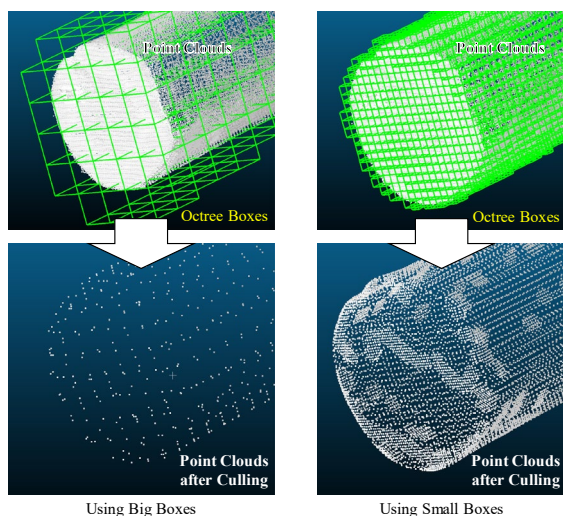


Figure 4. Examples of culling points by octrees

cloud point data as shown in Figure 4.

3.2.2 Smoothing Using Poisson's Equation

When creating a polygon mesh using the culled point cloud, one issue is noise within the point clouds, which is then calculated as part of the vertices, resulting in irregularities that differ from the actual shape. The laser scanning process functions by estimating the distance from time and phase differences caused by laser reflection, which implies that some noise is inevitable due to airborne dust or dirt on the equipment. Therefore, we allowed for the generation of polygon mesh containing some noise, then minimized its impact by smoothing the mesh. Specifically, we adopted a smoothing algorithm using Poisson's equation, as announced by Kazhdan et al. [3]. This is the process of calculating the average plane of the neighboring faces, preventing sharp irregularities and smoothing the entire surface as shown in Figure 5. We believe that this step allows for generating a polygon mesh that is minimally affected by mechanical noise. The resulting polygon mesh is archived in STL format. We opted to use STL because it is a universal intermediate file format commonly used in 3D CAD software in architectural systems and simulation and analysis software in other fields.

In this research, we tested the effectiveness of these methods in actual projects, the outcomes of which are detailed in the next section.

4 Application to the Project

4.1 Project Overview

An actual project to restore a traditional wooden building is adopted in this paper as its theme.

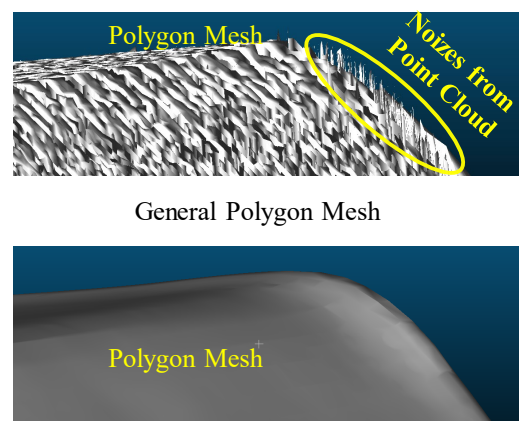


Figure 5. Smoothing polygon mesh

About 2,323 trees covering a volume of about 2,000 m³ were used as the materials for the mainframes; mainly Hinoki cypress and pine and square and round pieces of timber depending on the part. These were then processed into materials by carving out one column or beam from each tree.

The following is an explanation of the inspection tasks to serve as the model case for inspection. First, the timber to be inspected was laid on the ground in the direction for which its warp is parallel. The exposed parts in this state, which specifically constitutes both ends of the cut section comprising roughly 3/4 of the sides of the timber, are subject to inspection. In this instance, a blueprint of the designed cross-section with the original dimensions was laid between the timber and ground as necessary to compare the shapes. This process was carried out for all the timber and to move it and turn it over smoothly, the timber to be inspected was laid out on the ground by the day before the inspection, whereupon the timber that had already been inspected was moved and stacked in the stockyard in order. The new methods were then applied as part of this workflow.

4.2 Ways of Applying the Proposed Methods

4.2.1 Objectives

The first objective involved automatically executing inspections related to shape beforehand. The second objective involved archiving the point cloud data obtained as light and general data to be utilized in post-inspection processes.

4.2.2 Targets of Application

The targets were about 500 poles of round pine timber to be used as material for the main frame. This is because they had the most complex and unique shapes among the materials to be used, presenting the most significant potential impact of consequently applying the proposed methods.

4.2.3 Application Period and Location

The application took place between January 2019 and March 2020 in Iwate Prefecture, Japan.

4.2.4 Equipment Used

- 3D laser scanner (FARO Focus 3D S120)
- Point cloud editing software (FARO SCENE)
- Developed inspection assistance program
- A software package to execute algorithms to cull and generalize point clouds: Cloud Compare (free software)

4.2.5 Ways of Application to the Project

1. Inspection Assistance Methods

Each timber block had its shape 3D scanned twice. The first was when the timber was laid out the day before the inspection and the second was when the timber was turned over after the inspection and moved to the stockyard. To avoid missing any measurements, each timber block was scanned from two to four positions and the state of the timber pieces the day before the inspection is shown in Figure 6. There were two reasons for scanning the timber twice. The first was to scan the surface as a minimum requirement for automatic inspection prior to human inspection. Even if this is done beforehand, there are not enough surfaces exposed when pieces of timber are stacked and it was considered feasible to inspect the shapes when the timber is laid out on the ground. The second reason was to avoid adding steps to the usual procedures. To utilize the data from the scans in later processes, data is required for all the timber surfaces. However, the considerable effort would be needed to do so before the inspection, as a forklift would be needed to move and rotate the timber. Therefore, the second scan was carried out when the remaining surfaces would be exposed during the usual workflow.

The point cloud data scanned from multiple directions was registered using dedicated auxiliary software and converted to point cloud data in PTS format, which is a



Timbers in the stockyard



3D Scan

Figure 6. Statement of timbers the day before inspection

general intermediate file format, after being separated into files for each timber block.

Subsequently, the inspection assistance program was used on the point cloud data for each timber block to automatically generate the following dimensions while also overlapping the designed cross-section data.

- Outer dimensions of the timber: The width and height of the cross-section at both ends and the length of the timber
- Dimensions after processing: The design length and the distance between both ends of the materials carved out of the timber, the warp of the materials and the width and height of the cross-sections at both ends of the materials

To add, regarding the length between both ends when carving out the materials from the timber, the initial value was 250mm from the root side of the timber, which was set as a standard rule for the project because the pieces of timber ordered are 500 mm longer than the design.

2. Data Compaction and Generalization Method

The process of simulation the processing shape of the timber by the construction department on a post-process using polygon mesh data, using the popular computational design software programs Rhinoceros and Grasshopper. The processing flow was set up to first apply the processing rules written in the programming language to the 3D timber data before processing and then automatically generating the log shape after processing. To implement this processing flow, the 3D data to be input should be general-purpose surface data and the file size must be 10 MB or less. Since the point cloud data obtained do not meet this requirement, we attempted to transform the data obtained with the method proposed in the previous section.

As the target polygon mesh data specifications, the

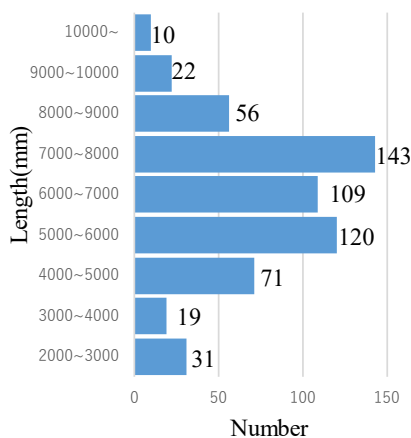


Figure 7. Statement of timbers the day before inspection

vertices of the triangular meshes comprising the data were set at intervals of about 10 mm. The reason is that after interviewing a designer who is considering machining and a carpenter, when considering machining with characteristic distortions and scratches on the timber surface in mind, the data suffices provided irregularities of 10 mm or more are expressed, because the conclusion has been obtained.

Specifically, since timber used in traditional wooden construction is often around 7,000 mm long, point cloud data at 9.6 mm intervals can be obtained by dividing with $9^3 = 729$ grids.

Then, a polygon mesh was generated using this point cloud as its apex and the surface was smoothed using Poisson's equation. These processes were carried out by combining multiple features available in the free software package CloudCompare.

The results of applying the above processes are explained in the following chapter.

5 Results and Discussion of Applying the Proposed Method

First, we will describe the results of 3D scanning of timber. We accompanied timber inspections to apply this method during a 32-day period between January 2019 and March 2020 and performed 3D scans of all 581 logs of round timber including re-inspection. The number of logs by length is shown in Figure 7. The shortest log was 2,350 mm and the longest was 16,968 mm, with a median length of 6,800 mm. The results of the inspection assistance method using these data and of the data compaction and generalization method are described and discussed in the following section.

5.1 Results and Discussion of Applying the Inspection Assistance Method

First, we will describe the results of testing this method on one representative timber log. A timber log 7,130 mm long, which is close to the overall median length and shaped similarly to many other logs, was selected as the test log and will hereinafter be referred to as the sample log. The first 3D scan was performed a day before the inspection, with the sample log laid out on the floor next to four other logs. The 3D scan was performed from seven positions around the five logs to reduce shielding as much as possible. The equipment positioning during the measurement is shown below. Four plastic balls, 145 mm in diameter, were placed around the log to serve as benchmarks during the registration process and laser scanning was performed at a resolution of 5,120pt/360°. This density corresponds to intervals of about 4 mm at a distance of 10 meters. Next, the data for the sample log were

extracted from the obtained point cloud data with point cloud editing software and saved in PTS format. Then, the inspection assistance program we developed was used to automatically generate the dimensional values required for inspection. The specific inspection items and dimensional values generated with the program are shown below. Inspection items: Length of 6,800 mm or more, W×H of the cross-section on the root side of the log of 550 x 550 mm or more and warpage within 150 mm ± 30 mm. The automatically calculated values included a length of 7,044 mm, a cross-section of 728 x 663 mm and warpage of 139 mm, which met the acceptance criteria. In addition, a cross-sectional layout view was superimposed on the point cloud data, so that one inspector could make a preliminary evaluation, even for shapes that could not be expressed numerically. Consequently, the conventional process of comparing the log with a full-sized paper diagram placed under the timber log at inspection could be omitted for this sample log. The preliminary inspection using this program is shown in Figure 8.

We will discuss the results of using this inspection assistance method by assessing the required man-hours. 20 minutes per log are required for the usual inspection. The inspection time is shortened by 10 minutes by omitting any comparison to a full-sized drawing paper. Conversely, the 3D scanning and data processing carried out by a single engineer requires about 30 minutes per

log. The above approach shortened 50 man-minutes out of 160, or about 31%.

In addition, the use of this method created added value that were inexpressible numerically. At the request of a highly skilled craftsman, we were able to confirm dimensions and shapes that were not assessable when inspecting the actual timber log in advance. There are two specific points, the first of which is warpage. The inspection items include confirming the parts that can be measured on the outside of the log. Using the point cloud data, we could measure warpage from the inside of the timber to the top, which is more important for construction. The second point is the cross-sectional shape of the timber when processed. In this case, we could assess the virtual cutting surface using the point cloud data, which demonstrates how a highly skilled craftsman can perform more sophisticated work when using this digital technology.

5.2 Results and Discussion of Applying Data Compaction and Generalization Method

We will describe the results of testing this method on the sample log. The point cloud data obtained in (1) are described as a text array of (x, y, z, intensity, R, G, B). The point cloud data of the sample log comprised 1,097,310 data points of heterogeneous density with a file size of 67 MB. As a first step, a three-dimensional octree

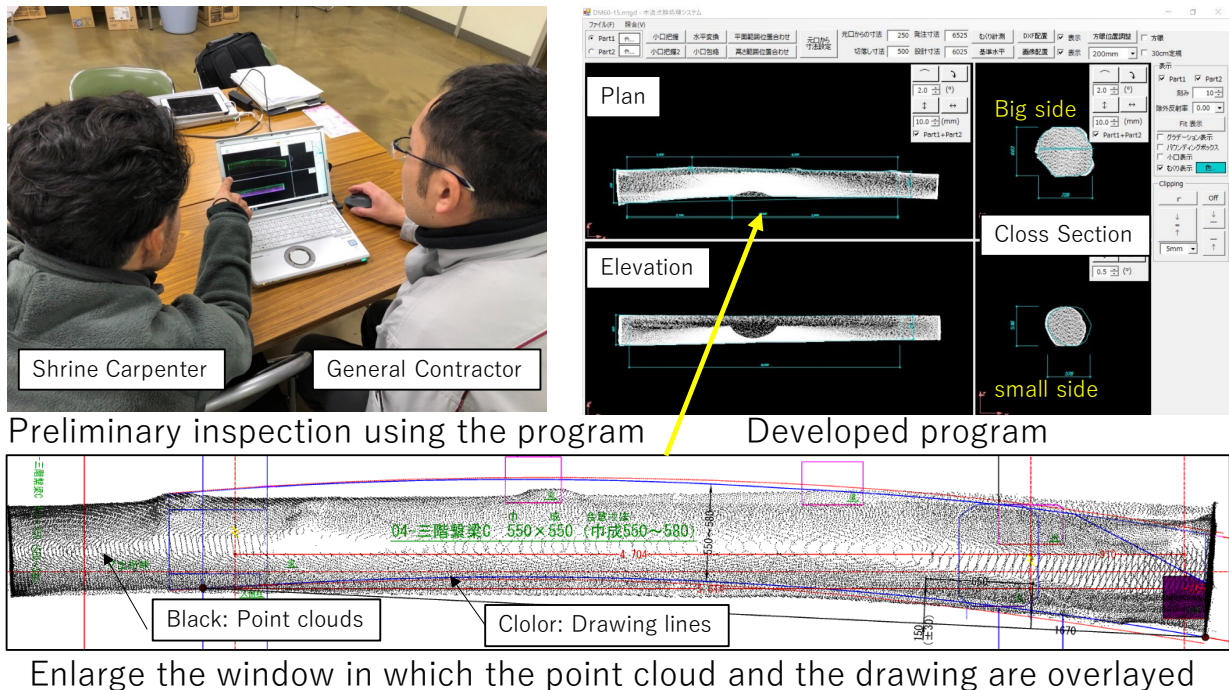


Figure 8. Statement of timbers the day before inspection

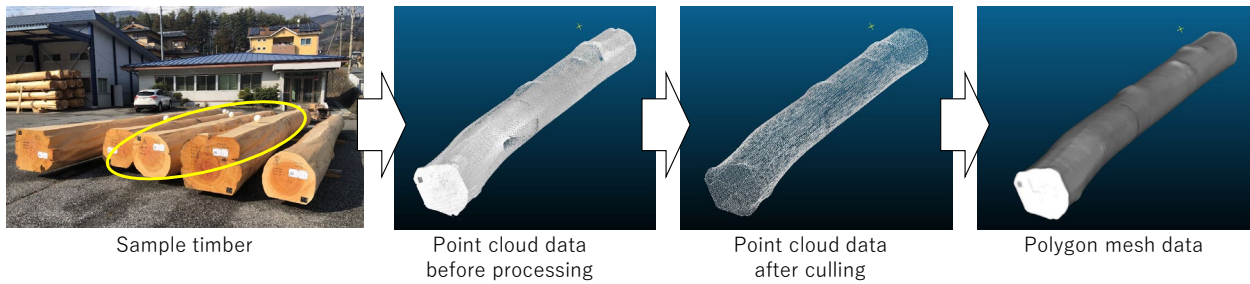


Figure 9. Procedure of data conversion for sample timber

was generated by dividing the data into 93 areas and only one point was left in the center of each area, reducing the data evenly to a density of about 10 mm intervals. Next, a polygon mesh comprising triangles and with each of these points as vertices was mechanically generated and the surfaces smoothed using Poisson's equation to produce polygon mesh data of the desired quality. When the data was saved in the STL format, the file size could be reduced by 88.4% to 7.6 MB. The data conversion procedure is shown in Figure 9.

The data created by the above procedure could be used for processing simulation, as shown in Figure 10. Specifically, the cross-sectional shape is defined as a regular hexagon inscribed in a circle of diameter 550 mm and timber is cut along the center line in the long axis direction. Usually, simulations are done with a simple BIM model for design purposes, but with our method, the real shape of the timber log could be used to plan more precise processing and extract potential issues. This demonstrates that compacting and generalizing the data obtained in (1) can enable more sophisticated work, including in later work stages.

6 Conclusion

In this study, we proposed a method to assist inspection using 3D scans of building material shapes and a data compaction and generalization method to facilitate use of these data in subsequent work stages. We also verified the effectiveness of these methods by applying them to a traditional wooden castle restoration project. Our results showed that the method helped save about 4,000 man-hours involved in inspecting building materials and that converting the obtained data into polygon mesh data about 90% smaller in size made them amenable for use in subsequent processing simulations. Our results also suggested the feasibility of a highly skilled craftsman using this digital technology to perform more sophisticated work than with conventional methods.

In future, we aim to investigate ways to efficiently manage the relationship between these data to use data obtained with such digital technologies more efficiently

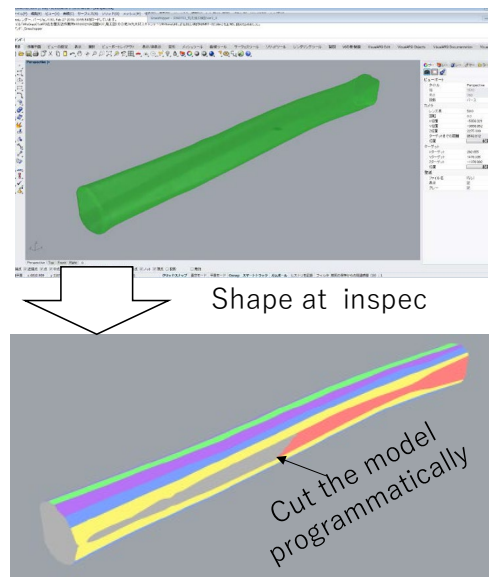


Figure 10. Processing simulation after inspection

in the overall architectural workflow and improve construction.

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