M.J. Schrapp, *Multi Modal Data Fusion in Industrial X-ray Computed Tomography*, Ph.D. dissertation, Fakultät für Physik der Technischen Universität München, Munich, Germany, 2015.

Abstract

In industrial non-destructive testing, X-ray computed tomography (CT) along with further imaging techniques play an important role in the investigation of large-scale samples. However, large-sized and heavily absorbing objects cause artifacts due to either the lack of penetration of the specimen in specific directions or by having data from only a limited angular range of views. In such cases, valuable information about the specimen is not revealed by the CT measurements itself and corresponding reconstructions suffer from limited information about object features.

Due to different physical interaction principles, additional imaging techniques are able to provide information that is complementary to the CT acquisition. Subsequently, a combination of all of these available data sets can be used to best characterize the object. In this thesis, we employ, besides X-ray CT, the following three distinctive imaging modalities:

An optical 3D scanner for surface detection, a new technique from ultrasonic imaging for the acquisition of internal edges and neutron CT as a fully complementary modality to X-ray CT. Additionally, further information obtained from available CAD data is used.

The optical 3D scanner is based on a triangulation and structured light approach. Complementary surface information is eminently helpful in concave regions, e.g., for turbine blades, since CT reconstructions suffering from limited penetration are not able to reveal this information. Ultrasonic data are obtained via an adapted and improved version of a synthetic aperture focusing technique (SAFT) and complement missing edge structures from X-ray CT.

We developed several approaches in order to incorporate valuable information from further modalities directly into the CT reconstruction process. Iterative reconstruction algorithms are most appropriate in dealing with missing information and are the best suited to include additional features from other modalities.

Our first algorithm presented in this thesis is a regularized version of the simultaneous algebraic reconstruction technique, denoted as RSART. It serves as a basis for further reconstruction algorithms and is able to handle a priori known surface data gained from an optical scanner. Additional edge information from ultrasonic imaging is incorporated into the CT reconstruction using a superiorization approach, a newly developed method for constrained

optimization; this allows precise localization of edges that are not resolvable from the CT data by itself. Superiorization, as presented in this thesis, exploits the fact that the regularized simultaneous algebraic reconstruction technique (RSART) is resilient to perturbations, i.e., it can be modified to produce an output that is as consistent with the CT measurements as the output of unmodified RSART, but is more consistent with the complementary ultrasonic data.

To be more precise, three superiorized versions are introduced: the first aims at minimizing the total variation (TV), a measure of image smoothness originating from the field of compressed sensing. The second version introduces an objective function that includes the a priori known ultrasonic data and a composition of both versions culminates in the final Edge PICCS (prior image constrained compressed sensing) algorithm. The application of superiorized RSART methods to measured data of a turbine blade demonstrates a clear improvement of image quality in the final volume.

To prove this quantitatively, we employ a cross correlation technique known as Fourier Ring Correlation (FRC) which is able to compare reconstruction outcomes without using a reference object.

In contrast to optical and ultrasonic imaging, which cover only particular features of a test specimen, computed tomography using neutrons provides a complete CT volume model. Neutron CT measurements were conducted at the ANTARES beam line at the Heinz Maier-Leibnitz Zentrum at the Technical University of Munich in Garching. Since neutrons interact with atomic nuclei in the specimen, data from such CT's are complementary to X-ray and provide high contrast for materials containing a sufficient amount of hydrogen (e.g., plastics, adhesive tapes, oil etc.). Thus, it is reasonable to combine relevant features from both modalities in a single volume. We developed a novel data fusion procedure, called Fusion RSART, where the X-ray reconstruction is modified to fulfill the available data from the neutron imaging and vice versa. The experiments, which were obtained from an aluminum profile containing a steel screw and attached carbon fiber plates, demonstrate that the image quality in CT can be significantly improved when the proposed fusion method is used.

A further application of data fusion is tomosynthesis. In tomosynthesis, typically large and inaccessible objects are investigated by the acquisition of a limited number of projections or a limited angular view. By means of additional CAD data, we are able to alleviate corresponding artifacts arising from undersampling. We address two distinctive issues: First, truncated projections are stitched and supplemented in a pre-processing step with available artificial projections obtained from ideal simulations of CAD data. Second, data from ideal simulations are utilized to improve the reconstruction results based on

an adapted version of the RSART algorithm. The methodology is applied on carbon reinforced plastic plates and reveals reconstructions with an improved contrast-to-noise ratio and reduced cone beam artifacts.