SAND2019-12508C

A Fast GPU-Based FFT Interpolant Algorithm for Synthetic Image and Volume Deformation

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Additional team members:

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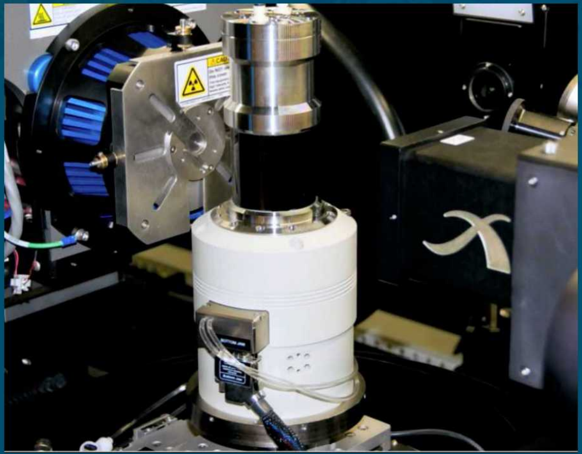

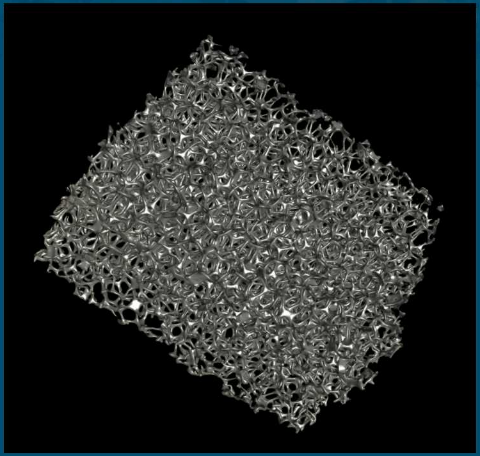

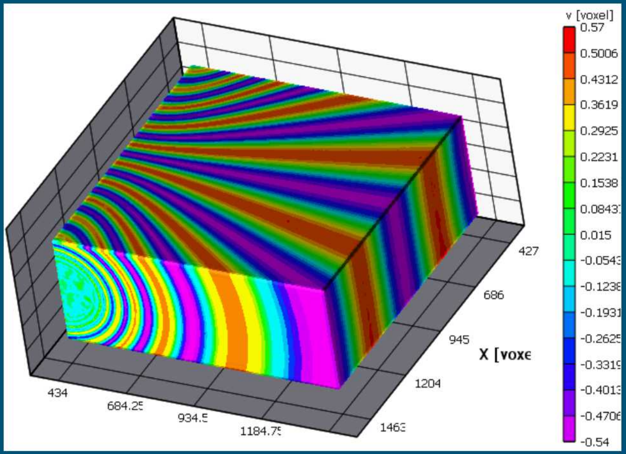

iDICs 2019

Portland, Oregon

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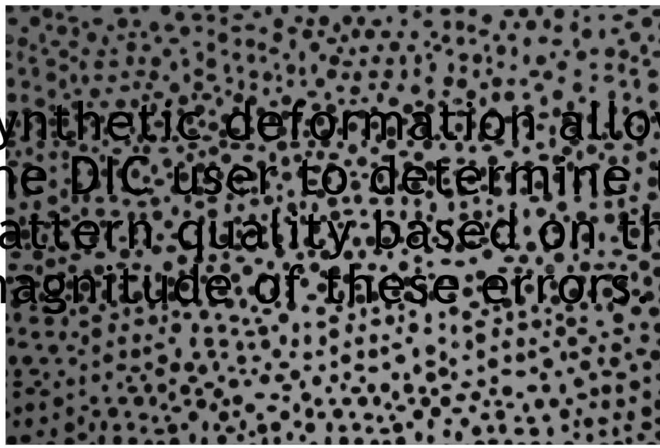
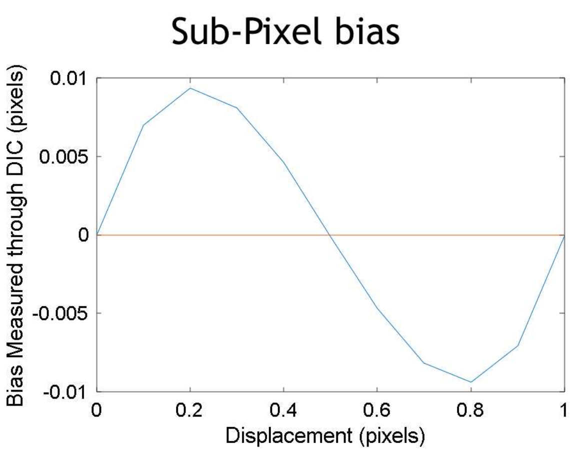
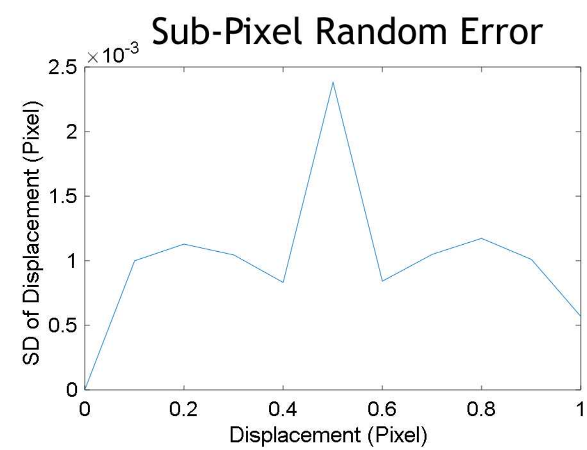
Synthetic image deformation has been an effective tool for 2D-DIC verification, and <u>error quantification</u>.

E.g. DIC suffers two systematic errors under rigid motion



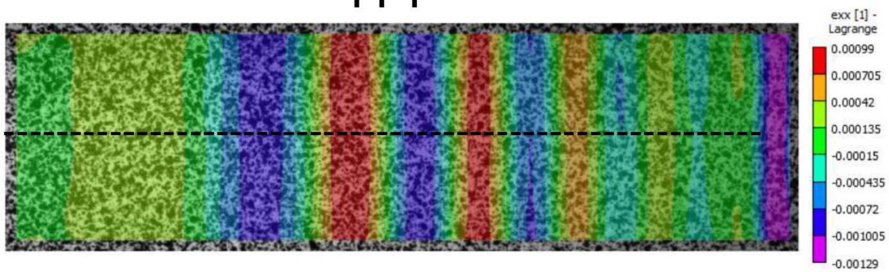
Synthetic deformation allows the DIC user to determine the pattern quality based on the magnitude of these errors.





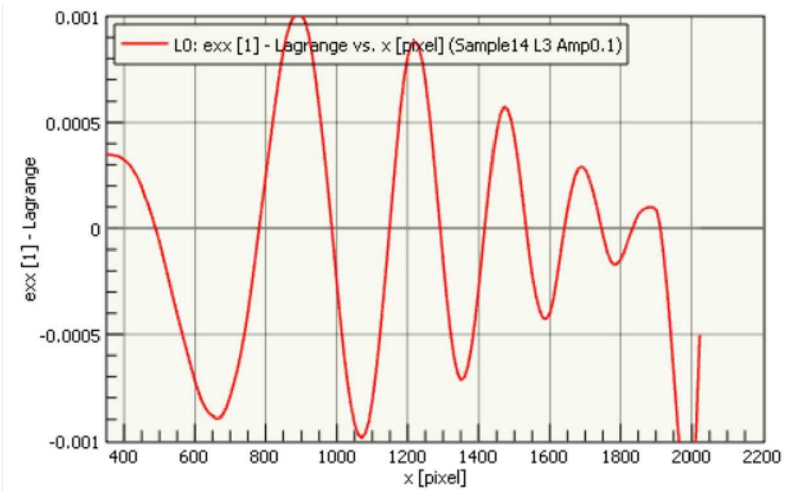
Recently, interpolated patterns have been used to study spatial resolution.

FFT

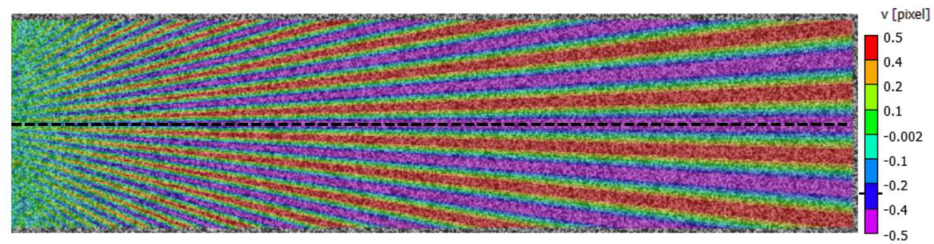


* DIC Challenge 1: varying strain

- Strain signal attenuates as frequency increases

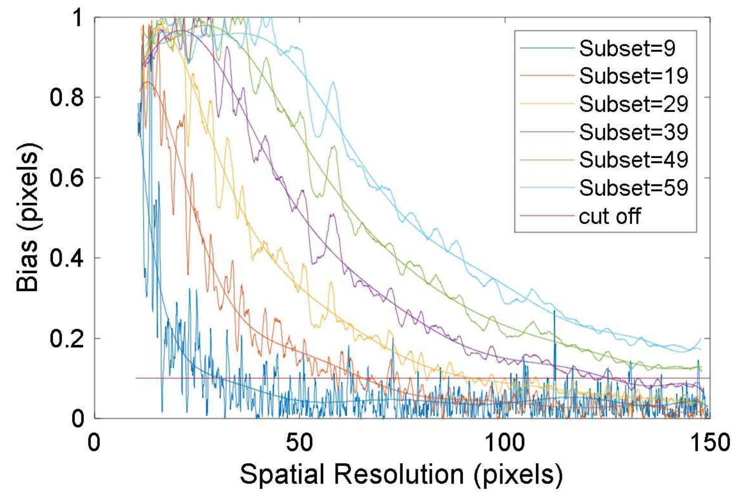


Boolean Model



F. Sur. (2018) J MATH IMAGING VIS

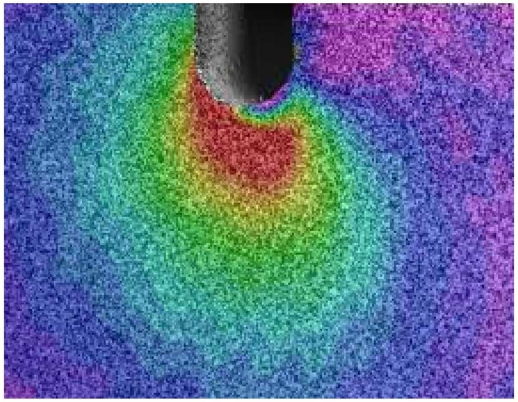
- Constant amplitude star pattern provides attenuation data for a wide range of displacement and strain frequencies.



The FFT method was attractive for DVC applications due to its ability to be used with real data.

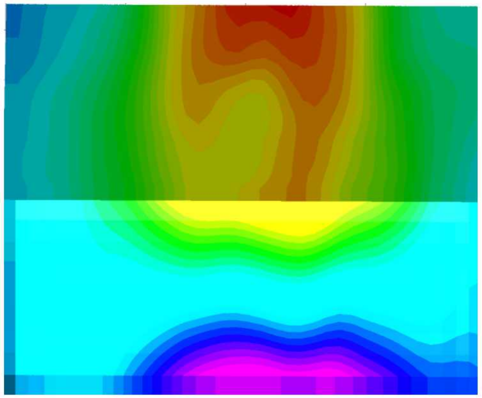
* https://sem.org/dic-challenge

The same problems arise in digital volume correlation (DVC)

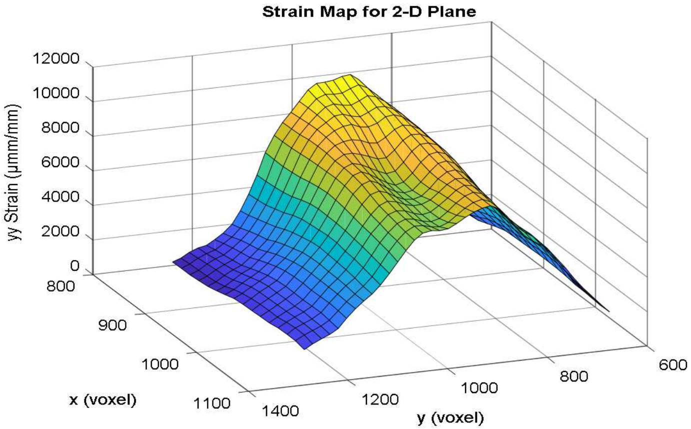


J.P. Parmigiani, JAMS (2012)

- Concentrated strains can be difficult to detect due to the spatial averaging of the chosen window.

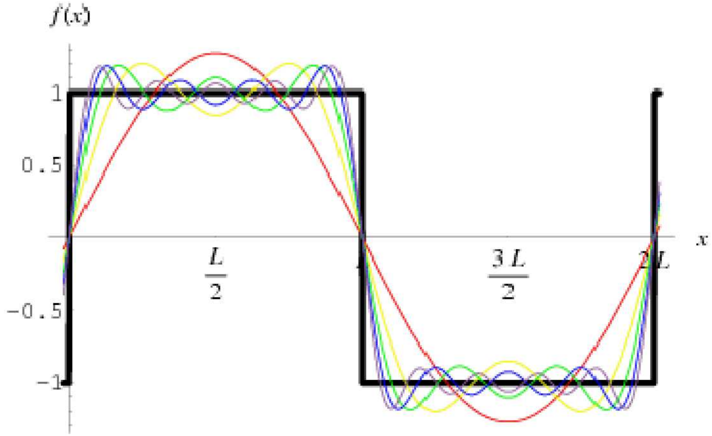


Al Foam subject to a reversed three point bend test



High strain gradients are also difficult to resolve

Fourier transforms are used for efficient image deformation.



* Weinstein, Eric W. "Fourier Series--Square Wave."

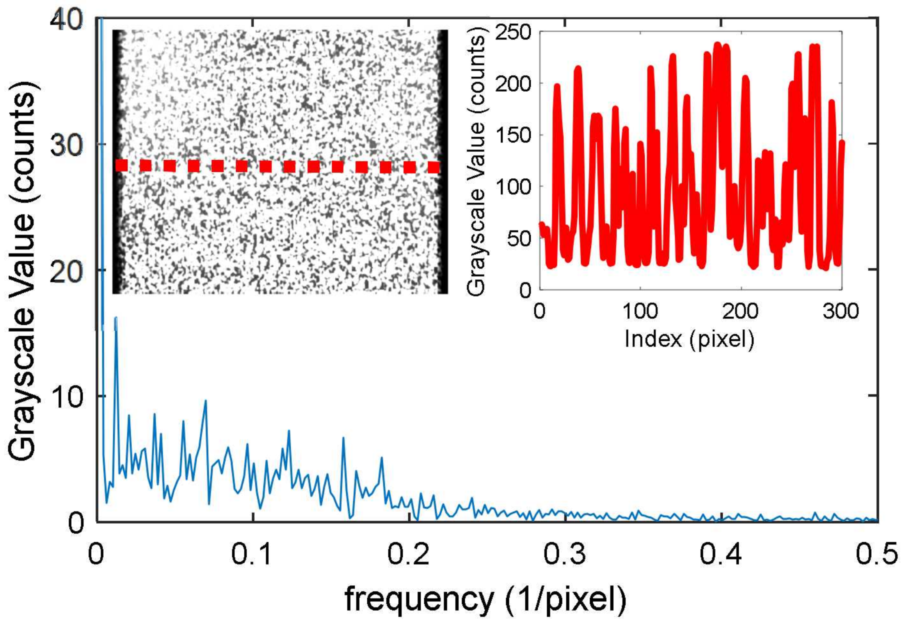
$$DFT\colon X_k = \sum_{n=0}^{N-1} x_n * e^{-\frac{2\pi i}{N}kn}$$

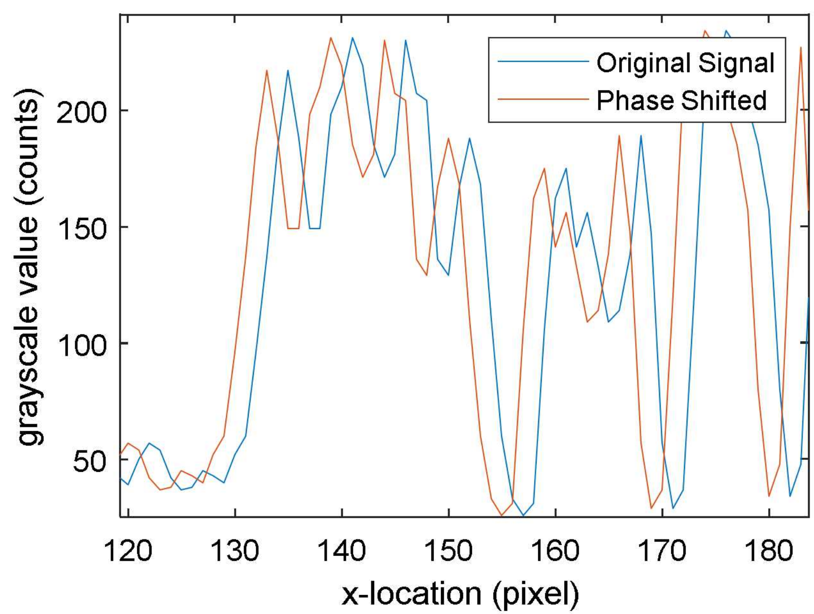
$$O(n^2)$$

$$FFT$$

$$O(n\log(n))$$

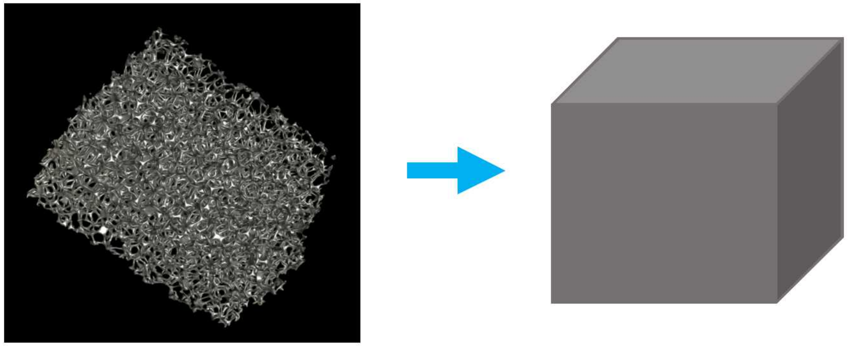
Fourier Phase Shift Equation $I'_{i,j} = \mathcal{F}^{-1}[\mathcal{F}(I_{i,j} * w_{i,j}) * e^{-2i*\pi*\varphi*\frac{k}{L}}$





* http://mathworld.wolfram.com/FourierSeriesSquareWave.html

Conversion to Volumetric



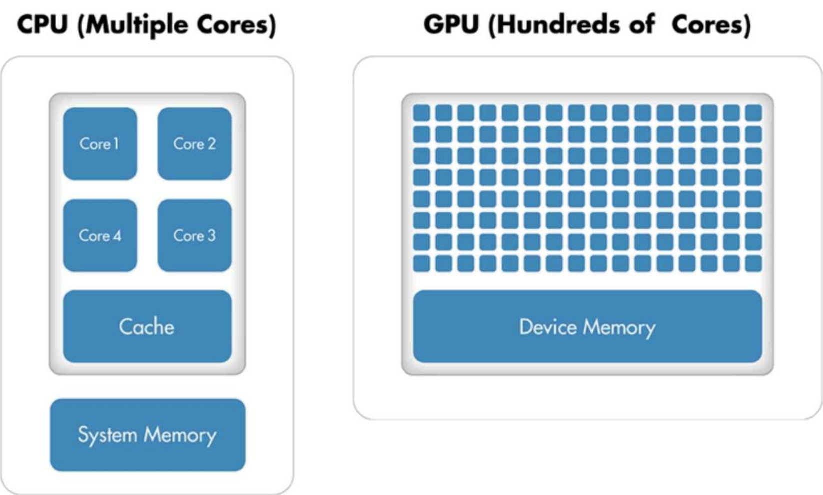
CT voxel array of dimension N^3

Number of operations for single dimension displacement:

$O(\log(N) * N^3)$ Per Tiff

CPU not ideal for large scale calculation

GPU-Based Processing



- Large number of cores allows for data parallelism.

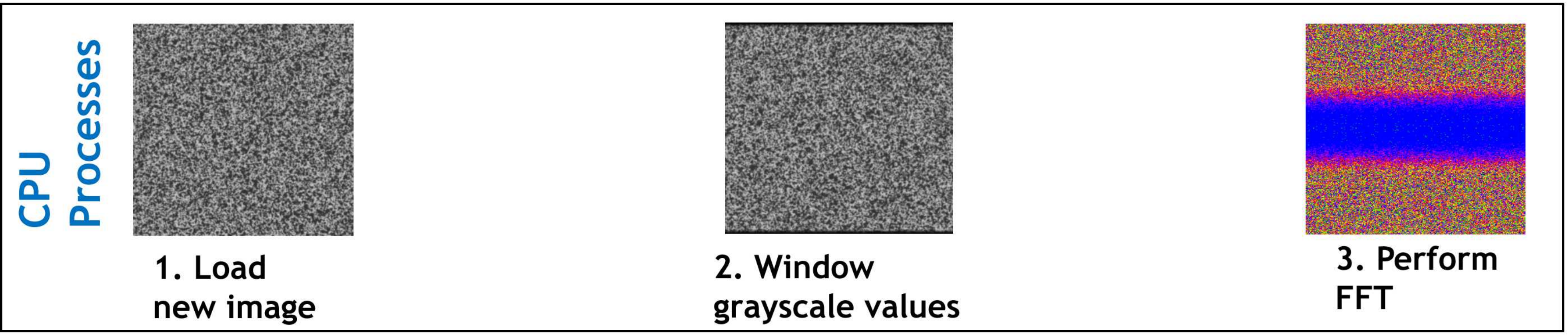
- Decreases operations/core.

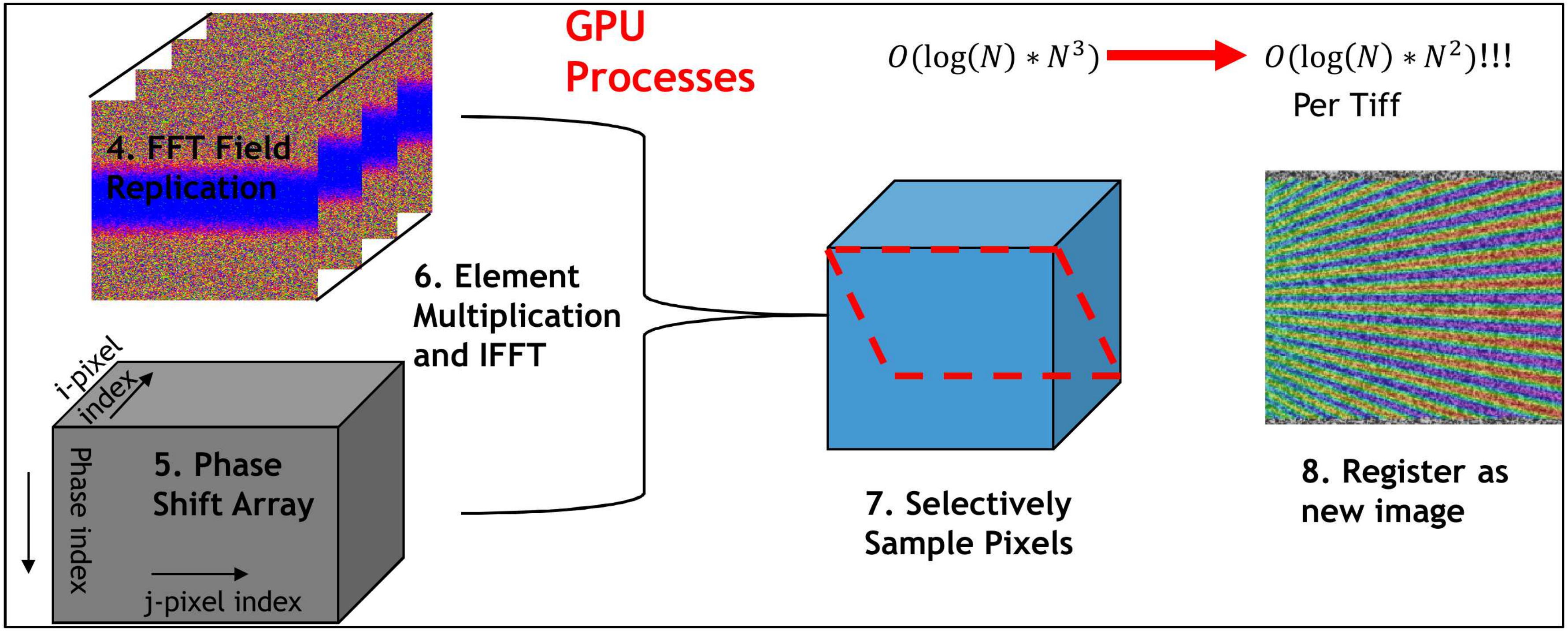
- Requires data restructure.

* J. Reese, GPU Programming in MATLAB

* https://www.mathworks.com/company/newsletters/articles/gpu-programming-in-matlab.html

Optimized Algorithm for CT Data

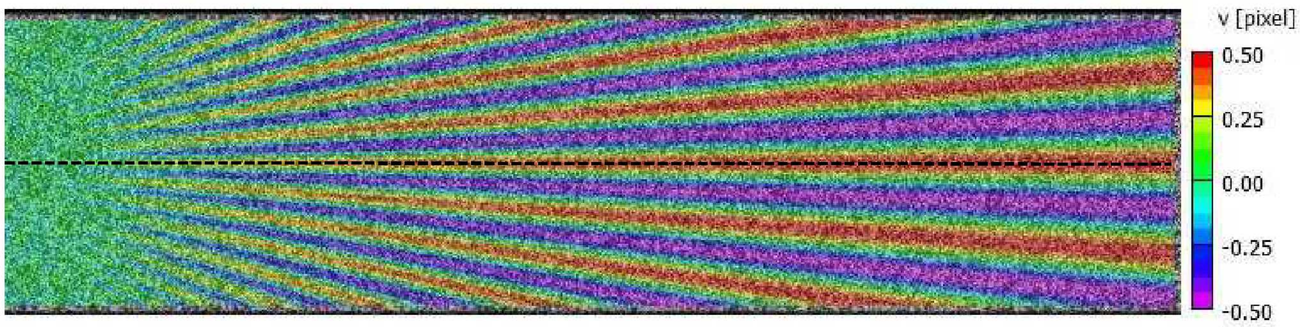




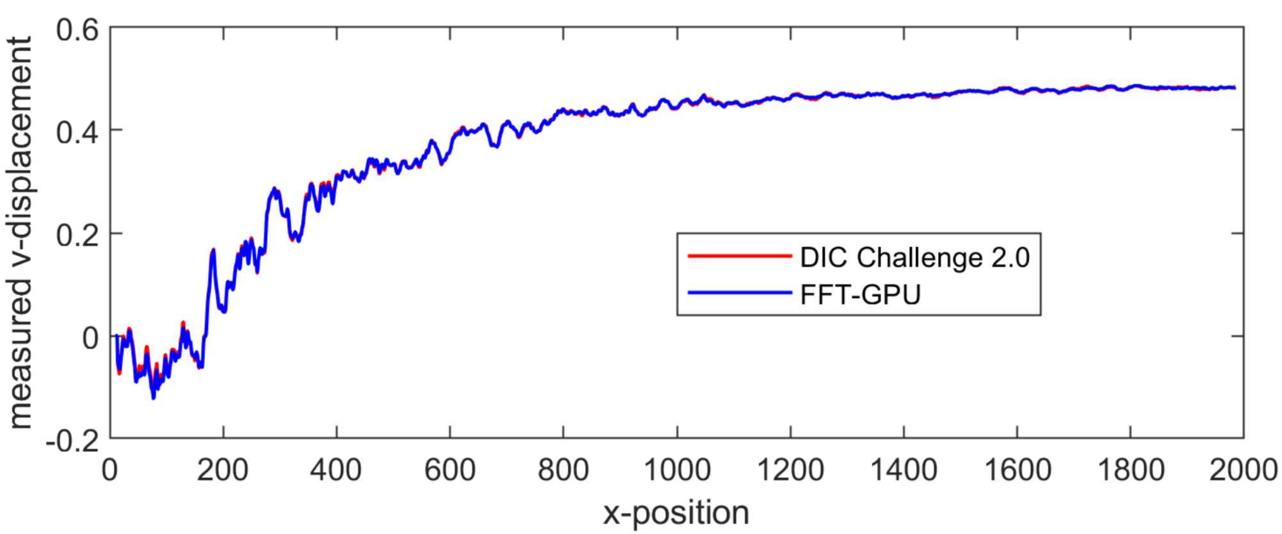
Improved code is much faster and maintains accuracy.

- Decreased time for a 501x2000 resolution image from11 minutes to 0.3 seconds on a local desktop for simple deformations.

- 1.8 seconds for complex deformations, Boolean method ~ 70 minutes on the same system. For full tiff stacks, computational cost is impractical.



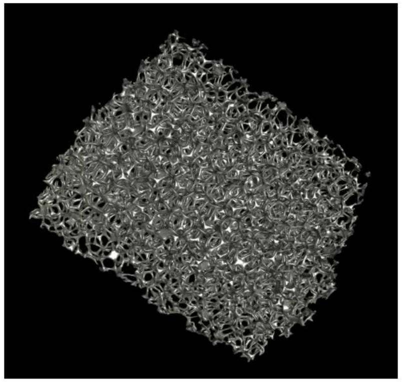
Star displacement pattern

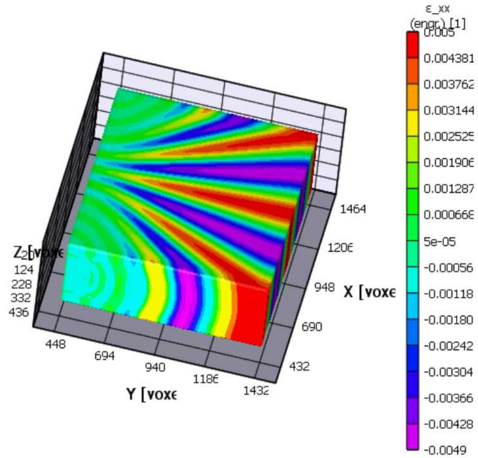


Displacement Results for Displayed Line Cut

Supplemental Material – high frequency pattern

Reference data

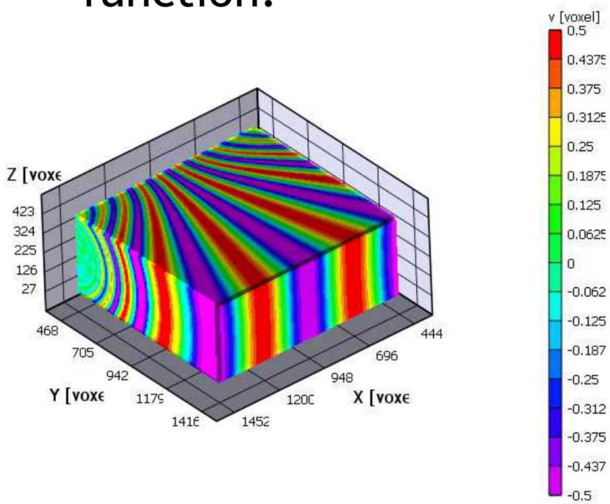




Star strain function.

Any pre-defined deformation. Especially those based on FE model.

Star displacement function.



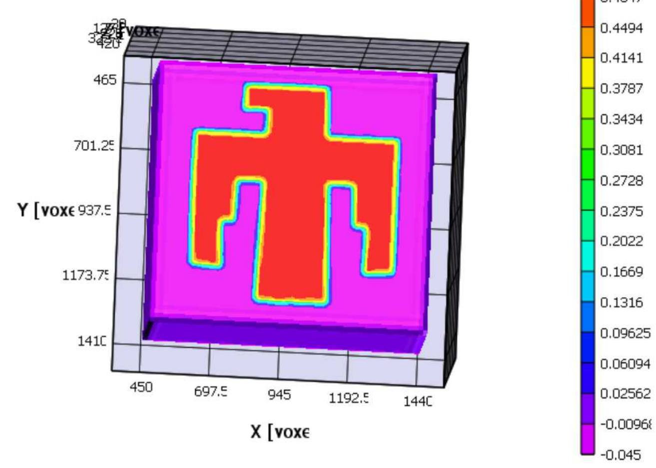
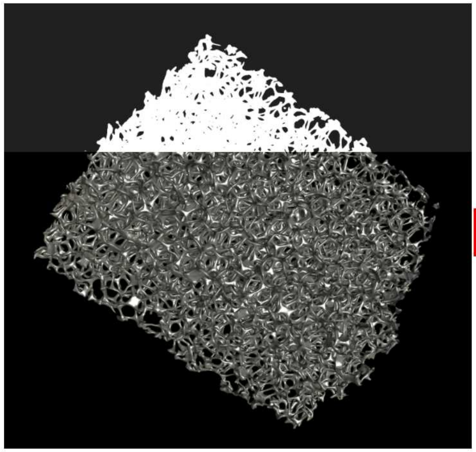
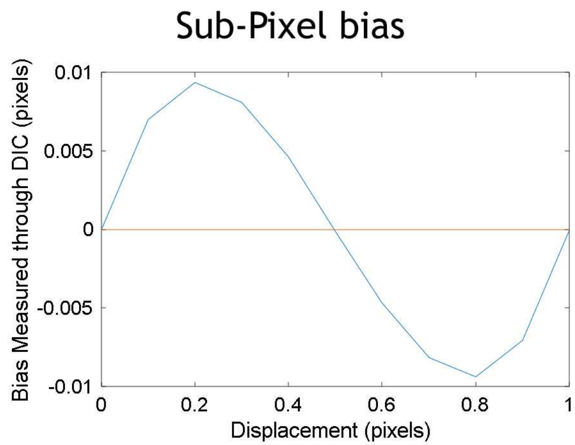
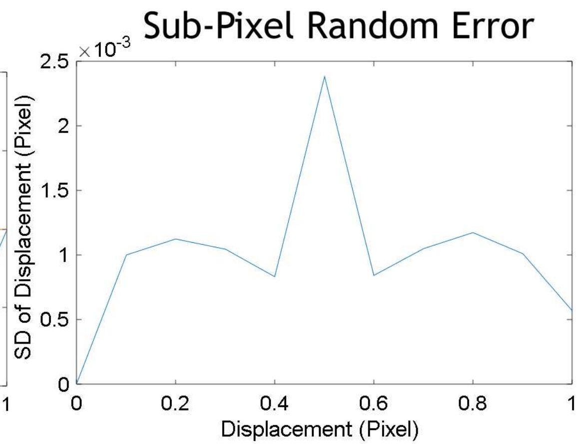


Image deformation used to quantify displacement resolution using rigid body motion.

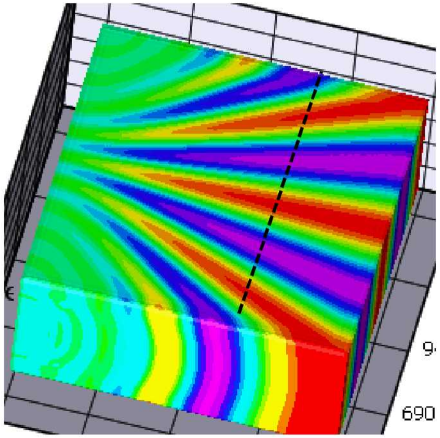


Rigid body displacement

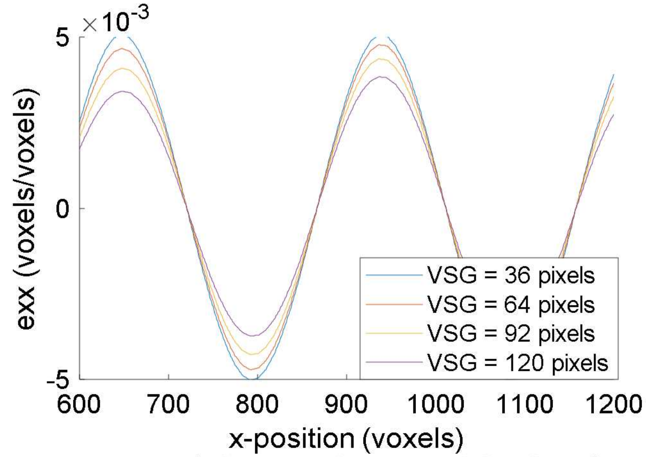




Spatial resolution studies can be performed using these deformed volumes



Star strain function



Virtual Strain Gage (VSG) Study for Strain Star Pattern

DIC displacement is usually described using the Lagrange description.

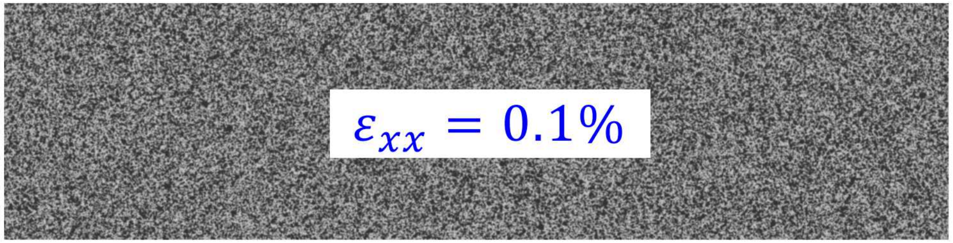
Lagrange	Eularian
$x = x(X, t) \longrightarrow u(X, t) = x(X, t) - X$	$X = X(x, t) \longrightarrow u(x, t) = x - X(x, t)$
X: *material coordinates*	X: *material coordinates*
x: *spatial coordinates*	x: *spatial coordinates*

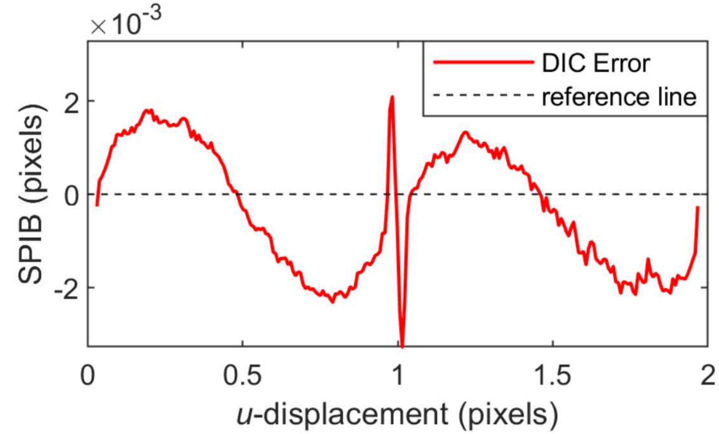
The phase shift input displacement should be described using the Eularian description for φ to get the correct Lagrange displacement.

$$\varphi = u(x, t)$$

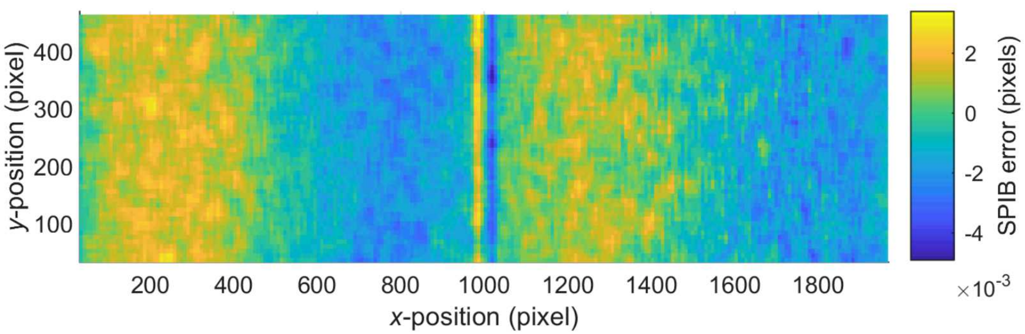
Fourier Phase Shift Equation $I'_{i,j} = \boldsymbol{\mathcal{F}}^{-1}[\boldsymbol{\mathcal{F}}\left(I_{i,j} * w_{i,j}\right) * \mathrm{e}^{-2\mathrm{i}*\pi*\varphi*\frac{\mathrm{k}}{\mathrm{L}}}]$

Issue of “ringing” near whole-pixel shifts





The issue occurs full-field and is not an artefact of averaging

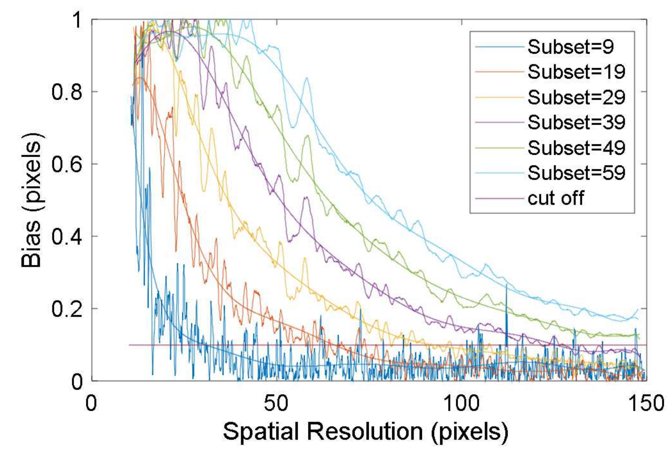


The cause is currently unknown and zero-padding does not resolve the issue.

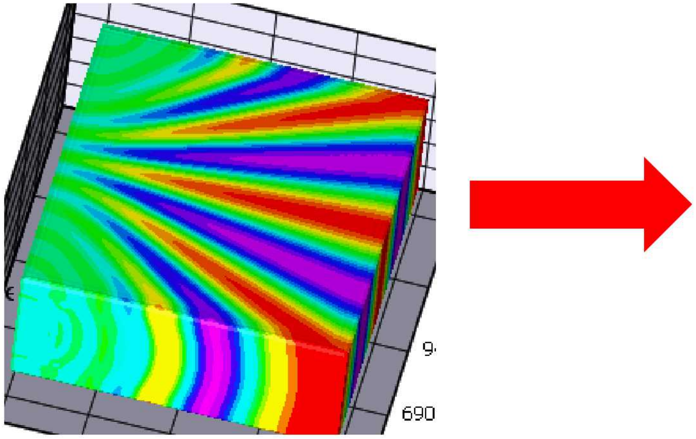
Conclusion

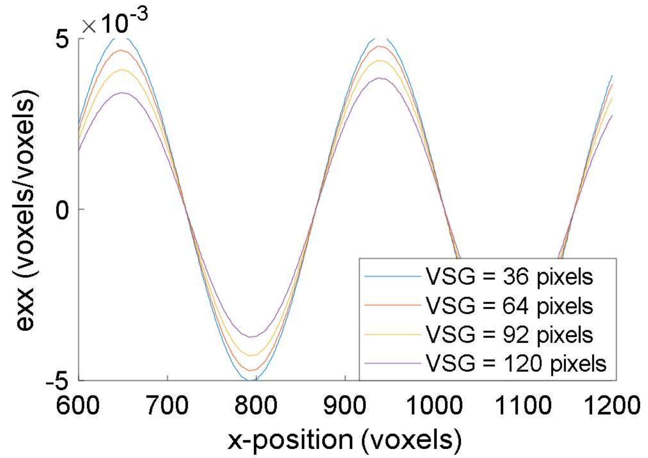
- Developed an FFT-based deformation code optimized for large data sets

- Accuracy of deformatio methods



- Can be used to quantify error in DVC codes





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