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Improved surface generation of multi-material objects in computed tomography using local histograms

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Abstract

During the last decade industrial computed tomography (iCT) has become one of the most important metrological procedures for internal inspection, where it sees wide-spread use in injection molding and additive manufacturing. Evaluating the CT volume data of multi-material objects represents a major technical challenge. Due to artifacts caused by beam hardening, an over-segmentation of strongly absorbing materials occurs, severely limiting the accuracy of dimensional measurements. The goal of the project presented is the development of an innovative artifact-reduced multi-material segmentation. This is applied to and tested on various complex reconstructed CT data sets. Global approaches show high signal-to-noise-ratio (SNR) but are not able to compensate for local deviations. For smaller volumes the data sets become more consistent, but the SNR decreases due to the reduced data volume.

Thus, a more localized approach for the volume image data has the potential to provide results of higher accuracy. With this newly presented algorithm it is now possible to perform segmentation of all materials, while eliminating over-segmentation errors as well as local noise artifacts almost completely for all tested datasets.

Keywords: Metrology, Computed Tomography, Surface Generation, Multi-Material Segmentation

1. Introduction

The advancements in injection molding and additive manufacturing methods in recent times have opened the market for the economic production of complex inner structures for both large-batch and small-batch series. In these sectors industrial computed tomography (iCT) has proven its suitability for the in-line inspection of a plethora of geometries and materials. However, the evaluation of CT volume data of multi-material objects still remains difficult to achieve and error-prone. Beam-hardening artifacts lead to an over-segmentation of strongly absorbing materials [1]. Dimensional measurements are therefore severely limited in their accuracy. Current methods are limited to global histogram analysis and watershed methods, which are not able to compensate for over-segmentation [2]. Optimization of this process is an important part of current research in computer tomography [3,4]

2. Methodology

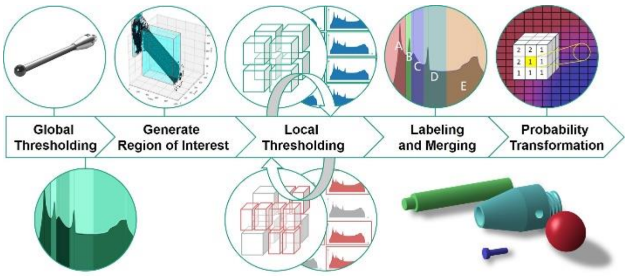
The goal of the research was to increase the accuracy of the multi-material segmentation process and reduce the influence of artifacts. In addition the improved mesh quality will reduce the necessary time for post-processing by the measuring technician as well as increase the reliability of the results.

Hereinafter the methology of the algorithm is presented. In a first step the setup and boundary conditions are explained. In a subsequent step the concept of the algorithm and the procedural steps are described.

2.1. Setup

The algorithm is programmed as an indepent library (.dll) in C++ using the IDE Visual Studio 2019 developed by Microsoft, USA, Washington, Redmond. For a performance evaluation it was integrated into the Fraunhofer IPK internal FLUX-Framework. To reduce the necessary computation times, the code was optimized for parallel processing on the CPU using OpenMP 2.0. For this purpose a computer with a 20-core Xeon E5-2698 CPU and 128 GB DDR4 RAM were used. For the evaluation of the algorithm a total of 15 different real multi-material datasets of varying complexity were used. Hereby multi-material is defined as the presence of a minimum of two materials. The meshes were compared to ordinary segmentation algorithms with the open source software meshlab developed by CNR-ISTI, Pisa, Italy [4]. No post-processing of the data such as decimation or smoothing was conducted.

Figure 1. Process Pipeline of the improved segmentation



2.2. Concept of the pipeline

To achieve the prior discussed goal a new sophisticated process pipeline was developed (Figure 1). This process pipeline consists of five steps which are briefly explained in the following.

Global thresholding: Using a subsampling of the dataset the amount of the materials present and their positions can be estimated.

Generate region of interest: Initial bounding boxes are calculated based on the global thresholding.

Local thresholding: Each of the initial bounding boxes is evaluated by a metric based on the local grey value histogram. The ratio between peak prominence and baseline serves as a quantifier when compared to a defined threshold. If the ratio is too low, the volume will be subdivided and the process is

repeated until all subdivided volumes satisfy the metric. For every subdivided volume a local threshold is subsequently determined using a multi-level Otsu algorithm [5].
Labeling and merging:
The data is locally labeled according to the local thresholds and subsequently checked for mislabelled voxels. These are corrected in an additional step. Afterwards the local volumes are remerged into a global volume dataset.
Probability transformation:
Labeled volumes are transformed into a set of probability volumes using a transformation kernel, similar to the works of [6]. This enables a sub-voxel accurate determination of the surfaces as well as a separation of the labels for an individual material. Finally the surfaces are calculated using a marching cube algorithm [7] and exported in the .stl format for evaluation.
Post-Processing:
A Connectivity Filter can be applied to each mesh separately to generate a more visual appealing result. This is only possible due to the prior segmentation in multiple material meshes.

3. Results

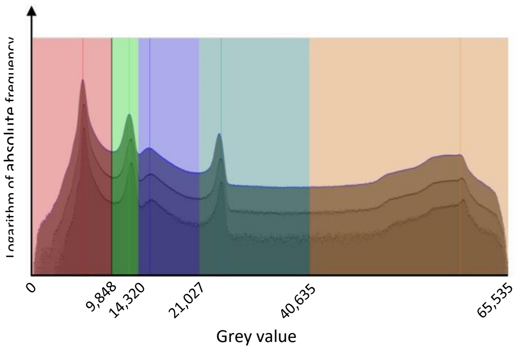


Figure 2. Multi-scale histogram of the presented dataset

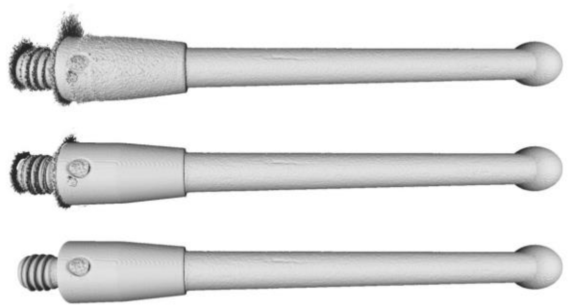


Figure 3. Surface of the multi-material object from top to bottom a) ISO50 b) new approach c) new approach with post-processing

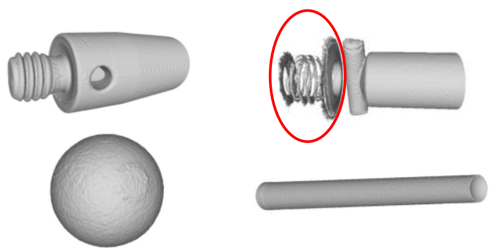


Figure 4. Segmented Materials sorted by their grey value intensity

An exemplary complex multi-material dataset of a tactile probe is presented. The dimensions are 421 x 228 x 1916 voxel with an isotropic voxel size of d_v = 30 µm. As seen in the global multi-scale histogram (Figure 2) four materials are present and strong metal artifacts are to be expected. The first peak of the histogram (red area) is associated with the background level.

The meshes generated with the ISO50 algorithm and the new implementation are presented in figure 3. The segmented materials are displayed in Figure 4.

4. Discussion

The results (Figure 3b and 3c) presented in chapter 3 show off major improvements in the surface quality when compared with the popular ISO50 (Figure 3a) algorithm, especially for the more absorbing thread area. A strong artifact reduction especially of the thread section is visible and a clear improvement of the surface can be identified. Contrary to present algorithms, a good segmentation of the materials is possible, especially for the intersections of the different materials. Only in figure 4b, marked with red circle, mislabelling – due to extreme metal artifacts near an intricate structure – is present. Additionally due to the local thresholds being higher than the first threshold which is used for the surface generation, the created meshes are substantially smaller than these of the ISO50 method. This behaviour is very substantial and is for the presented dataset up to nine voxels in radius. Considering a voxel size of d = 40 µm this results in a diameter difference of ΔD = 720 µm. These results were validated by the other mutli-material datasets whereas the artifact load of the generated meshes were reduced significantly and a multiple voxel more accurate determination of the surface was shown. It should be noted, that due to the additional processing steps, the computation time of the segmentation increased by roughly a magnitude from t = 3 s to t = 30 s for a dataset size of 480 MB. The time for post-processing is almost negligible and increases the computation time to t = 31 s. The RAM requirements increased as well to three times the size of the initial dataset with room for optimization.

5. Conclusion

The discussed newly developed algorithm achieves major improvements over previous implementations. Artifacts such as beam scattering are diminished significantly and surfaces can be determined much more accurately. A clear and correct segmentation of multi-material objects is now feasible.
The single drawback is the significantly increased computation time. However, considering that extensive post-processing is no longer necessary, as well as the suitability of the algorithm for parallel-processing, a net time win is achieved. In further works it is planned to parallelize the code on the GPU for speed improvements in the range of two magnitudes.

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