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Reproduction of shakuhachi from X-ray CT images by additive manufacturing

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ABSTRACT

A Japanese traditional wind instrument, shakuhachi, is made of bamboo, and it has a different timbre for each instrument. There are some invaluable shakuhachi crafted over 500 years ago and it is desirable for those to be protected appropriately. The purpose of this study is to restore the shakuhachi from the shape information recorded in advance just in case the instrument is lost due to unforeseen circumstances. Reproducing shakuhachi by additive manufacturing (3D printing) has been attempted based on the X-ray images taken from two directions. Then, it has been confirmed that the shakuhachi were sufficiently restored with the feeling of playing the original shakuhachi. However, since the irregularities on the surface of bamboo cannot be reproduced with images taken from only two directions, the appearance of the shakuhachi was quite different from the original one. In this paper, a 3D model was created by introducing the adjustment processing to the contour of the original shakuhachi from the X-ray CT image, and then the reproduction was attempted so that the shakuhachi has a shape close to the original one using 3D printer.

Keywords: Shakuhachi, Wind instrument, Additive manufacturing (3D printing), X-ray CT, Reproduction of cultural properties

1. INTRODUCTION

Shakuhachi is a wind instrument made of the root of natural bamboo. It is a kind of air-lead instrument that produces sound by the sound generation phenomenon called edge tone that occurs when the airflow from player's mouth hits the knife edge. The inner surface of the instrument is smoothly polished with a mixture of Japanese lacquer "urushi", polishing powder "tonoko", plaster etc. [1-2]. Due to the large individual differences of instruments, it is difficult to reproduce the shakuhachi as the completely same shape when it was damaged or lost by a disaster. In addition, there are shakuhachi that are not allowed to test the sound because the value is too high as cultural asset.

On the other hand, in air-lead instruments that acoustic energy generated by air column resonance is dominant, it is known that no change in timbre can be seen when the material is rigid to a certain extent. [1]. In this study, the reproduction method of the instrument using an additive manufacturing (3D printing) is investigated based on the shape information of the instrument recorded before damaged or lost due to unforeseen circumstances.

First, a 3D model of shakuhachi was created based on the X-ray photographs, and then the instrument was reproduced by using a 3D printer. As a result, it was confirmed that the reproduced shakuhachi was performable and partially kept the feeling of playing the original one [3]. Next, X-ray computed tomography (X-ray CT) images of the shakuhachi were taken, and then the 3D model and the reproduction of the instrument were conducted [4]. However, when extracting the shape with a constant threshold value for the luminance of the X-ray CT image, it is difficult to extract the contour of the shape accurately due to the large gap of the luminance between the bamboo part and the inner surface part coated by "tonoko". Because of the effect, it was confirmed that the inner diameter of the reproduced shakuhachi became smaller than the original one. Therefore, an adjustment process of the contour on the X-ray CT images was introduced for the 3D modeling, and the reproduction was conducted to make the appearance and the inner diameter be as close as that of the original one. [5].

2. Reproduction based on X-ray photographs

In this paper, 3D model was created based on the X-ray photograph of a real shakuhachi, and it was reproduced by using a 3D printer [3]. The original shakuhachi used in this work is an old instrument crafted by Shiro Yamaguchi (1885-1963). This shakuhachi is called "Shiro-kan" and well known as a valuable instrument [6]. The shakuhachi used in this work was found around 1969 with a crack on the top of the pipe, and it was consequently repaired and has been used.

Figure 1 shows X-ray photographs of the original shakuhachi taken from the front direction and the side direction. Since shakuhachi generally has an intermediate junction, the shakuhachi was photographed by being divided at the junction into the upper and the lower part. The upper two images in Fig. 1 were taken from the side direction. The lower two images were taken from the front direction. The inner diameters of the tube were measured every 30 pixels from the mouthpiece to the end of tube on the X-ray photograph, and the shape of the shakuhachi was estimated by elliptic interpolation. As the inner diameter of the shakuhachi was adjusted by "tonoko" etc., it was necessary to measure the adjusted tube not the substrate bamboo when measuring the inner diameter from the X-ray photograph. In this paper, the boundaries of the instrument were visually observed from the diameters on the photographs to build the 3D model. In addition, the magnification of the image caused by the positional relationship between the X-ray source and the subject was compensated.

The original shakuhachi and the reproduced shakuhachi by the 3D printer are shown in Figure 2(a) and (b), respectively. It is possible to produce sound by the reproduced shakuhachi, and the owner of the original shakuhachi stated in the introspection report that the feeling of playing is similar to that by the original instrument. However, it is impossible to reproduce the details from the X-ray photographs taken from only two directions.

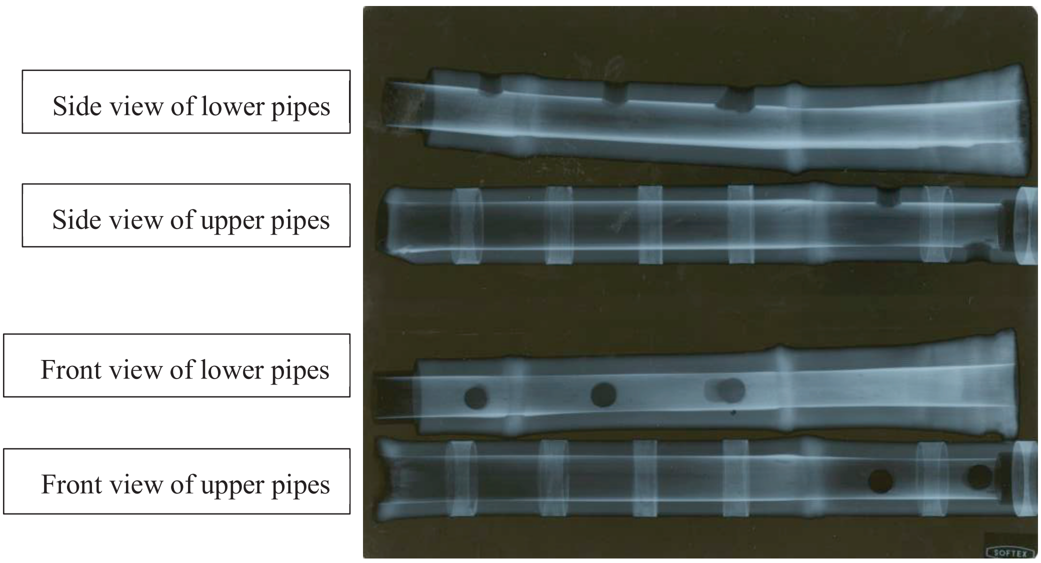

Figure 1 - X-ray photographs of shakuhachi

(a) Original shakuhachi

(b) Reproduced shakuhachi based on X-ray photographs

Figure 2 - Comparison between the original shakuhachi and the reproduced shakuhachi based on X-ray photograph

3. Reproduction Based on X-ray CT

The polygon data (STL file) are required to reproduce the shakuhachi using a 3D printer. STL file is a format of polygon data which represents the surface of the object by means of many triangles, and generally used in most 3D printers. Figure 3 shows a part of the polygon in a STL file, and that the surface is composed of many triangles. In the reproduction of shakuhachi shown in the previous chapter, the loft function in CAD software (whose function is to connect multiple contours smoothly) was sufficient to make 3D data of the shakuhachi since few values are obtained to represent the shape of the instrument. However, this method is insufficient to analyze more than two thousand seats of X-ray CT images. This chapter describes a method to create STL file from X-ray CT images and shows the reproduced result.

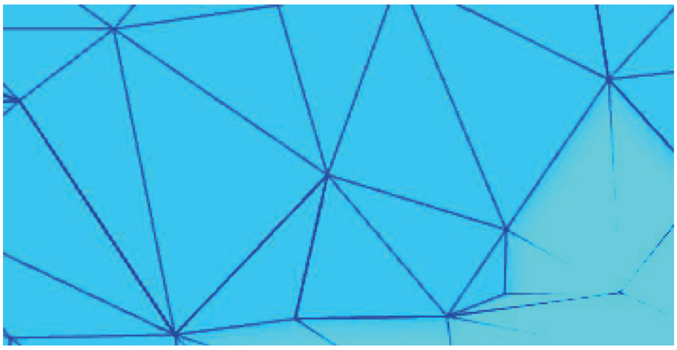

Figure 3 - Triangular polygon in a part of 3D model

3.1 3D Modeling and Making Polygon

Figure 4 shows one of 2048 seats of shakuhachi tomographic images taken every 150 μm by X-ray CT. These photographs are loaded in MATLAB to create 3D model. First, eight voxels are grouped into a cube for one analysis unit as shown in Figure 5. If the luminance value of each voxel is higher than a certain threshold level, the voxel is judged inside the solid. If the value is lower than the threshold level, the voxel is judged outside of the solid (red circle means inside, blue circle means outside in Fig. 5). Next, when the labels of the apex are different one another, the middle point among the apexes of the cube is marked as shown in Figure 6 (dark blue circle in Fig. 6). If all marks in each analysis unit are finished, a centroid (yellow circle in Fig. 6) is calculated. After that, the boundary surface is expressed by multi-triangle polygons using the centroid and the marked points.

However, some errors were observed in the represented 3D model. This seems to be a defect in polygon generating algorithm. Therefore, the polygon errors are repaired by the use of an application called Meshmixer, which can process polygons. Figure 7 shows the polygon errors, which needs to be repaired, indicated by Meshmixer. In Fig. 7, the blue marks indicate a hole of the mesh, the red marks indicate a non-manifold area and the magenta marks indicate a subregion (too small area). In order to create STL data that allows a 3D printer to read, the automatic repair by the application and the manual repair with the brush tool were repeated.

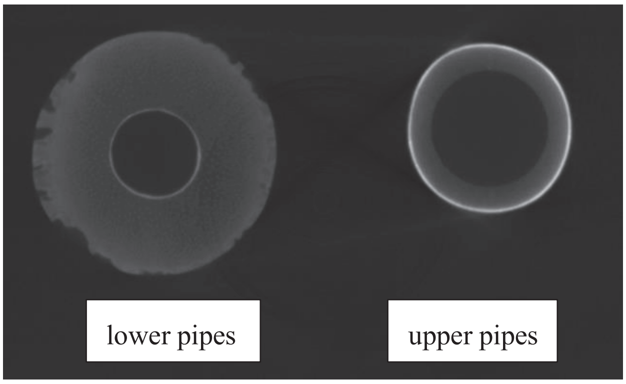

Figure 4 – X-ray CT images

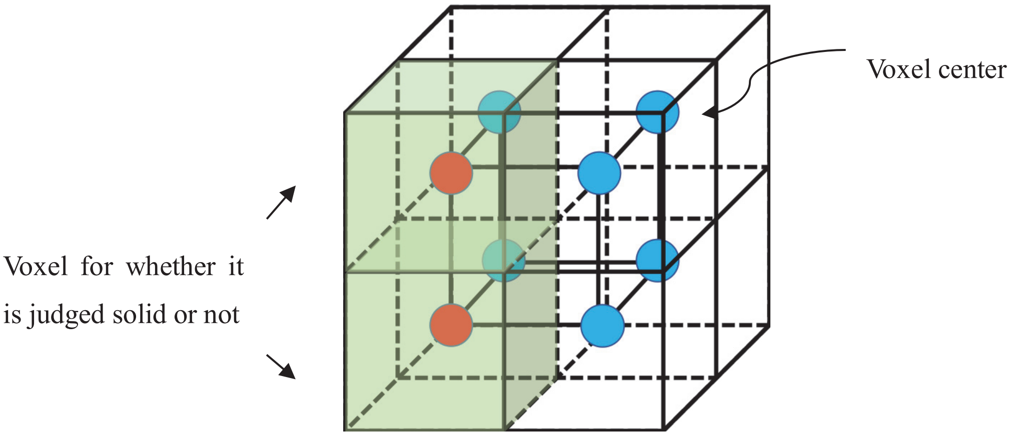

Figure 5 - Analysis unit (eight voxels) with voxel information in the center of voxel.

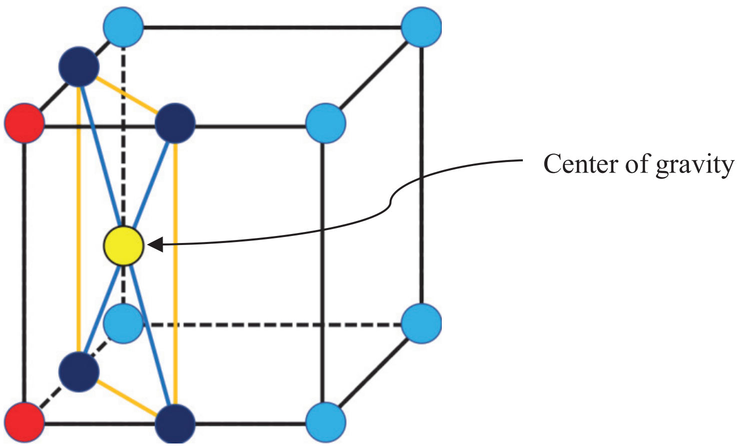

Figure 6 - Polygon creation from cube with voxel's inside and outside information at the vertex.

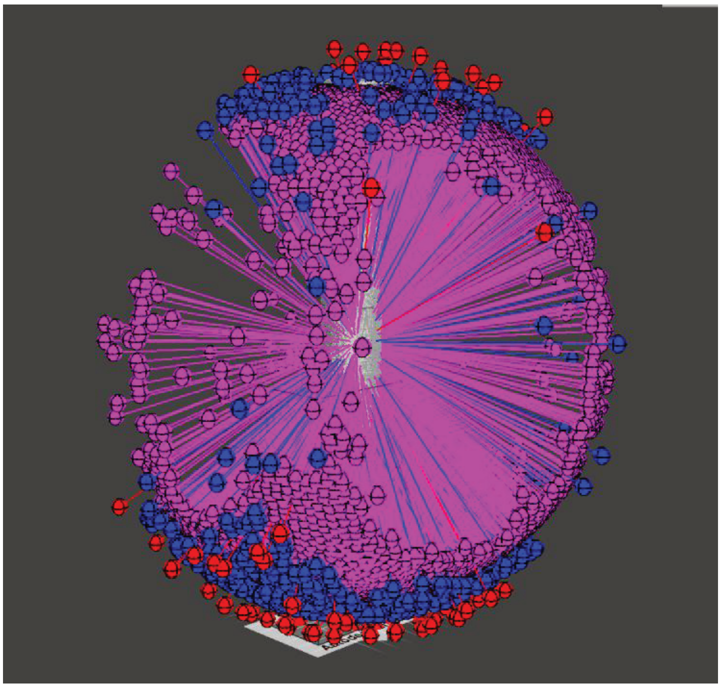

Figure 7 - Locations of triangular polygons displayed by Meshmixer

3.2 Reproduction of shakuhachi by 3D printing

In this paper, a 3D printer “DaVinci Pro” produced by XYZprinting was used to output the 3D models, which is a fused deposition modeling (FDM) type 3D printer. Since the maximum output size of the printer was limited to 200 mm × 200 mm × 200 mm according to the specifications of the printer, the shakuhachi was divided into four parts as shown in Figure 8. The printer was set to the lamination pitch as 0.3 mm and the internal density as 60%. As a result, it took about two and a half days to output the 3D models. After that, the joints except for the intermediate joints were bonded with glue.

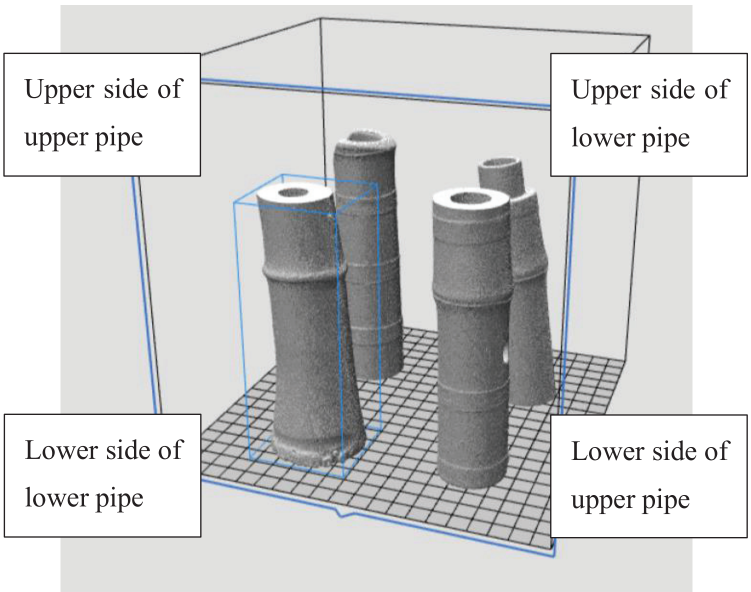

Figure 8 – The output from 3D printer

3.3 Reproduction result and evaluation

The original shakuhachi and the reproduced shakuhachi are shown in Figure 9 (a) and (b), respectively. On the outside surface of the reproduced shakuhachi, several granular protrusions were observed although they were not on the 3D model. It is considered that the filament was dripping due to injecting the excessive filament in narrow area when the 3D printer output the fine and complexed shape.

In this paper, the inner diameter at the upper end of mouthpiece, at the intermediate joint and at the end of tube were compared between the original one and the reproduced one in order to evaluate the reproduction accuracy of shakuhachi. Table 1 shows the comparison results of inner diameters. Any errors over 1 mm were not found between the 3D model and the reproduced shakuhachi. However, some errors over 1mm were observed at the upper end of mouthpiece and the intermediate joint between the 3D model and the original shakuhachi. Therefore, it can be concluded that there is a problem in creating 3D data rather than the problem in the reproduction accuracy of the 3D printer.

(a) Original shakuhachi

(b) Reproduced shakuhachi based on X-ray CT images

Figure 9 - Comparison between the original shakuhachi and the reproduced shakuhachi

Table 1 - Accuracy of inner diameter in the reproduced shakuhachi

	Original shakuhachi [mm]	Shakuhachi 3D Model / Error from the original one [mm]	Shakuhachi output by 3D printer / Error from the original one [mm]
Upper end of mouthpiece	22.35	21.05 / 1.44	20.91 / 1.30
Joint area (upper pipe)	23.56	22.46 / 0.83	22.73 / 1.10
Joint area (lower pipe)	18.12	17.97 / 0.94	17.18 / 0.15
End of tube	17.52	17.80 / -0.12	17.64 / -0.28

4. Inner diameter adjustment of 3D model

When creating a 3D model from CT images, the inner diameter was narrower than that of the original one. The reason may be that the contour is not extracted correctly as the luminance value of the part coated with “tonoko” etc. is extremely high comparing with the part of bamboo. Therefore, in this paper, an adjustment method is investigated for the inner diameter in the X-ray CT image. This chapter describes the adjustment method of the inner diameter and its effect.

4.1 Inner diameter adjustment method

In the adjustment of the inner diameter, the edges are detected from the brightness gradient after the X-ray CT images are binarized. Although 3D models are generally obtained from a binarized image, it is possible to make the solid area narrower by subtracting one pixel of the detected edge from the binarized image. Based on the result in the previous chapter, this operation was repeated six times, and the adjustments were performed to extend the inner diameter by six pixels.

4.2 Result and evaluation of inner diameter adjustment

Table 2 shows the reproduction accuracy for the inner diameter of the reproduced shakuhachi created by the 3D printer. By the inner diameter adjustment method for the X-ray CT image, the inner diameter was reproduced as precisely as that of the original shakuhachi.

In addition to adjusting the inner diameter, the weight was also considered by changing the output density of the 3D printer. The results are shown in Table 3. Reducing the density, the weight became closer to that of the original shakuhachi. As the density decreased, however, many faint gaps were recognized and the breath leaked from these faint gaps.

Table 2 - Accuracy after inner diameter adjustment

	Original shakuhachi [mm]	Inner diameter without adjustment / Error from the original one [mm]	Inner diameter after adjustment / Error from the original one [mm]
Hole of mouthpiece	22.35	20.91 / 1.44	21.17 / 1.18
Joint area (upper pipe)	23.56	22.73 / 1.83	23.54 / 0.02
Joint area (lower pipe)	18.12	16.18 / 1.94	18.10 / 0.02
End of tube	17.52	17.64 / -0.12	17.53 / -0.01

Table 3 - Changes in the output density of 3D printer

	Original	Reproduced, print density 90 % / Error from original one	Reproduced, print density 60 % / Error from original one
Upper pipe weight [g]	168	200 / -32	152 / 16
Lower pipe weight [g]	211	244 / -33	181 / 30

5. CONCLUSIONS

In this paper, the preservation of the shape information for an ancient Japanese instrument “shakuhachi” and the reproduction of the instrument from the preserved shape information using a 3D printer were investigated for the purpose of protecting cultural asset. The reproduction method based on X-ray images and X-ray CT images were carried out in this work. Although the reproduced shakuhachi based on the X-ray photographs was playable, its outside shape was different from the original one. Since more details of shakuhachi shape were observed by means of the X-ray CT images, a 3D model of shakuhachi was created again. Due to the high luminance value of the X-ray CT image in the inner part of shakuhachi coated by “tonoko”, the inner diameter adjustment method was employed so that the reproduced shakuhachi has more precise shape compared to the original one. Moreover, the weight of the reproduced shakuhachi was reduced as much as that of the original one by changing the output density of the 3D printer.

This paper presented that there was a possibility to reproduce a shakuhachi by a 3D printer if the shape information based on the X-ray CT images is preserved. The results strongly suggested that X-ray CT images should be taken for any invaluable shakuhachi designated as an important cultural property before it is damaged or lost due to unforeseen circumstances.

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