Appl Phys A (2010) 100: 653–661
DOI 10.1007/s00339-010-5648-6

Applied Physics A
Materials Science & Processing

Application of X-ray Computed Tomography to Cultural Heritage diagnostics

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Received: 28 August 2009 / Accepted: 9 March 2010 / Published online: 1 April 2010

Abstract Physical methods of diagnosis are more and more frequently applied in the field of Cultural Heritage either for scientific investigations or for restoration and conservation purposes. X-ray Computed Tomography (CT) is one of the most powerful non-destructive testing techniques for the full-volume inspection of an object, as it is able to give morphological and physical information on the inner structure of the investigated sample. The great variety of size and composition that characterizes archaeological findings and art objects requires the development of tomographic systems specifically designed for Cultural Heritage analysis. In the last few years our research group has developed several acquisition systems for Digital Radiography and X-ray CT. We are able to perform high resolution micro-tomography of small objects (voxel size of few microns) as well as CT of large objects (up to 2 m of size). In this paper we will mainly focus the attention on the results of the investigation recently performed on two Japanese wooden statues with our CT system for large works of art. The CT analysis was carried out on site at the Conservation and Restoration Center "La Venaria Reale", where the statues have been restored before their exposition at the Oriental Art Museum in Turin.

1 Introduction

X-ray Computed Tomography (CT) is a powerful non-destructive testing technique for the whole 3D inspection of a sample. CT has been recently introduced in the field of Cultural Heritage diagnostics, where it can be used for the investigation of different works of art, as it preserves the integrity of the object and gives morphological and physical information on its inner structure [1]. The knowledge of these features is very useful for determining adequate conservation and restoration procedures. Information can be retrieved as 2D cross-section images or 3D full-volume images allowing for the inspection and the classification of the object; moreover, by processing tomographic data, a 3D numerical model of the sample can be obtained for virtual reality applications or digital archives storage. The first attempts in adopting this technique for Cultural Heritage analysis have been done by means of medical CT scanners, usually with courtesy and permission of a hospital. However, the use of medical CT scanners gives good results only in case of analysis of samples with size and density similar to those of the human body, but this requirement is not always satisfied in the field of Cultural Heritage diagnostics, where various kinds of objects with different size and composition have to be analyzed. Moreover, as it is difficult to move the works of art from the place where they are located, it is very important to develop equipments easily movable. In order to fulfill all these needs, our research group at the Physics Department of the University of Bologna has developed several acquisition systems for Digital Radiography (DR) and X-ray CT [2, 3]. We have performed high resolution micro-tomography of small objects (voxel size of a few microns) and CT of large objects (up to 2 m of size), using different kinds of X-ray sources [4–9].

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2 Components of a diagnostic imaging system

Generally speaking, a diagnostic imaging system with X-rays, consists of:

– a radiation source
– an equipment for rotating the obiect or the source-detector system in order to acquire the digital radiographies at different angles, necessary to do the tomographic reconstruction
– a detector for digital images collection
– a computer for managing image acquisition
– a computer for image processing and rendering

As far as the X-ray source and the detector are concerned, different choices are possible; in any case when setting up a tomographic system it is important to take into account the characteristics (density, size) of the obiect to be investigated and the spatial resolution that one wants to achieve. Before describing in detail one of the CT systems developed by our research group for the investigation of large objects, we just want to recall briefly the main types of radiation sources and detectors that we have used as components of our diagnostics systems.

2.1 Radiation source

Microfocus and nanofocus For having high spatial resolution and avoiding the "penumbra effect", X-ray tubes must have a small focal spot. The tubes having a focal spot of the order of few microns are named microfocus and those having the focal spot of less than one micron are named nanofocus. Microfocus and nanofocus can operate only at low current level (few µA).

Industrial tubes For high currents and voltage up to 450 kV, industrial type tubes are used. Usually they have a cooled anode and current can reach several mA. These tubes can be used for radiography or CT of bronze statues several mm thick. Both microfocuses or industrial tubes operate in a continuous way.

Synchrotron light Synchrotrons are electron accelerators shaped like a large ring. Electrons can achieve energies of several GeV. If electrons are compelled to move out of their orbit by deflecting magnets or "*wigglers*", they emit an X-ray radiation named "synchrotron light". From the beam of photons, monochromator crystals can select photons of well defined energy (usually from 5 to 100 keV). The synchrotron light is a continuous radiation source and has the advantage to be monoenergetic and very intense. Monochromatization avoids beam hardening that is particularly strong for high density samples. The second major asset of synchrotron radiation source is the very high X-ray beam intensity, which is orders of magnitude higher than that produced by X-ray tubes. This high flux allows for rapid data acquisition at very high spatial resolutions, resulting in precise mapping of the internal structures of the sample [10, 11]. One of our experiments was performed at SYRMEP beamline of ELETTRA Synchrotron in Trieste (Italy) [12].

LINAC In a linear accelerator or LINAC (*LINear ACcelerator*), the electrons emitted from the cathode are "packaged" and accelerated against the anode by an e.m. wave of a suitable frequency (radio frequency). The radiation is emitted in the forward direction and the energy spectrum is continuous. Without suitable absorbers (filters) one can assume the "effective energy" (equivalent to a monochromatic source) to be $1/3$ of maximum energy or less. For applications in the field of Cultural Heritage the maximum energy should not be larger than 10 MeV, as there is the possibility of the activation of the objects due to the neutrons produced by photonuclear reactions. Several years ago we used a 9 MV LINAC to perform the CT analysis of an old roman jug filled with bronze coins [13].

2.2 Detectors

There are many types of assemblies for acquiring digital radiographies. For our researches we have developed and used mainly three detector types:

– a CCD camera coupled with a taper for micro-CT
– a CCD (or EBCCD) camera coupled with a fan of coherent optical fiber ribbons (multi-slice linear detector)
– a scintillating screen seen by a CCD (or EBCCD) camera (cone-beam CT)

Detector for micro-CT If the object under investigation is small (few mm) and if a good spatial resolution is required (of the order of few microns), then a micro-tomographic system is used. In this type of system phosphor is smeared over a FO taper or directly over a CCD. A microfocus or nanofocus is used as an X-ray source. A micro-CT system with a field of view of 30×15 mm^2, developed by our group, is shown in Fig. 1a [14], while Fig. 1b shows the 3D tomographic reconstruction of an ancient Roman tooth performed using this type of acquisition system [15]. The voxel size is about 30 µm.

Multi-slice linear array detector Detectors of linear array type are often used to obtain high resolution DR. A sketch of a new linear detector, developed by our research group, is shown in Fig. 2a. It is made up by a fibre optic (FO) fan that transports light over the photocathode of an EBCCD camera [16]. The fan consists of seven ribbons positioned as in Fig. 2b; this FO fan is a "geometry transducer" in the sense that it changes the geometry of the active area of the EBCCD from 1024×512 pixels to 5600×60, thus obtaining a large (5600 pixels), multi-slice (60) detector, with a pixel size of about 25 µm over a field of view of 130 mm.

CCD-based systems The detection system described herein was developed for diagnostics in "cone-beam tomography" mode. Figure 3 reports a sketch of the equipment that is composed of:

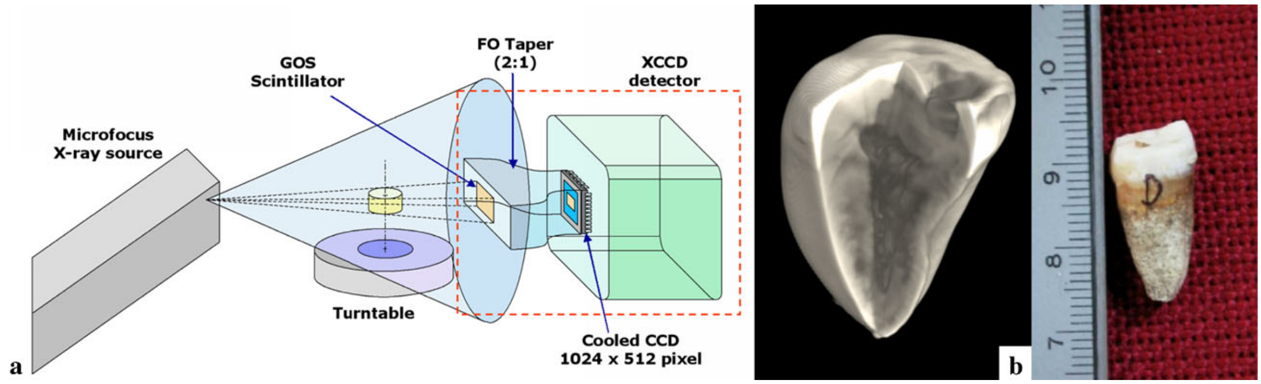


Fig. 1 **a** Diagram of the micro-CT system; **b** micro-CT of an ancient Roman tooth

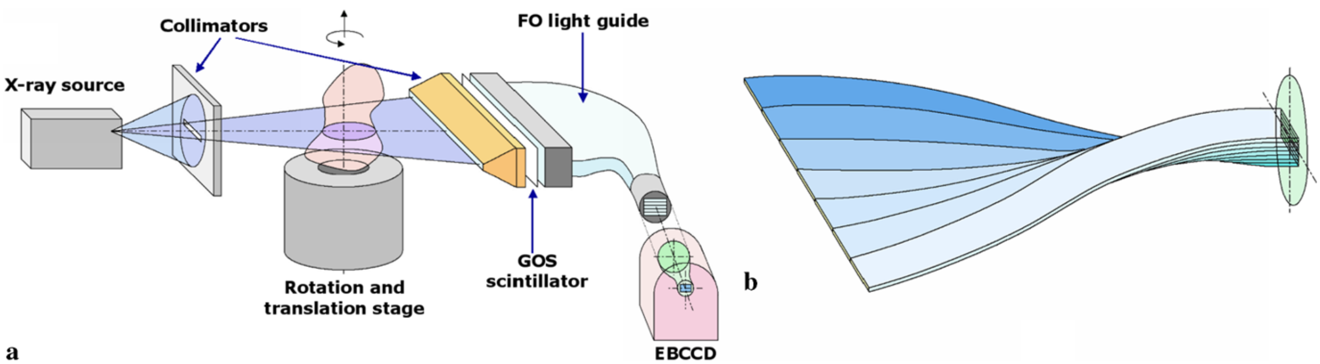


Fig. 2 **a** Diagram of the linear array system; **b** scheme of the linear detector

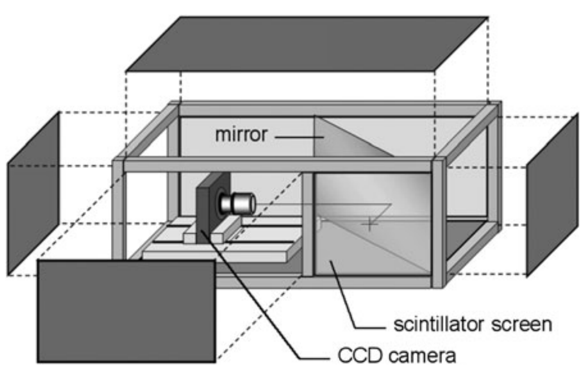


Fig. 3 Detection system composed by a scintillator screen coupled to a CCD camera, both positioned in a light–tight box. Lead sheets protect the camera from scattered photons

– a scintillating screen on which the X-ray beam generates the radiographic image of the object
– a 45 degree mirror, which reflects the image towards the CCD camera
– a CCD camera (scientific grade, usually cooled to decrease the electronic noise), equipped with a lens
– a collimator, located in front of the screen, which decreases the scattered radiation reaching the detector (sometimes the most important cause of image degradation)
– a pre-collimator, placed close to the X-ray source, which molds the beam

Each component must be chosen bearing in mind the energy range of the X-ray beam.

The pixel size in the radiographic projections depends on the number of pixels of the CCD camera and on the field of view of the detector, which, for a given CCD, is related to the focal length of the lens and to the camera-to-scintillator distance. Therefore this kind of detector is very versatile, as it is possible to change easily the pixel size according to the specific needs of the investigation to be performed. The use of the lens may introduce distortions in the images, but it is possible to correct them by means of suitable algorithms.

3 CT analysis of large Japanese wooden statues

Even if the object of interest is done by a material that allows the CT by a medical equipment (i.e. wood), sometimes the dimensions are so huge that it impossible to inspect it by standard equipment. Moreover, the big objects often cannot be moved from the places where they are located. In such a

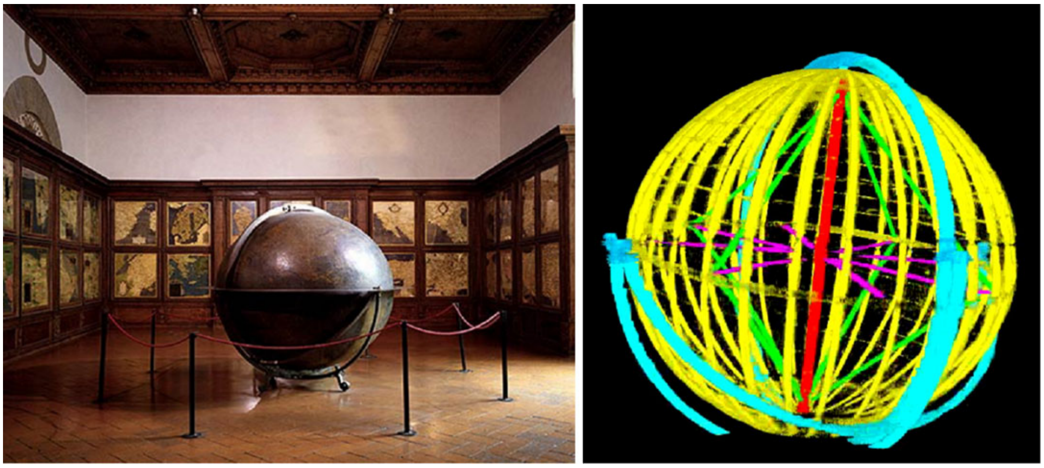


Fig. 4 A picture of the globe in the "Map Room" of Palazzo Vecchio (Florence) and a 3D tomographic reconstruction

Fig. 5 The two Japanes statues Kongo Rikishi (XIII century, *on the left*) and Tamon Ten (XVII century, *on the right*)

case it is necessary to transfer the inspection system on site. This was the case of the CT investigation that our group carried out several years ago on a big ancient globe (220 cm in diameter) created by the Dominican monk Egnazio Danti in 1567 and located at Palazzo Vecchio in Florence. Figure 4 shows a picture of the globe inside the "Map Room" and a 3D tomographic reconstruction, which highlights the different components of the iron inner structure. In order to perform the CT analysis of the globe, our research group developed a transportable system, expressly conceived for the investigation of large objects [17].

In the past year the Conservation and Restoration Center "La Venaria Reale" (Turin) asked us to perform CT investigations on two Japanese wooden statues of the XIII and the XVII century (Fig. 5), respectively called *Kongo Rikishi* (over 230 cm of height, including basement) and *Tamon Ten* (about 125 cm of height).

The diagnostic analisys was required as the statues had to be restored before their exhibition at the Oriental Art Museum in Turin. As always occurs when trying to perform on the field the CT of a big object, a special set-up was required in this case too. For that purpose we arranged a measurement system composed of:

– a transportable X-ray tube (200 kVp), movable on a vertical translation axis
– a rotating platform, where the statue is positioned
– a detector which can be moved both horizontally and vertically, by means of two translation axis. The detector is a CCD-based system, with a Field of View (FOV) of

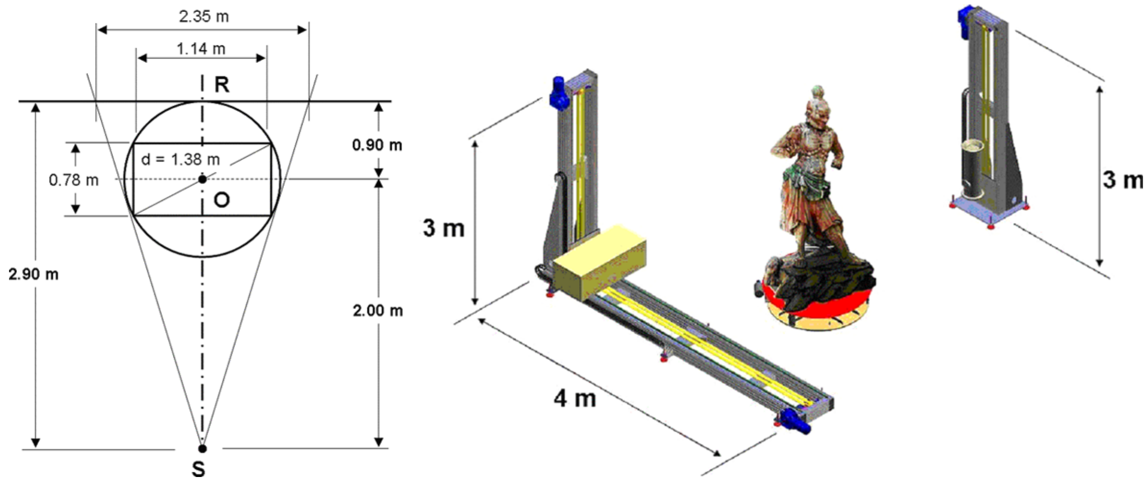
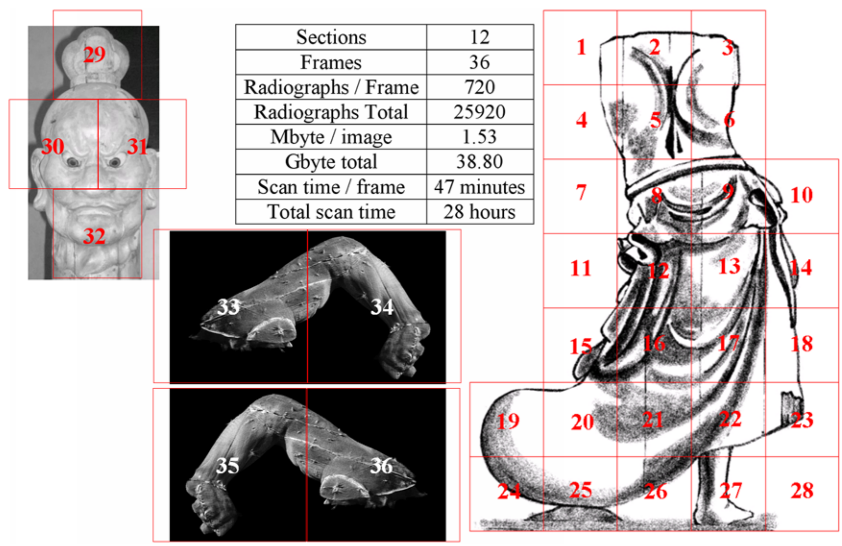


Fig. 6 Sketch showing the acquisition geometry for Kongo Rikishi scanning (*left*) and scheme of the experimental CT system (*right*)



Sections	12
Frames	36
Radiographs / Frame	720
Radiographs Total	25920
Mbyte / image	1.53
Gbyte total	38.80
Scan time / frame	47 minutes
Total scan time	28 hours

Fig. 7 Scheme of the 36 frames used to cover the entire area corresponding to the statue projection

450×450 mm^2. The scintillator is a 1 mm thick structured caesium iodide screen, coupled to a 2184×1472 cooled CCD camera

As the FOV of our detector is smaller than the object size, the so called *tile scanning* technique was necessary. Tile scanning is the term experts use when a CT is performed step by step by moving the detector to cover the object projection with a certain number of different frames. A thin overlap is required to match the different radiographs, obtained at the same angle, together in order to compose the whole one, as required by the reconstruction algorithm. The general set-up geometry of the CT system should take into account the maximum horizontal projection of the whole object, its height, and an empty strip above its top used to get the images required for the flat–field operation.

The best compromise between signal level and maximum projection size must be calculated in advance to maximize the acquisition speed and define the working area size. The sketch in Fig. 6 shows the situation for the case of Kongo Rikishi. In the same figure a scheme of the experimental CT system is also reported. The tile scanning geometry is depicted in Fig. 7, where all the different scanning frames are numbered. A set of 720 radiographs was acquired for each one of them. The same procedure was also adopted for the CT scanning of Tamon Ten.

3.1 Kongo Rikishi

The statue called Kongo Rikishi, which means “the Guardian of the Temple”, is an over 2 meters tall wooden statue, about one meter large at the basement. It dates back to the Kamakura Period (XIII century) and was realized by assembling many pieces of Japanese cypress wood (hinoki) by means of a complex technique called *yosegi-zukuri*.

The CT investigation was performed with the acquisition parameters listed in Table 1. It was decided to use a 2×2

hardware binning on the CCD in order to decrease the exposition time and to get also a more manageable dataset. Considering the FOV of the detector and the hardware binning, we obtained a pixel size on the detector of 0.625 mm. By taking into account the source-to-object and the source-to-detector distances the voxel size of the 3D tomographic reconstruction as a result is equal to 0.427 mm.

Table 1 Main acquisition parameters adopted for the CT of Kongo Rikishi

Tube voltage	160 kVp
Tube current	4 mA
Exposition time	2.2 s
Number of angular steps	720
Source-to-object distance	1978 mm
Source-to-detector distance	2890 mm
Hardware binning	2 × 2
Pixel size on the detector	0.625 mm
Voxel size	0.427 mm

The CT analysis has given very interesting information on the technique used to assemble the different pieces of wood and on previous restoration works. In fact the CT images put clearly in evidence the types of joints as well as several discontinuities between the wood pieces and the presence of putties and metallic elements, such as nails and screws, used in previous restoration works to assemble the pieces with damaged joints.

It has also been possible to assess the depth of the cracks visible on the surface and to notice the presence of the pith in the bearing element of the statue, which is an inner wooden upright of rectangular cross-section which holds up the structure from the right shoulder to the heel of the right foot. In Figs. 8, 9 and 10 several CT slices are reported together with 3D reconstructions of different portions of the statue.

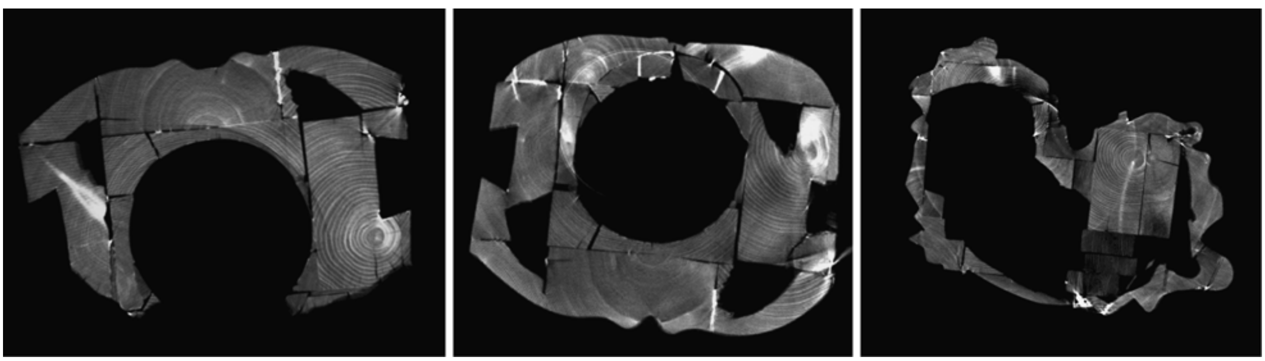


Fig. 8 CT slices corresponding to different portions of the statue (*from left to right*: shoulders, chest and upper part of legs)

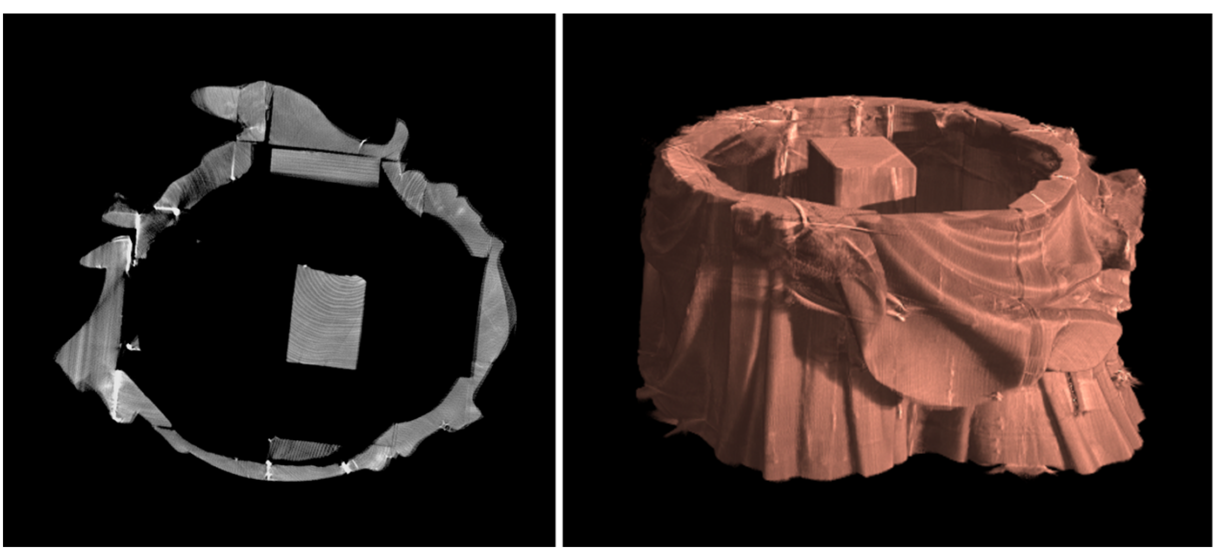


Fig. 9 CT slice and 3D reconstruction of the upper portion of Kongo Rikishi dress. Clearly visible is the inner upright of rectangular cross-section

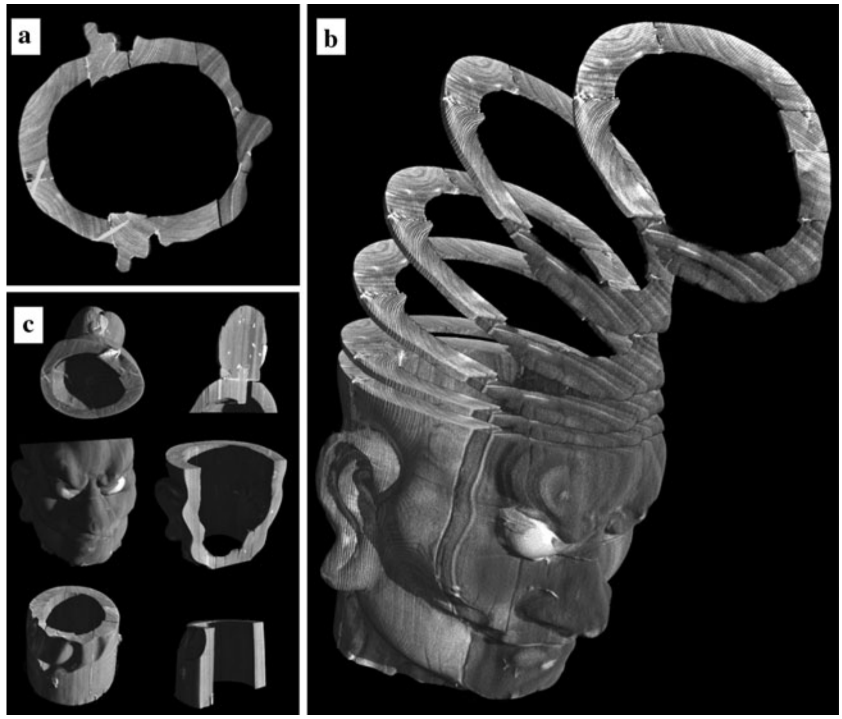


Fig. 10 **a** Slice of Kongo Rikishi head showing the presence of bamboo wooden pins; **b** 3D rendering, which highlights the process of volume reconstruction based on the superimposing of many slices; **c** 3D tomographic reconstruction of Kongo Rikishi head: virtual cuts

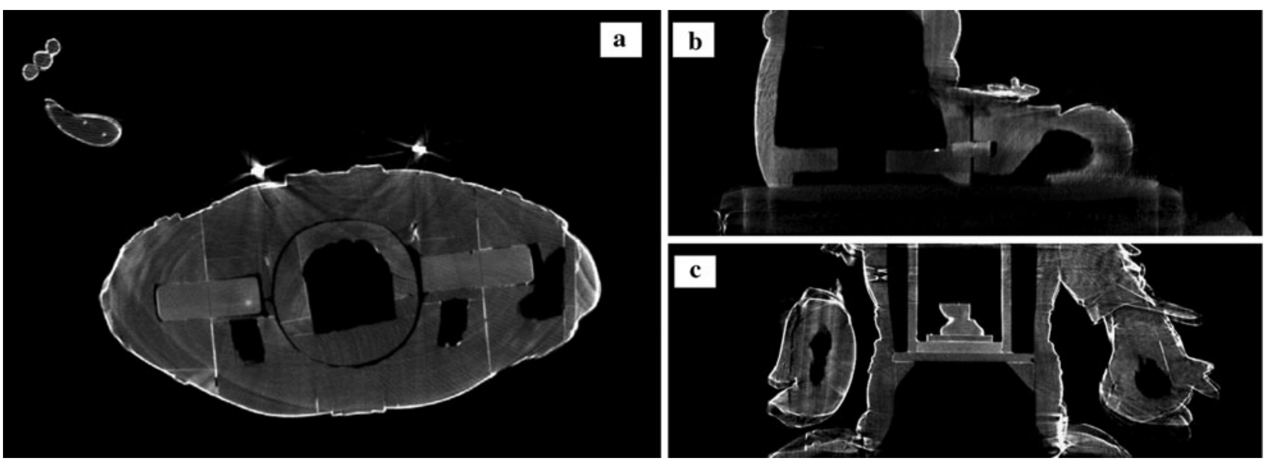


Fig. 11 **a** Tomographic slice showing the tenons used to join the arms to the body; **b**, **c** Sagittal and coronal sections *of the bottom part* of Tamon Ten body

3.2 Tamon Ten

The polychrome wooden statue called Tamon Ten dates back to the EDO period (XVII century) and symbolizes the "Guardian of the North", one of the guardians of the four horizons, which lives on Meru mountain. The statue is sitting on a painted and golden basement of wood and it has been made by assembling together several pieces of wood: the principal ones are those corresponding to the chest, the back, the legs and the mantle adjacent to the basement. The CT images display that the chest and the back are hollow inside and are joined by means of glue and nails, while the arms are joined to the body by two tenons. One piece of wood, hollow inside, makes up the legs and is joined to the upper body by means of two tenons (Fig. 11). CT images of Tamon Ten head, shown in Figs. 12 and 13, furnish very interesting information. From the sagittal section in Fig. 13 it is possible to notice that the face is probably made with a different kind of wood, in fact its radiopacity is clearly different from that of the other pieces of wood. Moreover it is the only element that has been attacked by woodworms. The chignon is made up by one piece of wood and is joined

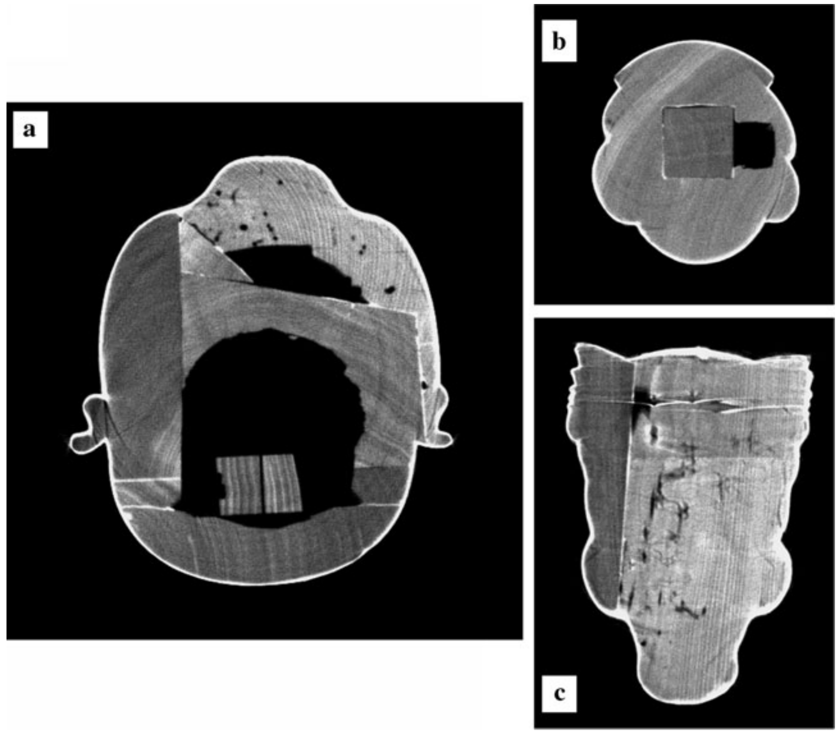


Fig. 12 **a** Cross-section of Tamon Ten head; **b** the cavity inside the chignon; **c** holes and galleries caused by woodworms in Tamon Ten face

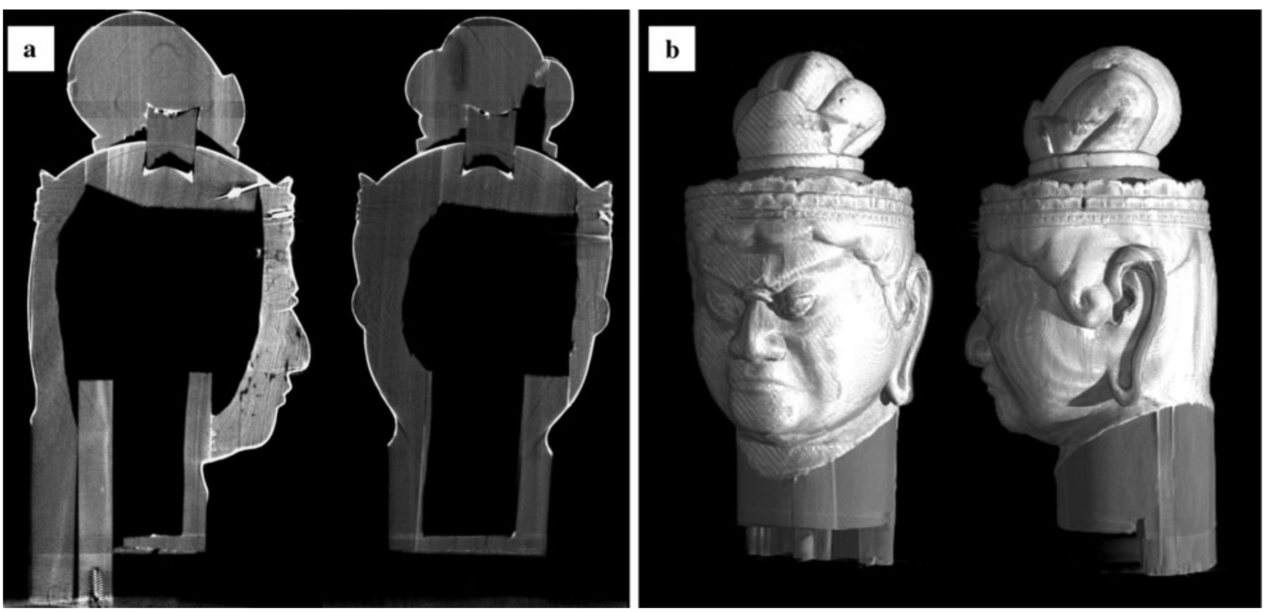


Fig. 13 **a** Sagittal and coronal sections of Tamon Ten head; **b** 3D reconstructions

to the head by means of a double tenon. Beside the tenon there is a square cavity, plugged in the upper part, probable evidence of a change of mind in the execution. The CT investigation reveals a good structural situation of the statue: the various pieces of wood are well joined and there are not considerable separations between them, except for the piece constituting the legs, that discharges its weight mainly on to the tenons that connect it to the upper body.

4 Conclusions

The strong interest in the development of transportable CT systems specifically designed for Cultural Heritage analysis on site has urged our research group to set up several acquisition systems that have been used already for the investigation of archaeological findings and works of art of different size and composition. In particular the tomography of large objects represents a challenge that we have overcome by developing a versatile and transportable CT system. Thanks to this system in the past year we were able to fulfill the request from the Conservation and Restoration Center "La Venaria Reale" (Turin) to perform CT investigations on two Japanese wooden statues of the XIII and the XVII century, respectively called *Kongo Rikishi* (over 230 cm of height) and *Tamon Ten* (about 125 cm of height). The results obtained are very satisfactory and the restorers have gained a large amount of information from the CT images. It is probably the first case world-wide of on-site CT analysis on statues of so large a size.

Acknowledgements The authors wish to thank the Center for Conservation and Restoration "La Venaria Reale" in Turin, where this work was carried out, for the fruitful collaboration in the CT analysis. The authors also wish to thank the Oriental Art Museum of Turin, where the statues are now located, and the "Fondazione per l'Arte della Compagnia di San Paolo", owner of the two statues, for supporting this work.

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