On the Influence of Ring Artifacts on Dimensional Measurement in Industrial Computed Tomography

Dierck Matern, Frank Herold, Thomas Wenzel

YXLON International GmbH, Essener Bogen 15, 22419 Hamburg, Germany

e-mail: {dierck.matern, frank.herold, thomas.wenzel}@hbg.yxlon.com

Abstract

For the dimensional measurement using industrial computed tomography (CT), we ideally use precise voxel gray value information from the tomographic reconstruction of the object of interest, an ideal surface representation extracted from this information, or both. However, tomographic reconstructions are influenced by a series of artifacts, for example ring artifacts, as these disturb the surface extracted from the volume. In this article, we will focus on the influence of ring artifacts and discuss possible improvements using a software-based ring artifact reduction method for the dimensional measurements. We compare a sinogram-featured algorithm with the original results in this survey, and provide an overview whether it should be applied in order to achieve dimensional measurements by CT as precise as possible.

Keywords: Ring artifacts, Artifact reduction, Dimensional measurement, Computed tomography, Metrology

1 Introduction

Computed tomography (CT) has become a widely used method for dimensional measurement (DM) of inner parts of arbitrary objects [1]. While for outer dimensions tactile measurements can be used, the interior is problematic for those methods if we do not want to destroy or dismantle the object. Ideally, a 3D reconstruction bears a close tomographic resemblance of the original object: a virtual volume is divided in small elements, the voxels, while each voxel consists of four values, that are three ordinates for the location in the volume and one gray value which is supposed to represent the material depending absorption of X-ray beams in the original object at the respective location.

For standard CT, we can use a set of projections where the object is rotated between an X-ray source and a detector. The detector consists of a certain amount of elements (pixels). However, these elements do not respond equally to X-ray, hence the detector has to be calibrated [2]. Imperfections of these calibrations are a possible source of ring artifacts [3, 4]. Unfortunately, there is no known method for a perfect detector calibration, although these ring artifacts are of particular relevance to CT.

Ring artifacts are ring forming structures within the tomographic slices. Concentric rings that are either lighter or darker than the neighborhood disturb the relationship between the gray values of the voxels and the absorption with a deterministic error. In the following, we discuss the influence of ring artifacts and the correction on a CT scan in order to identify the influence on DM using a CT system.
2 Materials and Methods

All measurements which were used for this study were performed on an YXLON FF20CT system equipped with the QUINDOS Reshaper package for DM evaluations, provided by HEXAGON Metrology [9]. The test object, an aluminum plate with a pattern of twenty-eight drilled holes (see Figure 1), has been calibrated with a tactile coordinate-measuring machine (CMM), so it allows to identify differences between the surface extracted from the tomograms and the calibrated values. This object can also be used for the calibration of a CMM or CT system, so it is a representative object for our purposes; it is designed to fulfill the criteria discussed in ISO 10360-11 by ISO/TC 213 WG 10 [8]. Since we want to analyze the influence of ring artifacts, we use both an “uncorrected” CT reconstruction and a “corrected” one where we have applied a method for the ring artifact reduction. Note that we use software methods only [4], so the used algorithms can be applied to virtually any CT system. The ring artifact reduction is part of the YXLON’s Geminy software package which belongs to the FF20CT.
The parameterization of the algorithm is dependent on the very CT system, especially the detector; however, the general procedure works as follows. First, a set of one-dimensional filters is applied to each line in the uncorrected projection in order to identify the noise. This includes random noise as well as static noise. Assuming the noise to be a stationary process, a time adapting ratio between the original projection and a projection where the noise is reduced is computed and then applied to the original projection; this is a secondary gain correction which parameters are computed online. Hence, because we use one-dimensional filters, this algorithm can be applied on linear detector arrays as well as flat panels, and because of the time adapting procedure, it is applied to the sinograms, but in an online applicable algorithm. This is a method developed for image improvement only; hence, it is not a trivial case if this algorithm has any influence on DM at all, which is the reason for our survey.

The procedure is as follows. First, the projections are acquired. Then we perform the reconstruction: one with and another without the ring artifact correction. The surfaces extracted from both reconstructions are used for the DM. The results are compared to values known from the calibration using a two-sided Wilcoxon signed-rank test [5], which is the appropriate test for this problem, as we have a coupled test and want to measure the influence of the ring artifact reduction. We measure the form of the holes as the diameter and the maximum to minimum difference, corresponding to a fitted circle, the maximum value where we exceed this reference, the corresponding minimum value where we are smaller than the average, the noise of these differences (estimated standard deviation), and the vertical and horizontal shift of the center of the holes. From the calibration, we know the positions and the diameter of the holes only. However, because the holes are drilled, we assume the noise to be “low”. In addition, we perform a Kruskal Wallis-test [6] for the variance to analyze for which holes we measure a significant difference. All tests have been performed using a significance level at 5% (that is, we reject the null hypothesis if the respective p-value is less than 0.05).

We used a total of 26 scans for a detailed survey. The scans were performed such that the intensities of the ring artifacts vary between the scans. To exclude further influences on the measurements, we fixed the scan parameters to 1440 projections and kept the focus detector distance (FDD) at 822mm, which is a fairly large FDD for the FF20CT. The majority of the scans were performed with a magnification of 6.5 with a voxel size of 21.38µm (cubic, distance between centers of two neighbor voxels); however, we also altered this parameter in several scans to vary the sizes of ring artifacts with respect to the tomographic size. In total, the magnifications are between 4.11 (voxel size: 33.82µm) and 8.22 (voxel size: 16.91µm). The FF20CT is temperature-controlled at 20°C (+/- 1K), which is the same temperature with which the object was calibrated. We changed the voltage and current for the scans in order to get different influences of the ring artifacts, that is, we used between 60kV and 140kV with a current between 20 and 70µA. The total power at the target of the microfocus tube was between 5.5W and 6W. A scan with a 0.5mm copper filter is also included. Before each scan, we calibrated both the machine and the detector to achieve the same starting conditions for each scan. Each test is performed both on all holes in a common set and on each hole individually.
Figure 3: Schematic view on the hole pattern and numbering of the holes. In red, errors are plotted. The lower edge in Figure 2 is on the right hand side. Errors are obtained from a ring reduced scan.

Figure 4: A tomographic slice without (left) and with (right) the ring artifact reduction (magnified), using the same scan and the same section of the tomogram. The ring artifacts are strongly reduced.

Table 1: Overview of the influences if we apply the ring artifact reduction. The diameter is biased by the maximum outliers, because due to material influences, it is known to be less than using a CMM.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Form</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Standard Deviation</th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased</td>
<td>Not significant</td>
<td>Improved</td>
<td>Not significant</td>
<td>Improved</td>
<td>Improved</td>
<td>Not significant</td>
</tr>
</tbody>
</table>
3 Results

An overview with all results can be seen in Table 1. We observed a significant decrease in the diameter (p-value < 10e-5). From the symmetry of a circle trajectory without any geometrically correction and using a cone beam CT, we know that we will always observe a reduced diameter [7]. In fact, the mean error is 0.0137mm without the ring artifact reduction, and 0.0134mm with this algorithm, hence the mean error is smaller using the ring artifact reduction, in contrast to the results of the statistical test. This contradiction can be explained due to the rank statistic in the analysis which is robust to outliers (while the mean is not), so we can state that the reduction in the diameter is measureable, but not drastically. For the tests performed per hole, 18 holes provided a significant reduction in the diameter with numbers 2 and 11 to 27. For the numbers, see Figure 2.

The form parameter is defined as the difference between the maximum exceeding a fitted circle and the minimum. Even though these two parameters are also included in the tests, we included this parameter to study their coupling. Even though we did not receive a significant difference in this parameter (p-value 0.0591), we observed five holes with a significant larger form without the ring artifact reduction (holes 15, 17, 18, 19, and 23) and three holes with a significant larger form with the ring artifact reduction (holes 1, 5 and 11).

The exceeding maximum, on the other hand, is significantly decreased (p-value 0.0014), and there are five holes significantly larger without the ring artifact reduction (holes 2, 17, 18, 19 and 23) and one hole with the ring artifact reduction only (hole 5).

For the minimum, we observed no significant changes in total (p-value 0.8212), but four significant exceedances without the ring artifact reduction (holes 18, 19, 23 and 27) and five with the ring artifact reduction five (holes 1, 7, 10, 11 and 21).

The positions of the holes are determined by a horizontal and vertical offset, respectively. The vertical offset (in the direction of the CT axis of the FF20CT) provides a significant improvement with respect to the measured coordinates from the calibration using the ring artifact reduction (p-value 0.0001). There were nine holes significantly worse positioned without using the method (holes 1 to 6, 16, 21 and 26) and three with using it (holes 7, 9 and 12). The mean absolute difference to the CMM based values is 0.0013mm without and 0.0012mm with the ring artifact reduction. The horizontal offset is not significantly different with or without the algorithm (p-value 0.3835), one hole is significantly worse without the algorithm (hole 24) and two with the application with the ring artifact reduction (holes 6 and 25). The mean difference in horizontal direction to the CMM based values is both about 0.0010mm with and without the ring artifact reduction.

At last, the standard deviation of the form is analyzed. Here the mean is a fitted circle, and using all measuring points of one hole, the standard deviation is estimated. Because we assume that ring artifacts disturb the surface, this is a very important test. The test provides a significant decrease using the algorithm in total (p-value < 10e-5) with eleven improvements in individually holes (holes 7, 13 to 15, 17 to 20, 22, 23 and 27) and one significant increase (hole 5). However, we do not have exact values for this parameter from the calibration, so implicitly we assume that this deviation should be 0. A measurement for the difference between the distributions of both, using a Kruskal Wallis-test, provided no significant difference between the two data sets (p-value 0.0923), and per hole, we measured six differences (holes 15, 17, 18, 22, 23 and 27).

4 Conclusions

To summarize the tests, we see that the only significant disadvantage of the software based ring artifact reduction, regarding the DM, is in the diameter. However, with the same data, the mean value of this parameter is higher without the application of the ring artifact reduction. This contradiction can be understood when we take the tests for maximum and minimum into account. While with the minimum
test no significant change was visible, the maximum showed quite the contrary. Therefore, we can
close that the ring artifacts lead to a biased interpretation, that is, the artifacts have a tendency to
increase the measured diameters rather than to reduce them, at least in our experiments. Because the
diameter is known to be lower using CT than using CMM, an increase in this parameter, even this
erroneous increment, will lead to a better performance in this task. However, we must consider that
this bias only masks the true geometric order and is therefore not necessarily a positive effect.
The form, which is the sum of the maximum and minimum distance to an average circle, was rejected,
even though we observed a significant improvement in the maximum distance. On the other hand, the
per hole analysis showed that more holes provided a significant better performance if we apply the ring
artifact reduction, but still the number of influenced holes was very low. Therefore we neither
observed a positive nor negative effect in this task.
Interestingly, we observed a significant improvement in the vertical adjustment while using the ring
artifact reduction, even though the positioning is based on a high statistic, as this is the mean of all the
measuring points for each respective hole. The horizontal offset did not increase or decrease
significantly. Still we did not expect a measureable vertical improvement, because the positioning
already is relatively exact without the ring artifact reduction.
The test for the standard deviation at the measured circle is interesting because it shows the influence
of ring artifacts on the surface. We assume that the holes themselves are relatively smooth and hence
we believe not to unnaturally smoothen the surface, even though this was not a provided parameter
from the calibration, because of two reasons. Firstly, the ring artifacts are ordered in horizontal plane,
and the object is oriented vertically, hence we measure the surface in a virtually rectangular angle to
the occurring ring artifacts. Secondly, in our experience, the procedure of drilling holes in an object
with the purpose to be calibrated and used for calibration is relatively exact, compared to our voxel
size, which is several micrometers in all scans.
Because of the importance, we provide two different test sets. First, we used as in all our scans the
Wilcoxon signed rank test. This test can be used for the coupled setting, but for the interpretation, it
implicitly assumes that the average is supposed to be zero. This assumption is only true because of the
two reasons mentioned above. The result is that we have a smoother and virtually more accurate
surface of the test object if we apply the ring artifact reduction. For the second test on this value, we
used a Kruskal Wallis-test, which is a nonparametric ANOVA test, so an analysis of variance [6]. The
interpretation is that we have a random variable, that is the standard deviation, and test if the two sets
(without and with the ring artifact reduction) originates from two different distributions. However, we
were not able to prove that to the given significance level.
In summary, the results suggest that we use the ring artifact reduction for the DM. The measured
advantages outweigh the disadvantage, that is, the slightly reduced diameter, because of the influence
of the outliers in the maximum.

5 Summary and Outlook
We have discussed the influence of ring artifacts on the precision of dimensional measurements in the
industrial application of computed tomography. CT is largely based on image processing, and the
software based ring artifact reduction (rather than moving the detector, [4]) adds another algorithm to
it, so its influence must be analyzed in advance. On the other hand, a mechanical solution is inflicted as
well, for example by a possible misalignment of the mechanical axis or inaccurate calibration of the
detector for the shifted positions. Therefore, its influences have to be analyzed, too, but on a larger
scale: because a mechanical ring artifact reduction cannot be applied on the very same scan as the
control, and physical parameters like humidity or aging of the X-ray source therefore have different
influences on different scans, the two test groups have to include a larger number of samples. We
included 26 scans, and for the same statistical significance, a test for the mechanical solution will have
at least twice as many scans (26 scans for each the control group and the group with the application of the ring artifact reduction), and only as few if we ignore the fact that we made use of the coupling in our tests, so we have the results for this algorithm only and excluded external influences on the scans. This accurate testing might not seem to be appropriate for practical solutions and the mechanical solution, but still has to be done in order to guarantee the precision of the measurements.

The tests themselves are standard statistical tests and applicable for our problem. The overall survey shows that the benefits outweigh the disadvantages by far. Furthermore, the only disadvantage observed was a slightly reduced diameter, which itself is unsafe, and we were able to identify the reasons for that behavior in the maximum outliers of the measured circles. In addition, this disadvantage could not be seen in the mean of the diameter offsets.

Interestingly, we observed an improvement in the vertical offset of the drilled holes. The interpretation is that ring artifact structures have themselves a measurable influence on the positioning in the reconstruction. Therefore, even if the application states that only positions and not the exact surface structure is important, it is recommended to apply the ring artifact reduction.

The most interesting results come from the analysis of the standard deviation at the measured circle. Because we assume that ring artefacts disturb the surface by being higher or lower than their surroundings, we assumed a disturbance of the surface which could be reduced by the ring artefact reduction, which we were able to prove. That the Kruskal Wallis-test did not measure a significant change in the distributions is explainable by the ratio between the voxel size and the size of this parameter, which is, in maximum, about 0.8µm, while the smallest voxel size is more than twenty times as big. Therefore, this measure is influenced by a digital noise, so we can state that we have measured a significant difference, but do not know its dimension.

In total, the results imply that one should apply the ring artifact reduction in the context of DM. The significant improvements, especially in the form and position, of measured results can be important in this task, especially if the measurements are expressed below the voxel size. Even though the algorithm is developed to improve the visual perception, its positive influence on the measurements is huge.

In the future, additional influences on DM will be analyzed. The influences of the material on the diameter are significant and outweigh the influence of the ring artifact reduction by far. Further, if we also want to analyze the mechanical ring artifact reduction, we will also have to understand the influence of the detector and the mechanical calibration of the system. Later can also be a source for further inaccuracies, so the geometrical misalignment is an important topic for our future work.

References

