On the Relationship of Edge Responses to Length Measurements in Industrial X-ray Computed Tomography

Dierck Matern and Frank Herold
YXLON International GmbH, Germany
{dierck.matern, frank.herold}@hbg.yxlon.com

Abstract

The determination of lengths is one of the tasks in the dimensional measurements [1]. Using tactile coordinate measurement machines (CMMs), we can find the length using two states: there is either contact of the probe with the surface or no contact, and the length is the difference between two contact points. In contrast, using X-ray computed tomography (CT), the information is included in volume element (voxel) positions, sizes and grey values. Latter usually are estimated absorption coefficients at the respective coordinates, averaged over the specific element. Hence, the information where specifically in this element the absorption occurs is unknown. Furthermore, there are many influencing factors which also alter the estimation of absorption, like scattering and beam hardening, the used spectrum of the X-ray source, and the absorption spectrum of the detector, or the number of used projections. Those properties can be shortly described as “image quality” if we understand the tomogram as a three dimensional image, resulting from the CT. Due to all of those factors, the surface is not as well defined as with CMMs. As a lot of those factors are usually properties of the individual scan and arise from the object itself, it is problematic to transfer results of the study of test artefacts onto the “real” objects. Therefore it sometimes can be more useful to analyse the local grey value distribution to determine an uncertainty of the length measurement, rather than transferring results from the tactile standards to dimensional measurement in X-ray CT. Especially, if we are interested in the lengths, it can be important to study the local edge responses (which is the influence of an edge of the scanned object onto the tomogram), as the length can be described as the distance between two edges. In this paper, we discuss this relationship between the assumptions of the surface determination and the quality if the underlying tomography with exemplary tomograms by validating the shape of the edge itself.

1. Introduction

The dimensional measurement (DM) is a specific class of metrology [1, 2]. There, the sizes of an object are of interest. More precisely, the tasks are obtaining distances between parts of the object; finding diameter or size from edge to edge, either of the whole object, or a partition; gathering information about the form, e.g., how far the measured object differs in form from an ideal geometry.
Recently, CT has been applied for this task [3, 4]. An object is scanned from different angles. Afterwards, a three-dimensional map, the tomogram, of the absorption coefficients is reconstructed [5]. DM can be applied because different materials have different absorption coefficients [2, 5], and therefore, a surface between the materials

can be found; for example, this can be found on the boundary of what is defined as the object and air, which has virtually no absorption.

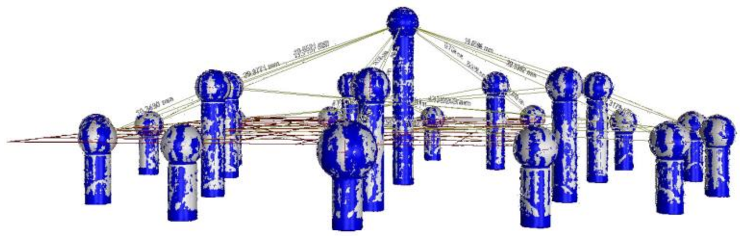

Figure 1. Example of the influences of materials. The reconstruction's extracted surface of a gauge is fitted to its ideal mesh. Noteworthy are the stripes on the spheres which are aligned with the other parts of the gauge.

However, there are different physical effects which inflict the potential of DM in CT. For example, the reconstruction is inflicted by misalignments of the system [6]. The magnification of the projection is the distance of the X-ray source to the detector (FDD), divided by the distance of the X-ray source to the scanned object (FOD) [5, 7]. If either of those distances is incorrect, the scaling of the object is different from the assumptions, leading to false measurements.

In the recent past, manufacturers started to qualify their products for dimensional metrology, for example, by measuring sphere distances in gauges as can be seen in Figure 1. The values are relatively low in comparison to the used voxel sizes in the tomogram, as they use the centre of the spheres for reference, which are means of a relatively large number of voxels [3]. With those methods, they demonstrate that the system geometry is correct within its specifications.

In contrast to the influences of the geometry, the surface properties can be assumed to be closer to the voxel sizes. For each voxel, only one grey value, the estimated absorption coefficient at its relative location, is present. If this is altered due to artefacts, the object border can be assumed at the wrong location. Even though there are algorithms that consider surroundings of several voxels for this surface determination [8, 9] (e.g., the assumption is the object to be smooth in respect to the voxel size), some of the effects may influence the whole region, so even with those algorithms, the found boundary will be incorrect. Unfortunately, most of the applied algorithms are not openly available, but the strategies for quality evaluation discussed here can be applied as well with alternate surface form assumptions.

For a qualification process of a CT system, standard measures like the form error [1, 2] can be utilized. However, this has little implications on other scans, where interesting parts may be occluded by other parts of the scanned object, inflicted by scattering [10], or the scan parameters might differ from the qualification procedure. As there are a lot of different parameters which can inflict the surface, other measures for the quality of the length measurements are useful. Those have to be based on the surface, as this defines this task of dimensional measurement, but also include its surroundings.

From a signal processing point of view, the edge of the object has a response in the tomogram, and this response can be influenced by disturbances [10]. In this study, influences of materials on these edge responses are analysed, and therefore, how these effects afflict the reliability of DM. In order to obtain the ground truth, several scans of an object are scanned without additional disturbances. Then, distortion objects are introduced in the setup. In total, the edge responses are analysed to get the information how reliable the surface determination process is. To evaluate this, two different measures are used: for once, the modulation transfer function (MTF) [11] which describes the transfer of frequencies on the steps from material to the exterior, and the Kullback-Leibler divergence (also known as relative entropy) [12], performed on fitted "ideal" curves [13] which describes the distance to the assumptions in the surface determination process. Therefore, the latter measures how "ideal" the edge is, and is closer to the tactile process, but it evaluates the quality of the assumptions of the surface determination process.

Figure 2. Gauge used for the experiments in front of the microfocus X-ray tube. The spheres consist of ruby. Only the upper two spheres are analysed in this survey.

2. Materials and Methods

The gauge used in this study consists of several ruby spheres, positioned on different heights, see Figure 2. Because they are fixed on cylinders of lighter material, there is some influence to begin with. Objects used for the distortion are made from aluminium, as this has a similar absorption spectrum as ruby.

In detail, from thirteen tomograms, twenty-two tomographic slices are extracted each, which results in a significant number of samples. The grey value distributions on the edge of the spheres are analysed, especially if there is a correlation between the direction of the distortion object, and the edge response. Those slices are extracted both horizontally and vertically, with eleven ones in each direction. In all slices, the power spectrum of the Fourier transform is computed in a directional manner, similar to the MTF; this is called "directional MTF" here. For the compliance to the standard ASTM E1695, we use the 10% mark as the representative [11].

The surface usually is assumed where the image gradient is the steepest [8]. The shift in the surface is usually described as the probing error [14]. For this study, this has two shortcomings: First, this measure works on the surface only, hence does not take into account if there are modifications on the surface other than noise; so anything that modifies the reliability of the surface measurement, hence the uncertainty itself, is ignored. Say if the slope on the edge changes, this keeps unnoticed by this measure. Second, the surface has to be known to estimate the probing error. Therefore, a more

generalized approach is feasible, which also measures the surroundings, but describes most clearly the influences on the surface.
In the experiments, a curve is fitted onto the grey values, located at the edge, from the inner material to the outside. Then, the Kullback-Leibler divergence is computed as a measure to an ideal curve, which is defined here as a generalized Gaussian curve [13]. This provides a measure on the distance between the assumptions and the “real” edge.

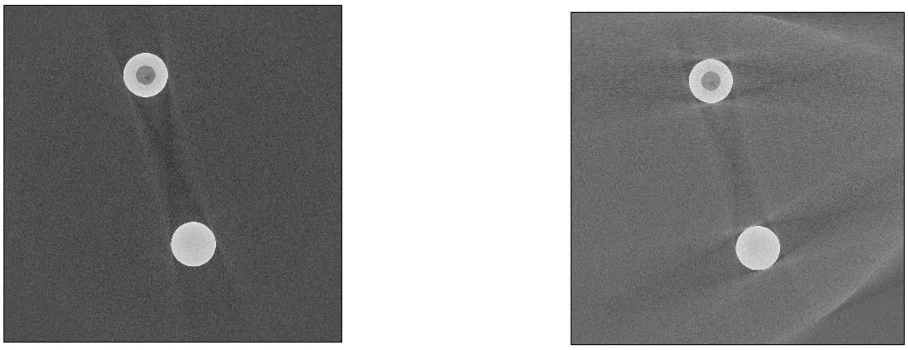

Figure 3. Example slices with the same object, without (left) and with (right) obstructing object. Disturbances in the surface are clearly visible.

For a known object, the curve used to estimate the surface provides ideally a unique turning point. Hence, a curve with a turning point at that specific location can be used. However, the used object is not calibrated in that matter; hence this also is a grade of freedom in the experiments. Hence, the parameters estimated are the position of this very turning points and the slope, represented by two grades of freedom.
Hence, in the experiments, the discussion is about two different measures: first the directional MTF, which measures the frequency on the edges in the tomographic slice, and second the suitability of (uncorrected) surface extraction methods. In addition, the correlation between those two measures is discussed, showing whether the MTF alone is suitable to determine the quality of the edge.

3. Experiments

Thirteen scans at two magnifications are used, six with and seven without obstructing objects. Those objects are used to modify the surface. Two spheres of the gauge are visible in the centre slice of the tomogram, see Figure 3. Those spheres also obstruct each other, giving the ground truth of the sensitivity.
The X-ray parameters and distance between the focus and the detector are fixed throughout the experiments. This is done to reduce the complexity of the interpretation. This study is performed to understand how the modifications of the surface change the certainty of the edge determination; the Kullback-Leibler divergence is used to show the applicability of the surface detection. Both values are compared direction-dependent.
The slices taken are both horizontally and vertically. Because the gauge has spheres which are fixated at the bottom, see Figure 2, the lowest angles are cut out. In the vertical slices, 0° is directed to the top. For each tomogram, several parallel slices are taken.

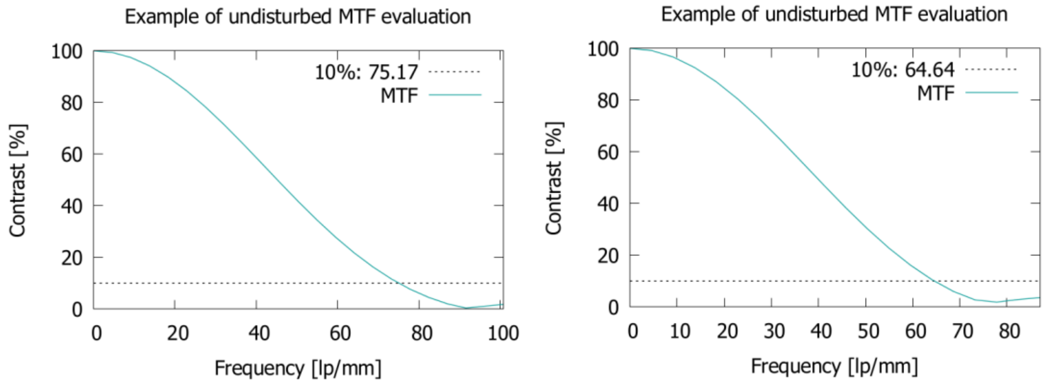

Figure 4. Directional modulation transfer function, without obstructing object, best (left) and worst (right) evaluation from the same slice, over both spheres. The two measurements are close to each other.

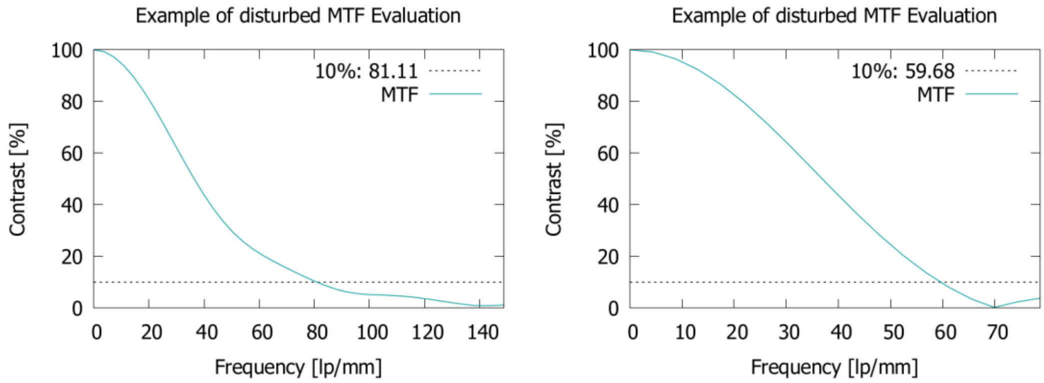

Figure 5. Directional modulation transfer function, including an obstructing object, best (left) and worst (right) evaluation from the same slice, over both spheres. The curves are more dissimilar than in the example without the obstructing object.

In Figure 4, the directional MTF is shown without the disturbing objects. As examples, the biggest and lowest estimation of the transfer of frequencies are presented. In Figure 5, the same evaluation is performed with the inclusion of an obstructing object. Visibly the slope of the MTF is altered on the left side, with a false implication on the 10% percentile.

In Figure 6, the comparison to the surface determination evaluation is shown. Here, both graphs are normalized to zero mean and standard deviation of 1 to provide a measure for comparison. Smaller disturbances can be seen on the places where the two spheres are shadowing each other. Without the normalization, a large difference between the two signals of the Kullback-Leibler divergence is visible. For a non-visual evaluation, the correlation between those two signals is computed. In the slices without the obstructing object, the Pearson correlation coefficient [15] is $\mathbf{-0.2336}$ with a standard deviation of $\mathbf{0.1632}$ and with an obstructing object, the correlation coefficient is $\mathbf{-0.0629}$ with a standard deviation of $\mathbf{0.1645}$. Therefore, a significant negative correlation between the Kullback-Leibler divergence and the MTF is observed in the clean tomogram, while those values are uncorrelated in the presence of disturbing objects.

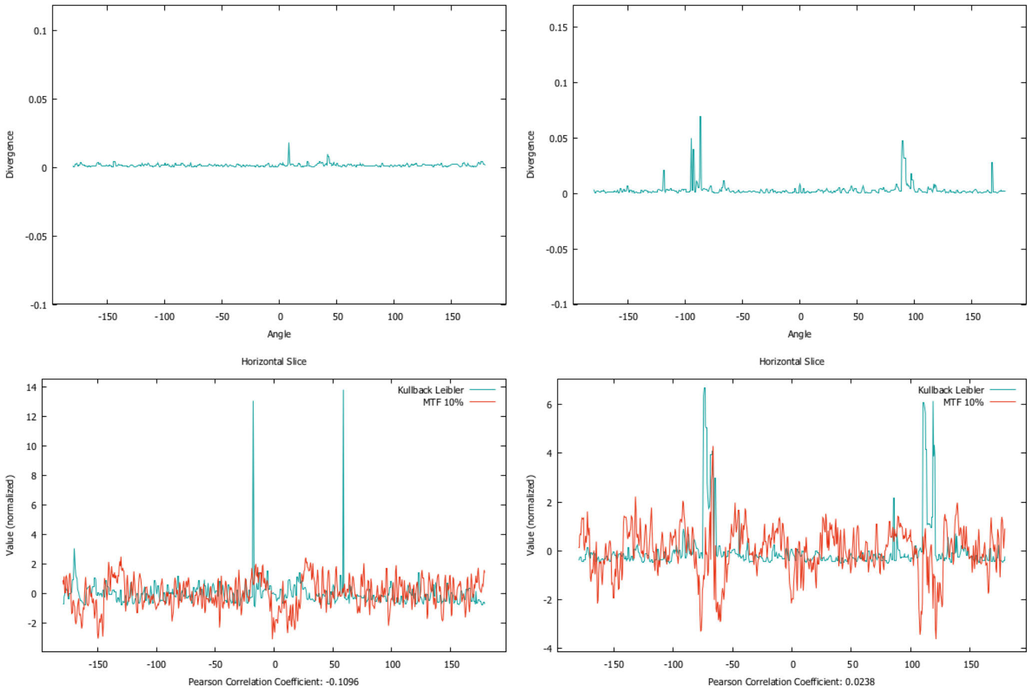

Figure 6: Angle dependant evaluations. On the top: Evaluation of the clean slice (left) and the slice with the obstruction object. The influence of the object is clearly measureable by the Kullback-Leibler divergence by several orders of magnitude. On the bottom: comparison with the directional MTF, left without and right with obstructing object. For this comparison, the signals are normalised to zero mean and standard deviation of one.

4. Conclusions

In this paper, the influences of obstruction materials on the surface with respect to the dimensional metrology are analysed. The chain here is from the assumptions implicitly or explicitly made in the surface determination algorithms over a measure of how suitable these assumptions are at a concrete example to standardised measures, namely the modulation transfer function.

This analysis is important, because of its consequences for the dimensional measurement. If the surface determination is disturbed by obstructing objects, this adds another level of uncertainty in the length determination. On the other hand, this should be predicted by measures which describe the image quality, because the surface determination itself is part of image processing, and therefore influenced by the same means.

The measures discussed in this paper are applicable with arbitrary objects, while the CMM-implied measure probing error is applicable with predefined and calibrated objects only. Hence, this cannot be measured in the very tomogram of the actual application. Therefore, this measure is for the qualification of the CT system in general only, without implications on the application of the customer.

The MTF is a measure for the transfer of frequencies and therefore the traceability of details, while the Kullback-Leibler divergence is a measure of suitability of the assumed surface. Even though they differ much in their interpretation, they show a moderate (negative) correlation in the experiments without any disturbing objects. Because of the widespread spectrum of edge responses, this is no coincidence: if the frequencies are not transferred correctly, the ideal step is altered, too. As the experiments show, this depends on the very direction of obstructing objects. The Kullback-Leibler divergence measures (in this case) the difference to the ideal transfer of the edge, where the response is assumed to be symmetrical. This assumption holds well in directions where no obstruction occurs, while in other directions, the curve of the edge response is biased, meaning that the turning point is shifted. This would result in a falsely positioned surface. However, by these experiments, the MTF alone does not provide enough information about the surface, but because of the negative correlation, it is enough for the qualification process, because the probing error will not introduce additional information in the ideal setting.

The Kullback-Leibler divergence used here does not react to symmetrical transformations which would leave the position of the estimated edge in place. Therefore, all reactions are measurements of biased estimations, which result in a shifting of the edge and a false length measurement. Furthermore, the MTF measures the transmission of the frequencies on the edge, hence the stability. Both are viable information for calculating the uncertainty of the very edge in real applications, and according to these results, should be considered if an uncertainty of the length measurement is desired.

An interesting question is if the modification of the edges can be corrected. For this, the very modification is of interest. The Kullback-Leibler divergence can be used to identify this. If the modification is considered, the location of the edge can be corrected, meaning an improved length measurement is possible.

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