HIGH-SPEED X-RAY COMPUTERIZED TOMOGRAPHY WITH A SCANNED ELECTRON BEAM SOURCE

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1. Introduction

Today there exist only a few tomographic devices which are able to produce fast sequences of cross-sectional images from an object. In medical diagnostics the electron beam tomograph (EBT) first introduced by Boyd et. al [1], is one example of such devices that use a scanned electron beam to produce X-ray computed tomography images with up to 50 frames per second - an image acquisition rate that is sufficient to investigate cardiovascular processes in human beings and animals. However, although the EBT has brought completely new perspectives to medical diagnostics, it is too slow for the investigation of other transient phenomena and processes in physics, biology, and technical sciences. Especially the investigation of two-phase flows requires frame rates of at least 1000 per second in order to visualize the transient behavior of relevant flow structures.

One device that has recently been built for studies on two-phase flows is the X-ray computed tomography apparatus introduced by Hori et al. [2]. It uses a circular arrangement of 60 pulsed X-ray tubes in combination with an annular X-ray detector slightly above the plane defined by the focal spots of the X-ray sources. High-speed tomographic data acquisition is realised by repeated sequential flashing of all sources giving a frame rate of up to 2000 images per second. Beside the complexity and costs of this system there is also a compromise in axial resolution since the 360° tomography inevitably requires that the source and detector plane have an axial offset. This in turn might cause problems to resolve small moving objects, such as particles or bubbles in a flow.

We devised and tested a novel computed tomography approach that utilises a scanned electron beam X-ray source to produce fast sequences of tomographic images. Contrary to classical electron beam tomography a linear deflection pattern for the electron beam is used and a non-annular detector arc records transmission data of an object from different projection angles. This approach gives the highest achievable axial resolution and is comparatively moderate in effort and costs. For the inverse problem we applied iterative image reconstruction techniques to reconstruct the density distribution from a limited data set. The method has been experimentally tested on static and dynamic phantoms with a frame rate of 1000 images per second and a spatial resolution of approximately 1 mm in-plane and axial.

2. Tomography System

Fig. 1 shows the principal design of the computed tomography system with a scanned electron beam source. For the generation of the electron beam a conventional high power electron gun with up to 150 kV acceleration voltage and 600 mA continuous electron current has been used. The beam is vertically directed onto a cylindrical tungsten target whose axis is orientated perpendicular to the beam axis. The beam steering system comprises focusing and deflection coils together with high power, high speed coil current drivers. All components of this system have been especially designed and optimized for this tomography application.

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During a tomographic scan the electron beam is linearly deflected from its axial direction by applying a sawtooth coil current pattern of 500 Hz frequency, thus producing a focal X-ray spot that moves forth and back between two turning points on a line segment on the surface of the tungsten target.

The optimal X-ray detector geometry for tomography is the one sketched in Fig 1. It is an arc of contiguous sensor elements that surrounds the object up to the prolonged axis of the target. In that way all the detector pixels are exactly aligned in one plane with the focal spot path. For the initial experiments, however, we used a smaller detector with 64 elements which we subsequently placed into different positions, simulating a larger detector in this way. The detector elements are CdZnTe semiconductor pixels of 1.5 mm x 1.5 mm active area, 1 mm depth and 1.6 mm pitch. The detector electronics, which is physically separated from the pixel array, comprises 64 two-stage transimpedance amplifiers with 1 MΩ transimpedance gain and 50 kHz bandwidth, followed by 12-bit analog-to-digital converters which sample the signals at 100 kHz in parallel and in synchronization with the beam deflection signal. The digital data is temporarily stored in a RAM array during the measurement and can be transferred to the PC after recording. The memory size allows a data acquisition for 0.8 seconds. The detector noise at no radiation exposure has been determined to be less than 2 LSB for all detectors.

The experiments were carried out in a vacuum box. Therefore, we mounted the source target, the detector and the phantom on an aluminum base plate which in turn was fixed at the bottom of the box (fig. 2). In addition to the primary components (target, detector, object) the setup comprised a 0.5 mm thick thermal shield of aluminum erected between target and object in order to prevent thermal radiation to damage sensible parts of the setup, and further a slit collimator that was placed in front of the detector array to filter out off-plane scattered radiation. The 64 coaxial signal cables connecting the detector elements with the data acquisition electronics together with detector high voltage supply and a few other signal lines have been passed through the wall of the vacuum chamber by means of a multi-pin vacuum-tight electrical connector. The electron gun and the beam deflection unit are on top of the vacuum box and the electron beam is guided through the ceiling of the box onto the target. The zero position of the focal spot, i. e. the spot position at no deflection, was adjusted manually by the operator. All experiments were carried out at 150 kV acceleration voltage, a beam current between 3 mA and 10 mA, and at 10⁻⁶ bar vacuum.

Fig. 1: Setup for a fast X-ray CT with a scanned electron beam source.
3. Data Acquisition

During a complete 1 ms movement of the focal spot 100 data samples are obtained at each of the 64 detector elements. This data matrix of one complete scan then consists of $N_D \times N_S$ measurement values, where $N_D$ is the number of detector elements and $N_S = 100$ is the number of source positions. In order to achieve a good angular coverage with the linear detector array we placed the detector in three different positions relative to the object when we made measurements on static phantoms. In this case is $N_D = 192$. For dynamic phantoms this approach was not applicable. Here we moved the detector as close as possible to the object giving $N_0 = 64$ detector values for each complete scan.

The reconstruction of the distribution of the X-ray attenuation coefficient within the measurement plane requires to compute the extinction values

$$E_{ij} = \ln \frac{I_{0,ij}}{I_{ij}}$$

for each pair $(i, j)$ of detector $(i)$ and source spot $(j)$. Thereby $I_{ij}$ denotes the X-ray intensity measured for an object and $I_{0,ij}$ the intensity measured at a reference, which may be a reference object with radiological properties close to the investigated object (e.g. a homogeneously filled vessel) or no object at all (zero-attenuation reference).

4. Image Reconstruction

Opposed to conventional X-ray computed tomography the linearly moving source produces data from a limited number of projection angles. This type of inverse problem is known as limited angle tomography (LAT) and has been widely studied in the past due to its importance for many practical computed tomography problems [3]. For the limited projection data set iterative image reconstruction algorithms offer some considerable advantages over modified filtered backprojection algorithms concerning artifact suppression, flexibility, and incorporation of a-priori knowledge. To perform algebraic reconstruction we consider the discrete spaces of the data, represented by the row vector $m$ with $m_k = E_{ij}$ ($k = i + j \cdot N_D$), and the image to be reconstructed, represented by the row vector $\mu$ containing the extinction values of the image pixels. Conventionally, the image is chosen as a square area between source and detector subdivided into a set of $N_P \cdot N_P$ pixels. In the particular problem we chose $N_P = 100$ and a pixel edge length of 0.5 mm giving a 50 mm x 50 mm cross-section area for reconstruction. The interrelation between data and image space is described by the weight matrix $A$ that contains the contributions of each pixel to the attenuation in each ray which is easily computed as the geometrical intersection of rays and pixels.
As algorithms to solve the inverse problem to the equation \( \mathbf{m} = \mathbf{A} \mu \) we tested the additive algebraic reconstruction technique ART [4], the multiplicative algebraic reconstruction technique MART [5], and the simultaneous iterative reconstruction technique (SIRT) [6]. Their correction formulas are given in table 1. Thereby \( n \) denotes the iteration step, \( i \) the pixel index, \( j \) the measurement value index, and \( \lambda \) the relaxation parameter. The starting vector is typically \( \mu^{(0)} = \mathbf{0} \) for ART and SIRT, and \( \mu^{(0)} = \mathbf{1} \) for MART. In theoretical studies with simulated data we found, that ART and MART are superior to SIRT concerning robustness and convergence behavior for the given problem. Therefore, the results discussed have been obtained using only these two algorithms.

### Table 1: Correction formulas for the three iterative image reconstruction methods.

<table>
<thead>
<tr>
<th>method</th>
<th>correction formula</th>
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<tbody>
<tr>
<td>ART</td>
<td>( \mu^{(n+1)} = \mu^{(n)} + \lambda (m_i - \mathbf{A}_i \mu^{(n)}) w_k^T )</td>
</tr>
<tr>
<td>MART</td>
<td>( \mu_i^{(n+1)} = \mu_i^{(n)} \left( 1 - \frac{\lambda}{\alpha_{\text{max}}} \left( 1 - \frac{m_j}{\mathbf{A}_j \cdot \mu} \right) \right) )</td>
</tr>
<tr>
<td>SIRT</td>
<td>( \mu^{(n+1)} = \mu^{(n)} + \lambda \mathbf{A}^T \left( \mathbf{m} - \mathbf{A} \cdot \mu^{(n)} \right) )</td>
</tr>
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#### 5. Results

Fig. 3 shows the reconstruction result for a static phantom which has been made to simulate tomography of a liquid-gas two-phase flow in a small pipeline segment. The phantom consists of an aluminum ring (pipe) of 44 mm outer diameter and 2 mm thickness enclosing a PVC cylinder (fluid) with six drillings (gas bubbles) of diameters between 1 mm and 11 mm. The reconstruction shows that it is possible to resolve all gas inclusions except the 1 mm one, which is lost in the noise. As a reference we used another phantom with the same properties but without drillings (gas-free fluid). We found that MART gives better results concerning image smoothness. Also, it can be recognized that there is some deformation in the object’s shape in regions close to source and detector. This is a typical artifact of limited-angle CT and may be removed by application of more dedicated image reconstruction algorithms.

Eventually we performed an experiment on the dynamic phantom that is shown in fig. 4. It consists of a DC motor driven rotating disk within an aluminum housing (cup) of 1 mm wall thickness and 40 mm outer diameter which can be filled with particles. Two steel pins of 3 mm diameter are fixed on the disk in order to force the particles to irregular movements by bouncing. Two other steel pins that descend from the cover of the cup prevent the particles from moving only along a circumferential path. As test particles we used small glass pearls from a necklace which are of 4.5 mm diameter and possess through-holes of 1 mm diameter. With the detector array this time arranged in a closer position to the object we recorded the irregular movement of the pearls during a time period of 0.8 s with a frame rate of 1000 images per second. As a reference we used the zero-attenuation reference.

Fig. 4 right shows single images of such a sequences for one, three, and ten pearls in the cup. The reconstruction algorithm in this case was MART. Reconstruction of a whole sequence took approximately 10 minutes on an Athlon 2000XP computer. Since in this scenario we have a well concentrated density distribution we achieve a good reconstruction quality even with a rather high angular limitation. It can clearly be seen, that also the through-holes in the pearls can be resolved when they appear within the imaged plane. This indicates, that we
achieve an axial resolution of at least 1 mm, which is much better than with any other EBT setup. The wall of the cup and the rotating steel pins are also reconstructed whereby again the walls appear incomplete in regions with lowest angular viewing range.

6. Discussion and Conclusions

We experimentally tested a fast X-ray computed tomography technique with a scanned electron beam source that may have a high potential in imaging of transient density changes, especially in two-phase flow problems. A first experimental investigation carried out with a fast scanning high power electron beam system and a 64 element linear X-ray detector in a vacuum box showed promising results concerning a qualitative reconstruction of object details and time resolution for imaging of a multiple particle scenario. So far, however, we have not reached the limits of this technique and will proceed to improve image reconstruction with algorithms that better cope with the limited-angle problem by incorporation of problem specific a-priori knowledge, such as known radiological density ranges, geometrical properties (e.g. particle/object sizes and shapes), as well as maximum expected density change rates in time. Further, an improvement of the experimental setup with a larger detector and a separate X-ray unit may lead to the limits of reconstruction quality that can today be estimated from simulated data.

Fig. 3: Reconstruction of a static two-phase-flow phantom. a) geometry, b) photography, c) ART result, d) MART result.
Fig. 4: Reconstruction results for a dynamic particle phantom. Left: photo and geometry of the phantom, right: images for the scenario with one (top), three (middle) and ten (bottom) particles.

References