

## Introduction to “Realistic Simulation of real CT systems with a basic-qualified Simulation Software - CTSimU2“

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### Abstract

The lack of traceability to meter of X-ray Computed Tomography (CT) measurements still hinders a more extensive acceptance of CT in coordinate metrology and industry. To ensure traceable, reliable, and accurate measurements, the determination of the task-specific measurement uncertainty is necessary. The German guideline VDI/VDE 2630 part 2.1 [1] describes a procedure to determine the measurement uncertainty for CT experimentally by conducting several repeated measurements with a calibrated test specimen. However, this experimental procedure is cost and effort intensive. Therefore, the simulation of dimensional measurement tasks conducted with X-ray computed tomography can close these drawbacks. Additionally, recent developments towards a resource and cost-efficient production (“smart factory”) motivate the need for a corresponding numerical model of a CT system (“digital twin”) as well.

As there is no standardized procedure to determine the measurement uncertainty of a CT system by simulation at the moment, the project series CTSimU was initiated, aiming at this gap. Concretely, the goal is the development of a procedure to determine the measurement uncertainty numerically by radiographic simulation.

The first project (2019-2022), “Radiographic Computed Tomography Simulation for Measurement Uncertainty Evaluation - CTSimU” developed a framework to qualify a radiographic simulation software concerning the correct simulation of physical laws and functionalities [2-6]. The most important outcome was a draft for a new guideline VDI/VDE 2630 part 2.2, which is currently under discussion in the VDI/VDE committee.

The follow-up project CTSimU2 “Realistic Simulation of real CT systems with a basic-qualified Simulation Software” will deal with building and characterizing a digital replica of a specific real-world CT system. The two main targets of this project will be a toolbox including methods and procedures to configure a realistic CT system simulation and to develop tests to check if this replica is sufficient enough. The result will be a draft for a follow-up VDI/VDE guideline proposing standardized procedures to determine a CT system's corresponding characteristics and test the simulation (copy) of a real-world CT system which we call a “digital twin”.

**Keywords:** X-ray Computed Tomography, task-specific measurement uncertainty, simulation, dimensional metrology, digital twin, standardization



## Introduction



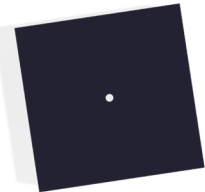
Currently, there is a wide variety of software systems for simulating X-ray computed tomography. Starting with aRTist [7], Scorpius XLab® [8] or SimCT [9], there is the in-house developed software from EMPA or the new in-house developed software WILCORE from Siemens Healthineers. Those software packages have in common that they are used to simulate generic CT systems. However, specific models of real-world CT systems are often not configured, as there is a lack of a standardized procedure to parameterize a CT system and to check further if the replica is good enough regarding a specific measurement task. The characterization of a CT system and the implementation of the determined parameters in the simulation software is often done by experts or the result of complex research and development. However, the more important aspect is that there is a need for a standardized way to check if the representation of the real-world CT-System is good to conduct, for example, a determination of the measurement uncertainty by simulation.

There are a few publications from Bircher et al. [10], Hiller et al. [11-12], Ferrucci et al. [13-14], and Binder et al. [15] that describe methods to characterize CT systems. However, those publications deal only partly or not at all with transferring those characteristics to the software. During the project CTSimU, a first study was conducted comparing digital replicas with their corresponding real-world CT systems. For this, different partners executed measurements with their real-world CT systems using a calibrated test specimen. The used parameters, either known or determined with their own established characterization methods, were implemented into the simulation software to create a digital replica. This replica was then simulated and evaluated in the same manner as the real-world CT scan. The results of this study have shown that a realistic simulation of a CT system needs minor uncertainties regarding the given parameters, a standardized method to characterize a real-world CT system, and a test to check if the replica is a good representation of the real-world CT system [16]. With the introduction of the following steps of the project CTSimU2, we want to close this gap.

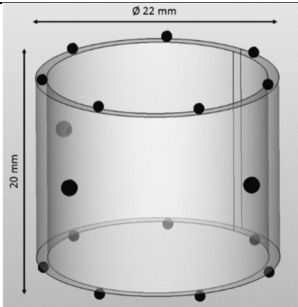
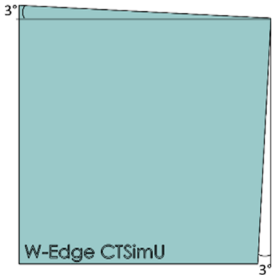
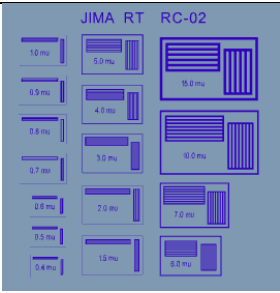
## Method

The development and verification of a digital replica (“digital twin”) can be divided into two parallel but connected objectives. Each of these objectives can be divided into several steps, as shown in Figure 1. The first two steps represent the definition of methods and procedures for the characterization of the real-world CT and the data acquisition (Step-DT-1 to 2). The aim of these steps is, at first, a literature research of existing methods, the classification of the found methods, and afterwards its application to several in the project available real-world CT systems. Different effects occur within a CT system that can be assigned to the following three components: system geometry, detector, and X-ray source. For each of those effects, different characterization methods can be applied. The following table exemplary presents two methods for each category:

Table 1: Overview of different characterization methods for different effects

	Components		
	System geometry	Detector	Source
Effect to characterize	CT machine geometry determination	Detector unsharpness	Focal spot
Test specimen	PTB hole grid standard made from Invar®. It contains a 40 x 40 equidistant grid of holes with a distance of 1.5 mm and a diameter of 1.0 mm. [17]–[19] and [24]	Duplex wire according to DIN EN ISO 19232-5 [20], ASTM 2597 [21]. Depending on the design, it contains a different number of wire pairs, with decreasing wire diameter and spacing	Pinhole camera, according to ASTM E1165 [22] and EN 12543-2 [23]
Picture			

Method	With this method, the characterization of the geometrical scale factor is possible. For this, it is necessary to take two radiographic images in opposite directions of the hole grid standard. The evaluation uses a pattern recognition algorithm to determine the mean grid distance from both images. [24]	The duplex wire has to be positioned in a way that it is close to the detector and rotated by 2 ° to 5 °. The evaluation has to be done with an image processing software. Especially the determination of the interpolated basic spatial image resolution is necessary. [20]	The characterization of a focal spot can be done with a pinhole camera following the instruction in EN 12543-2. The determination of the focal spot size is carried out by evaluation of the integrated line profile. [23]
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Components			
	System geometry	Source and Detector	Source
Effect to characterize	CT machine geometry determination	Focal spot size and detector unsharpness	Focal spot size and resolution
Test specimen	MSS-Zerodur multi-sphere standard by METAS consisting of two hollow cylinders with 14 steel spheres and three reference spheres [10].	Wolfram-Edge developed by CTSimU has 3 ° inclined edges to minimize aliasing effects [6]	Jima - masque developed by Japan Instruments Manufacturers association consists of stripes of different sizes and different distances [25]
Picture			
Method	The characterization method is based on evaluating radiographic images of the calibrated multi-sphere standard at different source-object distances. With this method, it is possible to determine the SDD and SOD with low uncertainties. [10]	The characterization of the focal spot and the detector unsharpness can be determined based on the modulation transfer function (MTF) of a profile perpendicular to the object edge, a highly absorbing material has to be used. [6]	The masque contains stripes, usually made of gold, with 1 to 2 μm height and has to be measured with high geometrical magnification. The focal spot size corresponds to the mean structure along the image, where the contrast is 2/3 of the gray values. [21-22]

The steps “Step-DT-1 to Step-DT-2” are followed by the evaluation of the parameters and the development of a generic model (Step-DT-3), which is then used in a fourth step to build the digital twin for a specific simulation software and a specific real-world system. The applied methods should be evaluated through a standardized evaluation toolbox to guarantee a reproducible and standardized way to build the digital replica of the real-world CT system in the following steps. One example of building a generic model of a CT system was already developed in the former project CTSimU through the JSON description [3]. Therefore, the described steps above represent the first main target: the development of a toolbox for building a digital replica in a standardized way. In Figure 1, this procedure is illustrated in blue color.

The yellow boxes show the second main target – the design of tests to assess if the digital twin sufficiently represents its real-world counterpart. This objective is divided into three steps (Step-T-1 to Step-T-3): (1) the definition of the requirements which have to be fulfilled by the digital twin in order to be applied for tasks in dimensional metrology, particularly for the evaluation of the measurement uncertainty; (2) the development of tests derived from the requirements of Step-T-1 to check whether the digital twin represents its real-world counterpart sufficiently; (3) the application of the developed tests on exemplarily configured digital twins to check the applicability and functionality of the tests.

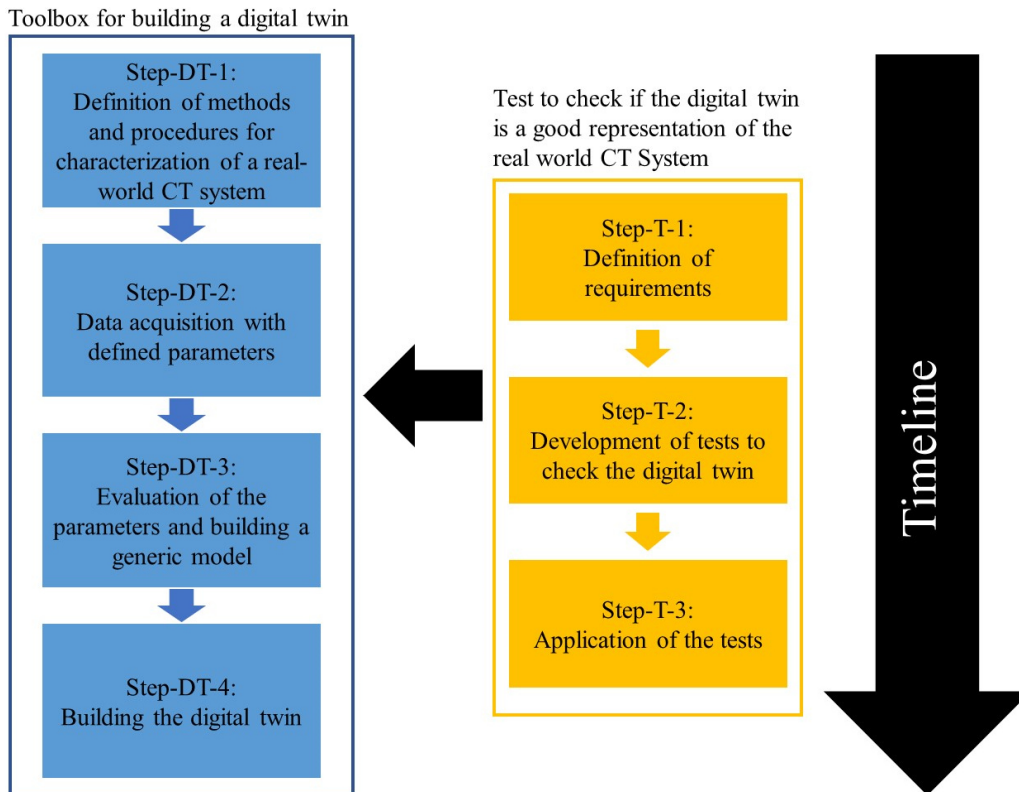


Figure 1: Concept of building a digital twin and characterizing it with a standardized test.

### Summary and Outlook

The project series CTSimU was initiated to develop a standardized way to determine the measurement uncertainty numerically through simulation. In a first step, a basic qualification framework was developed to check if a simulation software is able to simulate physical laws and functionalities correctly. The second step, which we have introduced with this contribution, is to develop a toolbox for building a digital replica of a real-world CT system (first objective) and developing a test to check if the digital replica is good enough to determine in a currently planned third project the measurement uncertainty numerically by simulation (second objective).

The objectives of the second project are divided into several steps. The first steps, Step-DT-1, literature research for existing methods to characterize a real-world CT system and the definition of requirements have to be fulfilled by the digital twin (Step-T-1), have already started. The first results are presented in this contribution. The next step is to derive measurement instructions and test the first methods if they are applicable and possible. The development of tests to check the digital replica will follow and are to be done in parallel to the described tasks above.

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