Non-Destructive Digitization of Soiled Historical Chinese Bamboo Scrolls

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***Abstract*—For about 2000 years, no paper was used as a media in China but writings and drawings were captured on bamboo and wooden slips. Several slips were bound together with strips and rolled up to a scroll. The writings and drawings were either brushed or even carved into the wood. Those documents are very precious for culture inheritance and research, but due to aging processes, the discovered pieces are sometimes in a poor condition and also soiled. Because cleaning the slips is not only challenging but also writings could be erased, we developed a method to digitize such historical documents without the need of cleaning. We perform a 3-D X-ray micro-CT scan resulting in a 3-D volume of the complete document. With our approach, we were able to investigate the scroll without any manual labor (e.g. unwrapping or cleaning). We showed that the method also works for heavily soiled scrolls where nothing is readable with the naked eye. This can help conservators to store all writings before they may be erased by the cleaning process. Finally, we present a manual technique to virtually unwrap and post-process the documents resulting in a 2-D image of all bamboo slips.**

***Keywords*-Bamboo and wooden slips, 3-D X-ray CT, Historical Chinese Documents, Document Digitization**

Figure 1. Soiled bamboo slips found near Jingmen, Hubei, China. The digitization of such slips can be very challenging and writings or drawings can be erased.

I. Introduction

For about 2000 years, from the Shang dynasty (17^{th} century B.D.) to the Jin dynasty (after 300 A.D.), the main media in China was not paper but writings and drawings were written on bamboo and wooden slips [1], [2]. The writings were either brushed or carved into the wood, depending on the dynasty [3]. Writing was done from top to bottom and the slips length ranged from 20 cm to 70 cm. Several slips were bound together with strips and rolled up to a scroll.

Nowadays, such scrolls and slips are a valuable source to increase knowledge of the life of the past. Due to aging processes, the discovered pieces can be in a poor condition. For example, in 2002, more than 37,000 pieces (called Liye Qin Slips, one of the most important archaeological discoveries in the last decade in China [4]) have been discovered from underground in a very poor condition, e.g., they are heavily soiled as shown in Fig. 1 [5]. The cleaning process can be very challenging for a conservator because the wood as well as the ink and the carvings can suffer from used chemicals and human imprudence.

One approach to reveal the writings of those soiled pieces of wood is to clean the fragments in meticulous detailed work. However, changing the preserving environment, e.g., brushing off the soils, exposes the slips directly to the atmosphere and they may oxidize rapidly. Moreover, cleaning and reading those timbers by hand is very time-consuming. Therefore, we will present a better strategy to read and digitize such historical documents.

Our approach is based on a non-destructive testing technique – we perform a 3-D X-ray micro-CT scan of the bamboo scroll and reconstruct the volume. 3-D X-ray micro-CT is normally used to detect defects within assembled materials but is becoming increasingly

(a) (b)

Figure 2. The bamboo scroll that was measured: (a) The image shows the bamboo scroll without contaminations measured in the initial experiment. (b) The bamboo scroll was covered and filled with potting soil and put in a plastic bag for the second experiment.

important for document digitization [6], [7]. The scroll scanned in our experiments was bought in China (Beijing) and measured without contaminations as well as heavily contaminated by potting soil to simulate a real world scenario. Finally we present a method for segmenting all slips of the micro-CT volume and virtual unwrap the scroll to visualize the slips in a single 2-D image.

Our contributions in the paper are:

1) We present an approach that is capable of digitizing a wooden object with carvings of any type (e.g. writings and drawings), even if the object is contaminated by potting soil.
2) When applying our approach before cleaning the document, the carvings are saved such that if certain writings or symbols are erased, the reconstructed 3-D volume can help the conservator to identify such spots and repaint the specific wooden slip.
3) We show a straight-forward manual method to extract and visualize all wooden elements with its writings and drawings for the conservator.
4) As we already have digital data, character recognition algorithms can be applied and writings or drawings can be digitized by a library immediately which is of a rising importance nowadays.
5) The approach is capable of scanning multiple scrolls at the same time. The limitation lies only in the dimension of the scanner itself.

II. Materials and Methods

A. The Scroll

The used scroll is made of bamboo wood and consists of 32 single slips with a size of $1.4 \times 15 \times 0.3\,\mathrm{cm}^3$ $(\mathrm{length} \times \mathrm{width} \times \mathrm{height})$ that are connected by strings. As getting a real historical scroll without testing the approach first is very difficult – and to the best of our knowledge no pre-work exists – we used a normal bamboo scroll that we bought in Beijing shown in Fig. 2(a). Each slip has carvings with the depth ranging from $0.2 - 0.5\,\mathrm{mm}$'s that represent either Chinese writings or drawings. The complete scroll includes a total of 584 Chinese characters with their height ranging from $3\,\mathrm{mm}$ to $6\,\mathrm{mm}$.

For the first measurement, the scroll was rolled up completely such that only the outer slips could be read with the naked eye. The inner slips were not visible at any time. Rolled up, the scroll has a diameter of about $5.5\,\mathrm{cm}$. With our second experiment we wanted to demonstrate that our method still works for a worst case scenario. As the scrolls are mostly discovered underground and tend to be dirty, we put the scroll in a plastic bag and completely covered and filled it with potting soil. With this measurement setup, it was not possible to see the bamboo slips anymore as shown in Fig. 2(b).

B. The Volumetric Scan

Before unwrapping the scroll, it first has to be digitized non-invasively by an appropriate technique. Several approaches are used for those purposes such as Terahertz [8], X-ray phase contrast [9] and 3-D X-ray micro-CT [10]. Common 3-D Terahertz systems have a maximal resolution of about $0.4\,\mathrm{mm}$'s per voxel but we know that the depth of the carvings are $0.2\,\mathrm{mm}$ or even lower. This can cause problems such that some writings may not be readable. Allowing very high resolutions, we chose a 3-D X-ray micro-CT scan to create the digital volume. X-ray phase contrast is also an option, however, those systems are not as available around the world as micro-CT such that libraries would have to carry their documents to the measurement centers.

All tests were performed with a commonly used micro-CT system consisting of a flat panel detector, an X-ray source and a turntable to rotate the object. A full-circle scan with 360° using cone beam geometry was performed [11]. The name of the geometry comes from the cone shaped coverage around the rotation axis as shown in Fig. 3 (blue object). The scroll was placed upright on the turntable. Because the scroll's diameter is constant over

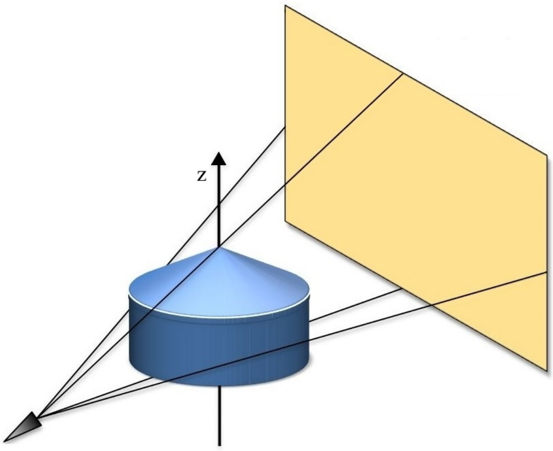


Figure 3. The 3-D X-ray CT measurement setup: The X-ray source and the flat panel detector are fixed while the blue, cone shape object is rotating around the z-axis. The object is completely covered by the rays emitted to the detector such that it can be fully visualized in the reconstructed volume.

Table I
OVERVIEW ON THE OPTIMAL SCANNER PARAMETERS FOR OUR TEST SETUP.

Parameter	Value
Energy	$130\,\mathrm{kV}$
Current	$1.088\,\mathrm{mA}$
Exposure time	$0.5\,\mathrm{s}$
Projections	1800
Source-object distance	$710\,\mathrm{mm}$
Source-detector distance	$1377\,\mathrm{mm}$
Detector pixel width	$0.2\,\mathrm{mm}^2$

the whole length, the emitted X-ray beam passes about the same material length for the entire set of projections. We tested with several scan parameters whereas those from Table I led to the best visual results.

C. The 3-D Reconstruction

All calculations were performed with the CONRAD framework for cone beam geometries [12]. For the reconstruction, the commonly used Feldkamp, David, Kress (FDK) algorithm [13] was applied. It consists of three major steps – cosine weighting, ramp filtering and back projection. For the 3-D case, the approach extends an exact 2-D reconstruction algorithm for fan-beam projections by adapting the cosine weightings. The FDK algorithm performs well for objects that are cylindrical with a small diameter, however, the output may suffer from cone-beam artifacts as it is rather high [14]. The voxel size of the reconstruction was $0.103\,\mathrm{mm}^3$. With the used parameters, the scan and reconstruction time was kept relatively low (about 1.5 hours in total).

D. The Segmentation of the Bamboo Slips

For segmenting the wooden slips, we chose a manual segmentation, because the scope of this work was not to provide an automatic segmentation algorithm, but to demonstrate that our concept of scanning historical bamboo scrolls or wooden objects with carvings works. Fig. 4 shows a slice of the measured soiled scroll reconstruction in xy-direction. The exemplary slice shows that the scroll was completely covered and filled with potting soil. Of course, this only holds for the contaminated measurement. The bright dots denote minerals (e.g. small stones, calcium or magnesium) in the potting soil, however, the reconstruction did not suffer from beam hardening or similar artifacts although no correction algorithms were applied.

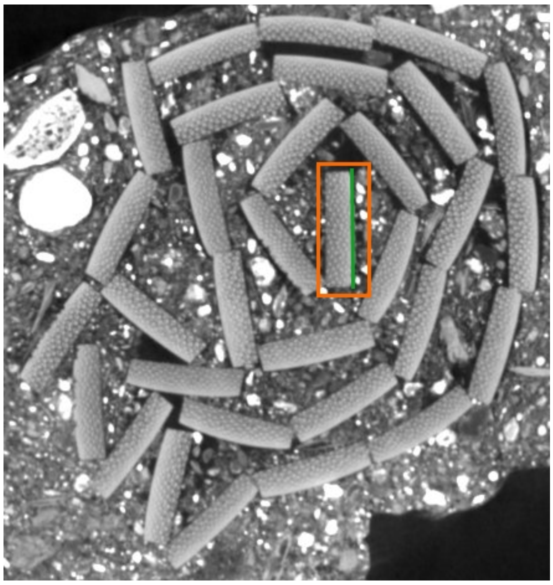


Figure 4. Exemplary xy-slice of the soiled bamboo scroll reconstruction. The bright dots denote minerals in the potting soil. The scroll is completely covered and filled with potting soil. One can see, that all 32 bamboo slips can be clearly identified within the slice. For the segmentation, every slip was extracted with a box (orange) and the volume slice along the surface including the writings was extracted (green line).

Figure 5. When investigating the yz-slice of a bamboo slip, we can observe that it is slightly curved complicating the segmentation.

After scanning and reconstructing the volume for both measurement setups, we extracted all 32 wooden slips separately by hand. This was done by cropping everything but a rectangular box around the segment that should be visualized (Fig. 4: orange box). As the wooden slips are not always even over the entire length but also curved (Fig. 5), some elements get shaded in the output. To counter this, we applied small rotations such that the Chinese characters and drawings can be seen. In a later automatic approach, this problem should be handled by the algorithm which should sample the pixels along the surface, no matter if the slip is curved or not. However, for this work, the slight rotations were sufficient. Finally, we sampled all points along a 2-D plane intersecting the surface of the writings (Fig. 4: green line) resulting in a 2-D image of the extracted slip.

E. Image Post-processing

For improving the output of the reconstructed volume, we applied some post-processing steps. First, all 32 extracted 2-D images of the bamboo slips were stitched together resulting in the unwrapped 2-D image of the complete scroll. Although everything can be read and seen, we can further improve the output by applying unsharp masking. This approach calculates a Gaussian blurred image and subtracts it from the original to create a sharper output $I_s(x, y)$. To binarize the scroll, we calculated the Hessian eigenimage of I_s [15], [16]. Therefore, we first smoothed the image with a Gaussian kernel resulting in $G(I_s)$ (radius $= 1$) and calculated the Hessian Matrix $\boldsymbol{H}$ at each image pixel (x, y) according to

$$\boldsymbol{H}(x, y) = \begin{bmatrix} \frac{\delta^2}{\delta x^2} G(I_s) & \frac{\delta}{\delta x \delta y} G(I_s) \\ \frac{\delta}{\delta x \delta y} G(I_s) & \frac{\delta^2}{\delta y^2} G(I_s) \end{bmatrix} \tag{1}$$

Afterwards, the eigenvalues λ_1 and λ_2 are calculated and the largest eigenvalue is stored in a new image at the position (x, y). This process highlights tubular- and plate-like structures (in our case the Chinese Writings and drawings) and eliminates possible shadows due to the waviness of the slips. In addition, we global threshold the image to receive a binarized output.

III. Results

Fig. 7(a) shows a photography of the original unrolled bamboo scroll with all its 584 Chinese characters and drawings. For the scan, the scroll was rolled up and put in the scanner. Afterwards, we segmented the slips with the previously described approach and post-processed it.

A. The Scan of the Clean Scroll

Fig. 7(b) shows the measured and reconstructed 2-D segmentation result of the clean scroll. All writings as well as the drawings can be clearly identified such that the document is digitized properly.

However, one can also see the problem that we described in Section II-D shown in Fig. 5. For example, the third slip from left is curved such that the lower part of the element gets increasingly shaded. The same problem can be observed for the last slip from the right. Whereas the upper and center part is illustrated correctly, the lower part is curved such that we already see the bamboo structure and the carvings get erased. Multiple slips have this curvy structure, however, we are still able to identify all characters.

Another occurring problem is that the surface of the bamboo slips are also slightly curved. When taking a look at the slips' surfaces in Fig. 4 we can observe that they are not straight. This yields to the bright area in the center of the elements that get more and more shaded outwards (e.g. Fig. 7(b) - Slip no. 5).

B. The Scan of the Contaminated Scroll

Fig. 7(c) shows the scanned and reconstructed 2-D segmentation result of the scroll that was contaminated by potting soil. Again, all Chinese characters and drawings are visible. At the border of some elements, we observe bright spots which are particles from the potting soil that are placed on the surface of the slips. If we would consider the real structure of the bamboo slips, this artifacts should disappear.

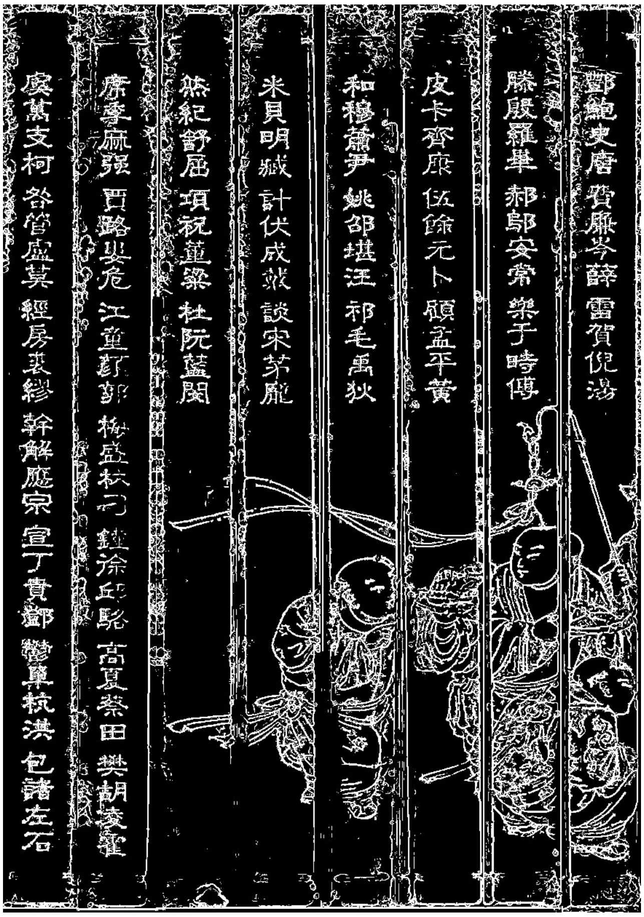


Figure 6. Eight binarized slips (Slip no. 17–24) of the scroll including writings and drawings after post-processing with the proposed method.

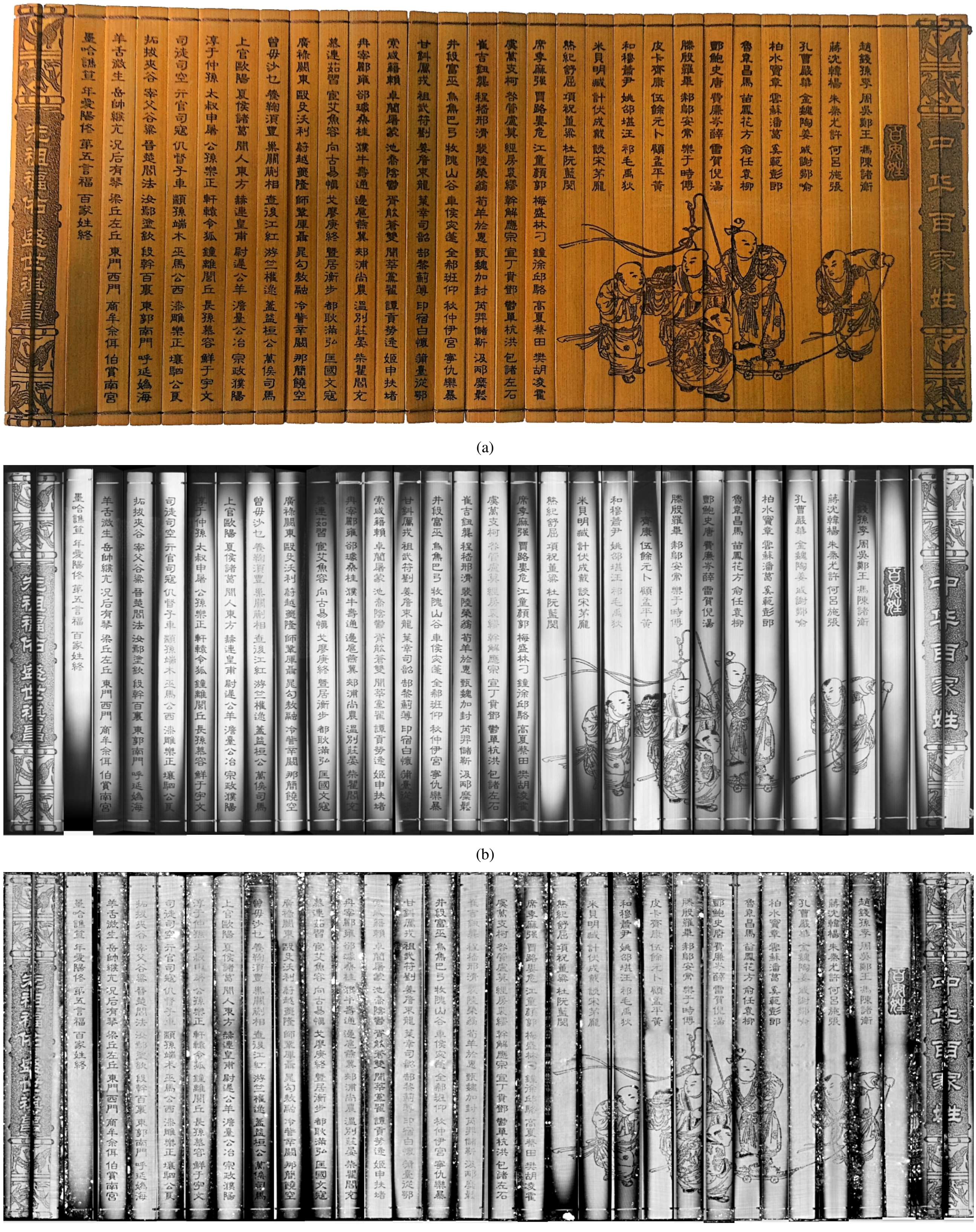
In summary, we can say that without cleaning the scroll, we can preserve all writings and drawings that are carved into the wood slips before cleaning the scroll, no matter how much soiled the document is. So far, we just experimented with potting soil, however, it has a wide variety of ingredients such as stones and minerals as we saw in Fig. 4.

C. Post-processing

Finally, the post-processing algorithm was applied. The exemplary binary results for seven bamboo segments (Slip no. 17–24) including drawings and characters can be seen in Fig. 6. The artifacts at the borders of the elements should disappear if we would consider the curved structure of the bamboo slips.

IV. Discussion and Outlook

In this work, we presented a method to digitize Chinese bamboo and wooden slips that are connected by strings and rolled up to a scroll. We performed a 3-D X-ray micro-CT scan followed by a manual segmentation.



(a) (b) (c)

Figure 7. The original and the reconstructed and processed scroll: (a) A photography of the unrolled original scroll that was rolled up and scanned by using 3-D X-ray micro-CT. (b) The scanned and 3-D reconstructed scroll without contamination after manual segmentation and virtual unwrapping. (c) The scanned and 3-D reconstructed soiled scroll after manual segmentation and virtual unwrapping. Although the scroll was heavily contaminated by potting soil, all characters and drawing are clearly visible.

The method is non-invasive and capable of creating a digital volume of the document without unrolling it. Furthermore, we show that there is no need to clean the scroll before scanning, because the contamination is mostly on the surface and not in the slips itself. This means, that if such a scan is performed before the scroll is cleaned by a conservator, writings that are erased by the cleaning process are stored and can be repainted. Without the method, they would be gone forever.

For future work, we can perform tests with real historical slips or scrolls. Of course, the same technique can be used for woodcuts. Although the presented approach is non-invasive, it should be mentioned that the X-ray radiation may harm the wood and accelerate the aging of the cellulose [17]. Therefore, an evaluation has to be done to find a set of measurement parameters that reduces the applied dose as much as possible. Not only CT parameters but also the reconstruction algorithm and appropriate filtering of the projection or volume data can help to reduce the dose by achieving an improved signal-to-noise ratio while keeping the original structure of the volume [18], [19].

The characters and drawings of the scroll that we used for our experiments were carved into the wood. It has to be investigated if the presented technique still works if the characters are only brushed but not carved into the bamboo. The success of the method will depend on the ingredients of the ink. For example, if the ink consists of metallic particles, the inks X-ray absorption differs from the cellulose and potting soil such that it can be visualized.

The manual segmentation is time consuming because every slip has to be extracted and processed separately. Therefore, an automatic segmentation approach should be developed. The algorithm has to detect the elements and extract the surfaces information, even in curved cases. We think that this will enhance the output such that the shaded, curvy areas would be digitally flattened yielding to a nicer output for the digitization process.

In summary, we think that our method can help libraries and conservators to preserve the structure and writings or drawings of historical wooden scrolls.

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