MUSICES - Musical Instrument Computed Tomography
Examination Standard: The Final Report Featuring Methods for Optimization, Results of Measurements, Recommendations, Checklists and Meta-Data Models

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Abstract
Digitalization of irreplaceable objects of cultural and/or historical significance as field of research is gaining more and more importance recently. The Germanisches Nationalmuseum (GNM) in Nürnberg, Germany, and the Development Center for X-ray Technology (EZRT) of the Fraunhofer Institute for Integrated Circuits (IIS) in Fürth, Germany, were jointly working in the MUSICES project, addressing issues of 3-dimensional (3D) digitalization of historically important musical instruments. This project was funded by the German research association DFG (Deutsche Forschungsgemeinschaft) and ends in January 2018. The project partners developed examination standards that, independent of the deployed devices and operating staff, are set to deliver high-quality 3D volume data sets representing musical instruments. Plenty of representative examples carried out during the project ensure the applicability of the technical parameters. MUSICES has been dealing with testimonials of the manufacturing of musical instruments during the last five centuries. From 2015 to 2017, more than 100 historically remarkable objects in the collection of the GNM were digitized by means of fully 3D image acquisition with X-ray CT. The CT measurements were performed at the EZRT site in Fürth, where X-ray systems with maximum radiation energies of between 60 and 9,000 keV are used for CT scanning and reconstruction, as well as means for multispectral material analysis and algorithms for the correction, visualization and evaluation of image data. Several methods were applied to optimize CT parameters via extended studies of simulated virtual data sets. In detail, the simulated data sets were based on a simplified virtual representation of the respective specimen. Its orientation with respect to the axis of rotation and in case of dual energy measurements the spectral quality of both partial data acquisition runs were varied computationally until the minimum Shannon entropy of the resulting reconstructed slices was achieved. Parameters identified in such a way beforehand were then applied for the real measurement. Based on the evaluation of all acquired 3D-images, standard procedures are proposed. The image data itself are made available to the broad public. Additionally, the final report published in 2018 provides various checklists for preparation, transport, positioning, best practice for measurement of various classes of instruments (wood/metal/mixed/other resp. size and shape), an elaborate data base structure description for long term archiving and methods for detailed image quality assessment.

1 Introduction
The digitalization of one-of-a-kind objects of high cultural or historical importance as field of research is gaining more importance recently (cf. e.g. [1-5]). The Germanisches Nationalmuseum (GNM) in Nürnberg, Germany, and the Development Center for X-ray Technology (EZRT), a department of the Fraunhofer Institute for Integrated Circuits (IIS) in Fürth, Germany, were jointly working in the MUSICES project, addressing issues of 3D-digitalization of historically important musical instruments. Funded by the German research association DFG (Deutsche Forschungsgemeinschaft), the MUSICES project partners drew up examination standards that are set to deliver
high-quality 3D image volumes representing musical instruments - independently of the deployed devices and operating staff [6]. About 100 representative examples carried out during the project ensure the applicability of the technical procedures. An international team of experts from European institutions (e.g. St Cecilia's Hall Concert Room & Museum in Edinburgh) has been advising the project team during their investigations. In general, MUSICES is dealing with testimonials of the manufacturing of musical instruments during the last five centuries and aims at the fully 3D image acquisition of musical instruments with X-ray CT.

1.1 A Representative Selection of Historically Relevant Instruments
From 2015 to 2017, more than 80 historically remarkable objects in the collection of the GNM were digitized. Another almost 30 musical instruments were provided by partner organizations, i.e. the Musikinstrumenten-Museum, Staatliches Institut für Musikforschung Preußischer Kulturbesitz (Berlin), the Ethnological Museum (Berlin), and the Museum for Musical Instruments at Leipzig University.

The CT measurements were performed at the EZRT site in Fürth (Bavaria), where X-ray CT systems with energies of radiation between 60 and 9 000 keV are used for data capture. Image reconstruction software as well as means for multispectral material analysis and algorithms for the correction and evaluation of image data were provided by the Fraunhofer EZRT.

The musical instruments are classified roughly into three groups, depending on the materials used in the specimen. These are purely wooden instruments like flutes and violins; purely metallic instruments, i.e. all brass; and mixed materials like wooden wind instruments with metal keys, flaps or ornaments.

Within all these groups, samples of very different sizes could occur. For example the “Viola da Gamba” (MI5) with more than 1725 mm height requires essentially different methods than a “Violin by Hummel” (MI419) which is about one third in length (600 mm).

Besides of the mentioned three groups, there are instruments which show a complex mechanical structure as well as material composition or which are solitary, for instance harps, portable organs respectively automatically playing figurines.

1.2 Preparation of a CT Examination
One focus lay on preparation and planning of the inspection. Since the advanced industrial CT systems as well as medical scanners usually are not directly located inside a museum or magazine, we looked closely to aspects of transportation and packaging of an instrument, such that positioning and exposure with X-rays can be done without opening the protecting cover of the object.

During the complete measuring campaign climatic conditions, i.e. temperature and humidity complying with the conservation guidelines must be guaranteed. Temperature and humidity inside the X-ray cabinet are supervised via additional sensors. Methods were developed for fixing a highly valuable object inside an X-ray cabinet for up to sometimes more than 24 hours. Vibrations, mechanical shocks and percussions must be avoided. Fragile instruments are fixed with a vacuum cushion and a dedicated support structure, built from a base plate and a Plexiglas tube which can be located at several positions inside the base (cf. Fig. 1). Only a special polyethylene fleece, which covers the Styrofoam blocks, is in direct contact with the specimen. Thus the fixature can be adapted easily to the particular shape of the various objects.
1.3 Use Cases
A second important task was to analyze in detail the specific motivations of organologists to perform a CT-scan of an – in many cases unique – instrument. In each case, the scientific queries pose different requirements on image quality, which is quantified by for example spatial resolution.

The following list shows frequent reasons for CT-examination, based on the experience with the 100+ historical instruments:

- a quick inspection to check structural integrity; medium spatial resolution (between 200 and 300 µm) required.
- region-of-interest imaging to obtain information within a certain region of the instrument, such as adhesive bonds, damages caused by insects or moisture, or cracks which reach the surface. Spatial resolution of 50 µm or even less is needed.
- the full coverage of the whole instrument with accuracy of 100 µm or better to derive blue prints for the reproduction of the instrument or parts of it (e.g. to produce spare parts).
- an analysis of materials in the interior of the instrument or beneath covering layers. This issue affords high accuracy and reproducibility of the reconstructed material densities, i.e. a density discrimination of around 10%.
- the generation of 3D-images used for virtual exhibitions, educational reasons or, gaining more and more importance recently, 3D-printings of showcase replicas.

An overview of the whole procedure is sketched in Fig. 2.
Figure 2: Sketch of the principal workflow of a CT-Examination (of historically important objects like musical instruments). The specific instrument defines the requirements and a particular use case, to which the CT system and its parameters of operation must match. As output a volume data set is delivered which is to be archived as well as evaluated by the respective experts.

1.4 Collecting of the Object Data Relevant to Measuring

Data about the materials and sizes are decisive for planning the measuring duration, calculating the costs incurred and judging whether the project is feasible. Based on a description of the object, measuring parameters and the optimum positioning of the object in the beam path can be determined. Therefore, this information should be provided during the initial communication with the testing institute and ideally should comprise the following:

- a list of all materials including information about the location in the object: as a rule of thumb, when the density of a material is larger than 4 g/cm$^3$ (metals) also small parts should be mentioned. Special attention should be payed to lead (also in white lead). The metals aluminium, brass and lead should be mentioned separately as they differ in X-ray attenuation. While small decorative inlays of low density materials, like tortoise shell, are not highly relevant, small metallic nails should be mentioned if possible. With respect to X-ray physics, an object consisting of paper, cloth, pine and beech is regarded as made of one material. Also brass and German silver are similar.
- dimensions: Determine the size of the bounding box (or a bounding cylinder) around the object including the mounting.
- wall thicknesses, material thicknesses – also approximately: if these cannot be measured using conventional methods.
- extended planar structures: If the object contains extended planar structures, their extensions and locations should be specified. Examples are the flat back of a guitar or the plane formed by metallic strings in a grand piano.
- maximum transmitted length: Set up the instrument in the orientation it will assume during the measurement. For each material that contributes considerably to X-ray attenuation, find the largest distance that a ray can travel through this material. For instance, for a guitar with a flat back this is not the thickness of the ribs, but the width of the back.
- variations in object geometry (shape and density): If the overall shape of an instrument varies, more detailed measures are required additionally. For a
crumhorn, for instance, the dimensions of the straight tube and the lower bend should be provided. Also for a double bass it can be useful to determine the size of the corpus and the neck. Locations, where the density differs strongly from the rest of the instrument, such as the area of the valves in a trumpet, should be indicated.

- information about possibility of disassembly and if necessary about removable parts.
- stability of the object: If an object is not stable and can also not be stabilized by the mounting system, this should be communicated to the operator of the CT facility. Cases in which parts of an object could change their position with respect to other parts during one scan or between two scans, for instance when manipulating the object position in the mounting system, should be indicated. Examples are partially loose joints of woodwind instruments or the keys in a keyboard instrument.
- weight: The weight of the object including the mounting should be provided especially for heavier objects like pianos.
- for sub-volume measuring (volume of interest, VOI) the dimensions of the section and its exact position on the object (Fig. 3). Basic data from the museum such as designation, inventory number, manufacturer, date and place of manufacture, owner/proprietor.
- brief description (shape and function)
- photo of the complete object
- for sub-volume measurements: Photos of the requested areas

Figure 3: Example for Total-Object Dimensions and Dimensions for sub-volume Measurements

2 Materials and Methods
In order to adapt the involved X-ray technology and the data acquisition process to the actual necessities of the musical instrument inspection, the following issues were treated:

- acquisition of very large objects, like a double bass or a tuba. In this context the meaning of „large“ is that the extension of the object’s X-ray projection exceeds the size of the imaging sensor in at least one spatial dimension.
- optimization of X-ray radiation characteristics, the sample’s orientation with respect to the X-ray field, and acquisition parameters (e.g. number of angular positions).
• improvement of methods for a reproducible characterization of the materials present in the instrument. In particular, this applies to unusual materials like leather, wood, bone or other organic materials.
• reduction of artifacts and distortions in particular with multi-material objects. Additionally, if required optimization of dual-energy techniques.
• processing and handling of big volume data sets is an important issue. For example, if the dimensions of an large bowed instrument are 1200 mm by 800 mm by 500 mm and the required spatial resolution is 100 µm in each direction, the volume image resulting from the CT measurement constitutes approximately 500 billion voxels each with at least 16 bit depth, ending up with 1 TByte size of a single data set.

2.1 CT Imaging Optimization
In order to optimize the image acquisition protocol we focused on the two parameters which have the most influence on the quality of a CT scan: Tube voltage and orientation of the specimen with respect to the X-ray beam. This optimization was done separately for the different instrument classes respectively use cases. Optimization is based on simulations of the instrument to minimize Shannon entropy. Virtually all possible different orientations with respect to the X-ray beam’s direction (cf. Fig. 7 for an example) or available X-ray voltages were simulated. Further details of this study can be found in [7].

2.2 Raw Data Handling and Processing
In CT the primary data are the angular projections. After data acquisition the volume images are obtained by the reconstruction software. Since the primarily measured projections might be repeatedly processed and reconstructed again later, for instance with improved artifact suppression algorithms, they are additionally stored. Obviously, facing these huge amounts of image data, issues of data compression, archiving, remote access and transfer were addressed. The procedure developed demands the primary projections to be stored on a 90 TB NAS (Network attached storage with 12 hard disks). Reconstructed volume images are transported from the Fraunhofer facility to the museum’s location, thus a physical separation of these data is guaranteed.

2.3 Data format and Data Base Concept for Meta data
In the MUSICES project, we decided to use DICOM as data format. DICOM is a non-proprietary medical data standard and can be processed by several software applications including several freeware products. Other data formats are depending on proprietary software and their future usability is not ensured. Due to the standards on archiving of medical patient data, the DICOM format ensures long term usability.

The quality of the X-ray image is characterized by the technique which is used, i.e. the source (current and energy), filter, detector, exposure time, reconstruction algorithm etc. Technical standards demand that all these parameters are documented in order to estimate the image quality and to make all scans replicable. We use a database called WissKi, which was developed at the Germanisches Nationalmuseum [8]. All entering fields are defined by the CIDOC-CRM-standard [9] which will be connected with the datasets in a bijective way. Hereby all information is bound to the actual data set.
3 Results

Within the three years project duration, more than 100 instruments have been fully 3D digitized. Out of these afore mentioned hundred-plus instruments, the measurement results of four distinguished examples are shown in the following.

More detailed descriptions and high quality photography of these instruments can be downloaded from the public digital collection of the Germanisches Nationalmuseum (http://objektkatalog.gnm.de/recherche) by searching the inventory number, for instance “MI5”.

3.1 “Viola da Gamba (Bass)” (by Hanns Vogel, built 1563 in Nuremberg) MI5

The largest instrument included in the study, which was measured with conventional (and not linear accelerator based) CT-systems, was the so-called “Viola da Gamba”. The bounding box of this instrument has dimensions of 1725 mm x 322 mm x 558 mm.

We had to extend the field of view in horizontal direction for the body three times and two times for the neck (cf. Fig. 4) in order to achieve the demanded best possible spatial resolution. Altogether, the whole projection data set is built up by 29 separate data acquisition runs, which resulted in 449 GB raw measured X-ray attenuation data. After reconstruction, a voxel dimension of 127 µm resulted.

A tube voltage of 220 kV was chosen and no additional filter was applied. The magnification was set to 1.5. At each vertical position, 2400 projections per 360° were recorded for the corpus and 1600 for the neck. Each projection was recorded with an exposure time of 199 ms, resulting in a total scan-time of nearly eleven hours.

![Figure 4: (left) Cross section of the neck of the Viola da Gamba (MI5), 114 µm resolution; (centre) 3D display of the lower body’s surface; (right) a display of the upper part of the neck and the head.](image)

3.2 Violin made by Hummel MI419

The wooden instrument with the highest spatial resolution achieved was a violin made by Hummel (MI419), which was scanned with extended field of measurement (Fig. 5). The industrial CT allows for distinguishing details of 50 µm size or less which generally cannot be achieved by medical CT systems. Among others the objectives of this inspection were to picture the different types of wood, gaps between different parts filled with air or with glue, and defects within the various wooden parts.

The scan was performed with tube voltage of 150 kV, exposure time of 500 ms per projection and 2000 projections per 360°, geometrical magnification was 2.9.
3.3 Bird Shaped Ocarina MIR240
As the ocarina has a size of only 50 mm by 31 mm by 50 mm, a high magnification of 5.3 could be used, resulting in voxels with edge length of 27 µm (Fig. 6). A tube voltage of 150 kV was selected without additional beam filtration to reduce the duration of the measurement and increase spatial resolution. 1200 projections were recorded, each one with exposure time of 1000 ms. The high spatial resolutions allows to visualize pores in the clay. Additionally the white paint all over the surface of the bird, containing lead is clearly distinguishable in the cross-sectional X-ray images.

3.4 Cornet “Červený” MI826
The measurement of a cornet was performed with optimized orientation of the specimen on the turn table. The tilt angle of 45° which was determined beforehand and proved to be the best orientation of the instrument to be scanned with as few distortions as possible with the complex structures present (Figs. 7 and 8). Because the X-rays have to travel through several millimetres of brass, a very high tube voltage of 600 kV (7.5 mm copper plus 1 mm zinc prefiltration) was chosen. Each of the 1600 projections was recorded with an exposure time of 750 ms. Geometrical magnification of 1.2 allows for 170 µm voxel resolution.
Figure 7: Modelling almost the entire instrument for the example of the cornet “Červený” (MI826). The simulations (right) predict 45° tilt as optimal positioning, whereby the tilt refers to the longitudinal axis of the initial pipe starting at the mouth piece and with respect to the rotational axis of the CT machine.

Figure 8: A comparison of the two orientations, 0 and 45 degree (green frame), which correspond to minimum and maximum entropy respectively show the improved image quality with the tilted instrument (profile and picture detail right hand side).

4 Discussion

During examination of currently more than one hundred historically important instruments the MUSICES-collaboration gained extensive and elaborate experience in transport and handling of musical instruments, in data acquisition and processing, and in reconstruction as well as in optimization of scan parameters.

A meta-data format comprehensively describing the measurement procedure was specified. Together with the optimized measurement protocols, case studies, a check list and a guideline for transport and handling of the historical objects the meta-data format is part in the resulting best practice guide.

As shown, instruments which are built of a single kind of material are relatively easily digitized with CT. Therefore, our work focussed on mixed-material instruments which contain relatively light wood and much more absorbing metal parts (e.g. clarinets).
All the know-how was summarized into a guide to perform Computed Tomography with historically relevant musical instruments. These recommendations were published in summer 2018 (download from [10]).

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References
9. The CIDOC Conceptual Reference Model (CRM) was invented by the ICOM Documentation Standards Working Group and CIDOC CRM SIG. It provides a semantic and formal structure for describing the implicit and explicit concepts and relationships used in cultural heritage documentation (ISO 21127:2014)