Tailoring x-ray tomography techniques for cultural heritage research
Bossema, F.G.

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Interactive visualisation of the interior and exterior of cultural heritage objects

A thorough understanding of the physical make-up of cultural heritage objects plays an increasingly significant role within material and art historical studies, as well as in conservation research. In tandem with scientific analytical methods, several 3D imaging methods are increasingly employed to obtain knowledge about an objects' manufacture, internal structure, origin and current state of conservation. Pieraccini and colleagues [144], for instance, identify five reasons for digitising collections using 3D imaging techniques: (1) to create digital archives; (2) to create physical replicas of artworks; (3) to provide remote accessibility; (4) to facilitate digital restoration; and (5) to monitor artworks over time. The exterior of objects can be imaged using surface scanning (e.g. structured light scanning or photogrammetry), producing a 3D representation which includes colour and texture information on the surface. The interior surface and internal structure on the other hand, can be captured using X-ray computed tomography (CT).

In recent years, surface scanning has become a popular tool in cultural heritage institutions to record and investigate archaeological and museum objects [6, 147]. Photogrammetry – a method that extracts a 3D surface model from a collection of

overlapping 2D images – has proved to be an accessible technique, since the acquisition can be performed with any camera, and by professionals as well as by the general public. Hence, many 3D models of cultural heritage objects can be found on popular online interfaces, such as Sketchfab [179], which, among others, hosts models by the British Museum [189] and the Metropolitan Museum of Art [118]. Some museums and institutions also use handheld structured light scanners to image their objects in 3D. 3D models are well-suited for outreach purposes and can increase accessibility of museum collections to audiences across the world [126]. X-ray CT is an absorption-based technique that provides a greyscale 3D image of an object, based on the density of its constituent materials. This 3D image can be sliced open virtually to reveal internal features. Investigations using CT imaging for cultural heritage objects have revealed valuable and sometimes surprising information, leading to, for example, a more accurate attribution to workshops or makers, a more detailed visualisation of the manufacturing process, or information on the present condition of the objects [37, 64, 81, 196]. The technique is not as easily accessible, both technologically and economically, as 3D scanning, since it generally requires objects to be brought to a specialised X-ray facility.

Besides their difference in capturing external and internal features, 3D surface scans and CT scans provide complementary information in regards to the models' surface as well. For example, if an object consists of a higher density material and lower density layers, a surface scan could capture the shape more accurately than the CT scan. On the other hand, CT scanning can recover a shape that was hard to capture using a surface scan due to glossy or transparent surfaces. Though both exterior and interior imaging techniques are used to investigate cultural heritage objects, few attempts have been made to combine various 3D imaging modalities [7, 77, 196]. Capturing and registering both external and internal features promises to be a powerful research tool for object-based investigation as well as for their digitisation [77]. It is challenging to fuse multiple 3D imaging modalities due to the diversity in shapes, sizes, and materials of cultural heritage objects and the different output formats of the various imaging techniques. There is also a lack of accessible and free software solutions that are capable of registering multiple datasets and visualising them interactively. To address this, a software solution has been developed to facilitate the fusion of 3D imaging datasets and provide an interactive environment for data analysis.

5.1   Related work and common practice

Working with surface scans, or 3D meshes in general, has a long history in fields outside of the cultural heritage sector. As a result, there is a wide range of software solutions available that allow for the editing and display of surface scans. Besides specialised commercial packages, such as Autodesk Maya [9] and ZBrush [117], there is a large community revolving around free and open source solutions. Two widely used examples are Blender [20], and MeshLab [52]. Furthermore, recent laptops and phones can come with native software able to open and display most 3D file types,

greatly facilitating the dissemination of such models.

There are multiple options for investigating and visualising CT data. Within the medical world, specialised software tailored to the scanner and purpose, is regularly supplied by the manufacturer of the hardware. Within laboratory settings, the use of free and open source software ImageJ [166] is widespread. While it is easy to view the data as a sequence of slices in ImageJ, its 3D capabilities are limited. For 3D visualisations of CT data, Slicer3D [71] is an open source solution that is used for both medical and academic purposes. There are also commercial options available, such as the versatile 3D visualisation programs VGStudio [201] and Avizo/Amira [192] but their cost limits their availability and suitability in cultural heritage institutions lacking sufficient funding. Another non-commercial option for volume rendering is Dragonfly [66], which offers a non-commercial licence for academic research. The fusion of different 3D data modalities, in particular CT and surface scanning has, to a limited degree, been addressed in other disciplines. For example, NASA launched the website Astromaterials3D [7], which provides interactive visualisations of space rocks, based on both a mesh of the exterior and X-ray CT data showing internal properties. However, no detailed protocol on how such registration was achieved has yet been made available. Other examples include forensic research [70, 200] and craniofacial modelling [99, 203].

In the cultural heritage field, different 3D data imaging modalities have also been combined. For example, Fried and colleagues [77], used CT scanning and photography to create 3D models of antique glass figures. These imaging modalities were chosen in order to overcome particular complexities that arise when attempting to scan transparent materials with 3D imaging techniques such as photogrammetry and structured light scanning. In their work, the CT data was used to provide the surface mesh if this was inadequately captured by the photography. To process the resulting images, multiple software packages were used, some commercial and some free and open source. Another example is the scan of the Sherit mummy (Rosicrucian Egyptian Museum), in which CT data and a structured light scan were combined using VGStudio [8]. Vandenbeusch et al.[196], acquired both a CT scan and a structured light scan of an Egyptian mummy mask from the British Museum collection. The two datasets were manually aligned in VGStudio [201] to obtain a combined dataset. That project, and the desire to optimise and automate this alignment process, was the inspiration for this work. As will be shown, the dataset of the Egyptian mummy mask will serve as one of the case studies for automated alignment and visualisation. Fusion of CT datasets and surface scans is not yet common practice for cultural heritage objects. The reasons for this are, firstly, that X-ray scanning facilities are not easily accessible due to the cost and the need to transport fragile objects, and secondly that, since the two datasets are recorded independently, a post-acquisition registration step is necessary. The latter often involves manual steps and the use of multiple software packages, sometimes open access, but also often commercial. This is labour-intensive and, depending on the packages used, can be costly. The lack of interactive data visualisation hampers optimal use by a wide range of users.

In this chapter, the second obstacle for integrating fusion of 3D imaging modalities into cultural heritage research is addressed via the development of an open-source

software package that provides tools for the multi-modal visualisation of CT scans, automatic registration with a surface scan, and interactive visualisation of the aligned 3D images.
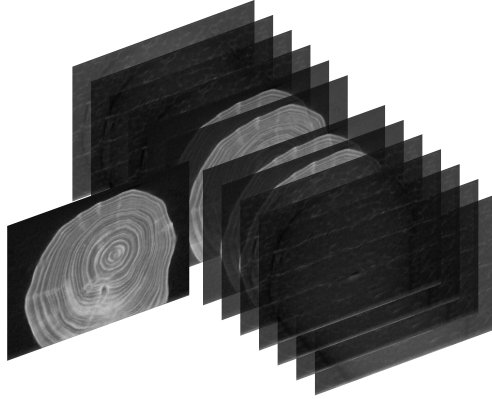
Figure 5.1: Stack of CT slices of a small wooden block.

5.2 Contributions and data availability

A plugin was developed within the open source and free 3D imaging software package Blender, enabling the combination of several 3D datasets. The reason for developing a new plugin is four-fold: i) existing single (commercial) visualisation packages often do not include all the required functionalities, such as the registration of multiple imaging modalities; ii) in existing commercial packages it is often impossible to access the source code and add or change functionalities; iii) by providing an open source plugin for an open source software package, it is accessible to all users and institutions; and iv) it is possible to continue development of the plugin and to add new features based on user experiences, with customisation and contribution open to all users. The plugin's acronym is INTACT - visualising the INTerior of Art through CT. The visualisation tool was developed as a collaboration between the Rijksmuseum and the British Museum. Four case study objects from the collections of these museums are presented, showing that the tool is versatile and cross validating that it can be used in different imaging facilities. The code is published at Zenodo, together with detailed step-by-step guidelines and a practice dataset (Figure 5.1, 5.2 and 5.5), including a CT scan and a surface scan that correspond to the provided instructions.

5.3 Material and methods

The INTACT plugin was developed for the open access software Blender. The decision to work with Blender was made for the following reasons: i) Blender runs on the

programming language Python, which allows users to easily build custom functions and plugins according to their own needs; ii) Blender is free and open source; and iii) the Blender Foundation safeguards older versions of the software, ensuring future compatibility of the tool, even if newer versions are released.

5.3.1 Data formats and visualisation

CT datasets consist of voxels, each with an assigned greyscale value based on the attenuation of the material of the object. These datasets are often represented as stacks of 2D slices (figure 5.1), each representing a cross section through the object. Two standard data formats are DICOM, commonly used in the medical field, and TIFF, commonly used in the computational imaging field. The cross sections are extremely useful for investigating detailed interior features that lie on a plane but it can be difficult to interpret due to the inherent limitations of looking at 2D cross-sections of a 3D object. It is, for example, difficult to find how internal features on the slice relate to the exterior and what their exact location is within the larger 3D object. Furthermore, characteristics that shed light on conservation issues or the process of making, are generally quite large and are not uniquely visible on a 2D plane. Visualising these features in 3D facilitates their interpretation, especially by cultural heritage professionals who are trained to look at materials and objects in 3D, and not as 2D cross-sections. For the plugin, the desired visualisation options of the CT data included both the 2D slices (figure 5.2b) and a 3D volumetric representation (figure 5.2c). Furthermore, in terms of functionality, there was a requirement for the tool to be able to dissect the volume representation in any direction, to focus on certain features, while allowing the corresponding 2D slice at the location of interest to be shown.

Surface scans are displayed as meshes consisting of a large set of triangles or faces, with associated colours and textures (figure 5.2d). A common type is the wavefront OBJ file format (.obj), which stores vertex coordinates, texture coordinates (UV) and normal. OBJ files can reference associated Material Template Library files (.mtl), that define material properties as color, reflectivity, transparency, and ambient, diffuse and specular coefficients. The Material Template Library files reference texture files (.png/.jpg/.tiff) to be applied to the 3D model. The way in which these files are created and their resulting quality/resolution is dependent on the hardware and method of data collection (e.g. photogrammetry with an affordable phone or structured light scanner with an expensive premium handheld scanner). For the plugin, the implemented option is an .obj file with material and texture files stored in the same folder. It should be noted, however, that it is possible to skip this step in the plugin user interface and instead use Blender's native capacity to load a large number of other types of 3D meshes. These, once loaded, can consequently be used in the next steps of the plugin. This opens up the possibility to use this plugin with any of the presently 3D mesh filetypes currently available in Blender.

When the surface and CT scans are aligned, the plugin is designed so that both the surface scan and the volume representation can be sliced through in tandem (figure 5.2e,f), to facilitate the evaluation of the relationship between the exterior

and interior features. As such, the visualisation is easy to manipulate and inspect interactively. Since the surface scan and CT scan are different data modalities, there is a requirement for a mesh to be generated from the CT data prior to registration of the two datasets. Surface scanning and CT scanning are not always available or co-located at the same institution. Therefore, through the plugin it is also possible to visualise data of either imaging modality individually. The presented visualisation tool is a post-processing tool, for use after the collection of datasets.
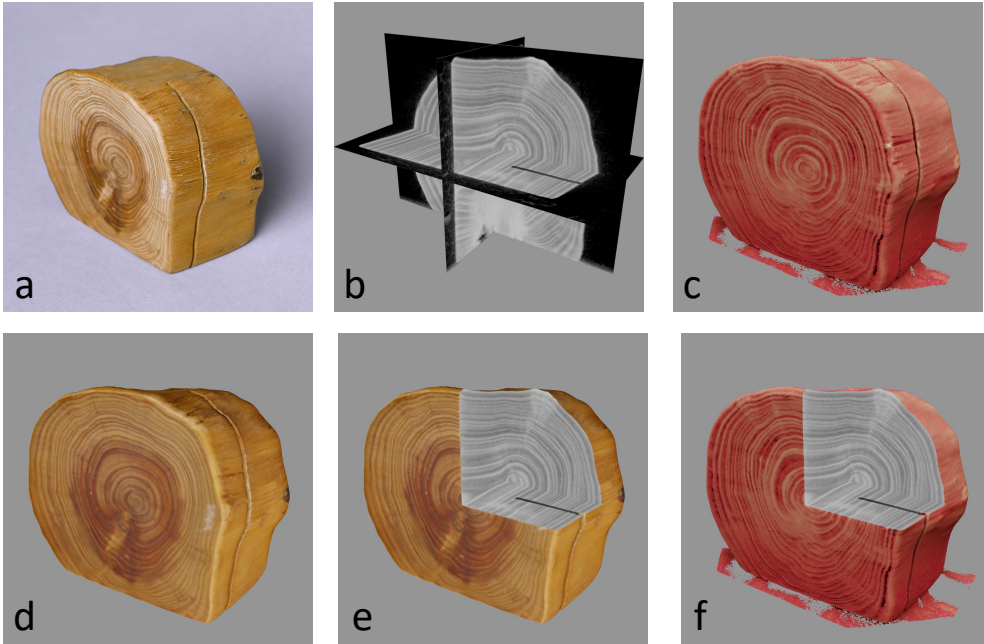

Figure 5.2: a) Photograph of a small wooden block (h 5cm x w 6cm x d 3cm), b) X-ray CT scan represented as orthogonal slices, c) CT 3D volume render, d) surface scan, e) combined image modalities showing surface scan and slices, f) CT 3D volume render and slices.

5.3.2 Code

The INTACT plugin was programmed in Python and builds upon and extends previous work. For CT data visualisation, both a volume representation and slice representation were desired. Furthermore, a function to generate a mesh from the voxel data was required to allow automatic alignment with the surface scan. The BDENTAL [57] plugin provided these functions and was therefore used as a base for the INTACT plugin. The code for loading DICOMs, generating the CT mesh and CT slices stems from there. The volumetric visualisation of the CT scan is achieved through displaying the data as a stack of thin slices. The user can choose the lower threshold of the displayed CT values. To align the two meshes (CT mesh, surface mesh), an iterative closest point (ICP) algorithm [207] was employed. In the plugin this alignment was done using an ICP implementation by Niels Klop [107]. Both these plugins have been released under GNU GPL licence, which means they can be used and modified freely.

The functionality of the INTACT plugin was extended by adding the capability to load CT data in TIFF format, to choose the colour of the CT volume render and to load a surface scan. Next, an interactive visualisation was designed. First, a clipping box was created using Blender's 'boolean' modifier. This modifier allows the box to cut into the surface scan and CT data, removing everything within its bounds from view. The CT slices were then parented to the clipping box, so that when it was moved, the corresponding slices could be shown on the three orthogonal sides of the box. In the final step, several image and video creation tools were included to make media for presentations and outreach. In this step the user can place the camera and render images from the same standpoint, choose the background colour of these images and make rotational videos along the x, y or z axes. The functionalities of the plugin were arranged in the user interface (UI) to make each tab correspond to a step in the workflow described below and to prompt the user to undertake actions in the right order.
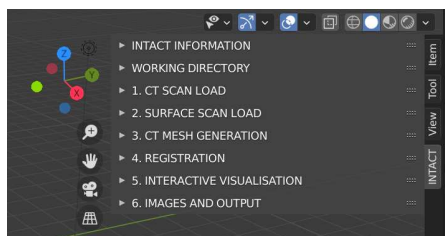
Figure 5.3: The plugin UI, each step in the workflow corresponds to a drop-down menu.
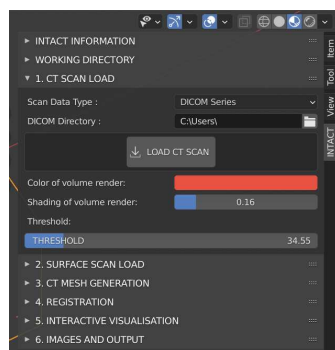

Figure 5.4: Example of the UI, the drop-down menus for loading the data and adjusting the visualisation of the CT volume representation.

5.4   Results

5.4.1   Workflow for generation of the interactive visualisation

To use the INTACT plugin, the user first needs to install Blender and download the .zip file containing the plugin. After installation, the workflow to set up the interactive visualisation interface consists of the steps outlined below. Within the plugin UI, each step is represented by a drop-down menu (see figure 5.3, 5.4). The workflow is also represented as a flowchart in figure 5.5 and detailed steps can be found in the guidelines in appendix B. A video recording of the workflow for the wooden block used to create figures 5.1, 5.2 and 5.5 is provided in the online Supplementary Material of [43], along with a short output video.

1. Load the CT data (DICOM or TIFF).

2. Load the surface scan data (.obj).

3. Determine a threshold value for the CT volume representation and generate a CT mesh.

4. Register the surface scan to the CT mesh by first performing an initial manual alignment and then using the ICP algorithm to refine the alignment. Several options for this step are provided. The user can enable/disable the scaling of the surface scan, in case of imperfectly calibrated scanning hardware. Furthermore, several parameters of the ICP algorithm can be altered, such as the number of iterations and the percentage of outlying vertices that is allowed. While these options may be of interest to advanced users, the standard settings have proven to work for our case studies. Lastly, if either the surface scan or CT scan are incomplete, manual selection of parts of the two meshes can be carried out to ensure registration occurs only based on correctly scanned sections. Carry out visual inspection to determine whether sufficient registration accuracy has been achieved.

5. Set up the interactive visualisation environment:

   (a) Generate CT slices.

   (b) Generate a clipping box that allows the simultaneous slicing of the CT volume representation and surface scan.

   (c) Link the CT slices to the clipping boxes. The side of the box then shows the cross-section of the object at that location.

   (d) Cut the CT slices to only show the interior (making the surrounding air transparent). Either based on the surface scan, if available, or based on the chosen threshold, if only a CT is loaded.

6. Set up camera and video options to create images and videos.
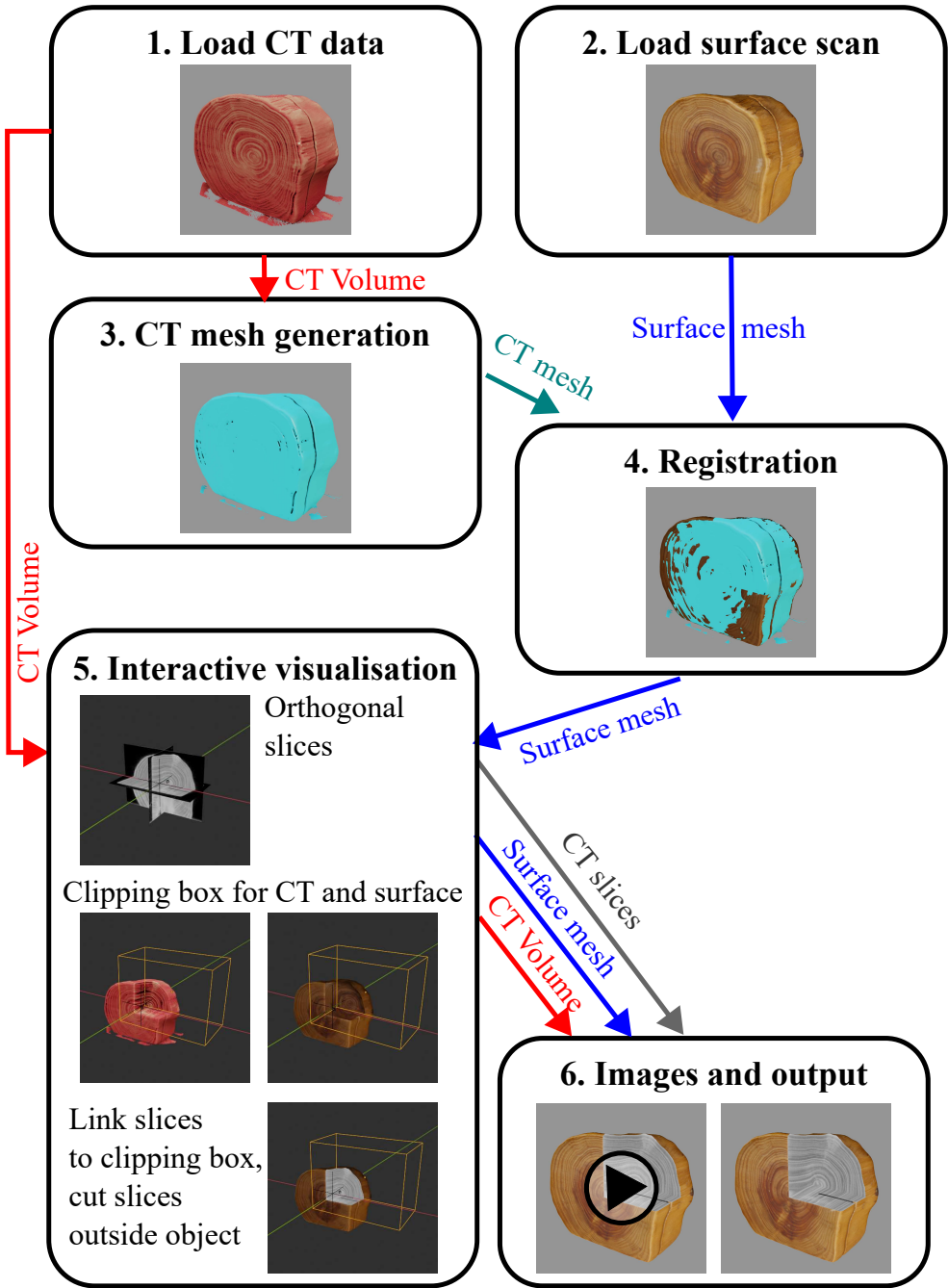
Figure 5.5: Flowchart of the workflow to combine CT datasets and surface scans. The results of the application of the visualisation tool developed to the case study objects are presented in figures and videos.

5.4.2   Case studies

The versatility of the visualisation tool is demonstrated with four case studies (figure 5.6), showing the diversity of sizes, shapes and materials the plugin can be applied to. Below, the objects and the challenges related to each are described, as well as the questions that guided the data acquisition and analysis. The objects were investigated to answer questions about their manufacture, their material nature, and their current conservation state.

   The objects from the Rijksmuseum collection were CT scanned at the FleX-ray laboratory [53], and those of the British Museum objects were carried out at the in-house CT facility of the Scientific Research Department at the museum. The structured light scans of all four objects were acquired using an Artec Space Spider [97]. For the visualisations, the CT scans and surface scans were downscaled to allow investigation without the need for a powerful computer. The parameters of the case study datasets can be found in the online Supplementary Material of [43].


Figure 5.6: Case study objects. 1. Jaguar figure (British Museum, Am,+.165). 2. Cutlery case (Rijksmuseum collection, object nr. BK-NM-3086). 3. Bottle in the shape of a whale (Rijksmuseum collection, object nr. BK-KOG-1382) 4. Mummy mask (British Museum, EA 29472). Images 1 and 4 are © The Trustees of the British Museum, 2 and 3 © Rijksmuseum, Amsterdam.

1. Turquoise Mosaic jaguar figure

Size: h 17cm x w 9 cm x d 14cm.

The Turquoise Mosaics are a group of objects from Mesoamerica, dating between the 14th Century and 1521, nine of which are housed in the British Museum. The group includes a seated figure (Am,+.165), thought to be a jaguar, fashioned from wood (Cedrela odorata) and intricately decorated with tesserae of multiple different materials including turquoise, malachite, pyrite and mother-of-pearl (Pinctada mazatlanica) shell [187]. The tesserae are attached to the figure by a layer of pine resin covering most of the wood surface. Ongoing research into this object is focussed on its method of manufacture, its constituent materials and its current condition.

The CT images and 3D surface render visualise the interior of the jaguar and give insights into its construction, showing that several pieces of wood were used in making the figure, rather than a single piece (figure 5.7). A key advantage of combining the CT and surface scans of the figure is the connection between the material properties and their appearance: tesserae with visually similar colours have clearly different densities, readily showing a distinction between, for example, (less dense) turquoise and (more dense) malachite, without the need for destructive analysis or time-consuming point-by-point analysis. The figure is under further investigation and further findings will be part of a forthcoming publication on the Turquoise Mosaic objects.
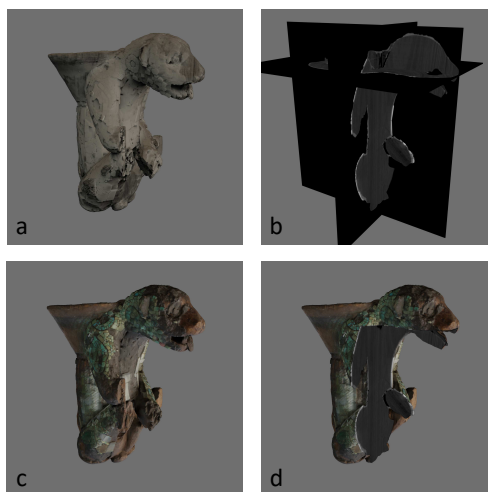
Figure 5.7: Images made with the INTACT plugin of the Turquoise Mosaic jaguar figure: a) CT volume render, b) orthogonal CT slices, c) surface scan, d) registered surface scan on CT volume and cut through the object showing orthogonal slices.

2. A 17th-century cutlery case

Size: h 22cm x w 2,5cm x d 3,4cm.

This early 17th-century encasement [158] has three cavities that once held pieces of cutlery. The case is made up of a variety of materials, with a stiffened paper internal structure covered by a purple velvet exterior, which is elaborately decorated with silver thread, gold thread, and small pearls in floral motifs. Questions about this object were related to its manufacturing process, in particular, how the internal compartments are constructed, what materials were used throughout the object, and whether the velvet exterior was pre-embroidered or not. The challenges during CT scanning arose from the materials in this object, as the metal threads caused image artefacts in the 3D reconstruction, which were mitigated by filtering the X-ray beam [106]. For the registration of the CT scan and surface scan, a further challenge was the rotational symmetry of this object (both the front and back of the case had similar decorations), making an accurate initial, manual, alignment necessary based on distinct features such as missing pearls. The lid and case were surface-scanned separately (figure 5.8a), to also show the intricately decorated part of the case that slides into the lid (figure 5.8b). Both scans needed to be registered to different parts of the CT scan. This was done by manually selecting the registration area for the ICP algorithm (see for more detail the INTACT User Guidelines in appendix B.

The CT scan of the 17th-century cutlery case allowed us to gain insight into how a variety of materials were used in its construction. The inner compartment, divided into three, is made from (stiffened) paper, and is held together by a surrounding outer shell made of leather. The absence of any holes in this leather outer shell suggests that the velvet exterior was pre-embroidered, and then attached using glue, not stitched onto the case. The registration of the surface scan to the CT scan in particular allowed the path of materials that are visible on the exterior to be traced as they are folded inside. An example of this is the golden threaded decoration running vertically along the object, as well as around the rim of the cap. Being able to access the 3D model exactly at this point (figure 5.8d), to reveal the corresponding slice (figure 5.8f), clearly showed that gold thread extends into the object only very slightly, which strengthened the hypothesis they were in fact glued, rather than stitched onto the velour.

Figure 5.8: a) Surface scan of the cutlery case and lid - aligned using the CT of the full object, b) surface scan of the case only, c) CT volume representation and surface scan of lid, d) surface scan, cut open to show the CT slices, e) corresponding vertical slice, f) corresponding horizontal slice.

3. Bottle in the shape of a whale

Size: h25 x w30cm x d11.

A 17th-century whale shaped object with a shoe sole and cork-tail that functions as a bottle [155], is a rather curious object hypothesised to have been made as part of a test to become a master in the cobbler's guild. The object is mostly made of leather, alongside a wooden heel, a cork, and metal reinforcements. Questions related to the object were focused on its crafting process and use: how and why was it made? Is the object fully hollow, which would have allowed it to hold liquid, or is it merely suggestive of a bottle? The challenges for CT scanning were mainly its odd shape. To obtain a full CT image, multiple scans were recorded with the source and detector at different positions, also called 'tiled scanning' [37]. The object was held upright in a plastic container, to facilitate tiled scanning and to make sure the tail, which contains metal, did not overlap with the rest of the object on any radiographs acquired throughout its rotation to avoid metal streaking artefacts on the main body of the whale. For structured light scanning, the dark and reflective surface provided a challenge, as well as the object's deep mouth that made it difficult to reach all the corners with the light beam.

3D visualisation of the CT data provided valuable insight into the construction of the object, such as the fact that the top part of the whale is constructed from just one intricately shaped piece of leather stitched along the back of the whale's tail. Inside the object, we can trace this stitching along the inner sole, where multiple pieces of leather from the bottom converge and are attached to one another (figure 5.9a). Furthermore, it quickly became clear the object is in fact fully hollow, even under the tongue (figure 5.9b), indicating that it could have in fact been used as a bottle and perhaps was not merely decorative. The overlay of the 3D surface scan and the CT data visualised features that had previously gone unnoticed when inspecting this object with the naked eye alone. While the presence of circular features reminiscent of eyes had been noted before, the overlay of data clearly revealed two additional circular marks on top of the whale's body (figure 5.10). What their function was or what these represent exactly is unclear at this stage, but they might be a pair of blowholes.
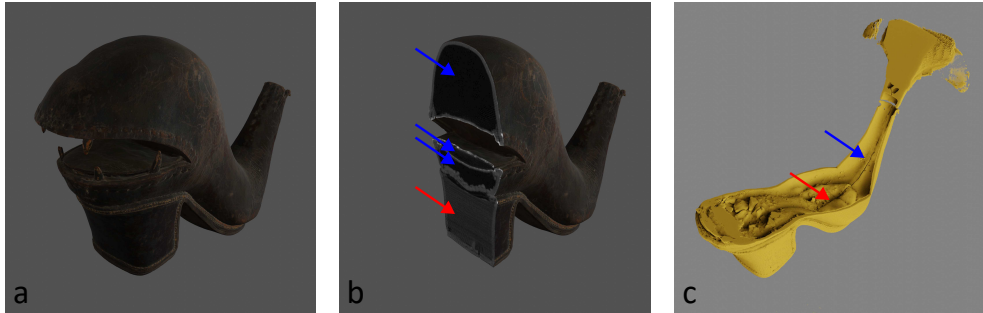
Figure 5.9: a) 3D surface scan of the body part of the whale. b) Slicing through the 3D surface scan, showing the corresponding CT slice, revealing the hollow spaces inside the object (blue arrows) and tree rings in the heel (red arrow). c) The volumetric representation of CT data cut through, to visualise the stitch along the back of the tail (blue arrow) as well as multiple pieces of leather converging in the insole (red arrow).
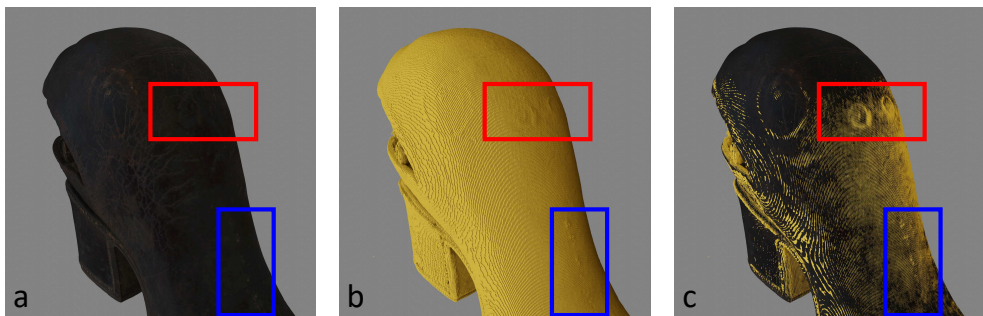

Figure 5.10: Detail, showing eye and blowholes, a) Surface scan, b) CT scan, c) CT and surface scan overlay. The volumetric representation of the CT data (in yellow) clearly reveals two circular features that had previously gone unnoticed (red box). In the blue box we see marks that are presumably made by stitches.
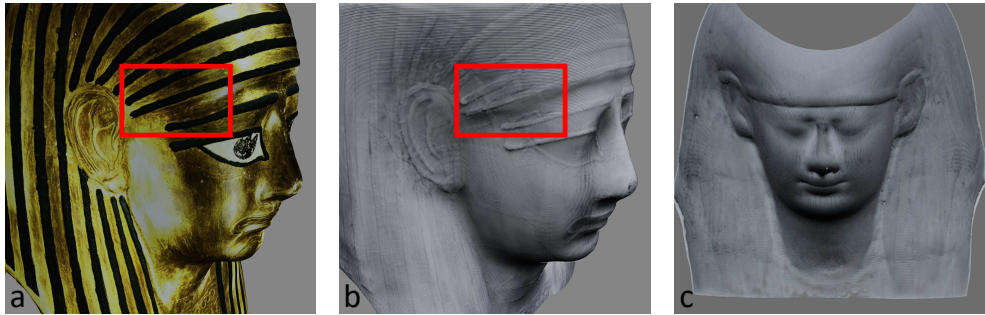
4. Mummy mask

Size: h 44cm x w 22cm x d 31cm.
The ancient Egyptian mummy mask [188] is dated from the mid to late Ptolemaic Period (second to first century BCE). The mask is made in cartonnage: layers of textile covered with plaster, onto which a layer of paste was applied before its decoration with painting and gilding. Due to the mask's width being greater than the field of view of the X-ray imaging detector, a region of interest CT scan was performed, capturing the mask in the region of the face only (Vandenbeusch et al., 2021). The reflective gold surface was a challenge for surface scanning. For the fusion of the two scans, moreover, the hollow interior, thin mask walls and partial CT data posed a challenge. Accurate registration of the scans required focusing on areas captured by both methods. The CT segmentation captured both the inner and outer surfaces of the mask within the region of interest, while the surface scan captured the outer surface of the entire mask. Accurate registration therefore required manual selection of vertices only within the region of interest and outer mask layer for both the surface scan and CT segmentation. This was a challenge because the outer and inner layers of the mask are very close together due to the thinness of the mask walls (for more detail please refer to the guidelines in appendix B).

In figure 5.11 the results of registration and visualisation using the INTACT plugin are shown. The CT slices give insight into the construction, for example the nose is made up of more layers of textile than the rest of the mask; these layers act to thicken and reinforce this potentially fragile region. On this object the colours and decorations are of importance, and the combination of the imaging modalities is of high value. An example is shown in figure 5.12: on the CT images, patches can be identified within the vertical stripes. Switching to the surface scan and cutting the object open, shows that these patches correspond to the gold and that they are visible where the gold leaf overlaps. This shows that the gold was applied as sheets and then polished.
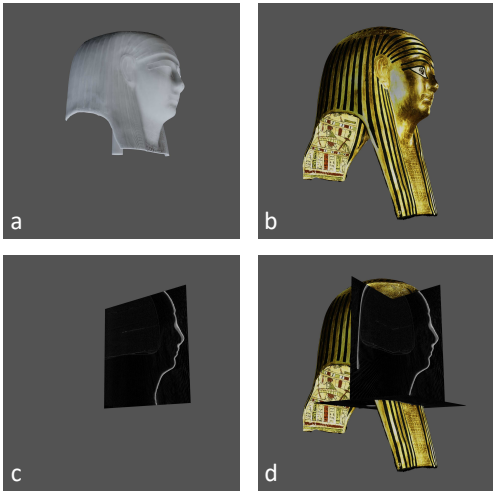
Figure 5.11: Images of the mummy mask, generated using the INTACT plugin. A) CT volume render, b) surface scan (note: the interior of the object could not be captured with structured light scanning; a mirror of the outside surface is represented here, rather than its actual undecorated interior), c) a CT slice, d) the surface scan registered with the CT scan, showing orthogonal slices (coronal and sagittal views are visible) where the object is cut open.

Figure 5.12: a) Surface scan of the mummy mask, b) CT scan of the mask, registered to the surface scan (red boxes indicate regions of overlapping gold leaf), c) CT scan showing the mould impression on the mask's interior surface.

5.5 Discussion and conclusions

The objective of this work was to create a single open-source and free workspace for cultural heritage experts to inspect two different types of 3D data in tandem: surface scans and CT scans. It combines colour and texture information on the exterior with the interior features, relating what can be seen with the naked eye to the structural composition, which leads to knowledge gain, optimised object analysis and improved digitization of objects. The plugin provides a free and simple to use interactive environment to examine 3D images for museums and heritage institutions. The plugin is openly available for use and fully enables customisation/extension, therefore it is hoped that it will be further developed based on user experience.

The INTACT plugin provides a way to interactively visualise and analyse 3D CT data, with a few simple steps. Users can view the volumetric representation of the data, as well as virtually cut the object open to see the 2D slices. This facilitates the inspection of internal features both in 2D and 3D. If a surface scan is available, the INTACT plugin provides all the tools and an easy step-by-step guideline to register this onto the CT data and to simultaneously inspect and cut open both datasets. After alignment is complete, the resulting transformation parameters can also be exported and used in other visualisation software packages. The processing times and file size limitations are dependent on the hardware used. For the case studies, we decided to downscale the CT scans and surface scans to ensure the workflow and interactive visualisation could be carried out on a laptop for accessibility to a broad audience. The processing time of the registration was then in the order of minutes and the entire workflow to obtain the interactive visualisation takes less than 15 minutes. Higher resolution visualisation and output images could be created when a more powerful computer is available.

The INTACT plugin was developed with ease-of-use for a broad audience in mind. The diversity in size, shape and materials of cultural heritage objects makes generalisability a challenge, since each unique object may require object-specific tailoring of acquisition and visualisation. Experienced Blender users can freely use the large sets of tools already included in Blender alongside the plugin to improve their data and the visualisation, for example by the mesh repair tools if the surface scan contains holes. The plugin is provided fully open-source, so other researchers are invited to extend it to the users' specific use cases. The versatility of Blender will allow dedicated and experienced 3D software users to self-optimise the potential of the plugin, by for example designing more complex, sophisticated and object-specific visualisations and videos. To this end, the plugin is provided fully open-source on GitHub and those who would like to contribute are encouraged to do so via that platform. The version used for the images in this manuscript is provided on Zenodo, along with the sample dataset that was used to create the Guidelines and the images in this article.

During the development of the INTACT plugin, datasets of a small wooden block and four accessioned museum objects were used, from two different facilities. The case studies show the importance of 3D imaging techniques for cultural heritage research, as

well as the added value of combining multiple techniques to retrieve more information for research. Additionally, the resulting images and videos are exceptionally well suited for outreach purposes. Future work could include extending the features of the visualisation tool with automatic quantified assessment of registration accuracy, automatic segmentation of materials, overlaying of multiple meshes in cases where multiple surface scans were acquired [152], and integration of output with other platforms, such as interactive PDFs [186] and open access online platforms for dissemination purposes.