Investigation of Non-circular Scanning Trajectories in Robot-based Industrial X-ray Computed Tomography of Multi-material Objects

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Abstract: In this work the application of six-axis robots for robot-based industrial X-ray computed tomography (CT) imaging is investigated. In contrast to classical Cartesian manipulators with a turntable used in industrial cone-beam CT, robots offer increased flexibility regarding scanning trajectories. The increased flexibility with respect to scanning trajectories helps to gather highly informative content from alternative ray paths for a high-quality 3D reconstruction of the object to be scanned. Using numerical simulations we show that this additional informations increase the image quality of a CT scan of a multi-material measuring object, consisting of tantalum spheres and a carbon structure.

1 INTRODUCTION

Industrial X-ray computed tomography (CT) nowadays is an important non-destructive testing method and is well established in production industry as a flexible tool for quality assurance and process optimization (De Chiffre et al., 2014). Since time-to-market constantly decreases in industry, sensing and automation technology is seen as a key technology to develop the autonomous production of the future. For imaging technologies like CT it is therefore consequent, to work on CT systems based on flexible robotic manipulators. Medical CT systems are already equipped with robotic manipulator (Fieselmann et al., 2016), (Ouadah et al., 2017), (Zhao et al., 2019), industrial robot-based CT systems are arising as well, for example, used for quality control in the automotive industry. The robot's advantage compared to classical Cartesian manipulators in CT is its flexibility to reach a wider range of positions in space. Acquisition trajectories beyond a single circular one can be advantageous with respect to the resulting image quality in industrial as well in medical applications (Herl et al., 2019), (Noo et al., 1998), (Katsevich, 2005), (Ouadah et al., 2017). The increased flexibility with respect to scanning trajectories helps to gather highly informative content from alternative ray paths (X-ray projections), resulting in high-quality 3D reconstructions of the object to be scanned. Particularly, when scanning multi-material specimens, consisting of low and high absorbing materials, additional ray paths prevent the formation of metal artifacts to a certain extent. In this paper, the advantages of non-circluar trajectories using a virtual Kuka KR 15-2 robot are shown by means of numerical simulations, whereas positioning errors of the (real) robot are neglected in the simulation.

2 X-RAY COMPUTED TOMOGRAPHY

X-ray based inspection is widely used in industrial manufacturing (De Chiffre et al., 2014). The difference between X-ray inspection systems based on radiographs and X-ray CT is the fact that CT uses plenty of X-ray projection images to reconstruct the inner structure of a specimen in terms of a 3D voxel volume. Each voxel represents the local attenuation coefficient of a workpiece (material) to be scanned. Typically, those voxel datasets are displayed as gray-value slice images or a 3D rendering image as shown exemplary in Figure 2. Usually, projection images are generated in a circular trajectory on a machine bed using a Cartesian manipulator system with a turntable as shown in Figure 1. In such a setup, X-ray source and detector remain fixed and the specimen, placed on the turntable, turns around in, e.g., 1000 angle steps. In each angle step, the X-ray detector acquires one pro-

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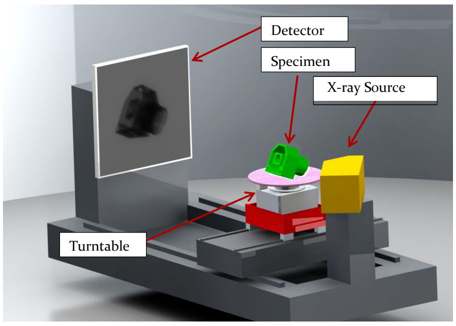

Figure 1: Schematic illustration of a standard cone-beam CT scanner using a circular trajectory.

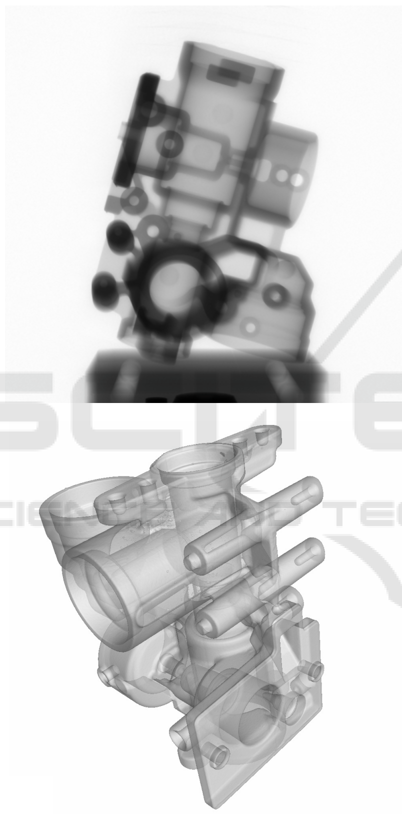

Figure 2: Projection image (top) and 3D rendering image (below) of a casting.

jection image. This set of projection images is then reconstructed to a 3D voxel volume (De Chiffre et al., 2014).

3 BENEFITS OF NON-CIRCULAR TRAJECTORY

In this work, we focus on two advantages for the application of non-circular scanning trajectories. A possible system configuration is shown in Figure 3.

In industrial CT there are several mathematical and physical conditions and limitations that restrict the obtained image quality of a CT image. First of all, in circular cone-beam CT there is a data-sufficiency problem: In order to reconstruct a 3D volume mathematically correct, projection data from certain directions are needed that fulfill the so-called *Tuy-Kirillov* conditions (Tuy, 1983). The most important one of these conditions states that every plane that intersects the volume has to intersect the trajectory of the X-ray source. Using a circular trajectory, this condition can be fulfilled for all volume points in the middle plane, but not in other planes of the volume. Therefore, the further the point is away from the source plane and the higher the aperture angle, the stronger the forming of image artifacts (so called cone-beam or Feldkamp artifacts) in the resulting dataset will be. By using robots and adapting the scanning trajectory, the *Tuy-Kirillov* conditions can be fulfilled, resulting in a high-quality CT image.

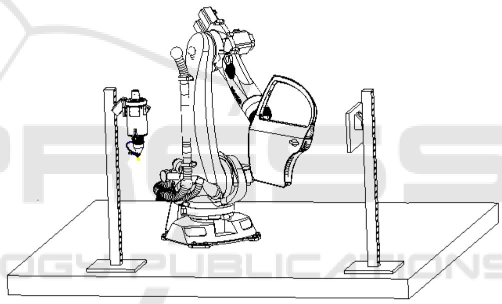

Figure 3: Schematic illustration of a possible CT scanner setup using a robot as manipulator.

Secondly, most reconstruction methods assume a linear model of penetration length and attenuation based on Lambert-Beer's law in order to calculate the local attenuation coefficient of a material. But as the spectrum of X-ray sources is polychromatic, this model is not true. As a consequence, one is faced with beam-hardening and metal artifacts, especially when scanning objects consisting of low and high absorbing materials, for example multi-material objects made from metal and plastic. Some of the measured and attenuated X-rays contain information that cannot be interpreted correctly by the used models, resulting in beam-hardening and metal artifacts. Therefore, these strongly attenuated X-rays should be ignored by the reconstruction algorithm.

In order to fulfill the mentioned *Tuy-Kirillov* conditions, projections from different directions are necessary. For example, using projections from several tilted circular trajectories and using only attenuation values of specific X-rays can increase the image quality and the dimensional accuracy of reconstructed objects significantly (Herl et al., 2019). In this work, we show that image artifacts due to almost total absorption can be decreased by using a robot and a non-circular scanning trajectory.

4 ROBOTS AS MANIPULATORS

In this work, we investigated a robot-based CT as shown in Figure 3. Using such a setup, source and detector are mounted in fixed positions and the robot handles (manipulates) the specimen. Besides this setup, other configurations are possible. Medical CT scanners for example use a C-bow to handle source and detector using one robot (Fieselmann et al., 2016). Other configurations are based on one robot for source and one to handle the detector while the specimen remains fixed. It is further possible to use robots on linear rails to further enhance the working volume or to additionally use a turntable.

Generally speaking, it can be said from a theoretical point of view that, the more directions a voxel is scanned from, the higher the image quality of the resulting reconstructed volume will be. Thus, a scanner fully performing a sphere-like trajectory would be ideal to penetrate each voxel out of every possible direction. However, this can not even be achieved by a six-axis robot. The reasons are: The specimen in mounted on a fixture and source and detector can not move into that fixture. For some positions, the robot's hand would mask the cone-beam. Those projections also have to be omitted. Further, even a six-axes industrial robot can not reach any position and orientation in its working volume due to its joint angle limits.

Figure 4 shows possible projection positions (green area) the robot can approach based on the conditions mentioned before using numerical calculations based on geometric assumptions. Using homogeneous coordinates and *Denavit-Hartenberg* parameters, the possible positions the robot can approach were determined.

5 EXPERIMENT: SIMULATION STUDY

As mentioned earlier, the robot can not reach all spatial positions on the virtual sphere. We determined the feasible positions using geometric assumptions. Using homogeneous coordinates and *Denavit-Hartenberg* parameters of the Kuka KR 15-2 robot, the possible positions of the robot can be estimated.

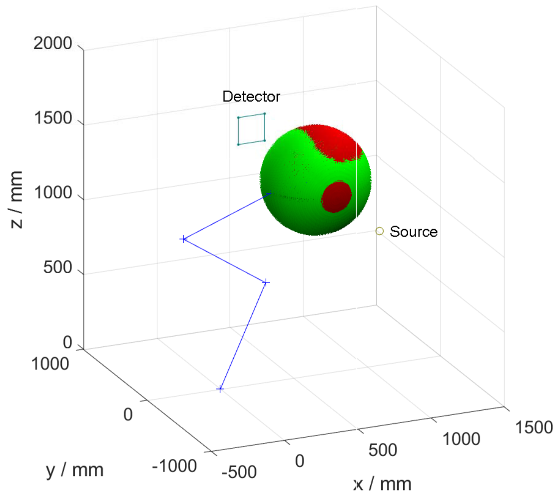

Figure 4: Calculated projection positions in space for the non-circular case: The robot main axes are visualized as blue lines, reachable projection positions as green area, unreachable ones as red area. The robot base flange is mounted on the x/y plane and reaches the projection positions with its tool flange (TCP), pointing to the center of the object. The X-ray source is visualized as a circle and the X-ray detector as a square.

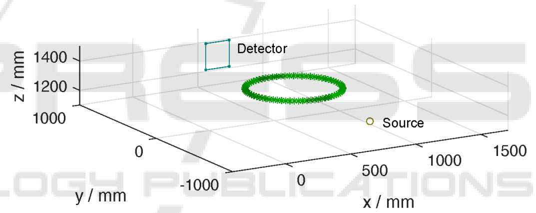

Figure 5: Projection positions for a standard circular CT scan using a turntable. The X-ray source is visualized as a circle and the X-ray detector as a square.

In this simulation experiment, the center of the object was located $x = 650$ mm and $z = 1300$ mm from the base flange of the robot. Further, a distance from the center of the object to the tool flange of the robot of 200 mm was modeled as specimen fixture. In a real approach, one would build up this fixture of low density foam material in order not to compromise the imaging process. Ideally, the robot could turn the specimen around in a full sphere so that the X-ray system can gather information from all directions. Due to certain technical limitations, this is not possible. We cannot reach some positions on top of the sphere because of the robots wrist angular range limit of ± 135 degrees. Further we omitted those positions where the hand of the robot moves into the relevant X-ray beams. All positions inside a cylinder of 200 mm in diameter with the central X-ray as center line were omitted. Using a 5 degree pattern for azimuth angle from 0 to 355 degree and elevation from 0 to 175 degree, in total 1859 spatial coordinates deliver the position data for the following simulations.

The output of our calculation is a set of spatial coordinates (see Figure 4) we passed over to our X-ray simulation tool *XLab* from *Fraunhofer EZRT* (Reisinger et al., 2011). We computed noise-free virtual projections of the virtual specimen out of carbon as shown in Figure 6 using the X-ray simulation parameters, summarized in Table 1.

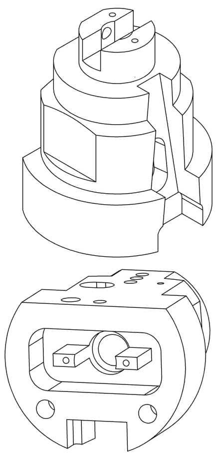

Figure 6: The simulated specimen is 3 cm tall and made out of carbon.

In order to clearly show the benefits of non-circular CT scanning trajectories, we additionally modeled four tantalum spheres of 6.5 millimeter diameter and one sphere of 4 millimeter in diameter and added it to the virtual specimen, so that it can be treated as a multi-material object with low and high density material contributions. For 3D reconstruction to a voxel volume, we used a modified algebraic reconstruction technique (ART) (see (Herl et al., 2019)).

In total, we simulated one non-circular (see Figure 4) and one circular (see Figure 5) trajectory. The results of the simulations are summarized in the following section.

Table 1: Simulation parameters.

Specimen materials	Tantalum and carbon
Tube voltage	225 kV
Tube current	0.02 mA
Focus detector distance	2000 mm
Magnification factor	2
Detector pixel size	0.469 mm
Detector pixel grid	512×512 pixels
Detector noise	off

6 RESULTS

The results of the simulations in term of slice images using the two different scanning trajectories are shown in Figure 7 and Figure 8.

When comparing Figure 7 and 8 we can clearly see that the non-circular CT trajectory results in a much higher image quality (no streak artifacts) due to the fact that the additional information from the non-circular trajectory compensates the impact of almost fully absorbed rays (due to the high dense tantalum spheres) in the reconstructed volume and, as consequence, reduces image artifacts significantly. The circular trajectory mainly suffers from partial total absorption due to the high density tantalum, where the non-circular trajectory, performed by the (virtual) robot, suffers much less from those physical restrictions.

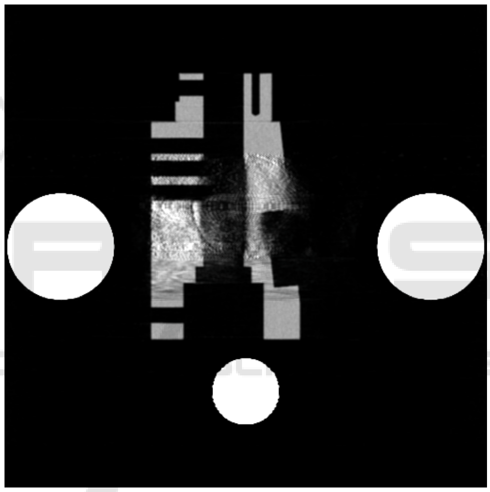

Figure 7: Reconstruction using circular scanning.

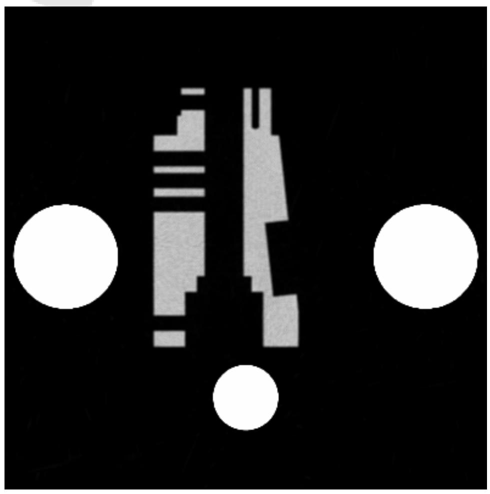

Figure 8: Reconstruction using non-circular scanning.

7 CONCLUSIONS AND OUTLOOK

We investigated a non-circular trajectory for robot-based X-ray CT and its application for the reconstitution of a multi-material object using numerical simulations. Within the study we calculated a set of feasible robot positions to obtain a set of X-ray projection images to reconstruct a voxel dataset. Further, we simulated a standard circular CT and visually compared the results of the two reconstructions qualitatively. We have shown that when using additional information from different non-circular directions, a much higher image quality can be expected in contrast to a standard circular scan. Future work will focus on optimization methods for robot CT path planning, taking trajectory and accuracy limitations of robots, material and geometrical properties of various specimens as well as object and scan-specific X-ray interaction effects into account. Furthermore, experiments using a real robot-based CT system will be performed in the near future.

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