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# Digital Volume Correlation for Materials Characterization

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**Abstract.** Digital Volume Correlation (DVC) using x-ray computed tomography (CT) is commercially available and therefore becoming more widely used. As with any new capability, there are a number of important performance limits to check, including, drift, noise, and rigid-body translations. Sandia National Laboratories has a unique set of x-ray machines and digital x-ray detectors that allow for multiple configurations to best accommodate DVC. This talk will cover a number of important details for making reliable volumetric measurements, including; CT calibration, noise sources, and system component drift. These errors are illustrated using comparisons with rigid-body translation tests.

## Introduction

Quantitative measurements obtained from computed tomography (CT) data have typically been limited to dimensional information and material density. Buried within the data however, is the potential for much more. The development of a digital volume correlation (DVC) diagnostic has added to the suite of quantitative data, usable within 3D non-destructive evaluation methods. This paper will outline the implementation of a DVC diagnostic using CT at Sandia National Laboratories.

Diagnostic development is one of the core research areas within Sandia National Laboratories Engineering Sciences Center. The desire to combine extensive experimental data with modeling and simulation drives the need to continually develop and improve diagnostics.

Advances in x-ray machines, digital x-ray detectors, CT data acquisition speed, and data processing speed have opened the door for a DVC capability. The results will bring 3D insight into material properties under varying degrees of loading. In turn, the data acquired will be used to increase the robustness of the models used by much of Sandia National Laboratories.

## Digital Volume Correlation

Digital volume correlation (DVC) is based on the theory developed for digital image correlation (DIC). DIC was developed in the early 1980's [1]. DIC typically uses optical methods to acquire digital images of objects of interest during testing. Often these objects are painted white and then speckled with a contrasting color, typically black, to provide a high contrast image for tracking. During the post-test image analysis, the speckles are registered from image to image during the test's progression as the object deforms. The analysis provides full field shape, deformation, and motion measurements. These measurements however are either 2D (2D-DIC) or 3D (stereo-DIC) *surface* measurements.

DVC is a volumetric extension of 2D-DIC. DVC takes the idea of speckles, image registration, and tracking and expands them to a volume for an object of interest. An initial 3D volume is created non-destructively. This can be done using computed tomography (CT), magnetic resonance imaging (MRI), confocal microscopy, etc. The initial scan serves as the reference, un-deformed volume. As an external force is applied to the part, additional scans are continually acquired, documenting the deformation progression. Instead of using a painted-on speckle pattern, image registration is based on features within the part. The resulting analysis provides volumetric shape, deformation, and motion.

2D-DIC is built on the idea of optical flow and grey value conservation, which has been used for particle tracking and image registration. However, because DIC is used for strain measurement, the general accuracy of traditional machine vision tracking was not adequate, and specialized techniques were developed for use in experimental mechanics. Primarily, these involve using a subset, or region of pixels, to ensure that a unique match can be found. This subset is then matched using an optimization process to find the best solution for the subset parameters between a reference frame and any following deformed frames. During the matching process a minimization function, sum-squared differences (SSD) for example, can be used to determine the displacements, u and v, and any change of shape of the subset, typically an affine shape function. In order to solve for the displacements in a subpixel sense, interpolation of the image is required and is included in the minimization process mentioned above.

In order to have enough information to obtain an accurate subpixel match, there needs to be a number of features contained in the subset to obtain a robust solution. Theoretical work indicates [2] that the matching quality is proportional to the image noise and inversely proportional to the sum square of the image gradients. Image gradients in this context refer to the contrast difference between bright and dark areas contained in the subset. For an adequate match, approximately 3 speckles or features need to be contained within a subset to minimize errors, with good contrast images [3]. However, when the contrast is compromised or the image noise is large, as is often the case with DVC, larger subsets may be required. Unfortunately, because only the central point of the subset is reported for results, you cannot make your subset arbitrarily large, as the shape function is linear and will only represent linear displacements across the region. Therefore, some compromise will be needed between smoothing applied by the subset shape function and noise due to the noise and contrast quality contained in the subset.

The extension of 2D-DIC to DVC is actually more straightforward than the extension to stereo-DIC. 2D uses a square subset with u and v displacements calculated by minimizing on the contrast contained in the image. DVC simply extends this to the third dimension supplied by the CT scan data, and uses a cubed subset to find u, v and w displacements based on the 3D voxel imaged from the sample. The math is the same as in 2D, with the simple addition of another dimension. The implementation however is much more difficult because of the size of the 3D datasets. The number of subset solutions becomes large very quickly causing solution time issues. In contrast, stereo-DIC uses a pair of cameras that are calibrated along with the 2D-DIC matching between the two cameras to triangulate a point in 3D space. DVC inherently contains the 3D results in the fact that it is volume data that is being correlated on.

The challenge with all the DIC techniques is obtaining a high-contrast low-noise image to be used for calculating the displacements. This is a particular challenge for

DVC, where the contrast comes from the varying density differences in the sample, which for many engineering materials are small – leading to low contrast. The feature size must also be optimal so that the subset is adequately small to correctly represent the underlying displacement being solved for; but not too small because features must also be fully resolved by the CT scan so as not to introduce aliased information which negatively impacts the matching quality and therefore the solution.

## DVC Experiments

### *3.1 Experimental Overview*

In order to full understand the accuracy and capabilities of the DVC process and software analysis, several controlled experiments were conducted. A target item was developed using various sizes of aluminum spheres cured inside of an epoxy.

**Fig. 1.** Aluminum spheres within cured epoxy

An initial CT scan was acquired to verify the distribution of the aluminum spheres. The sample was scanned utilizing an Yxlon FXE 225.99 microfocus x-ray machine and a Varian 2520 digital x-ray panel. The x-ray system was operated at 100kV, 400µA (36W output). The detector acquired images at 3.5 frames per second and averaged 16 frames per projection. There were 1099 projections acquired. The scan was completed in 94 minutes. The source-to-detector distance was 1073.649mm; source-to-object distance 307.498mm. These distances provide a 3.5x magnification and a 36.4µm voxel size.

A sample CT slice is shown in Figure 2. This sample proved adequate for an initial analysis. Ideally there would be more features; however for static and rigid body motion testing, there are enough features and the spacing between features is sufficient.

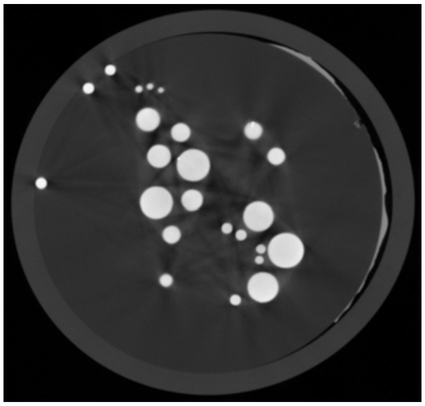

**Fig. 2.** Sample CT slice

*3.2 Single Scan Self Correlation*

The first experiment was a system check. The initial CT scan was correlated with itself. The resulting data should exhibit no deformation or movement. This was also an opportunity to better understand the capability and requirements of the software, understand variation from analysis to analysis, and potentially increase the accuracy of the analysis by varying subset size, step size, and number of initial guesses (the 3 parameters used to control the solution in DVC). For all analyses presented in this paper, a subset size of 69, a step size of 7, and 3 starting points were chosen. Figure 3 below demonstrates the movement from the reference with itself in the u, v, and w directions. The correlation outputs data as u, v, and w, corresponding to undeformed x, y, and z directions. As expected, the output displayed zero shifting in any of those directions.

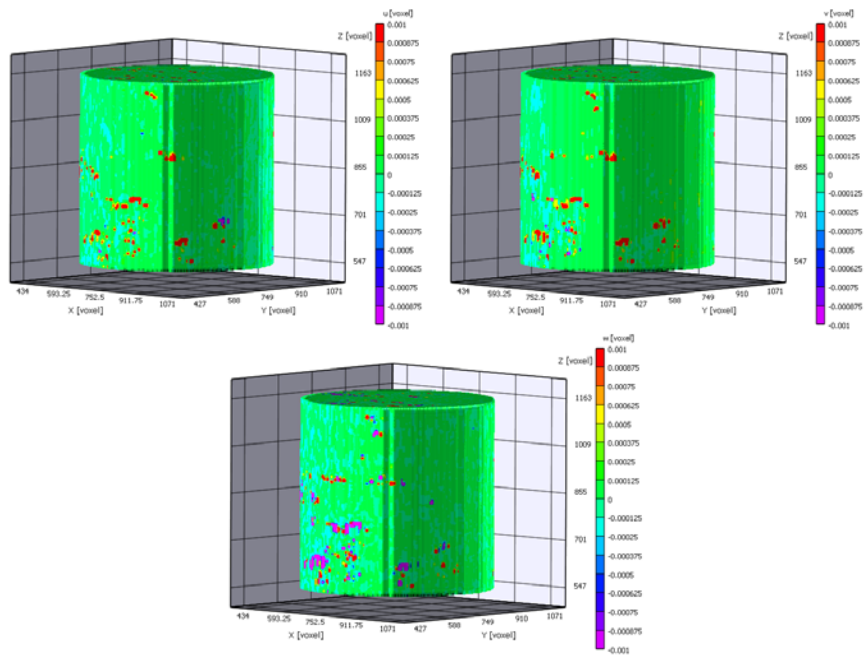

**Fig. 3.** Reference scan self correlation

Table 1 below shows the statistical ouput of this analysis. The scaling on the images can oftentimes be misleading so it is important to combine both the images and statistical output to fully understand the results of the anlysis.

**Table 1.** Reference Scan Self Correlation

| | u (voxel) | u (μm) | v (voxel) | v (μm) | w (voxel) | w (μm) |
|---|---|---|---|---|---|---|
| Mean | 1.35E-04 | 4.93E-03 | 1.25E-04 | 4.55E-03 | -9.69E-05 | -3.53E-03 |
| Standard Dev | 1.62E-03 | 5.90E-02 | 1.61E-03 | 5.85E-02 | 2.47E-03 | 8.99E-02 |

*3.3 Multi-Scan Noise Floor Determination*

The next experiment was to acquire multiple data sets only moving the part rotationally to acquire the CT data, i.e. the part is nominally stationary in u, v, and w during the CT. Once again, the resulting data would ideally exhibit no deformation or movement. This was however not necessarily expected due to x-ray machine and detector variations. The results would instead provide a noise floor for the test setup and DVC analysis parameters. The correlation algorithms allow for sub-voxel measurements. Understanding the noise floor would in turn provide a lower limit for sub-voxel measurements. Figure 4, below, displays the results of two repeat CT scans. There were four total scans taken over a six hour period.

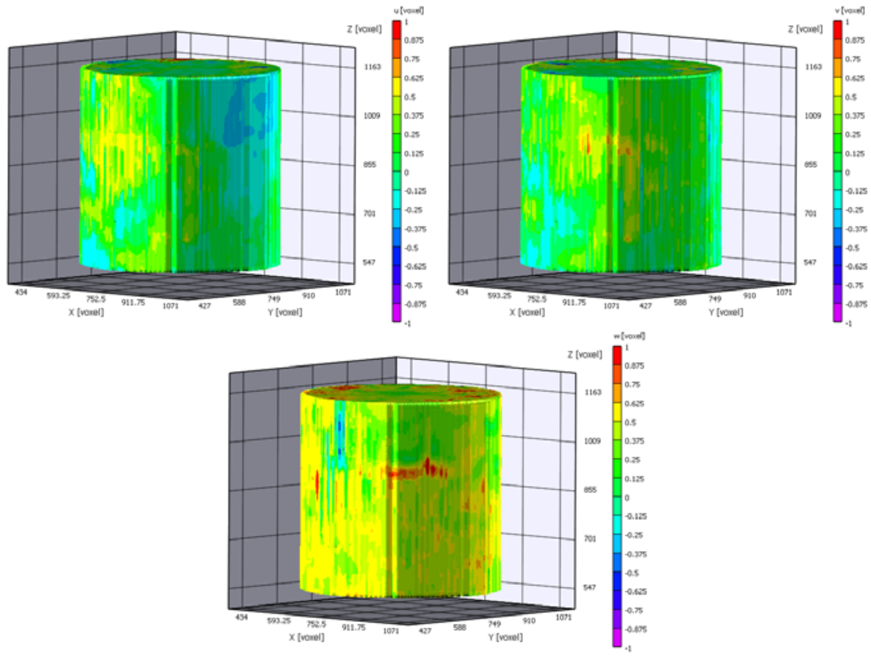

**Fig. 4.** Correlation between scans 1 and 2 without movement

Tables 2 through 4 show the mean noise floor between different scans for the scans. Shifting in the x and y directions were minimal. Shifting in the z direction however was significant when correlated with the first scan. After the first scan however, comparing scans 2 with scans 3 and 4, it is apparent that any sources of noise or may have settled out.

**Table 2.** Correlation between CT scans without movement (u)

| | Scan 1&2 | Scan 1&3 | Scan 1&4 | Scan 2&3 | Scan 2&4 | Scan 3&4 |
|---|---|---|---|---|---|---|
| Mean (voxel) | 0.131 | 0.088 | 0.037 | 0.172 | 0.091 | 0.145 |
| Mean (µm) | 4.763 | 3.203 | 1.335 | 6.271 | 3.308 | 5.279 |
| Standard Dev (voxel) | 0.296 | 0.346 | 0.432 | 0.336 | 0.299 | 0.355 |
| Standard Dev (µm) | 10.762 | 12.59 | 15.73 | 12.22 | 10.88 | 12.91 |

**Table 3.** Correlation between CT scans without movement (v)

| | Scan 1&2 | Scan 1&3 | Scan 1&4 | Scan 2&3 | Scan 2&4 | Scan 3&4 |
|---|---|---|---|---|---|---|
| Mean (voxel) | 0.138 | 0.085 | 0.084 | 0.202 | 0.185 | 0.222 |
| Mean (µm) | 5.006 | 3.079 | 3.052 | 7.343 | 6.761 | 8.082 |
| Standard Dev (voxel) | 0.291 | 0.371 | 0.452 | 0.362 | 0.286 | 0.363 |
| Standard Dev (µm) | 11.600 | 13.50 | 16.46 | 13.17 | 10.40 | 13.23 |

**Table 4.** Correlation between CT scans without movement (w)

| | Scan 1&2 | Scan 1&3 | Scan 1&4 | Scan 2&3 | Scan 2&4 | Scan 3&4 |
|---|---|---|---|---|---|---|
| Mean (voxel) | 0.447 | 0.615 | 0.698 | 0.267 | 0.343 | 0.187 |
| Mean (µm) | 16.28 | 22.38 | 25.39 | 9.728 | 12.51 | 6.797 |
| Standard Dev (voxel) | 0.205 | 0.351 | 0.451 | 0.160 | 0.161 | 0.181 |
| Standard Dev (µm) | 7.460 | 12.78 | 16.40 | 5.822 | 5.866 | 6.598 |

Averaging the standard deviation values across all scans provides a noise floor value. Any deformation or movement needs to be larger than the noise floor in order to be detectable. Table 5 provides the mean noise floor value from the correlations presented in tables 2 through 4.

**Table 5.** Mean noise floor

| | u | v | w |
|---|---|---|---|
| Noise Floor (voxel) | 0.344 | 0.354 | 0.252 |
| Noise Floor (µm) | 12.52 | 13.06 | 9.154 |

*3.4 Rigid Body Translation*

Next, a basic translation test was performed. An initial scan would provide the undeformed data. The part would then be translated in one direction and the CT scan repeated. In this case, the resulting data should demonstrate a corresponding shift in the direction the part was moved, while the other axes (assuming stage movement is true) would display zero movement or at least be consistent with the noise floor data in section 3.3. For this experiment, a vertical translation (z-direction) was used. A translation in the y-direction would result in a change in magnification. A translation in the x-direction would cause problems during the reconstruction as the software automatically centers the reconstruction.

Based on the results of the second experiment, the translation should be greater than the highest noise value to avoid having a movement smaller than the noise floor. The mean noise floor value across six correlations, as reported in table 5, in the z direction was 0.252 voxels (9.154µm).

After the reference scan, the sample was shifted 10µm in the z-direction. As previously stated, these translations should be larger than the noise floor. The first translated scan would in face just be a check of the noise floor experiments. Upon completion of this initial translation scan, the part was then translated another 10µm for a total movement of 20µm. This was repeated over five scans, not including the reference scan, for a total 50µm shift from the reference scan. Figure 5 shows the movement in the u, v, and w directions as a result of the 20µm z shift. The data from the 10µm looks very similar to the images in figure 4; it matched up with the noise floor values as expected.

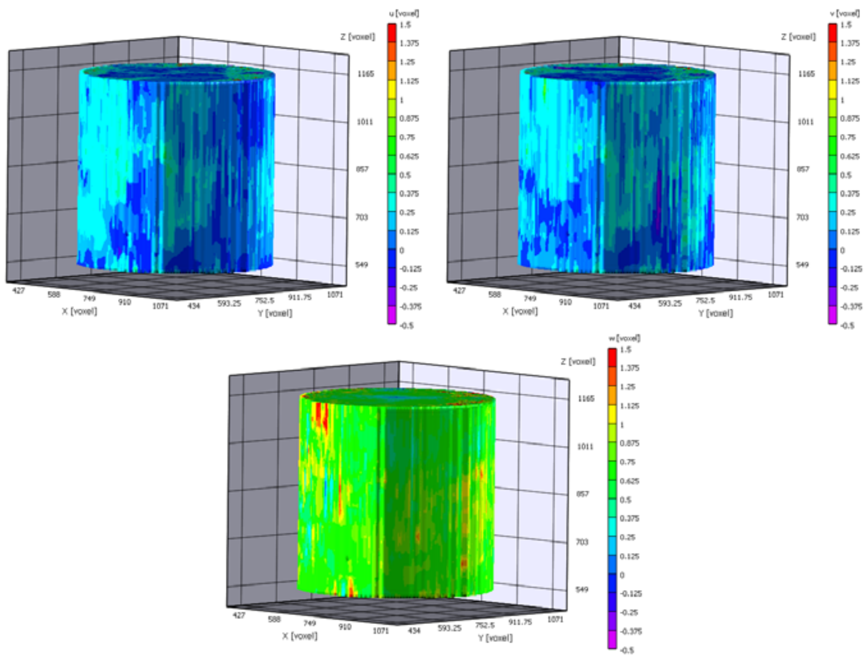


**Figure 5:** Correlation between reference scan and 20µm translation

Figure 6 shows the movement in the u, v, and w directions as a result of the total 50µm shift; comparing the first scan with the sixth scan.

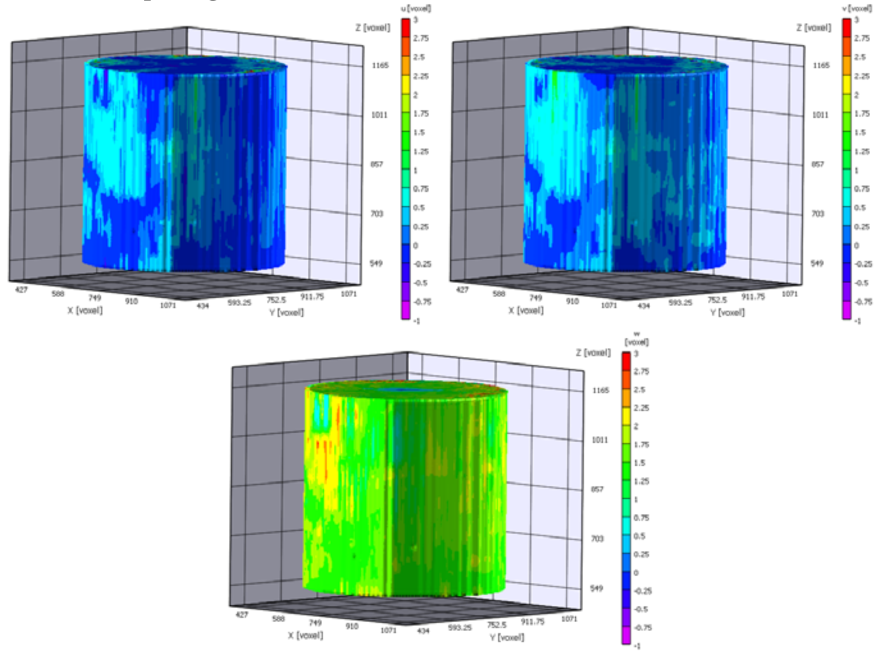

**Figure 6:** Correlation between reference scan and 50µm translation

Tables 6 through 10 show the average shift and standard devation across the entire volume for each shifted scan correlated with the reference scan. Data in the u and v directions are consistent with the noise floor data in the second experiment. The part was translated 10µm at a time in the z direction and the resulting data in w is within reason.

**Table 6.** Correlation for 10µm movement in z-direction

| | u | v | w |
|---|---|---|---|
| Mean (voxel) | 0.166 | 0.151 | 0.451 |
| Mean (µm) | 6.037 | 5.493 | 16.41 |
| Standard Deviation (voxel) | 0.270 | 0.279 | 0.158 |
| Standard Deviation (µm) | 9.812 | 10.150 | 5.746 |

**Table 7.** Correlation for 20µm movement in z-direction

| | u | v | w |
|---|---|---|---|
| Mean (voxel) | 0.136 | 0.119 | 0.683 |
| Mean (µm) | 4.966 | 4.346 | 24.85 |
| Standard Deviation (voxel) | 0.231 | 0.244 | 0.235 |
| Standard Deviation (µm) | 8.415 | 8.897 | 8.541 |

**Table 8.** Correlation for 30µm movement in z-direction

| | u | v | w |
|---|---|---|---|
| Mean (voxel) | 0.163 | 0.166 | 1.024 |
| Mean (µm) | 5.951 | 6.049 | 37.28 |
| Standard Deviation (voxel) | 0.343 | 0.371 | 0.329 |
| Standard Deviation (µm) | 12.473 | 13.487 | 11.994 |

**Table 9.** Correlation for 40µm movement in z-direction

| | u | v | w |
|---|---|---|---|
| Mean (voxel) | 0.164 | 0.164 | 1.037 |
| Mean (µm) | 5.974 | 5.981 | 37.75 |
| Standard Deviation (voxel) | 0.330 | 0.348 | 0.336 |
| Standard Deviation (µm) | 12.017 | 12.675 | 12.239 |

**Table 10.** Correlation for 50µm movement in z-direction

| | u | v | w |
|---|---|---|---|
| Mean (voxel) | 0.092 | 0.130 | 1.504 |
| Mean (µm) | 3.356 | 4.725 | 54.753 |
| Standard Deviation (voxel) | 0.350 | 0.335 | 0.348 |
| Standard Deviation (µm) | 12.737 | 12.191 | 12.682 |

## Results

The experiments presented in this paper demonstrate that a volumetric DIC capability is feasible in a standard industrial computed tomography setup. A software program developed by Correlated Solutions worked well with the volumetric data acquired on CT systems at Sandia National Laboratories.

An initial experiment provided an opportunity to better understand the capabilities of the volumetric correlation software. A reference dataset was correlated with itself and the results are consistent with zero shift and minimal noise.

After acquiring an initial scan for self-correlation, several more scans were acquired to determine the noise floor of the system. The noise floor provides a limit for the minimum feature that can be detected by the system. It appears that the noise floor levels out as the machine is operated. It was recommended by the manufacturer that a 30 minute run-in time be observed before acquiring data. For this specific setting, the noise floor values averaged around 5µm. It will be worthwhile to acquire noise floor data at other x-ray machine and detector settings. Perhaps the most prudent thing to do is to acquire noise floor data before any volumetric correlation is attempted. Characterizing the noise floor at every possible x-ray machine and detector setting would prove rather tedious.

The final experiment presented was a simple rigid body translation test. The part was moved in the vertical direction (z-direction) in 10µm increments over 5 scans. This resulted in a total 50µm translation. The resulting volumetric correlation was consistent with these movements. There was one data point (40µm translation) that did not match as well as the other correlations. This likely stems from a low resolution staging system and will be addressed in future experiments. The data was also noisier than expected. It is suspected that this results from a lack of features within the test sample. While the sample was sufficient to perform a volumetric correlation, it was not ideal. The correlation algorithms rely on a varied speckle pattern across the area of interest. Without those speckles consistently distributed across the subsets, the correlation algorithm has minimal features to work with. This could cause inaccuracies in results. The stepper motors used for this experiment do not have the resolution necessary for translations of this magnitude. A 10µm translation was commanded by the system but without feedback control, the actual movement cannot be accurately determined.

A final experiment was conducted after the volumetric correlation experiments were completed. One of the potential sources of error is system drift. It is a well-known fact that the focal spots of this and similar x-ray machines have the tendency to move during the course of a scan. Additionally, as it is warmed up, the digital x-ray detector's response may drift as well. System drift was determined using a target with features that could be tracked using 2D DIC software. The target was imaged periodically while the machine was operated over a long period of time (hours). In order to increase the accuracy of the results and avoid any bias from detector burn-in, a beam shutter was utilized. This initial analysis only provided drift in the x and z directions and not drift in magnification (y) as the DIC software is not setup to calculate movement in that direction. The x-ray machine was operated with a 36μm focal spot size over a 2 hour period. Figure 7 below plots the system drift in pixels during that time in the x and z directions.

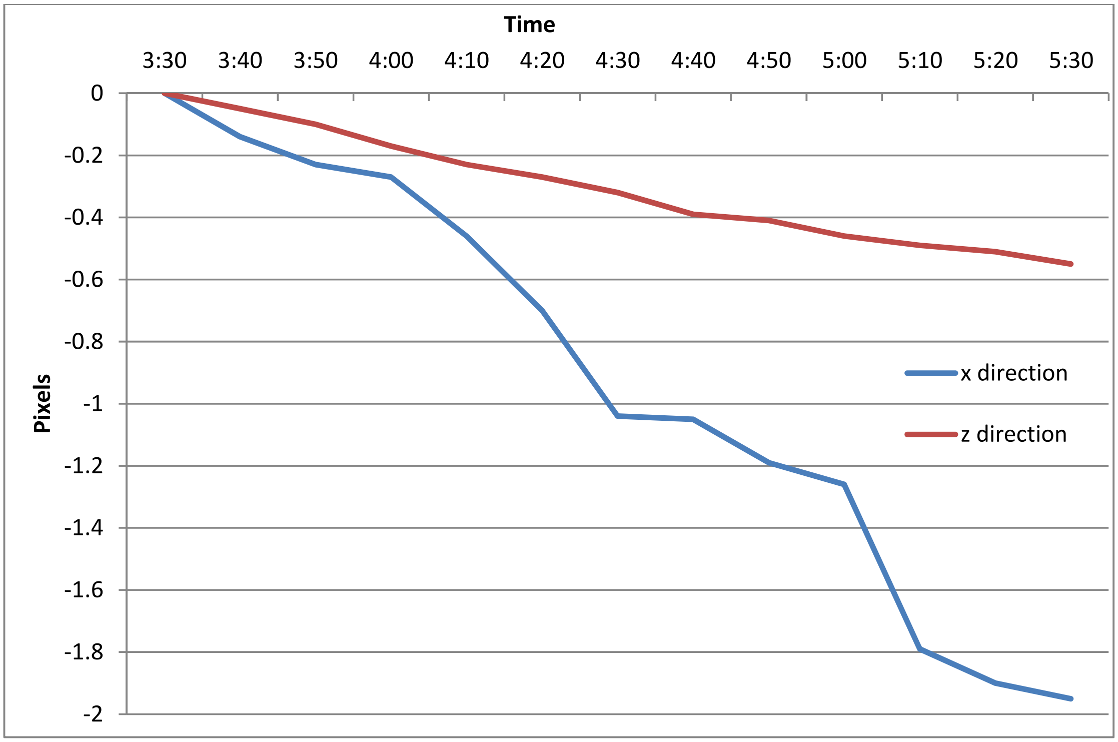


**Figure 7:** System drift over a 2 hour period

It is not immediately clear how system drift would affect the volumetric correlation results. Over a long scan like this, drift would cause unsharpness in the image. However, because multiple scans are being compared, it is thought that the system drift may not be as problematic as initially suspected. This idea of system drift does warrant more exploration.

## Path Forward

Going forward, there are several experiments that will be conducted as the capabilities and limitations of volumetric DIC are explored:

- Repeat the translation experiment with nanometer precision stages to confirm displacement accuracy and noise floor.
- Accuracy of the CT system calibration has come into question. Improvements to these procedures will be investigated.
- A tensile stage built specifically for CT systems has been acquired. The system will be utilized to conduct a simple compression test once a more ideal sample has been finalized.

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**References**

[1] M. Sutton, J. Orteu, and H. Schreier. *Image Correlation for Shape, Motion and Deformation Measurements.* New York: Springer, 2009.

[2] Y. Wang, M. Sutton, H. Bruck, and H. Schreier. "Quantitative Error Assessment in Pattern Matching: Effects of Intensity Pattern Noise, Interpolation, Strain and Image Contrast on Motion Measurements." *Strain*, vol. 45, pp. 160-178, April 2009.

[3] P. Reu. "Introduction to digital image correlation: Best practices and applications." *Experimental Techniques,* vol. 36, pp. 3-4, Jan./Feb. 2012.