Translational Computed Tomography: A New Data Acquisition Scheme

Theobald FUCHS\textsuperscript{1}, Tobias SCHÖN\textsuperscript{2}, Randolf HANKE\textsuperscript{3}

\textsuperscript{1}Fraunhofer Development Center X-ray Technology
A Cooperative Department of IIS Erlangen and IZFP Saarbrücken
Dr.-Mack-Straße 81, 90762 Fürth, Germany
\textsuperscript{2}Fraunhofer Institute for Integrated Circuits IIS,
Department Process Integrated Inspection Systems
Am Wolfsmantel 33, 91058 Erlangen
\textsuperscript{3}Julius-Maximilians-University Würzburg
Faculty for Physics and Astronomy
Chair for Materialcharacterization by X-ray Microscopy
Am Hubland, 97074 Würzburg

Abstract. Today, most computed tomography (CT) systems acquire projection data from several hundred to thousands of directions by employing multi-row (2-D) or flat-panel detectors (cone-beam for 3-D imaging). It is important to notice the following fact: modern CT systems all rely on a rotational movement. The most widely utilized reconstruction algorithms, as for instance the well-known Feldkamp method, are based on filtered back projection (FBP). These algorithms afford a series of projection images covering an angular range of at least 180°.

1. Introduction

Today, X-ray Computed Tomography (CT) is widely used in non-medical applications, e.g. for industrial non-destructive testing (NDT) or as a tool in research and development laboratories [1, 2]. Although, various CT data acquisition methods have been developed to meet the different applications, today, all systems are based on a rotation of the object. Alternatively, this can be achieved by rotating the detector and the source of x-rays around the object, but mathematically both methods are equivalent.
Figure 1: Scheme of the classical parallel beam geometry. The conventional data acquisition for CT imaging requires transmission measurements from at least 180° view angle. In industrial non-destructive testing, usually the X-ray source and the respective detector are fixed and the object is rotated mechanically in-between.

The CT principle is shown in fig. 1 by its most simple realization, the classical translations-rotational data acquisition scheme. In order to increase the scan speed, today most systems use a fan-beam-type or even cone-beam geometry, and acquire more than one slice during a single rotation by employing multi-row or flat-panel detectors (for a comprehensive introduction into Computed Tomography in general, see e.g. [3]).

A well-known alternative to physically truthful 3-D image reconstruction is a technique called digital Tomosynthesis which requires a co-planar movement of X-ray source and detector on each side of the object. While the number of acquired images as well as the view angles are limited and minimized for data acquisition during a Tomosynthesis measurement (in comparison to the rotational 3-D CT), the resulting image quality is accordingly worse, and most often, Tomosynthesis is not an equivalent substitute for a fully 3-D CT.

Nevertheless, in reality there are numerous objects which are desirable to be inspected by X-ray CT but do not allow for a rotational movement, like e.g. very heavy objects which cannot be accessed from all directions. For instance, such an object could be a pipe, positioned in the corner of a building (fig. 2) or a cable channel located inside a wall.
**2. Material and Method**

Within this contribution, we propose a new data acquisition method called Translational CT [4].

The new technique is based on a linear, translational-only movement of the X-ray source (fig. 3). Given a certain distance of the source $x_S$ to the object, each detector position $y$ defines a different ray angle $\theta$ with respect to the object. This allows for acquiring a set of various view angles. Or, seen from a single detector position, each source distance corresponds to another projection. After recording transmission images for a manifold of different source-to-object distances the single data sets are merged by sorting the rays according to their angular orientation. Thereby, the $t$-coordinate describes the shortest distance of the X-ray to the center of the field of measurement (FoM).

The new method is derived from the observation that both, the direction (the angle) and the shortest distance of each ray with respect to the object changes, if the distance between the X-ray source and the detector is modified. In other words: the rotational movement is substituted by one or more linear movements of the X-ray source towards the object to be inspected.

The new translational data acquisition scheme is mathematically described in a 2-D plane by the following two equations:

First, there is a relation between the ray angle $\theta$, the source position $x_S$ and the associated detector channel $y$:

$$\tan \theta = \frac{y}{x_S + 2R_m}.$$

Secondly, the distance $t$ is given as a function of the ray angle and the source position.

$$t_\theta(x_S) = x_S \cdot \sin \theta + R_m \cdot (\sin \theta - \cos \theta).$$
Each single ray is defined by the two parameters, \( t \) and \( \theta \). Using the two equations, the region within the complete parameter space, which is covered by the translational movement, can be determined.

**Figure 3:** Scheme for data acquisition with linear translation of the source only. The operating expense is much less compared to a rotational set-up. The detector (green vertical line) is fixed behind the object. The blue circle (radius \( R_{M} \)) indicates the field of measurement (FoM), which encloses the cross-section of any object therein. As can be seen from the red arrows, the angle of the rays travelling through the object changes as the tube is moved towards or away from the object.

The ray hitting the detector’s surface at exactly 90° is referred as the central ray of the X-ray source (hereby the \( x \)-direction is defined). The angle of the central ray with respect to the fixed object does not change while the source is translated, thus no additional information is acquired. Deliberately, the central ray is shifted to the edge of the FoM. In consequence, the regions next to the central ray are expected to yield the poorest image quality. Further, it is obvious, that the angular range of rays which can be achieved by translational-only movement is restricted to less than 90° in the limit of an infinitely long detector and the source positioned adjacent to the object (\( x_{S} = 0 \)). Fig. 4. demonstrates this matter of fact.
In order to overcome this intrinsic weakness of the translational approach, we implemented an extended data acquisition scheme employing two translations (fig. 5).

Virtual data were generated for a phantom which resembles a pipe with several details inside, e.g. smaller pipes or cables (fig. 2). During each linear translation of the X-ray source, 200 positions were sampled, with 0.1 spacing relative to the radius of the FoM which is taken as unit: $R_M = 1$. Thus, the source-to-object distance varied between 0 and 19.9, which is equivalent to approximately 10 times the diameter of the object. The virtual detector was simulated with 512 pixel and 0.01 pixel-to-pixel increment. Thus, the linear dimension of the detector is equivalent to approximately 2.5 times the object’s diameter. In
the case of two linear movements (fig. 4), both were simulated with identical parameters, as described above.

For comparison, a complete set of data were simulated in parallel beam geometry (fig. 1). Explicitly, for each of 200 angular positions within 180° range the FoM (diameter 2 in arbitrary units) the attenuation profile was sampled by 256 parallel rays with a distance of 0.01. The reconstruction was carried out with a complete 180° data set, as well as with reduced angular ranges of 120° and 90° degree in order to compare the degradation of image quality with the respective results for the translational technique.

For image reconstruction a state-of-the art ART (algebraic reconstruction technique) algorithm was used throughout the whole study [5]. From fig. 4 it is obvious, that a straight forward filtered backprojection approach would only lead to inferior image quality due to the intrinsic incompleteness of the projection data. All images have 256 by 256 pixels with 0.01 by 0.01 pixel size relative to the FoM.

### 3. Results

Fig. 6 shows the reconstruction from a conventional rotation-based data acquisition in parallel beam geometry. The image quality for the complete angular range of 180° is perfect, while rapidly degrading when the range is reduced to 120° and 90°. The angular range utilized can be directly seen from the contour of the wall of the outermost tube.

![Figure 6: Reconstructions from parallel beam data with an angular range of 180, 120 and 90 degrees, respectively (from left to right). All images were reconstructed with an algebraic reconstruction technique ART.](image)

Fig. 7 shows the respective results of the Translational CT technique with one translation only respectively two translations with 90° angular offset.
Obviously, the image quality obtained by a single translation is not sufficient (fig. 7, left hand side). By adding a second translation, with the direction of source movement shifted by 90°, the image quality improved significantly (fig. 7, right hand side). As predicted, the least information can be derived along the central rays (upper left corner). Apart from this, the simulated bundles of four by four cables are depicted clearly (left side), as well as the larger tubes including the slits and holes (bottom right).

At this point, it is necessary to emphasize that the same standard ART reconstruction was applied to all data-sets. Yet there has not been made any adaption or optimization for the translational case. Nevertheless, the results achieved with two translations are already comparable to a rotation about 90° angular range, which is equivalent to 100 projections according to the parameters used in this study.

4. Summary and Outlook

We have shown by simulations that imaging of cross-sections based on CT reconstruction is feasible with a translation type movement of the X-ray source only. Without rotation of the object or the equipment we were able to depict the details within most parts of the section of a large pipe.

It has to be noted that the details in the object under examination are characterized by a high contrast with respect to the background. A quantitative interpretation of the reconstructed pixels is still a little bit more difficult.

The simple way of data acquisition, proposed in this paper, should enable 2-D and 3-D imaging of those objects, which are commonly thought as not accessible to CT measurements, e.g. pipes in a close distance to other objects or the structure inside of walls or large machinery. An extension to a 3-D Translational CT imaging by making use of 2-D flat panel detectors goes without saying.

Of course, our new technique can be used in all cases, including those, where the object is accessible from all sides, but a rotational mechanical set-up is difficult to achieve, e.g. for on-the-field measurements of pipelines, power generators, cable channels or electrical equipment. Since the translational set-up is simple and straightforward (cf. fig. 8), it...
can be preferable to the mechanically more complex and expensive rotational set-up. One particularly promising application of the Translational CT is the 3-D inspection of freight containers, which are typically too large and too heavy to be rotated.

**Figure 8:** Proposed set-up for a system realizing the Translations CT method. Adjustment of the set-up is simple and straight forward. Since the linearity of a typical translational axis (1) is highly accurate, the main issue is the alignment of the flat panel detector orthogonal to the direction of the source movement.

Nevertheless, the image quality achieved by Translational CT method is worse compared to a complete parallel beam data set, measured during a 180° rotation of the object or the X-ray source and the detector, respectively.

Future efforts will be made in improving the quality of the Translational CT reconstructions by exploring several ways:

- taking into account a-priori knowledge about the object
- applying non-equidistant sampling of the source positions
- considering more sophisticated acquisition geometries, for instance three translations at 0°, 45° and 90° (cf. fig. 9)
- optimizing the translational scan parameters in general, i.e. necessary dimensions of the detector and the source travel distance
Figure 9: Proposed set-up for a system realizing the Translations CT method.

Further mathematical analysis of the translational data acquisition will help to optimize the scan parameters. Since the results of the simulation study are very encouraging, current efforts aims at a specification and realization of a prototype Translational CT system. Its novel capabilities will be explored in various applications, in particular in inspecting parts of an aircraft like the tail fin and the elevators which cannot be assessed by rotational CT data acquisition. In addition, application of the Translational CT for testing issues in the field of civil engineering is highly promising, too.

References


[4] European patent pending