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Optimisation of workpiece manipulation for multimaterial measurements in industrial computed tomography

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Abstract

Industrial Computed Tomography (CT) has been regarded as a powerful tool in the field of dimensional metrology due to its holistic approach to 3D coordinate measurements. Several factors influence the measurement outcome and thus the uncertainty of measurements. The orientation of the workpiece in the CT system and the source-object distance play an important role. Workpiece orientation has to be chosen so that effects of beam hardening and Feldkamp artifacts are minimised. In this study, we want to present a method for optimising these manipulation parameters for dimensional measurements; the main focus is on multimaterial workpieces. The method is based on a ray-tracing simulation algorithm, which searches for the optimal manipulation parameters to minimise artifacts and maximise magnification. First, a CAD file containing the workpiece geometry and material data are loaded. A bounding sphere containing the workpiece is defined and the source-object distance (SOD) is minimised so that the sphere is entirely within the CT cone beam field of view. Then, for each workpiece angle, rays are traced as straight lines from the X-ray source to each detector pixel. Subsequently, the photon energy is iteratively optimised so that for each projection angle a mean transmission value of 14% is achieved. The algorithm evaluates the local projection integrals and chooses the orientation that minimises the maximum integral. Finally, the algorithm ensures to conditions to avoid Feldkamp artifacts are satisfied. This method is validated by designing multimaterial test artifacts and comparing the computed manipulation parameters with those determined empirically.

Keywords: Computed Tomography, dimensional measurements, multimaterial measurements, workpiece orientation, setup parameters, magnification, simulation

1. Introduction

Industrial X-ray Computed Tomography (CT) is the only non-destructive testing method able to inspect and measure the full geometry of an object, including the inner surface and non-accessible features, without altering or damaging it [1]. Recently, CT has been regarded as a promising technique in the field of dimensional metrology. CT settings are chosen by the users and can affect the accuracy of measurements. In particular, workpiece position and orientation strongly influence the measurement outcome [2]. In this study, we present a method to optimise the position and orientation of multimaterial workpieces. Subsequently, we report results of an experimental investigation to show the relationship between workpiece orientation and measurement accuracy, in order to validate the method.

2. Method

CT image quality, as well as the accuracy of CT measurements, depends on the local projection integral along the ray path, which represents attenuation of X-rays after travelling through an object. The X-ray intensity after traversing a particular material length is given by the Lambert Beer law [3]. Moreover, the local projection integral depends on workpiece position and angular orientation. If the values of the local projection integrals increase, artifacts due to beam hardening or scattering reduce image quality and therefore measurement accuracy. In this sense, a reasonable choice for workpiece manipulation is to minimize the projection integrals [2]. On the other hand, if a portion of the workpiece surface is perpendicular to the CT rotation axis, reconstruction artifacts may occur and impair measurements [4]. Therefore, optimising workpiece position and orientation is a complex process that needs to take these phenomena into account. Some methods were suggested to optimise workpiece manipulation for monomaterial workpieces, e.g. [2]. However, the state of the art lacks a procedure for dimensional measurements on multimaterial workpieces.

2.1. Ray-tracing simulation of CT scans

The identification of the best workpiece orientation and position can be achieved by means of a ray-tracing simulation of CT scans. First of all, we model the X-ray source as a monochromatic point source, whereas each ray is represented by a straight line from the source to each detector pixel. The rays intersect the workpiece and are attenuated (Figure 1). The geometry of the scanned object is represented in terms of an STL file (Standard Triangulation Language) that represents the workpiece surface as a point cloud and vectors normal to triangles formed by each set of three neighbouring points.

In general, a multimaterial workpiece consists of m different materials, each one featuring a linear absorption coefficient $\mu(E)$ that depends on the photon energy E.

Once the source-detector distance (SDD) is set, we consider the smallest sphere that contains the workpiece. We move this sphere along the source-detector line so that its distance from the source is minimised, while still being entirely within the X-ray cone beam field of view. In this manner, the resolution of projection images is maximised, while ensuring complete reconstruction. We proceed by optimising the workpiece angular orientation. We consider a set of angular orientations

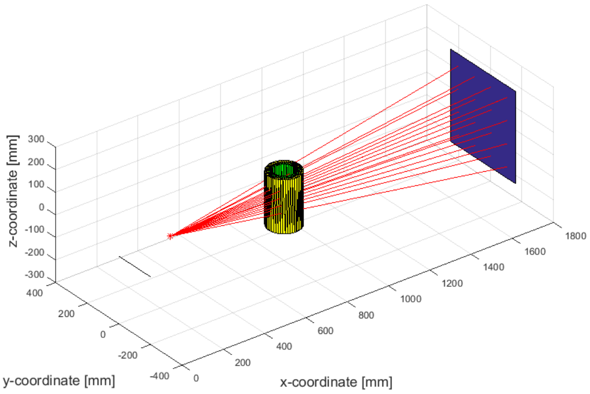

Figure 1. Ray-tracing simulation of a CT system.

$(\varphi,\phi,\gamma)_i$ for increments of 10°, where φ is a rotation angle about the X-axis, γ is the rotation about the Y-axis (also the projection angle), and ϕ is a rotation around the Z-axis. For each $(\varphi,\phi)_i$, we compute the intersection points between rays and mesh triangle for each projection angle γ. At each projection, we evaluate the penetration lengths $d_{1,j}\ldots d_{m,j}$ related to the j-th ray. Then, we perform a transmission-based optimisation of the photon energy by considering an optimal transmission ratio of 14% in terms of mean squared error (MSE) that maximises image quality, corresponding to a value of projection integral equal to 2 [5]. The optimal photon energy minimises the MSE of the projection.

Now we can evaluate the linear absorption coefficients $\mu_1(E^*),\ldots,\mu_m(E^*)$ at the optimal energy E^* and finally the projection integrals. The optimal orientation $(\varphi,\phi)_{opt}$ is the one that minimises that maximum projection integral.

Finally, we check that the number of triangles with normal vector parallel to the rotation axis is smaller than a tolerance value to avoid reconstruction artifacts. This occurs by evaluating the angle between each normal vector and the rotation axis. The critical condition is when this angle is next to zero. If this condition does not hold, we choose the second-best orientation and check the condition again.

3. Description of the investigation and results

In order to validate the suggested method, we implemented the algorithm into a software application and performed an experimental investigation on a test workpiece consisting of polyoxymethylene (POM) and aluminium hollow cylinders (Figure 2). Since this workpiece is axis-symmetric, we can vary just one angle for simplicity.

We calculated the maximum projection integrals for each angular orientation and concluded that the best orientation is 30°. The computation time was approximately 10 minutes. Subsequently, we measured the innermost and the outermost diameters of the assemblies at different heights.

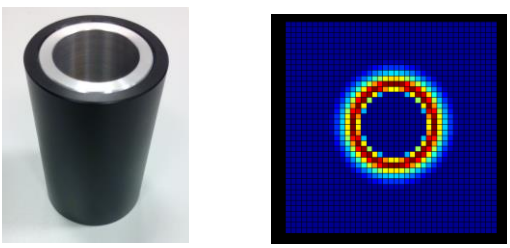

Figure 2. Left: multimaterial test workpiece consisting of POM (black) and aluminium (grey). Right: distribution of the local projection integrals.

We performed a calibration of the parts with a tactile CMM and performed CT measurements with the workpiece at 0°, 30°, 60° and 90°. Then, we evaluated the error of CT measurements with respect to the calibrated values. Figure 3 shows the error of measurements at a depth of 0.5 mm from the upper surface. It is possible to see that the orientation that minimises the error is 30°, in accordance with predicted results.

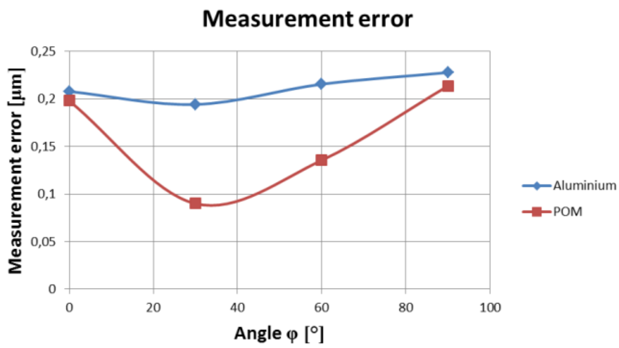

Figure 3. Measurement error in µm of the outermost diameter as a function of the workpiece orientation.

4. Conclusions

In this study, we suggested a method to optimise position and orientation of a multimaterial workpiece for CT measurements. The method is based on a ray-tracing simulation that evaluates the minimum source-object distance, optimises the average photon energy and determines the best orientation based on the minimisation of the maximum projection integral. The algorithm also checks a condition to avoid reconstruction artifacts.

An experimental investigation was carried out to validate the proposed method. CT measurements were performed on a multimaterial test workpiece and compared with calibrated values. Experimental results matched predictions.

Future work at the Laboratory of Machine Tools and Production Engineering (WZL) of RWTH Aachen University will deal with investigating the influence of a metrological feature of interest on the optimal orientation.

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