Tailoring x-ray tomography techniques for cultural heritage research

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Conclusion and outlook

In this thesis, we identified the challenges and opportunities related to CT scanning of cultural heritage objects and to contribute to the broader adoption of this imaging technique within the museum research context by developing algorithms and techniques tailored to cultural heritage. In this chapter we will first summarize the contributions and limitations of the work presented in this thesis. We then present the research that was initiated or inspired by the work presented in this thesis. In the last section we provide perspectives on future work and identify where the main possibilities and challenges lie.

6.1 Contributions and limitations

The contributions of this thesis can be classified into two categories: 1) technique development and 2) application in the cultural heritage domain. Each chapter outlined a novel method or approach, which was consequently applied to a case study from a museum collection. Below we will outline the contributions and limitations per chapter, first on the topic of the technique development and then on the application in the cultural heritage domain.

6.1.1 Technique development

In **chapter 2**, we discussed the key characteristics of cultural heritage objects that require flexibility of the CT scanning setup. To be able to capture the multi-scale features in the interior of cultural heritage objects, it is necessary for the setup to be flexible in image resolution. Because of the varying shapes and sizes, the CT scanner needs to have adjustable source and detector position, to facilitate tiled scans of larger and irregularly shaped objects. The diversity in materials in art objects poses a challenge due to the image artefacts that can arise with higher density components in particular. It is therefore important that there is flexibility in object positioning to find the optimal orientation for each object. The requirements for a scanning setup that are discussed in this chapter may not be feasible to obtain for most museums due to the cost of highly flexible laboratory scanners. However, we show the importance of the close collaboration between imaging experts and art experts to move this interdisciplinary field forward.

In **chapter 3**, we developed a novel method for the dendrochronological investigation of large wooden objects with X-ray imaging. Instead of a full circular acquisition trajectory, the object is moved on a linear trajectory. The images thus acquired span a small angular range. If the object is placed so that the section faces the source, we showed that it is possible to obtain sharp images of the tree rings that lead to similar tree ring measurements as the traditional method of high resolution photographs. This method is of high importance, because it opens up a wide range of objects for dendrochronological investigation, which where undatable before due to the inaccessibility of the tree rings from the outside. The technical limitation lies mostly in the needed orientation of the wood. This is usually along the length of a wooden plank, which means that high X-ray energy and power is needed. Moreover, it means that the length of the plank needs to fit between the source and detector, limiting the size of the object. Our method does provide the means to scan larger objects than with regular CT imaging, but more research could be performed to further eliminate barriers for the X-ray imaging of large objects for dendrochronological investigation.

In **chapter 4**, we proposed a marker-based acquisition protocol combined with sophisticated post-processing algorithms to use in-house X-ray facilities for 3D CT imaging. The goal was to make optimal use of existing hardware to obtain 3D reconstructions of objects. We obtained a standard reconstruction from the in-house CT scanner at the British Museum. We then compared the results of this CT-scan to the results obtained by applying our method in the British Museum, the J. Paul Getty Museum and the Rijksmuseum. Although these facilities have different hardware and thus the resolution of the reconstruction differs, we were able to show that the same features are visible in the reconstruction of a small wooden test object throughout the three facilities. This method is still limited to those museums that have an in-house X-ray imaging facility. The algorithms that were developed are moreover not user friendly for cultural heritage professionals. The impact of this work could be increased by developing user interfaces. Despite these limitations, this novel method allows for the application of 3D CT imaging in-house in more museums.

In **chapter 5**, we presented a software solution to provide an interactive environment for the visualisation of CT scans and surface scans. The object experts are used to handling the objects and looking at them closely. The addition of a surface scan that shows the colours and textures of the object therefore greatly enhances their engagement with the CT data, which is often represented as 2D greyscale slices through a colourful 3D object. The solution presented is a plugin for 3D visualisation software Blender. It provides all the tools for loading the different data types, making a mesh out of the CT scan and registering the surface scan to the CT scan. It then guides the user through the steps to setup an interactive environment to inspect the different data types simultaneously, also giving the option to slice the volumes open and show the CT slices. In the last step, a few tools are provided for making simple images and video's for presentation, documentation and outreach purposes. To facilitate further analysis of data, additional tools should be added to the plugin. In next projects, the tools should be tested and evaluated by cultural heritage professionals. The application of this tool requires some knowledge of software Blender and is therefore not directly accessible for all users. By providing an extensive user guide and a step-by-step user interface, we have however attempted to mitigate this drawback.

6.1.2 Application in the cultural heritage domain

In **chapter 2**, we showed the added value of an expert-led acquisition process by scanning a musical instrument, a 17th century cornett. The feedback loops in which the object experts inspected live X-ray images and intermediate reconstruction results allowed us to adjust the scanning process. We acquired high resolution region of interest scans based on the intermediate analyses that would not have been acquired if the experts had not been present on the spot to steer the process. This not only answered the initial question, but additionally questions that arose during the scanning process. Thus more information about the object was gained by actively involving the object experts.

In **chapter 3**, the line trajectory acquisition method was applied to a large chest from the Rijksmuseum collection. It was reported to be the chest in which Hugo de Groot escaped his imprisonement at Castle Loevestijn. Using the new method, we were able to capture more tree rings than were visible on a photograph of the same plank. Although this proved the efficacy of our approach, unfortunately, it did not lead to a tree ring series that was long enough to cross-date with reference chronologies.

In **chapter 4**, the marker-based imaging protocol was applied to an object from the J. Paul Getty Museum collection. The 3D reconstruction obtained using our new methods led to knowledge about the production process that was unknown before. Different layers of plaster and metal rods were clearly visible. From the CT scans it could be deduced that the object had been reconfigured from an earlier model to its current shape by breaking it up and adding layers of material to create a new shape.

In **chapter 5**, several objects were used to illustrate the added value of a visualisation tool that combines CT imaging with surface scanning. Two objects from the British Museum collection were presented: a mummy mask and a turquoise mosaic jaguar. From the Rijksmuseum collection we presented two other objects: a shoe in the shape of a whale, that is also a bottle, and a cutlery case. In all these case studies, new information was gathered by the scanning and visualisation about the making process, material use and relation between external and internal features.

6.2 Continued research

In this thesis we have shown the knowledge gain from applying our newly developed methods and techniques on case studies from museum collections. The research presented in this thesis often sparked new questions which led to further research on objects and publications in the cultural heritage domain. Each of the chapters has led to a related publication by colleagues from the cultural heritage domain. Although these publications are not presented as part of this thesis, they were a direct result of the research presented here.

The CT scan of the cornett in chapter 2, led to further research into its making process and the question whether the combination of two woodtypes could have been original or more likely a later restoration [64]. The *Holy woman with lantern*, which was also featured in that chapter, was dated and its provenance was determined based on the CT scan. This led to insights in the Dutch wood trade [63]. The success of this CT scan led to a new project, investigating a panel painting attributed to Rubens' studio for dendrochronological dating. The CT scan contained a surprise: the painting was not painted on the oak backboard as orginally thought, but on a tropical wood board that was glued onto the oak board. This result has important implications for the analysis and dating of panel paintings [60].

The acquisition technique presented in chapter 3 led to further investigation of the chest to determine its age and provenance [61], was featured in the NPO (Dutch national television) television series *Historisch Bewijs* (Historical Evidence)[11]. The research team received the NWO Team Science Award for this interdisciplinary collaboration in 2021 [51, 67].

The newly acquired knowledge about the making process of the *Python Killing a Gnu* in chapter 4, will be included in a catalogue detailing the sculpture collection of the J. Paul Getty Museum (author: Madeline Corona). The challenges for CT scanning the cutlery case for chapter 5 were the metal threads in the object, which led to streaking artefacts in the reconstruction. These image artefacts were mitigated by filtering the X-ray beam, which led to a publication on the topic of tailoring the acquisition process to the object [106]. The other objects presented in chapter 5 are under further investigation and the conclusions of data analysis may lead to further publications.

6.3 Outlook

As outlined above, there is much to be won by integrating CT scanning as a research tool within the cultural heritage research practice. There are however challenges for broad implementation of CT scanning for cultural heritage, such as the accessibility of scanning facilities and the difficulty of moving precious collection objects. In the future, hopefully CT will become more accessible to museums for the investigation of their objects. A first step was made by making optimal use of existing hardware in museums in chapter 4. To increase the impact of this work, the developed algorithms should be accompanied by user friendly interfaces that are implemented in the X-ray suites. It is important to increase the accessibility of the algorithms developed in this thesis, such that on the longer term these can be used by museum professionals independently from a computational expert.

The interpretation of the data should be more accessible to increase the impact of CT imaging in the cultural heritage domain. We have provided a starting point with the plugin for Blender in chapter 5. The addition of colour information, three dimensional representation of the object and an interactive environment to inspect these datasets will lead to better understanding of the data and consequently more information can be retrieved from the datasets. In future projects, the fusion of other - 3D and 2D - imaging methods in an interactive way may be investigated. In the past years, the reproduction of art objects by employing 3D printing techniques and the perception of these reproductions has been investigated [130]. It would be interesting to explore the potential of these techniques for making CT scans more accessible for both researchers and the wider public.

One aspect that is often discussed in the cultural heritage field is the potential damage to objects due to the radiation. The energy of the X-rays and the exposure time influence the quality of the data and determine the effective radiation dose the object receives. The potential effect of the radiation exposure depends on the settings of the scan and the characteristics of the object [17, 83]. This potential effect has not yet been sufficiently investigated and would be an important topic for the investigation of cultural heritage with CT imaging.

Apart from the implementations of existing methods within the museum context, it is interesting to develop novel algorithms and data processing tools to automatically detect features within the data. Over the last years, image processing has been applied for example to read unopened letters [59]. Using machine learning methods, automated feature detection could be achieved. For example, it would be possible to look into automated tree ring detection, tool mark detection, classification of objects and many other applications.

The algorithms and case studies presented in this thesis show the importance of close collaboration between imaging experts and object experts. On the one hand, investigation by CT scans leads to new insights, new questions and further analyses of cultural heritage objects. On the other hand, the specific challenges presented by the diversity of cultural heritage objects give rise to the need to tailor acquisition processes and develop new algorithms. Thus, both the cultural heritage field and the CT imaging field benefit from this interdisciplinary research.