

# Post-Processing of Musical Instrument 3D-Computed Tomography Data for Conservational Applications

Niko Plath<sup>1</sup>, Sebastian Kirsch<sup>2</sup>

<sup>1</sup>Institute of Systematic Musicology, University of Hamburg, Germany

<sup>2</sup>Germanisches Nationalmuseum, Nürnberg, Germany

## Abstract

Industrial 3D-computed tomography (CT) has been established as a powerful method for non-destructive examination of objects of cultural heritage in restoration and conservation science. The produced data not only provide views into internal parts of objects, but also hold a lot of information accessible through subsequent applications. This work presents utilizations of 3D-CT data and demonstrates possible workflows based on the use of non-specialized personal computers and open source software.

## 1. Introduction

High resolution industrial CT can achieve X-ray data with a spatial resolution of around 100  $\mu\text{m}$  which opens the method for many fields of research, but also presents challenges regarding post-processing. One of these is the required high-performance computational resources to process the achieved amount of data: Scanning of an entire violin with a spatial resolution of 100  $\mu\text{m}$  yields a reconstruction consisting of up to 8000 single images with 2.5 Megapixels resolution which can have an overall cumulative size of more than 60GB. Another challenge is the need of expertise to be capable of handling the data in order to extract available information. Last but not least, common solutions are based on proprietary, mostly very expensive, software.

The research project MUSICES is developing a standard for computed tomography of musical instruments [1]. It mainly includes the technical settings, important steps for the storage of metadata and advices for mounting and transport to ensure a high quality in imaging and data handling. In addition to this fundamental research, the current work presents approaches to post-processing the recorded CT data in order to make the obtained information easily accessible for further research.

## 2. Hardware requirements

All described processes are intended to run on a current personal computer, only a few hardware requirements have to be considered. Due to the mentioned size of the datasets, working memory is most crucial; at least 16GB of memory is needed, 32GB is preferred. Since several processes challenge the graphics card, a standalone GPU leads to smoother image navigation and decreased rendering time. All given information is considering the technical disposability in 2017. All suggested programs are open source / freeware and work on Windows and Linux.

## 3. Description of workflow

All following examples refer to the open medical standard DICOM (Digital Imaging and Communications in Medicine) as a starting point. The file format is widely accepted, and compared to proprietary formats a lot of free viewing and processing software is available.

### 3.1 Preprocessing of DICOM files

To minimize the needed computational resources, the cross-sectional images are rotated and cropped in a way that they show only the proposed region of interest (ROI). This can be batch-processed with script languages like *Python* which support handling of DICOM files. To preserve dimensional units, note to carry the pixel spacing information from the imported header when exporting the edited slices. For a first approach, the images can also be downsampled by a factor of 2 (reduces the needed memory to  $1/2^3$ ).

### 3.2 Segmentation and classification of sub-volumes

Segmentation allows to distinguish and extract sub-structures with homogeneous properties from a heterogeneous object. It is widely used in medical applications to discriminate tissues or to generate content-related regions in machine vision. Open-source medical image analysis software is available to a great extent and can be utilized for the examination of musical instruments. Although there are comprehensive and powerful programs like *3DSlicer* or *ImageJ* the authors suggest using *ITK-Snap* for the segmentation process, which has a more limited range of functions but is specialized on semi-automatic segmentation (based on region growing) and performs well even with large-scale data sets [2]. Each voxel is allocated to exactly one of the defined sub-volumes, therefore different sub-volumes cannot overlap, which is crucial for subsequent applications like physical modelling or rapid prototyping. Note that filtering or re-meshing the individual sub-volumes can destroy this ratio.

### 3.3 Extraction of surface data

Since sub-volumes are generated according to their homogeneous properties, the respective surface data adequately describes a body. This leads to a massive reduction of data. Handling, therefore, is simplified (3D meshes of instrument parts can easily be sent per email) and individual sections can be stored in databases for specific research tasks. For the exact determination of the surface, a scan with as less noise and other image errors (e.g. metal artefacts) as possible is necessary. However, even for an excellent scan the exported surface meshes (most commonly stored as .stl files) may have diverse defects, e.g. self-intersecting faces, non-manifold edges or unreferenced vertices. The software *MeshLab* is recommended for this purpose, which provides various automated mesh cleaning filters. A reliable way to obtain a clean and watertight mesh is a Poisson Surface Reconstruction (the algorithm is implemented in *MeshLab*) but note that since this is actually a re-meshing, individual sub-volumes could overlap afterwards [3].

### 3.4 Processing of Sub-Volumes

Sub-volume data can be utilized for physical modelling (e.g. Finite Element Method), thus allowing for evaluation of the vibroacoustic behaviour of instruments, even in non-playable condition. With regard to conservation issues physical modelling can also provide insights into the structural behaviour of displayed instruments under long term mechanical loading [4]. The 3D modelling software *FreeCAD* provides a module to perform simple finite element analysis (FEA), *OpenFOAM* is mainly a tool for computational fluid dynamics but also includes FEA. Certainly, to get scanned complex geometries with heterogeneous material properties working well in physics simulation software is still a challenging task [5].

Since historical instruments are in many cases not in playable condition, exact copies are a big desire. Using extracted surface data of CT scans, whole instruments can be reproduced with high geometric precision as well as missing parts for restoration purposes [6]. Manufacture may be obtained by additive (3D printing) or subtractive methods (CNC milling). Several consumer

3D printers based on fused deposit modelling (FDM) can achieve a vertical spatial resolution of 200  $\mu\text{m}$ , printers based on stereolithography (SLA) realise comparable resolutions in all axes.

From a vibroacoustic viewpoint the substitution of complex materials like wood is difficult. Although it is possible by now to print composites of wood and polyester, the exact orthotropic material properties are not yet reproducible. Nevertheless, rapid prototyping can be utilized e.g. during pre-planning of restoration projects or to aid the understanding of complex mechanical details, in workshop and exhibition.



*Fig. 1: Exemplary results of the proposed workflow (clockwise): photo of the kit violin, cross-sectional CT image (inverted grey values), rendering of segmented sub-structures, finite element model from surface data of the bridge.*

### 3.5 Measurements and technical drawings

The software *ImageJ* is proposed for performing high precision measurements on the scans at any location i.e. on otherwise inaccessible parts. Also thickness mapping is possible which can be a useful tool to illustrate the distribution of wall thicknesses or material densities. The results can provide useful information for further research or technical drawings. The latter can also be

produced using the 3D data itself, since CAD software like *FreeCAD* can produce technical drawings directly from the achieved surface data.

### 3.6 Dendrochronological dating

Cross sections of CT data can be utilized for dendrochronological dating [7]. The required resolution depends on the smallest distance between the annual rings, but usually a spatial resolution of 80  $\mu\text{m}$  to 100  $\mu\text{m}$  is sufficient. Using cross sections as a basis has a lot of advantages in cases that certain wooden parts are covered with dark varnish or the part to be analysed is implemented in the instrument like in the case of a patch under the soundboard of a violin.

## 4. Case study: Kit violin

The proposed methods are exemplarily applied to one object scanned during the MUSICES project: a so called kit violin (pochette), a small violin built in the 17th century in Italy, mainly used during dance lessons (see Fig.1). For X-ray CT methods this is a challenging object, because like most musical instruments, it consists of various materials with highly differing densities (in this case including conifer wood, ivory, ebony and mother of pearl). The cross section illustrates the curved shape of the body and the top plate. A slight buckling in the top plate is observable, caused by the sustained pressure of the sound post. It is possible to conduct measurements at any point of the top plate or body as well as distances between the annual rings. The segmentation image visualizes spatial disposal of the different instrument parts (e.g. positioning of the sound post) and allows further applications like e.g. rapid prototyping. Using physical modelling the vibrational behaviour of parts like the ivory bridge could be analysed and virtually compared to e.g. a bridge made out of maple.

The presented results show straightforward and inexpensive ways to handle and process CT data of musical instruments, which are easily transferable to a wide range of objects of cultural heritage with various requirements in conservation, restoration or technological issues.

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