The PolyCT – Increasing the sample throughput using multiple rotation axes

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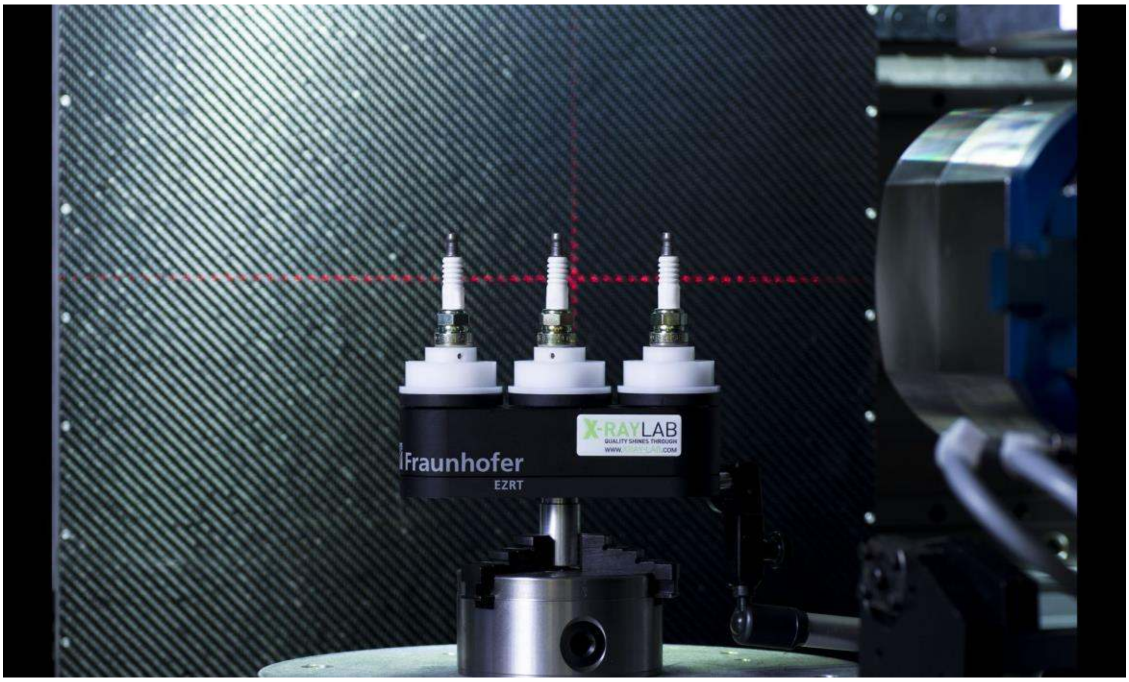
Abstract

Modern industrial computed tomography undergoes continuous improvements by innovative software and hardware solutions. One major focus is set on pushing the resolution limits and the general quality of CT data. For industrial applications, probably the most important aspects are high efficiency and cost minimization, which are mainly targeted by reducing the time for CT data acquisition and processing.
The PolyCT represents a straightforward attachment, which makes it possible to scan multiple objects in one CT scanning procedure. Therefore, a stationary bank is clamped into the CT chuck transferring the usual rotational motion from one axis into three autonomously rotating axes. Thus, the three axes (equivalent to three sample holders) allow simultaneous CT scanning of objects side by side. The idea behind PolyCT is to make it compatible to most industrial CT scanners on the market and as easy to handle as possible.
The advantage of the PolyCT is the increase of sample throughput by the factor of three. Moreover, the side by side arrangement of the multiple axes requires less projection angles for every object scanned and produces less artifacts compared to a normal scan where three objects are rotated with one collective rotation axis. Even highly absorbing materials can be scanned because the side by side axes prevent an overlapping of the objects in the X-ray path. When using 2k or 4k detectors, the total amount of detector pixels can be used very effectively in combination with less projection angles.
The Fraunhofer reconstruction software processes the CT raw data and does not require any intervention with the existing system architecture. Possible distortion artifacts are compensated resulting in equal CT image quality.
We will introduce the working principle of the PolyCT and we will present first scanning results under various aspects. The advantages of such scans will be illustrated by comparing them to usual CT scans of multiple objects and the impact on image quality, resolution, artifacts and measuring accuracy will be further evaluated.

Keywords:

PolyCT, sample throughput, artifact reduction, multiple axes.



1. Introduction and strategic goal for industrial application

Modern non-destructive CT imaging plays a significant role in numerous industrial branches, such as the automotive industry. Its contribution in the realms of quality assurance or research and development (R&D) is huge since the state-of-the art imaging in 2D and 3D enables very elegant and valuable possibilities to increase the quality of different materials or parts.
However, the good reputation of CT imaging is often faced with the accusation that the technique with all its uncontested benefits is still an expensive one. The costs for CT scanning are basically dependent on the acquisition and maintenance costs of industrial CT scanners. Since the price for CT scanners is not expected to drop significantly, a major potential for cost reduction – and one motivation for the development of the PolyCT – is to minimize the scanning time. Alongside the cost factor, the possibility to increase the sample throughput with a usual CT scanner is the main goal, which might even be more important to industrial branches depending on the types and numbers of parts, which require non-destructive checking and where the cost factor plays only a minor role.
The common approach to reduce the scanning time or to increase the sample throughput is the scanning of multiple parts at once, which is often accompanied by taking a loss in resolution and scan quality. Using the same rotation table for numerous samples causes an overlap of several parts, arising in artifacts, lower contrasts or a loss of information (especially with highly attenuating materials) as well as longer reconstruction times regarding the separation and post-processing of the single (sub)volumes of less image quality. With the development of larger detectors characterized by massive numbers of pixels, the PolyCT represents a perfect upgrade for most of the CT scanners enabling an increased sample throughput while maintaining high quality CT scans by exploiting the entire potential of modern X-ray detectors.
In the present paper, we compare PolyCT scans to usual CT scans and discuss the potential and the limitations of this new device.

2. Technical setup and operating principle of PolyCT hardware and software

The PolyCT (**Fig. 1**) represents an easy-to-handle upgrade kit for any CT scanner, which is mounted onto the CT chuck. The main body consist of an aluminum block with three similarly rotating and mechanically coupled sample holders on its topside. At the bottom side, the central axis pierces though the body and is directly clamped into the CT chick. When the CT table starts to rotate during a CT scan, the central PolyCT axis transfers the rotation movement to the three PolyCT axes, while the main body remains stable and is held in place by a connected stand.

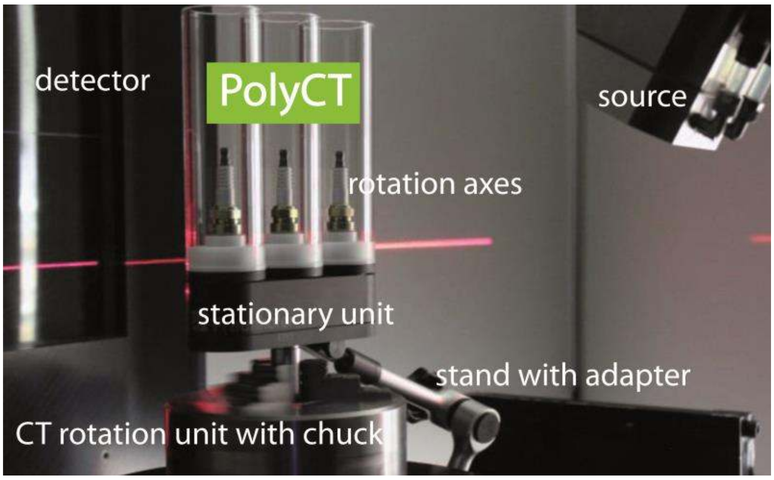


Fig. 1 PolyCT setup installed in a standard CT scanner.

A highly precise transfer of main CT chuck to the PolyCT rotation axes is secured by a backlash-free gear transition (**Fig. 2**). In order to place the PolyCT most precisely into the perfect position, the PolyCT is equipped with a laser cross-hair unit, which must be used to find the perfect orthogonal alignment of the device between the tube and the detector. For best scanning results, the CT system must be pre-adjusted ensuring a beam plane orthogonal to the detector surface.
The aluminum block as the basis must be perfectly stable and immobile during the scanning process. Therefore, the stabilizing stand can optionally fix the PolyCT block to the CT scanner using either a magnetic base or a suction pad.

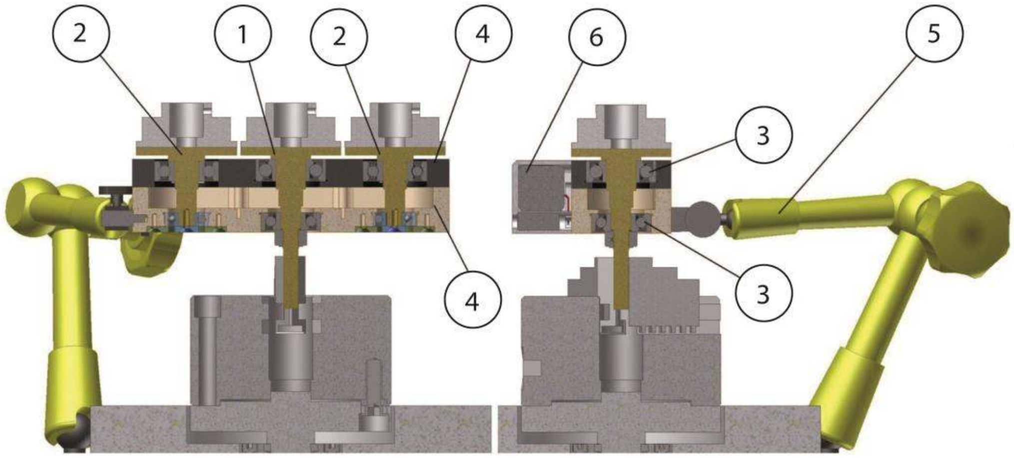


Fig. 2 Structural design of PolyCT (front view and side view), from Leisner et al. (2017). The PolyCT is clamped into the CT chuck transferring the CT scanner rotation axis into three aligned PolyCT axes (central (1), left (2) and right (2) axis). The latter are mechanically connected to the central axis rotating in the exact same manner. The precise and similar movement is achieved by angular contact ball bearings (3). The whole system is confined by an aluminum housing (4). A stand (5) ensures the static and stable position of the apparatus during the CT scan when the three axes are rotated. A laser cross-hair unit (6) helps to pre-install the most precise and horizontal position of the PolyCT before CT scanning is carried out.

The three rotation axes lead to an optimum use of the whole detector field (see also **Figure 5c**). Corresponding to usual CT scans, a PolyCT scanning procedure is of the exact same manner and can be performed like any usual CT scan in your in-house scanner. The only change is the reduction of projection numbers (see also section 4.).
The special PolyCT software automatically recovers the scan parameters and one has the choice to use the PolyCT software for different measurement settings (single, double and triple reconstruction) depending on how much parts are meant to be scanned at once. It is also possible to scan two sample at the outer rotation axes, when the sample size is too large for a triple arrangement. The software calculates each rotation center by the known physical distance and the applied magnification.
The Feldkamp type reconstruction is available for Windows 7® CUDA and OpenCL environment, which gives the opportunity to work with solid processing speed using standard PCs. The final data includes up to three separate data sets in the Fraunhofer reconstruction format *.rek, which is compatible and readable by common visualization software or tools.

3. Results: Comparing PolyCT scans with standard CT scans

In the following section, two different types of samples (cathodes and probes) are presented as comparable scans i) in the usual way and ii) using the PolyCT device. The term “standard CT” refers to a “normal” scan where the usual, main rotation plate or sample holder of a typical CT scanner is equipped with three parts at once moving the whole package around the main rotation axis.
The first application of cathodes for X-ray tubes reveals the challenge of collecting high quality CT data when parts consist of highly attenuating materials. The classic way is to place the cathodes in a triangular arrangement (**Fig 3a**). This set-up allows reducing the total diameter of the package to achieve the best resolution (voxel size) possible. However, the highly attenuating material of the cathodes avoids sufficient X-ray penetration through the samples because they cover each other over larger traveling distances. Thus, contrast loss along certain penetration angles and increased noise levels occur. Moreover, the surface accuracy is reduced.
The second possibility is the “aligned” arrangement of the cathodes (**Fig 3b**). While ensuring a better X-ray penetration in most of the angles, the insufficient aspect ratio and the very poor X-ray penetration along the maximum diameter of the package cause low contrasts and deformed surfaces. Furthermore, the voxel size is slightly larger due to the enlarged maximum diameter.
In contrast, the PolyCT scan (**Fig 3c**) shows no significant artifacts or deviations in contrasts. Due to the simultaneously working rotation axes the cathodes do not overlap during the scanning process and surface deformation does not occur. Although the voxel size is the same as in the “aligned” set-up, the number of projection angles is extremely reduced because of the minimization of the detector area required for one cathode. Therefore, the total scanning time can be significantly decreased compared to the “aligned” arrangement.

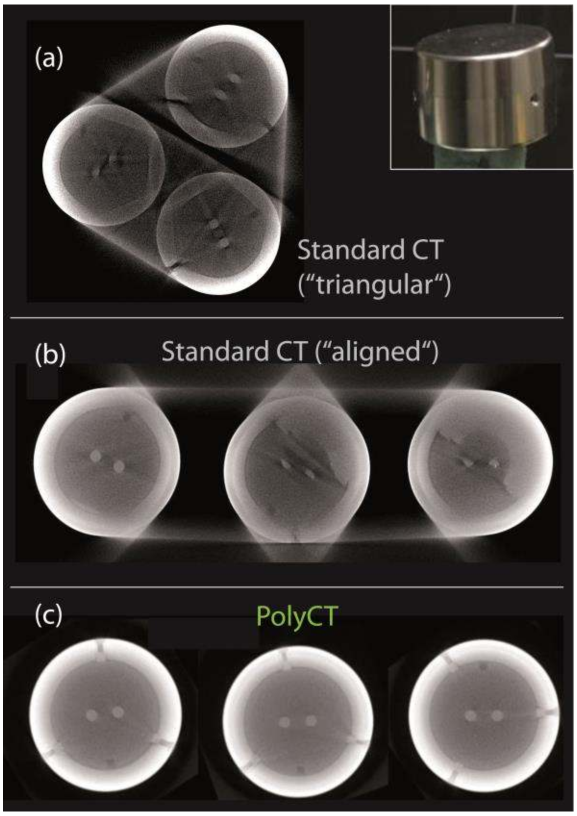


Fig. 3 Cross sections of simultaneously scanned X-ray cathodes as shown in the right upper corner. a) "Triangular" setup to achieve a relatively small voxel size by placing the cathodes closely together. b) "Aligned" setup to ensure better X-ray penetration while the cathodes are less covered by each other during rotation (except in 90° and 270° degrees). c) PolyCT setup with three autonomous axes. The single cathodes don't cover each other preventing the formation of artifacts. Additionally, the number of projections is reduced due to subdividing the detector plane into three (sub)areas (see also **Fig 5**). Modified after Leisner et al. (2017).

The second example shows a probe revealing the same characteristics as described for the cathodes. The use of the PolyCT device leads to a noticeable improvement in image quality accompanied by far less scanning time. The first probe's cross section (**Fig 4a**) illustrates the lack of blurring artifacts in the PolyCT scan and the very accurate shape compared to the standard CT with three simultaneously scanned probes aligned in a row.
The second cross section (**Fig 4b**) shows some fissures, which are hard to visualize when artifacts occur. The PolyCT data set, however, can reveal even the fine structures very accurately and without restriction. This example shows how potential defects inside the material might get overlooked when artifacts or poor image quality are dominant.

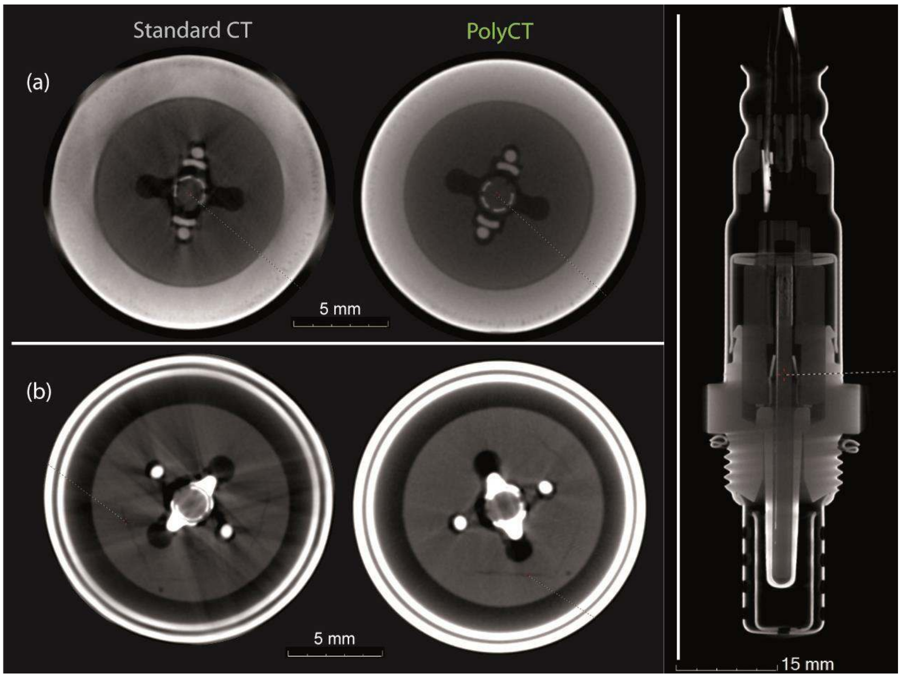


Fig. 4 Comparison of two CT cross sections of the same probe as shown at the right-hand side. "Standard CT" refers to the positioning of objects as shown in Figure 3b. a) Note the (blurring) artifact reduction in the PolyCT scans. The data set appears less noisy and the object's shape is accurately reconstructed. b) Due to the improved PolyCT image quality, all the internal fissures in the core material are detectable while some fractures are missing in the "standard CT" data set.

4. Discussion: Advantages, limitations and verification of measuring accuracy

The results of the comparative CT scans of X-ray cathodes and probes show the power of the PolyCT device and a bunch of advantages that come into play when standard CT scans run into difficulties.
Preventing the occurrence of annoying artefacts, the reduction of the scanning time due to the small diameter of the object to be rotated is a major achievement. When a CT scan is meant to achieve the best resolution possible, then the subdivision of detectors makes no sense, however although the PolyCT is not able to create the smallest voxel size possible, the less required rotational steps and the reduction of artifacts might challenge higher resolutions of less quality.
Dividing the detector into sub-units points to another useful application in times when new types of (4k) detectors come into play, especially for elongated samples (**Fig. 5**). To achieve the best resolution possible, an elongated sample must be subdivided into single scanning volumes (**Fig. 5a**), which means extraordinary scanning times, further processing and huge datasets using 4k detectors. Since a 4k detector still allows the acquisition of high quality image data when only a certain detector area is used, a lot of potential is wasted due to lost detector fields, when fitting complete the sample height into the detector plane (**Fig. 5b**). The PolyCT is able to use these such “lost” detector fields by “splitting” the detector into separate areas (**Fig. 5c**). Thus, the it allows using the entire detector area while taking the same amount of scanning time as for the single probe arrangement achieved in **Figure 5b** but incorporates three samples instead of one preventing artifacts as shown in **Figures 3 and 4**.

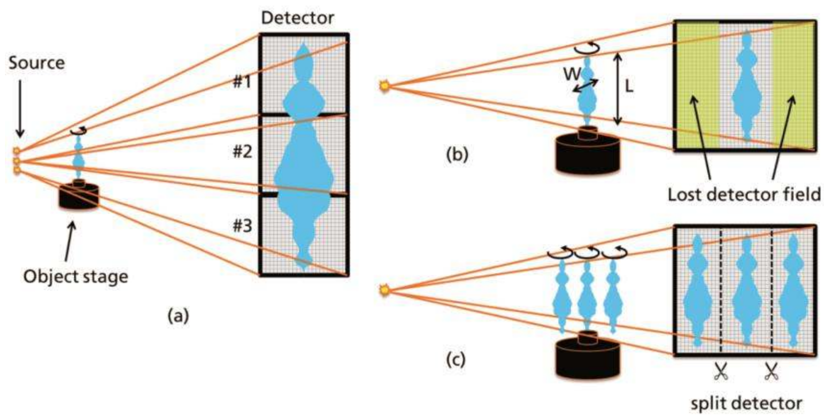


Fig. 5 Optimal use of the detector plane in different manners for an elongated object, from Leisner et al. (2017). a) Dividing the object into three separate CT volumes gives the maximum resolution but longest scanning and data processing time as well as the largest data sets. b) A single scan of the object allows a mid-level resolution but a certain loss of detector field. c) “Splitting” the detector into separate areas, the PolyCT allows using the entire detector area with the same scanning time achieved in (b) but incorporates three samples instead of one without creating artifacts as shown in Figures 3 and 4.

The PolyCT demonstrates its high value when dealing with highly absorbing materials in combination with an elongated shape. Usually one would counteract highly absorbing materials by increasing the tube voltage. But firstly, this action leads to a reduced resolution and secondly, every CT scanner is in a way limited for high power currents and might simply not have the right tube installed. For such combinations, the PolyCT bypasses the missing tube power by keeping the required X-ray penetration depths as small as possible. This is how you can still manage CT scanning of multiple parts with less power, shorter scanning time and better image quality.

Another crucial factor is the measuring accuracy or the comparability of the three PolyCT axes between each other. Since the PolyCT does not achieve the maximum resolutions, the topic of CT metrology is hard to evaluate.
One approach is to perform an actual/nominal comparison of the same part, once positioned on the central axis, and then subsequently scanned on the additional axes (**Fig. 6**). Comparing the deviation shows, that the overall discrepancy between the reconstructed 3D-models for the central and the lateral (left) axis is very small. In this particular case, the mean deviation was smaller than the reconstructed voxel size, which is therefore below the resolution limit. However, using the PolyCT in applications of precise metrology must be taken with caution. One exception might be using a defined calibration object, which guarantees an accurate performance of the CT scanner, a precisely reconstructed voxel size and separate PolyCT volumes. For a detailed review on the impact of tilt angles of the separate rotation axes, see Leisner et al. (2017).

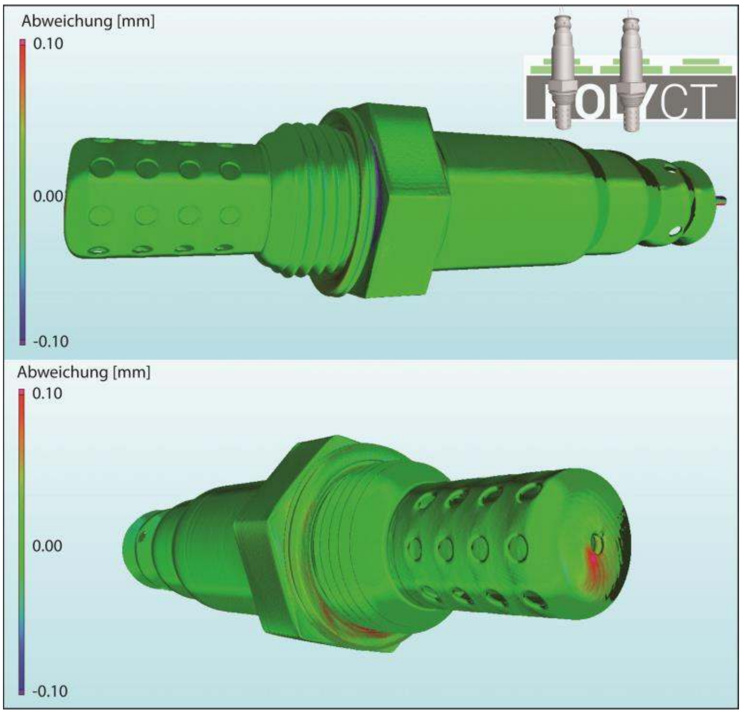


Fig. 6 Nominal/actual comparison of the same probe once scanned in the central PolyCT axis followed by a scan in the left PolyCT axis. As shown by the green coloring, the 3D reconstructions originating from both probe positions are basically alike. The average deviation in this example was less than the reconstructed voxel size.

5. Conclusions

The PolyCT has shown some high potential for the industrial need for reducing the scanning time, or rather for increasing the sample throughput. This holds particularly for highly attenuating, elongated parts, when a certain reduction of maximum resolution is allowed. The system is easily installed, does not influence the existing hard- or software of the CT scanner and has numerous major advantages:

- Increase of sample throughput
- Reduction of scanning time
- Improvement of CT data quality by significant reduction of artifacts
- Efficiency increase of existing CT systems
- Use of “lost detector fields”
- Compatible to all standard CT systems
- No interference with mechanical controls or software
- Quick installation by easy locking mechanism
- Automated (sub)volume separation by real-time reconstruction
- Commonly used reconstruction data format

Finally, further testing of the PolyCT performance is required for parts with very complex geometries being prone to artifacts, especially at the outer edges of the detector (left and right axes of the PolyCT).

6. References

Leisner J, Salamon M, Reisser J, Kreutner C, Reims N, Uhlmann N, Brock A, Kinzinger J, Hartnagel U (2017) PolyCT – Upgrade for Industrial CT-Scanners. ASNT Annual Conference 2017.

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