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Multi-Material Empirical Artifact Correction (MEAK): Efficient Algorithm for Correcting Beam Hardening Artifacts in Multi-Material CT

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Abstract
Industrial X-ray computed tomography (CT) has become a well-established method for the fast, complete, and non-destructive measurement of workpieces. However, in multi-material components containing highly absorbing materials, beam hardening artifacts result in systematic measurement errors [1]. Existing approaches to artifact reduction, such as the use of hard prefilters and multi-spectral CT (MSP-CT) methods [2], require additional measurement time and reduce the contrast-to-noise ratio (CNR) [3]. This contribution introduces the Multi-Material Empirical Artifact Correction (MEAK), a novel correction method that reduces beam hardening artifacts without increasing measurement time and can be seamlessly integrated into existing processes. Comparative measurements demonstrate that MEAK reduces both linear and non-linear artifacts, preserves the CNR, and halves the measurement time compared to MSP-CT.

artifact reduction, measurement time reduction, multi-material, metrology

1. Introduction

CT has become a well-established method for the fast, complete, and non-destructive measurement of workpieces. However, multi-material components containing highly absorbing materials, such as metals, are subject to beam hardening artifacts. These artifacts cause systematic measurement errors and limit the applicability of CT for dimensional metrology [1]. A common method for reducing beam hardening artifacts is the use of strong pre-filters to harden the X-ray spectrum. However, attenuating lowenergy photons reduce the contrast-to-noise ratio (CNR), leading to increased measurement uncertainty. MSP-CT methods combine measurements acquired with different spectra to correct artifacts, but the additional measurements result in longer measurement times and often lead to a reduced CNR [2]. The MEAK method, presented in the following, extends the empirical beam hardening correction (EBHC) introduced by Kyriakou et al. [3]. MEAK reduces both linear and non-linear beam hardening artifacts without requiring additional measurements or prior knowledge of the CT system or the workpiece.

2. Materials and methods

2.1. Method

The approach is based on EBHC and has been further developed to meet industrial requirements. It accounts for both linear and non-linear artifacts. Artifact reduction is achieved using base volumes, which are calculated from the measured data and represent the artifacts in the reconstructed volume. The measured volume is corrected by applying a weighted linear combination of these base volumes.

2.2. Method validation

To validate the method, a measurement of an industrial connector made of several materials was performed. The scan was carried out at 270 kV, 80 W, using a 1-mm-thick tin prefilter. The measurement time was 10 minutes. The results were compared with those of the MSP-CT and high-resolution MSP-CT (MSP-CT HR) methods, among others, for which a second measurement was performed at 160 kV, 50 W, and with a 1-mm-copper prefilter, with the same measurement time. This doubled the total measurement time for the MSP-CT methods to 20 minutes, compared to 10 minutes for MEAK. All other parameters were kept constant.

3. Results

Figure 1 shows the results of MEAK in comparison to the correction methods EBHC, MSP-CT, and MSP-CT HR. EBHC is unable to correct non-linear partial volume artifacts, and high-frequency striping artifacts remain visible. MSP-CT significantly reduces artifacts but fails to preserve the CNR, as evident in the resulting point clouds. MSP-CT HR delivers the best performance in terms of artifact reduction and CNR preservation. However, it requires a second scan, thereby doubling the total measurement time (see Section 2.1). MEAK effectively reduces both linear and non-linear artifacts in a single scan while maintaining CNR.
It therefore provides a time-efficient alternative to multispectral methods, particularly in industrial applications requiring high image quality and throughput.

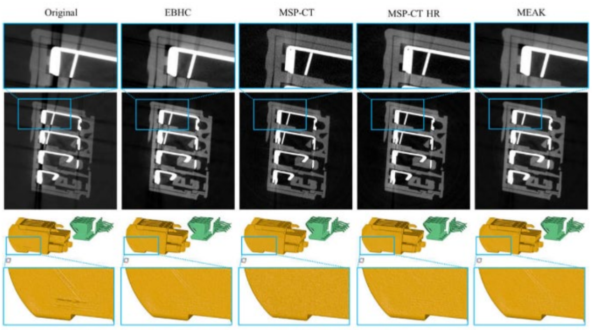

Figure 1 Example volume sections of the uncorrected initial volume of the connector measurement (left), as well as the resultant volumes after corrections using EBHC, MSP-CT, MSP-CT HR, and MEAK. The lower row shows point clouds in STL-format generated from the volume data for both materials present in the object (plastic: gold; metal: green).

4. Summary and outlook

MEAK has been presented as a practical algorithm for reducing beam hardening and partial volume artifacts in CT measurements of multi-material components. Compared to multi-spectral methods, MEAK achieves a well-balanced combination of image quality and measurement time: linear and non-linear artifacts are significantly reduced, the contrast-to-noise ratio is preserved, and the measurement time is halved relative to MSP-CT HR. The method has been experimentally validated on representative multi-material workpieces and integrated into the WinWerth® measurement software.

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