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Image stitching strategies for tomographic imaging of large objects at high resolution at synchrotron sources

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ABSTRACT

Several image stitching strategies for the X-ray tomography (CT) of large objects at high resolution are reviewed and analysed. Each allows one to increase the reconstructed volume whilst keeping the voxel size constant. The methods are compared using experimental data that have been collected at the Daresbury SRS (Stn 16.3) and ESRF (ID15) synchrotron sources. A new stitching method is presented and applied which is based on the shifting of the object with respect to the axis of rotation.

1. Introduction

X-ray microtomography is emerging as an extremely versatile and widely used means of 3D imaging the microstructure of all sorts of natural and synthetic materials and structures. The 3D virtual volume is reconstructed from a set of 2D images (projections) of the object acquired by rotating the object through a range of angles from 0° to 180°.

Typically a scintillator is placed between the object and the detector to produce a projection in the visible spectrum which is then magnified and recorded by the detector. For a given detector, higher magnification implies a smaller imaged volume. Often, only a small region of interest in the object needs to be imaged, but at high resolution. Although the object is larger than the field of view of the detector in this case, artefacts are often negligible in practice [1,2]. However, there are a variety of situations where it is desirable to image a large volume, but also to resolve fine details. In these cases the results of two or more scans have to be combined. A good example is the growth of a crack in a fibrous metal matrix composite [3]. Here high spatial resolution is needed to monitor details regarding the crack path and its opening as it by-passes reinforcing fibres, but a significant volume is required if the composite is to contain a sufficient number of fibres from an engineering viewpoint.

Various image stitching strategies can be used to image large objects at high resolution. The underlying idea is to combine scans that cover different parts of the object. The results are stitched to produce either a composite projection or a composite reconstructed slice (2D image of a cross-section through the object normal to the axis of rotation (AOR)). Although stitching techniques are starting to be applied commercially, relatively little has been published in the open literature on the subject, particularly as regards the details of the methods employed.

In this paper, different image stitching strategies are applied to data sets that have been collected at two synchrotron sources (ESRF and Daresbury Laboratory) and their efficacy and advantages identified. One way of increasing the volume that can be reconstructed at a given spatial resolution is simply to move the object across the detector, whilst keeping the axis of rotation fixed. Perhaps surprisingly the benefits/drawbacks of this approach do not appear to have been analysed in any detail before.

This paper is organised as follows. First, different image stitching techniques are discussed. Then, a new stitching method is considered. Finally, the experiments are presented and the results compared and analysed.

2. Stitching techniques

There are broadly speaking two classes of stitching techniques. In the first class, overlapping projections from different scans are stitched together and the volume is reconstructed from these new

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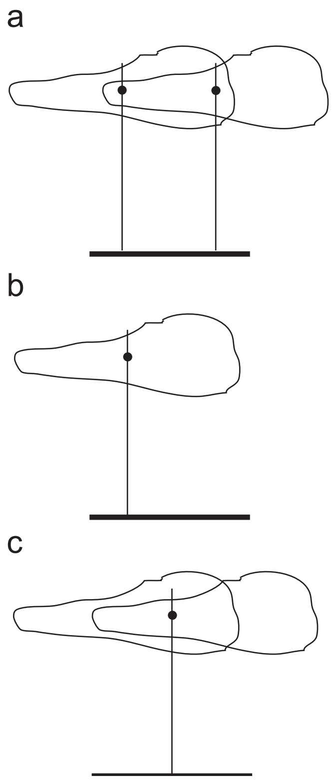

Fig. 1. Stitching methods: (a) shifting AOR methods (Methods I and III), (b) half-object acquisition (Method II), (c) object shifting method (Method IV). The black bar represents the CCD illuminated from the top while, the object rotates about an axis coming out of the page. The black dot marks the AOR.

projections. In the second class, volumes are reconstructed separately from different scans. Then, these volumes are merged to form the composite volume.

In the following 'angle' refers to the rotational angle of the object.

2.1. Method I: shifting axis of rotation + projection stitching

In this approach, at every angle the object is imaged using two or more positions of the camera w.r.t the object, see Fig. 1a. Each set of individual overlapping projections is stitched together to form composite projections that are used for the reconstruction. One way of acquiring the individual projections would be to translate the camera, or equivalently the object, along with the axis of rotation back and forth at each angle for which projections are acquired. However, practically it is often more efficient to run a whole scan for each position of the AOR. The stitching of individual projections is being widely used in X-ray microscopy to produce one or more large composite 2D radiographic projections although these are rarely reconstructed into a 3D volume: at the SSRL (USA), for instance, a mosaic of 6×6 images (each $13.9\,\mu m^2$) has been merged to form a composite projection [4]. At the SLS (Switzerland) 4×5 individual projections (each $3\,mm^2$) have been stitched [5]. Indeed a patent exists that covers the registration and stitching of such projections [6]. In Ref. [7] the object in a lab-CT-system is moved w.r.t the camera during its rotation in order to reduce ring artefacts in the reconstructed slices (the time delay integration (TDI) method).

In order to stitch the projections from two scans (taken at the same magnification) four parameters are required: first, the difference in the acquisition angle recorded for two matching projections needs to be known. And in order to match two projections a 2D vector and an angle θ have to be known by which one projection has to be shifted/rotated (in the plane of the projection) w.r.t the other one in order to perfectly match them. If θ is non-zero, then the angle of the AOR w.r.t the CCD data series has changed between the scans which usually one would try to avoid.

When projections to be stitched are displaced parallel to the AOR (vertically), each of the sets of projections to be stitched can be reconstructed separately. Inaccurate stitching will be visible as a disturbed set of slices at the boundary between the two volumes. However, in the case of stitching projections displaced normal to the AOR (laterally) the correct matching of the projections is crucial as they all contribute to the reconstruction of a slice. Inaccurate stitching will give rise to artefacts generally in all slices of the volume.

The registration of two projections can be achieved at a coarse level from the recorded translational movement of the AOR between the scans. More accurate matching can be achieved by employing various image registration techniques, see e.g. Ref. [8]. Image cross-correlation is a relatively simple method of image correlation and optimised methods on the sub-pixel level have been developed (see e.g. Ref. [9]). However, the method may work better with some objects than with others as it relies on correlating the features appearing in both the images. Another way of extracting the matching parameters is by tracking features either integral to the object, or fiducial markers attached to the object specifically for this purpose.

2.2. Method II: half-object acquisition

An elegant way of combining two scans to form one volume is a technique also known as 'half-acquisition'. This method is being used for example, at the ESRF (see, e.g. Ref. [10]). Typically the AOR is positioned near to one side of the CCD and the object rotated by 360°, see Fig. 1b. The projections of the second half of the scan are flipped and stitched to the corresponding projections of the first half of the scan. As the only free parameter for the matching is the centre of rotation the image registration can be easily calculated. Another advantage of the method is the fact that no movement of the AOR is required and hence less error is introduced. However, the method does not allow one to combine more than two scans. A reconstruction algorithm for half-object acquisition is included in the ESRF reconstruction software PyHST [11].

2.3. Method III: shifting axis of rotation + volume (slice) stitching

In this method, several scans are carried out such that the projections overlap as in Method I (Section 2.1), see Fig. 1a. The slices from each scan are reconstructed to form separate volumes. Then, the reconstructed slices from each of the scans are merged to produce a combined volume. To enable the merging of two or more volumes by stitching slices together it is necessary that the angle of the AOR w.r.t the CCD data set is the same for the scans (otherwise the volume has to be rotated and new slices need to be produced). In order to find matching slices the offset between the slices for the different scans needs to be known. This corresponds to a shift of one projection w.r.t the other. To match two slices, one angle and one distance must be known. The angle corresponds to the offset between the acquisition angles of the scans, the distance to the movement of the AOR.

The stitching slices method has been used, for example, in electron tomography [12] and serial-section polishing tomography [13]. An automated microtomy process with light microscopy is presented in Ref. [14] where each slice is made up from several