Digital Archiving of Archaeological Remains Using X-Ray CT

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Abstract: - Various applications have been found for the ability to use computers to display the shape of archaeological objects, such as earthenware vessels, earthenware figurines and stone vessels. These applications include the technology used for creating survey maps, making precise measurements, preparing replicas and creating web content. However, since surface measurements are commonly conducted using lasers or with the stylus method, it is difficult to measure complex surfaces, internal configurations, thicknesses and volumes. In the present research, with regard to easily breakable earthenware vessels, earthenware figurines and stone vessels, we propose a method for easy storing of accurate 3D data obtained with an industrial X-ray computed tomography (CT) device. The 3D surface image obtained can be used for measuring the thickness and volume of earthenware vessels, for reproducing their shapes by using polygons, and for constructing high-resolution surface models. The present method has been utilized for measurements of actual archaeological objects, for the preparation of duplicates (replicas), and for the creation of web content, and its effectiveness has been verified.

Key-Words: - 3D modeling, digital archive, archaeological objects, X-ray computed tomography, 3D printer

1 Introduction
With the advancement of digitalization and 3D modeling of buried cultural properties, the ability to use computers to display the shape of archaeological objects such as earthenware vessels, earthenware figurines and stone vessels has various applications. Such applications include the technology used for preparing survey maps, making precise measurements, preparing duplicates (replicas), creating web content and performing damage simulation [1-2]. However, since the surface is commonly measured using lasers or the stylus method, it is difficult to determine accurately the internal configuration, thickness and other such parameters. In addition, due to the complex surface shape of earthenware vessels and figurines, measurements are highly prone to error, which requires the construction of surface models.

When performing surface measurements with lasers or stylus devices, it is necessary to create surface models from multiple directions (e.g., front and back), after which these models are pasted together. In this case, it can be difficult to match the pasted parts, and if the shape is complex, it is highly likely that important characteristic points at the edges might be lost. Furthermore, it is difficult to perform measurements when the surface is highly uneven or the configuration of the surface is such that certain parts of the surface are masked. In comparison to lasers and stylus devices, industrial X-ray computed tomography (CT) devices are capable of determining the configuration of the entire specimen in several minutes. Also, in terms of resolution, if a space of about 30 cubic centimeters is measured by using between 512 and 2048 cubic voxels, it is possible to attain a resolution of around 0.585–0.146 mm.

With a focus on easily breakable earthenware vessels, earthenware figurines and stone vessels, we propose here a method for easy storing of accurate 3D information on a computer, and present a case study of the application of this method. The obtained slice images can be used for the representation of the specimen with polygons and can serve as a high-resolution display model. In this regard, the proposed method has been utilized for measurements of actual archaeological objects, the preparation of replicas and the creation of web content, and its effectiveness has been verified.

2 Conventional methods
2.1 Measurement devices utilizing lasers or the stylus method
At present, after the fragments of discovered earthenware vessels are cleaned, they are dried and sorted, and the collected fragments are processed individually for each vessel. Next, the original shape of the vessel is restored, with consideration given to any missing fragments. Finally, images of the fragments are recorded in bulletin reports. However, these operations consume considerable effort, and there are increasing numbers of cases where a large number of the archaeological objects unearthed during the period of preparation for digging are not processed.

In recent years, recording methods utilizing 3D measurement techniques have been employed, and laser measurement devices are used for surface measurements [3] from the point of view of a) high resolution, b) safety (no damage incurred), c) high speed, d) automatization and e) low cost. Laser-based measurement devices measure the surface configuration by collecting reflected laser light irradiated onto the surface of the specimen. Commercial devices utilize the laser scan method (Konica-Minolta VIVID700, VIVID900) and the laser slit method (Cyberware, Voxelan) among others. However, depending on the target object, certain regions might absorb the laser or the laser might not be registered when it is reflected at sharp angles or off an edge, and in all such cases the respective parts are effectively unmeasurable. In addition, Kada et al. have proposed a method for generating a solid model from surface models (solidization), in which the results from measurements taken from above and below the object are pasted together. However, it is difficult to perform solidization based on a surface model by pasting complex surface models in the case of thick objects with complex shapes, such as vases. Jomon-style earthenware vessels and earthenware figurines are characterized by numerous protrusions and other uneven regions, which complicate the contours and, together with the fact that the thickness is often considerable, make the application of the solidization method difficult. Furthermore, even if the configuration is measured from multiple directions with the surface measurement method, it is necessary to exercise extreme caution when connecting the obtained parts, which reduces the accuracy and the resolution of determining the surface area and the circumference of the object.

In this regard, CT is an effective tool for resolving such problems. In CT, changes in the X-rays with which the object is swept are measured, and an image of the internal configuration of the object is created with a computer. Although in a broader sense CT includes technologies such as magnetic resonance imaging (MRI) and positron emission tomography (PET), in the present paper we use CT to refer to X-ray CT. In comparison to MRI, X-ray CT requires less time for examination, its spatial resolution is higher, its penetration rate is also higher, and the devices are relatively cheaper. In 2002, Watanabe et al. proposed an automatic reconstruction method for archaeological objects, which is based on a surface model constructed with X-ray CT scanning [5]. With the capabilities of computational environments at that time, in comparison to surface models, the amount of data in voxel models was larger and it was necessary to use specialized hardware. However, with recent advancements in computing capabilities (i.e., increased memory available, operating systems with 64-bit addressing and improved capabilities of graphics adapters), common personal computers with commercial graphics adapters can be utilized directly for processing voxel models.

For this reason, we propose a technique in which an ordinary personal computer is used for saving and converting 3D images of archaeological objects into a database, and the obtained group of 3D images can be used to perform measurements on existing archaeological objects, prepare replicas and create web content.

3. Measurement of archaeological objects with industrial CT devices

3.1. Industrial CT devices

The CT device used in this study was the YXLON MG452 (X-ray energy of 450KeV, YXLON International Ltd.). CT devices can be divided into two main groups, medical and industrial, where medical CT devices are used in hospitals for examinations and testing, and such devices are used exclusively for examining human bodies. In comparison to medical CT devices, the intensity of the X-ray source in industrial ones is greater, and the beam is of the fan type. Targets for measurement with such CT devices include resins, car engine blocks, electronic components and others, and since the examination is non-destructive [6], it can be applied to earthenware and stone vessels.

3.2. Measurement techniques for archaeological objects
Industrial CT devices use the turntable method for measurements, making it possible to perform collective measurements within the operational range of the device. The group of slice images obtained with CT devices is outputted in the DICOM (Digital Imaging and Communications in Medicine) image format, which is the standard for digital imaging and communication in medicine. A solid model is then constructed from the slice images, and the model is processed with the Volume Extractor Ver.3.0 software.

Here, we performed measurements of (1) an individual earthenware vessel, (2) individual parts of an earthenware vessel and (3) a collection of multiple parts of an earthenware vessel. As these measurement methods depend on the size of the earthenware vessel, as much as possible, small parts were placed and measured together. With regard to the obtained 3D images, it was most efficient to divide and process them interactively on the computer screen. Furthermore, with the collective measurement, it is not necessary to unwrap the specimens, thus avoiding accidental damage to them during the measurements.

Fig. 1 (left) shows an example of a restored Jomon earthenware vessel excavated at the Ueno-daira archaeological site at Morioka city, where all the fragments were measured simultaneously. Fig. 1 (right) shows the iso-surface display for the captured 3D image.

Fig. 2 (left) shows a collection of fragments of an earthenware vessel (34 fragments of a single Jomon vessel unearthed in 1975 during preparations for excavation at the Kakinoki-taira archaeological site), and Fig. 2 (right) shows the iso-surface display for the 3D image, which was obtained with a single measurement after suspending each of the fragments of the earthenware vessel shown while stored in a styrofoam box.

Fig. 1. Separately measured fragments of an earthenware vessel

Furthermore, Fig. 3 (left) shows specimens which were measured without being unwrapped, and Fig. 3 (right) shows the iso-surface images of these multiple earthenware vessels. In this way, easily breakable fragments and small vases can be measured together, which is a clear advantage over the laser measurement method.

Fig. 2. Collection of fragments of an earthenware vessel

Fig. 3. Collective measurement of multiple earthenware vessels

4. Reconstructing 3D shapes

4.1. Overview of Volume Extractor

In order to construct a precise replica model of archaeological remains, we utilize Volume Extractor (VE), a practical 3D image processing software package which was researched and developed at Iwate Prefectural University, Japan. The development of VE was initiated in 1998, and Ver. 3.0 is presently available for use[7-9].

VE can be used for transforming arbitrarily segmented 3D images into triangular polygon data, editing the resulting image, and creating actual models using a 3D printer or a rapid prototyping device. In VE, it is possible to perform continuous processing of the inputted 3D image, including image processing, segmentation, image display and 3D shape reconstruction. Furthermore, since the design of VE allows for all functions to be easily navigated through dialog menus, it is sufficiently usable even for individuals without experience in 3D image processing.

The software is compatible with reading CT images in the general DICOM image format. By adopting the DICOM standard, it is possible to achieve uniformity...
of interconnections and databases of CT images between different devices. Furthermore, it is also compatible with image data in RAW, BMP and TIFF formats. RAW indicates that the raw data has not been processed, and usually represents image data as pixel values when used as an image format.

The software supports cross-section, iso-surface and volume rendering display methods, as well as any combination of the three. The 3D images are referred to as "volumetric images" or "3D volumetric images", and volume rendering is a rendering (image generation) technique for the effective display of volumetric images. VE can perform high-speed display of 3D images by utilizing Graphic Processing Units (GPUs) for the volume rendering. It is possible to output 3D images and 3D shape models prepared with VE into files. Furthermore, output to the DICOM image format and other shape model formats is supported, such as DXF, MFG, VRML and STL (stereo lithography, a widely used general-purpose format used in rapid prototyping).

4.2. Processing sequence
In the case that earthenware shape (STL data) is outputted by using a 3D printer or a rapid prototyping device after being extracted from CT images, it is necessary to perform preliminary processing of the image data and posterior processing of the reconstructed polygon data. In general, 3D printers print the lines where the structural data crosses the horizontal surface, thus yielding a structure of stacked layers. For this reason, it is necessary for the cross-sections of the reconstructed shape to be closed. In other words, the line crossing the horizontal surface needs to be continuous in order to prevent contradictions.

Step 1) Extraction and editing of the necessary parts
Only the 3D image containing the part for extraction is cut (clipped) from the 3D image obtained by CT. Furthermore, by utilizing relevant editing techniques, any unnecessary areas or areas containing artifacts are removed from the clipped 3D image.

Step 2) Histogram based segmentation
By using the classification segmentation function based on histograms, the brightness of all areas apart from those corresponding to the earthenware is set to a specific value or a specific range, thus leaving only the brightness values for the earthenware.

Step 3) Image filtering and editing for the clipped image
The image filter of VE incorporates garbage removal and smoothing functions. For this purpose, the present function regards the surface of the earthenware as smooth and presents a clear image of the earthenware boundary. In the case that it is necessary to close the surface of the clipped image, by using relevant editing functions, the clipped surface is given the same brightness value as that of the extracted earthenware. If iso-surfaces are generated by applying process 5, the cross-section of the generated surfaces crosses the surface of the earthenware, thus forming a closed shape.

Step 4) Generation of 3D shape data
The 3D shape is reconstructed by taking the brightness values representing the earthenware boundary as iso-surfaces. In the case that the amount of iso-surface data is too large, the 3D image data is compressed, and either iso-surfaces are generated or the generated iso-surfaces (polygon data) are deleted. Although the processing of compressed 3D data is fast, the surface shape is broken. For this reason, it is possible to generate shapes with higher accuracy if the 3D data is not compressed and the generated iso-surface data is processed with the data removal algorithm.

Step 5) Colorizing 3D shaped data
In order to create texture on the surface of the earthenware vessels, the vessels are rotated at 15–30 degrees with the aid of a turntable and a 360-degree image is recorded. Each obtained image is then processed with Adobe Photoshop and a texture image is constructed. Fig. 4 shows a texture image obtained from the earthenware vessel shown in Fig. 5 (left), and Fig. 5 (center) shows the virtual model with the texture image pasted with cylindrical mapping. Fig. 5(right) is the replica model. In particular, regarding the configuration data for the surface of the earthenware vessel obtained in Step 4, we used the ZEdit software provided by Z Corporation (editing software for color and texture mapping) to paste the texture image around a vessel.

Fig. 4. The prepared texture image
5. Evaluation of molds prepared with a 3D printer

In order to shorten the measurement time, the measurements were performed with a slice thickness of 0.5mm. We then prepared replica models from these 3D images by using a 3D printer. The time for constructing each replica model from acquiring the data until the preparation of the model was roughly several hours up to half a day. Fig. 6 shows the real model and the replica model of the earthenware vessel with texture mapping, respectively. Fig. 7 shows an example of a replica prepared by extracting a single fragment from the image showing fragments of the earthenware vessel (Fig. 2). Fig. 8 shows the replica model without texture mapping. Fig. 9 (right) shows the replica model of Jomon earthenware mask. In addition, Fig. 10 shows a sample prepared in the VRML (Virtual Reality Modelling Language) format, where the sample is displayed with Cortona3D Viewer 6.013 (a VRML viewer) [10]. In this way, it becomes possible for archaeological objects such as earthenware vessels and earthenware figurines to be viewed from their reconstructed models via the Internet.

In this study, the ZPrinter 450 used for molding reproduced the structures with high accuracy, and no rounding of the edges was observed. However, since the coloration was performed on powder, some discrepancies in color and decreased saturation were observed. For this reason, with respect to the reproducibility of color and texture, it is necessary to adjust and colorize the texture image in accordance to the particular 3D printer.
6. Conclusion
We have proposed a method for simple and accurate
digitalization of easily breakable earthenware vessels,
earthenware figurines and stone vessels by using an
industrial CT device, and presented the application of
this method. Regarding complex configurations where
the surface was difficult to measure by using
conventional laser measurement, the proposed method
allowed us to determine the thickness and other
parameters of the internal configuration safely and
quickly. Furthermore, a 3D image was constructed
from the measured slice images, after which
high-resolution replica models and web content were
prepared. In conventional molding methods, replicas
are prepared by specialists who prepare a mold of the
original with silver foil or silicon, after which the mold
is filled with resin and the replica is deburred and
colored [11]. It was shown that with the proposed
method, processing time and labor could be reduced to
a tenth or twentieth that of conventional methods, and
an accurate replica model can be prepared even by a
beginner.
The potential problems associated with preparing
replica models from 3D images obtained with a
commercial CT device are (1) the measurement error
when obtaining 3D images (resolution of the CT
device), (2) the conversion error when converting the
scanned object into polygon shapes and (3) the error
associated with the layer thickness when molding the
replica with a 3D printer. In this regard, in the case of
earthenware vessels, the problem in (1) can be avoided
by improving the resolution of the CT device and
increasing X-ray intensity. Regarding (2), the
approximation method used in the conversion into
polygon shapes leaves traces of layers, and an overall
rounding of the edges emerges. It is therefore
necessary to exercise considerable caution with
respect to data reduction when using the polygon
approximation method and converting the model into
polygon shapes. Although the layer thickness in (3)
depends on the capabilities of the 3D printer, at
present the limit of the resolution of 3D printers is of
the order of 0.1mm, which is unlikely to cause any
major issues. In the light of these problems,
conventional molding methods acquire the original
shape of the actual specimen, and thus have an
advantage in reproducing patterns and edges.

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