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Registration of a priori information for computed laminography

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ABSTRACT

Reconstructed 3D volumes from computed laminography data suffer from blurring artefacts due to the laminographic geometry. Such losses in quality can be compensated for by integrating a priori information about the test object into the iterative reconstruction process. However, this requires the position of the a priori model to be fitted exactly to the measured data. A (semi-)automatic 2D-3D registration algorithm which only requires a minimal additional user input and is based on a mathematical optimization problem is presented. Using measurement data obtained by simulating X-ray projections of the laminographic scanner CLARA the algorithm is validated.

1. Introduction

Over the last few decades, computed tomography (CT) has become a well-established and widely used method of nondestructive testing.

It allows a 3D analysis of the interior structure of an object using X-rays and mathematical reconstruction algorithms. To this end, the object is placed on a rotation table between an X-ray source and a detector, which provides irradiation images of the object (Fig. 1). The object is then rotated by 360° while an entire data set of projections from all angles is obtained. From these images a volume representing the density distribution of the object can be computed using mathematical reconstruction algorithms.

Still there are some test cases in which this powerful technique for investigating the test object's inner structure is not applicable. For instance, if a planar object, i.e. a potentially very large but extremely flat object, is to be measured using CT two major problems arise. The first of which is caused by the extreme differences in the object's diameters in longitudinal and transversal direction. As CT relies on a full rotation of 360° the object needs to be penetrated by X-rays from each direction. In order for the X-rays not to be fully attenuated when passing through the object in longitudinal direction, their energy has to be sufficiently high which in turn leads to very weak contrast in transversal directions and may result in unusable measurements. The second problem is encountered when aiming for a high magnification ratio. The latter is increased by reducing the distance between object and X-ray source. Especially for fine-structured planar objects the feasible magnification factor may require the object to be so close to the detector that a full object rotation is no longer possible without causing a collision of object and X-ray tube. Both these problems are solved by computed laminography (CL). Contrary to traditional CT, for this X-ray technique, neither does the axis between source and detector need to be perpendicular to the rotation axis, nor does the rotation performed necessarily need to measure 360°. There are numerous different CL geometries, some relying on linear or planar translations of the components (classical CL), and others representing a tilted version of the traditional CT geometry using a 360° rotation (CLARA) [1] (Fig. 2). Using this trajectory, the object can be placed arbitrarily close to the X-ray tube without risking a collision with the latter, thereby enabling an appropriate magnification factor.

2. A priori information

While allowing for a high-resolution measurement of planar objects, computed laminography also has some limitations. Most important, the 3D reconstructions computable from CL data exhibit an anisotropic depth resolution in beam direction. In case of the CLARA geometry, this is due to the constrained ray directions which can only provide limited information. Since the axis of rotation is not perpendicular to the axis between source and detector, the information gained is not as complete as in a CT where the object can be irradiated from all sides. Therefore, CL reconstructions typically show artefacts and blurring orthogonal to the so-called focus plane which lies normal to the rotation axis. This also results in the fact that the object's density cannot be reconstructed faithfully in an absolute sense but only in a relative way, so that the object's structure is still reconstructed correctly but not with the correct density values. Furthermore, CL data cannot be

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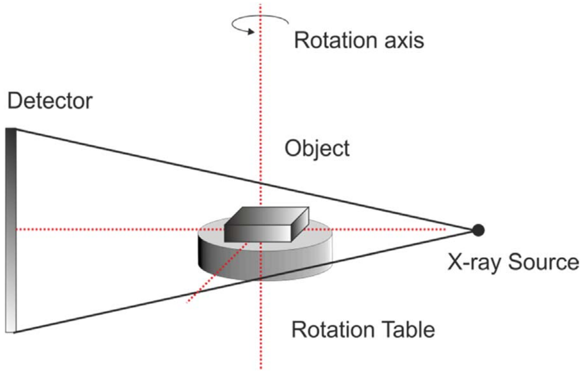

Fig. 1. Industrial CT set-up.

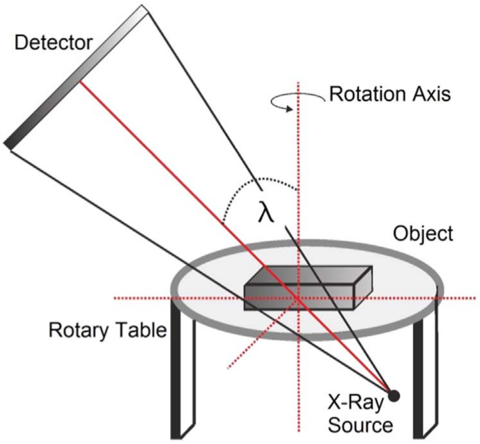

Fig. 2. CLARA geometrical composition.

reconstructed using standard CT algorithms of filtered back projection type like the Feldkamp algorithm [11]. Instead, iterative methods like SART (simultaneous algebraic reconstruction technique) [2] have to be applied. This constitutes an advantage since iterative methods allow the use of geometric a priori information about the object. This prior knowledge may consist of the object's surface given by a mesh model or a CAD (Computer aided design) file. It allows restricting the reconstruction to areas where the a priori information predicts material to be present and avoid reconstructing empty air areas. This greatly reduces the typical laminographic artefacts by forcing them from the air area the into the material area leading to an increased contrast and defect detectability.

The SART algorithm models the measurement process as a system of linear equations and tries to solve it iteratively. Let the 3D volume consisting of n voxels with indices $j = 1,\ldots,n$ be described by $f \in \mathbb{R}^n$, the measured rays be given by p_i, $i = 1,\ldots,m$ and ω_{ij} correspond to the fraction of the i-th ray p_i passing through pixel j. Then, each SART iteration reads

$$f_j^{(k+1)} = f_j^{(k)} + \lambda \bullet \frac{\sum_{p_i \in P_\alpha} \left(\frac{p_i - \sum_{l=1}^{n} \omega_{il} f_l^{(k)}}{\sum_{l=1}^{n} \omega_{il}} \right)}{\sum_{p_i \in P_\alpha} \omega_{ij}}, \tag{1}$$

where $\lambda \in \mathbb{R}$ is a relaxation factor, chosen depending on the structure and material composition of the inspected object, and P_α the set of rays belonging to projection $\alpha \in \{\alpha_1, \ldots, \alpha_p\}$. A priori information can easily be integrated into this reconstruction process if it is given as a second, binary voxel volume g of the same dimensions as the volume to be reconstructed, i.e. $g_j \in \{0,1\}$ with g_j indicating whether voxel j contains material or not. In this case, the a priori SART iteration step is given by

$$f_j^{(k+1)} = f_j^{(k)} + g_j \bullet \lambda \bullet \frac{\sum_{p_i \in P_\alpha} \left(\frac{p_i - \sum_{l=1}^{n} \omega_{il} f_l^{(k)}}{\sum_{l=1}^{n} \omega_{il}} \right)}{\sum_{p_i \in P_\alpha} \omega_{ij}} \tag{2}$$

This straight-forward integration of a priori information not only increases the convergence speed of the reconstruction process but at the same time offers the possibility of reducing the blurring artefacts characteristic for computed laminography reconstructions as well as increasing contrast. As a result, defects become more easily detectable [3,4]. As a priori information given CAD or STL (stereolithography) data or data obtained using a different method of nondestructive testing can be used. In most cases, the a priori data available does not coincide with the measured CL data concerning orientation and scale of the test object and therefore cannot be used without prior registration. This implies the need for a preprocessing step determining the transformation which positions the a priori data to properly fit the measured projections.

3. (Semi-)automatic registration algorithm

Image registration has become a growing field of research with new algorithms keeping pace with the development of new imaging techniques and sensor hardware. Besides the traditional challenge of 2D-2D image registration, the ever expanding processing power of modern computers also brings the registration of volumes into focus. An overview of registration methods can be found in Refs. [6,8,9]. For our problem the obvious approach of reconstructing the measured CL data to obtain a 3D volume which can be registered to the a priori data of the same dimensionality cannot be pursued as the traditional CL reconstruction is severely degraded by blurring artefacts. Thus, instead of using a 3D-3D registration algorithm, the 2D projections are to be registered directly with the 3D a priori data, without prior reconstruction (Fig. 3). A strategy to perform such a 2D-3D registration [10] for CT projections and a 3D mesh model has been proposed in Ref. [7]. It registers 2D projections to a 3D STL model in order to compute a variance-comparison during the CT reconstruction. The proposed method to determine the rotation can be adapted to CL and is used in our approach to work with volume data instead of mesh models.

A new algorithm solving this 2D-3D registration problem was developed and is discussed in the following. In order to register a given a priori volume, an affine transformation that consists of

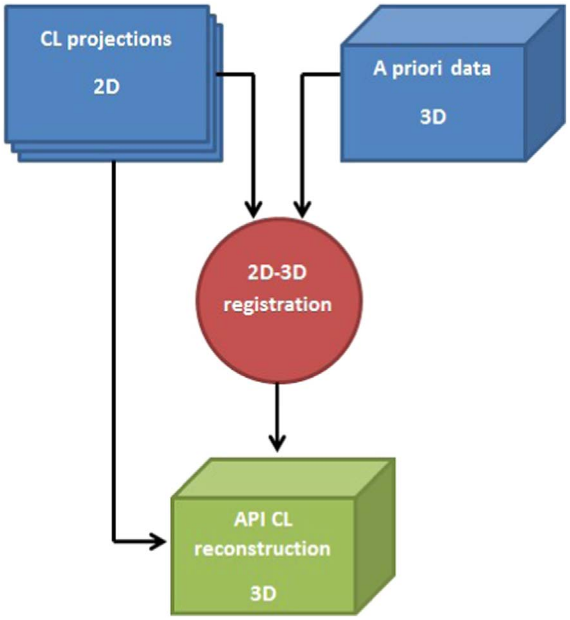

Fig. 3. A priori reconstruction based on 2D-3D registration.