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Update on the DVC Challenge: Role of XCT Equipment and Scan Parameters on DVC Accuracy

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ABSTRACT
Digital Volume Correlation (DVC) calculates 3D, full-field, local deformation field from *in situ* X-ray Computed Tomography (XCT) volumetric images. The accuracy of the DVC measurement depends directly on the quality of the images, which is in turn governed by the selection of XCT equipment and scan parameters. However, the literature provides little guidance about the effect of XCT equipment and scan parameters on the accuracy of the DVC measurement. In this paper, we report on results from the DVC Challenge, an interlaboratory study organized by the Society of Experimental Mechanics. Six participants acquired reference, repeat and rigid body motion scans of a syntactic foam specimen using distinct XCT systems with ~10 µm voxel size, such that DVC analysis provided a means to evaluate the effect of XCT equipment and scan parameters on the measurement accuracy. The syntactic foam provided an excellent speckle pattern, such that any measurement error could be attributed to temporal distortion (error between repeat scans), spatial distortion (error due to rigid body motion), and uncorrelated measurement noise. All combinations of XCT equipment and scan parameters resulted in high-quality scans that enabled sub-voxel and sub-micron measurement accuracy; for the repeat scans with typical DVC parameters, displacement error ranged from 0.1 to 0.6 µm. Rigid body motion experiments revealed significant image distortion in certain XCT datasets. The most significant factors in determining DVC accuracy were (1) XCT equipment selection, (2) scan duration, and (3) voxel size. DVC and XCT best practices are recommended based on these results.

Keywords: Digital Volume Correlation, X-ray Computed Tomography, Error Assessment, Interlaboratory Study, Distortion

INTRODUCTION

Digital Volume Correlation (DVC) extends the classical two-dimensional Digital Image Correlation (DIC) algorithms [1] into three dimensions [2], and recovers the local, internal, and full-field 3D displacement and strain fields of a specimen by correlating images acquired in the reference and deformed configurations. Consequently, the DVC measurement quality depends directly on the accuracy of the acquired images. Despite this, there exists little guidance in the literature for the selection of appropriate equipment and imaging parameters to minimize DVC error, or even on the repeatability of DVC measurements between laboratories. To this end, this presentation reports on an interlaboratory study organized by the DVC Challenge subcommittee of the Society of Experimental Mechanics[1], which was designed to assess the role of laboratory X-ray Computed Tomography (XCT) machine selection and imaging parameters on the accuracy of DVC measurement. Laboratory XCT is selected since it is perhaps the most common *in situ* 3D imaging technique used within the experimental mechanics community.

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[1] https://sem.org/dicchallenge

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METHODS

An interlaboratory study was designed to evaluate the roles of XCT acquisition equipment and scan recipes on the accuracy of DVC measurements. To this end, six participants were recruited to acquire XCT images of a syntactic foam specimen.

To initiate the study, cylindrical syntactic foam specimens were distributed to the participants. Each specimen had a diameter of 4.8 mm and a height of 7 mm, and contained ~37% volume fraction of hollow glass microballoons (GMBs) with a nominal diameter of 60 µm. When imaged by XCT with a voxel size ~10 µm, the porosity created a high-quality speckle pattern suitable for DVC measurement. Each participant acquired a reference scan, two "repeat" scans of the sample in the same location, two "axial motion" scans of the specimen after it was displaced axially by 1 mm, and two "radial motion" scans after it was displaced radially by 1 mm. The participants developed their own scan recipes based on their XCT experience and intuition, with voxel sizes between 7 and 18 µm.

Each set of scans was correlated using commercial DVC software (Vic-Volume, Correlated Solutions) to calculate the apparent deformation field using standard procedures described in Ref. [3]. By nature of the rigid body motion experiments, any deviation from purely rigid body motion could be attributed to XCT imaging noise (marked by random fluctuations in the measured displacement), spatial distortion (displacement gradients due to rigid body motion), and temporal distortion (systematic differences between consecutive scans in the same location).

RESULTS

Each of the six participants provided high-quality XCT reconstructions of the foam samples prior to and after rigid body motion. Consequently, the DVC analysis achieved subvoxel and subpixel measurement error, as obtained by analyzing the spurious displacements in the "repeat" scans (Fig. 1). Consistent with classical experimental and theoretical DIC error analyses, our experiments showed that DVC error scaled proportionally to noise and inversely with subset size. Most importantly, this indicates that good DVC results can be achieved with a variety of XCT equipment and appropriate scan recipes. However, the magnitude of error as well as the asymptotic minima of the error curves varied for the different datasets, indicating that the XCT equipment introduced unique, systematic distortions in the reconstructions.

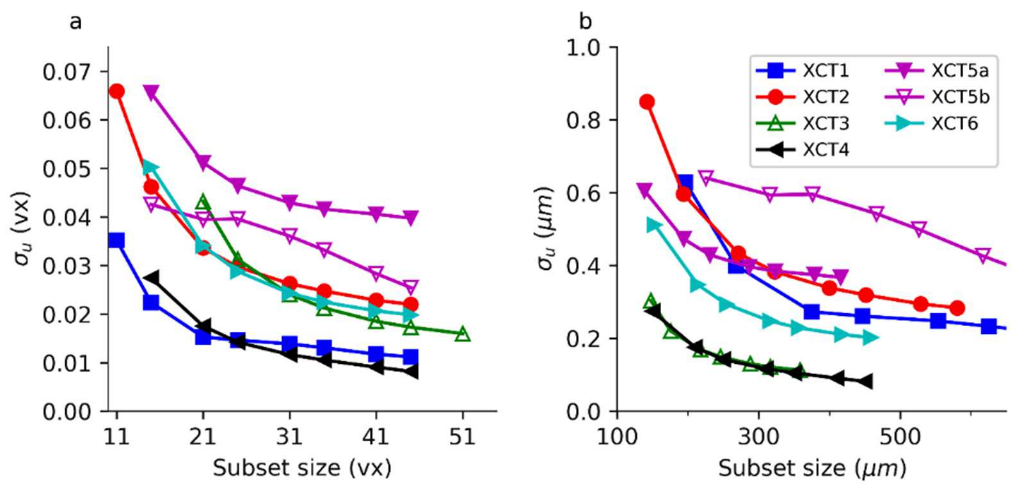

Fig. 1 Comparison of DVC accuracy based on repeat scans with no axial motion. DVC random displacement error as function of subset size in (a) voxels and (b) µm. Error is sampled in the axial direction

Analysis of the "axial" rigid body motion experiments confirmed the presence of systematic spatial distortion in the XCT reconstructions (Fig. 2). The magnitude of error ranged from less than 1 µm for scans XCT3, XCT4, and XCT5, but exceeded 3 µm for scans XCT1, XCT2 and XCT6. Many of these distortion patterns have never been reported in the literature, and they portend challenges in generating fully generalizable distortion correction algorithms to correct for spatial distortion in all types XCT equipment. Moreover, these measurements confirm that systematic errors in the DVC measurement due to specimen motion can be much more significant than random noise in the images.

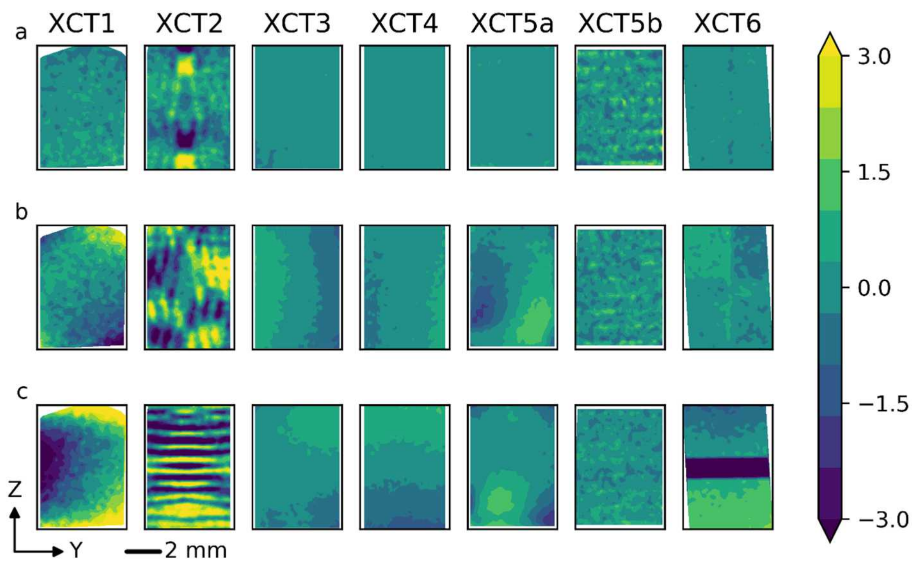

Fig. 2 DVC measured displacement in Axial 1 scans, showing (a) spurious displacement in x direction, (b) y direction and (c) z direction. Rigid body motion is subtracted from the data. Color scale is in μm. Note that XCT 1 data exhibits a circular crop due to vignetting of the radiographs

CONCLUSION

An interlaboratory study has studied the roles of XCT equipment and scan recipe selection on the suitability of the reconstructed tomograms for DVC analysis. Careful design of the rigid body motion experiments as well as data analysis allowed the authors to attribute spurious DVC measurements to random noise, systematic spatial distortion, and systematic temporal distortion in the reconstructions. Correlation of repeat scans (without rigid body motion) acquired by each participant resulted in superb DVC displacement measurements with sub-voxel and sub-micron accuracy. However, evaluation of consecutive scans in the same location, as well as scans after rigid body motion identified considerable systematic spatial and temporal distortions that were roughly an order of magnitude more important than random image noise.

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