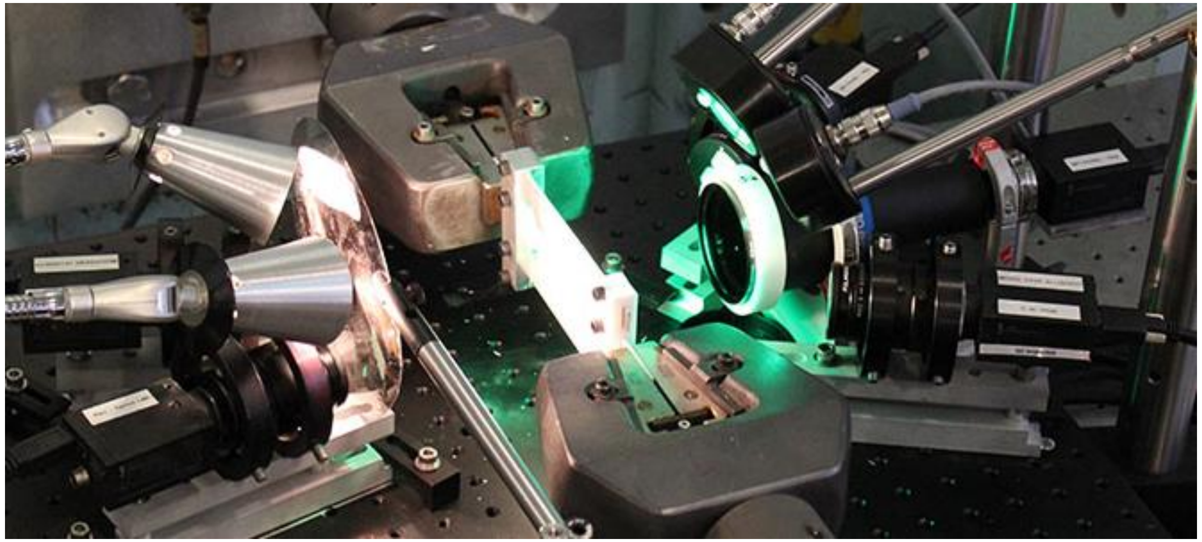
SAND2023-04600C

SAND2023-#### C

Basics of Digital Image Correlation (DIC)



Elizabeth Jones and Amanda Jones

Welcome to Basics of Digital Image Correlation (DIC)

Course Description

- Developed by the International Digital Image Correlation Society (iDICs)
- Abbreviated version of DIC 101 (https://idics.org/courses/)
- Follows the *Good Practices Guide for DIC* (https://idics.org/guide/)
- Uses the DIC Challenge images (https://idics.org/challenge/)

- Complements vendor-based training, on-the-job training, and other standards such as VDI-2626, ASD-STAN EN 4861, and application specific standards in ISO and ASTM.

Outline

- Basic, high-level DIC concepts
- Design of DIC measurements
- Preparation for DIC measurements
  - Camera calibration
- DIC processing techniques
  - Strain calculations
- DIC reporting requirements

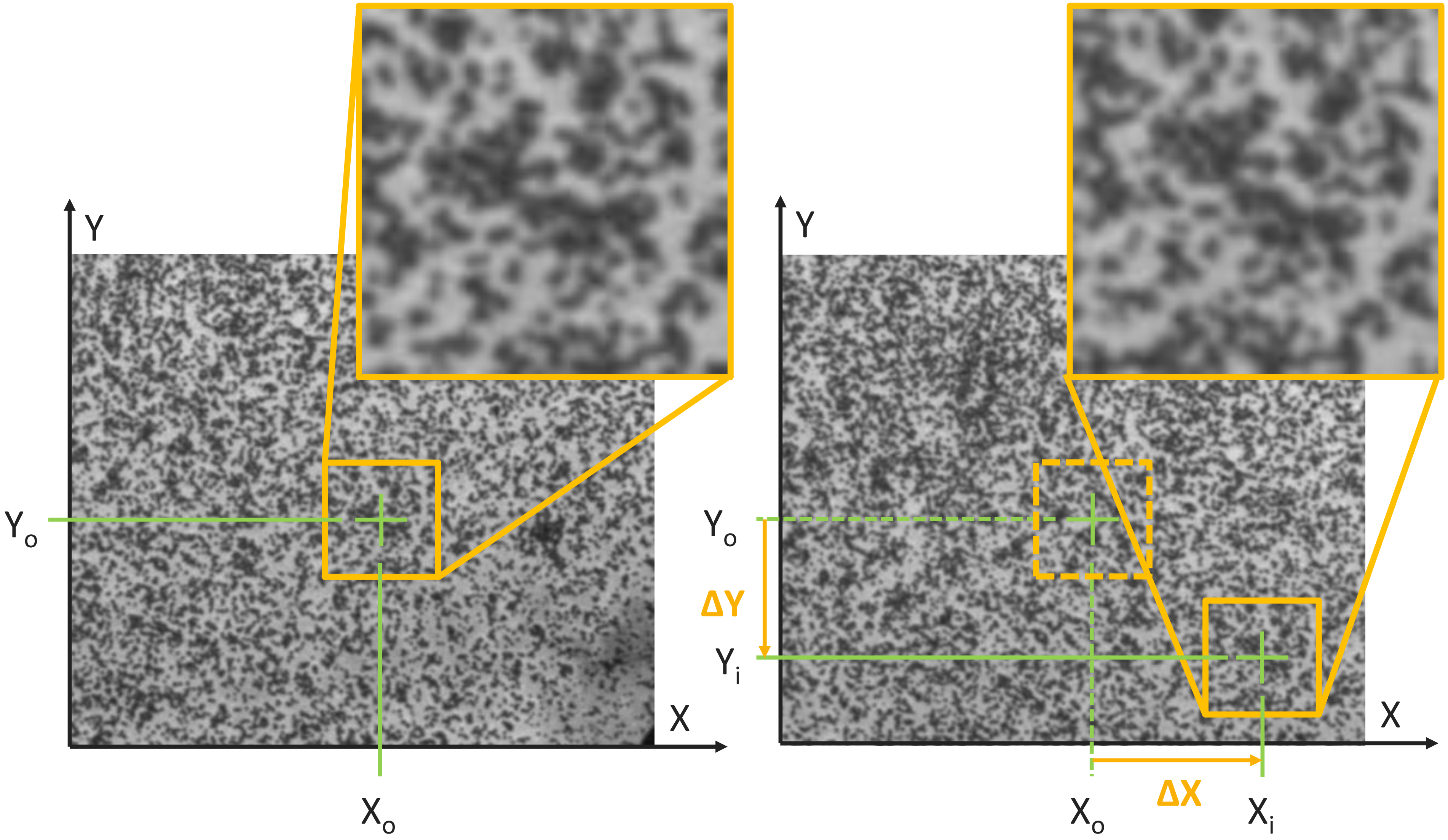
DIGITAL IMAGE CORRELATION (DIC)

INTRODUCTION

"Keep the dots in the box." -- Prof. Samantha Daly

- Digital Image Correlation (DIC) is a diagnostic technique providing full-field shape, displacement and strain measurements on the surface of a solid specimen

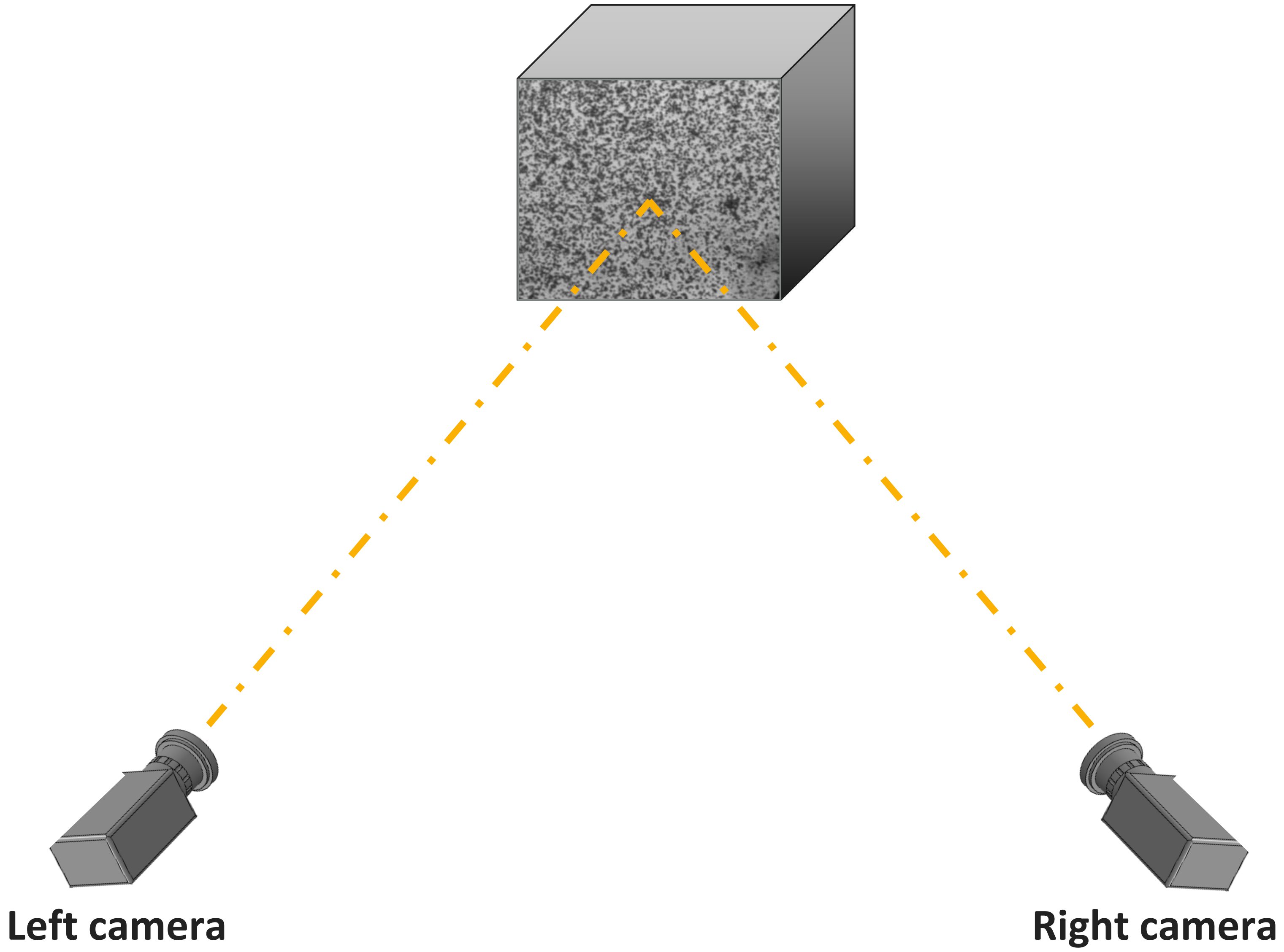
- Advantages:
  - Optical (non-contact)
  - Full-field
  - Length- and time-scale independent



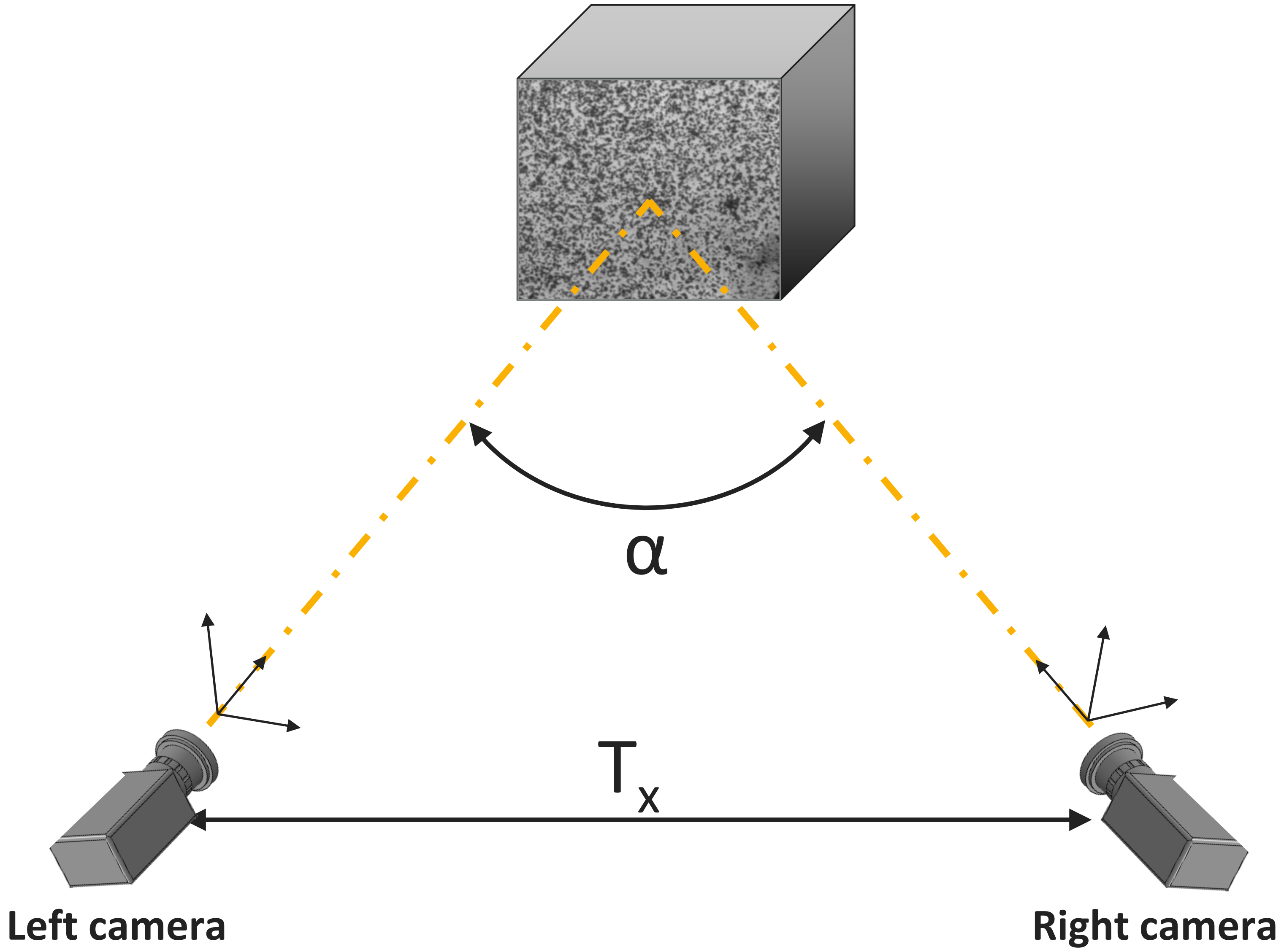
Reference (undeformed) image

Deformed image

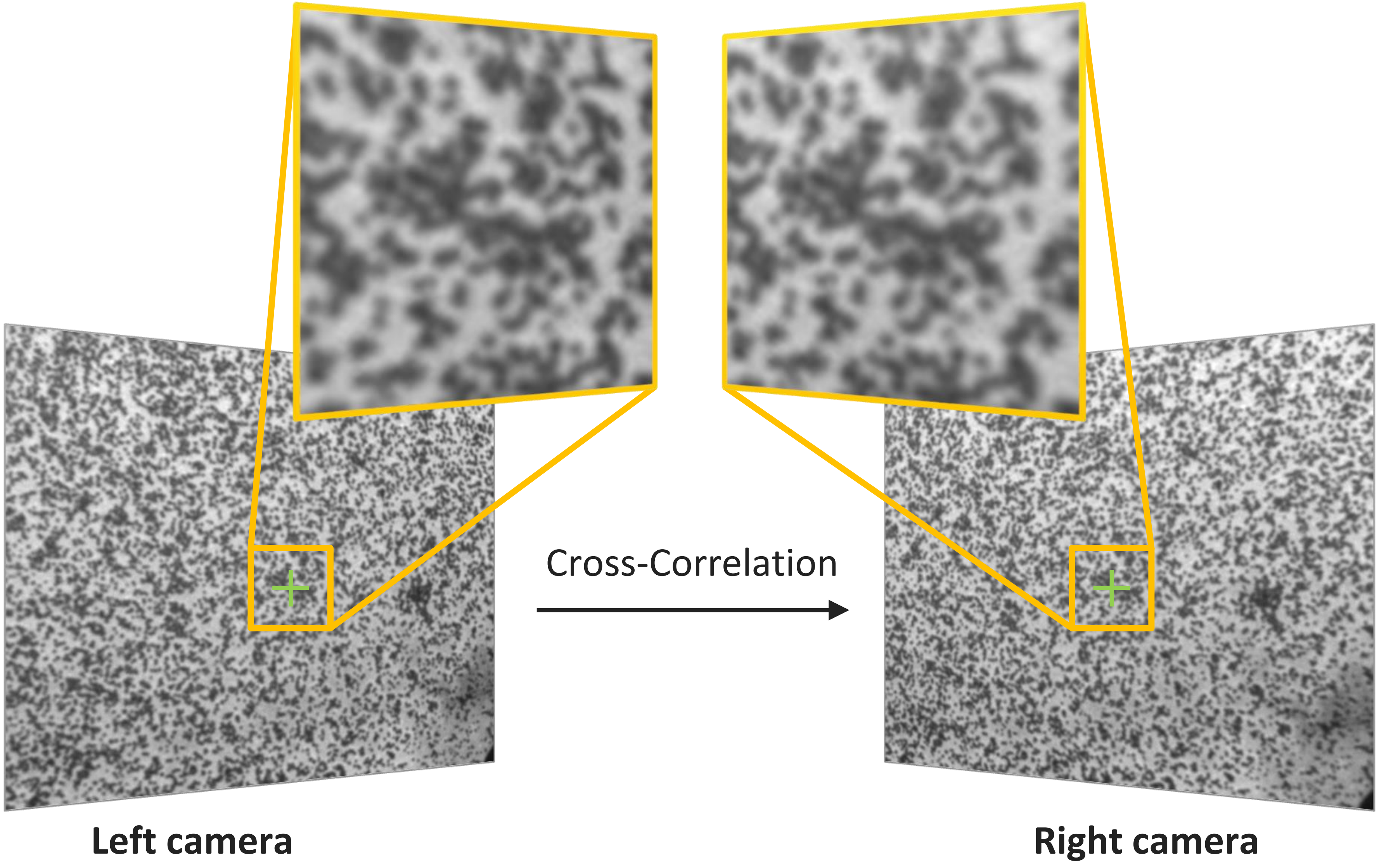
Stereo-DIC utilizes two camera viewing the test piece at an angle to obtain 3D coordinates and displacements.



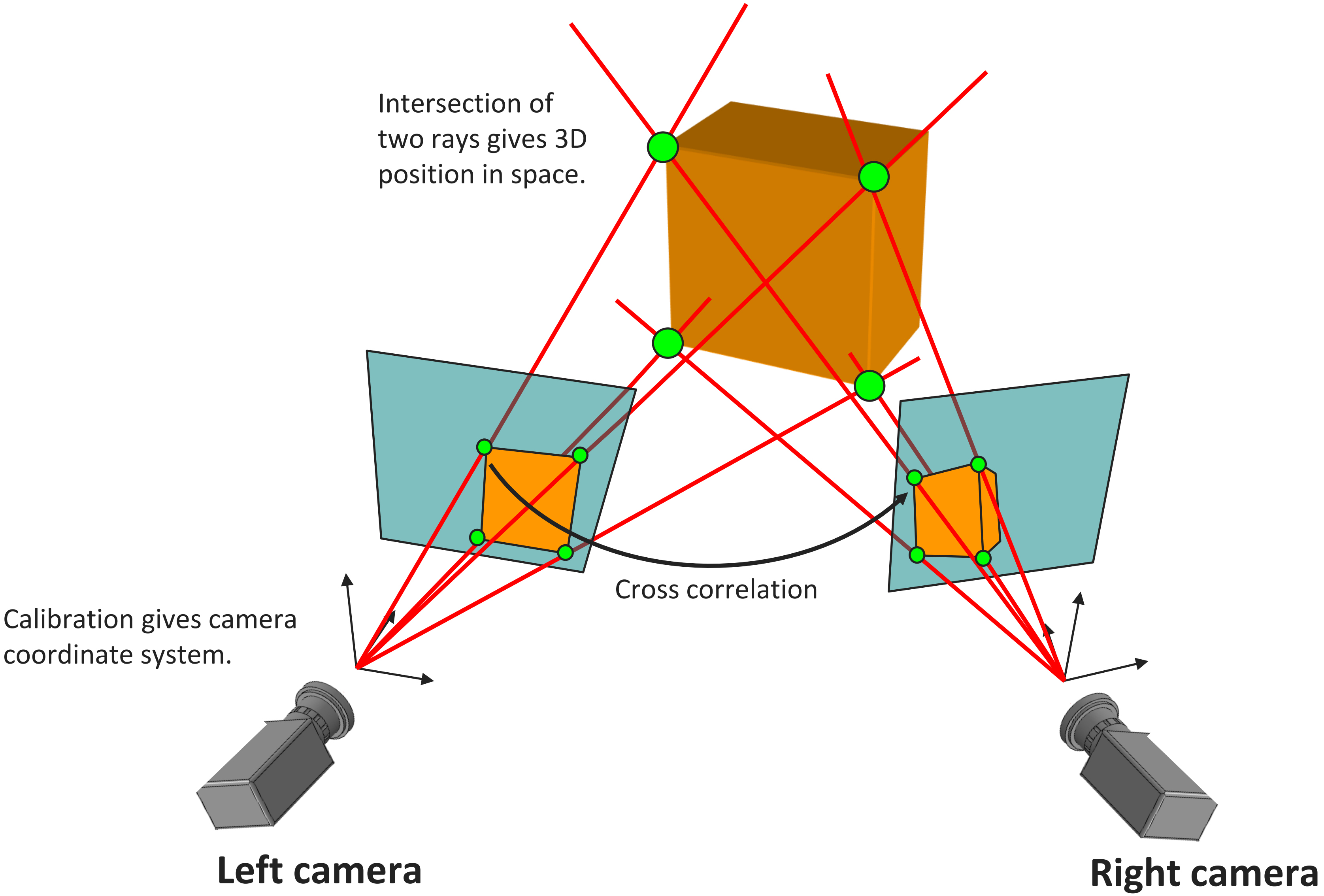
1. Relative location of one camera with respect to second camera and local camera coordinate systems determined through calibration.



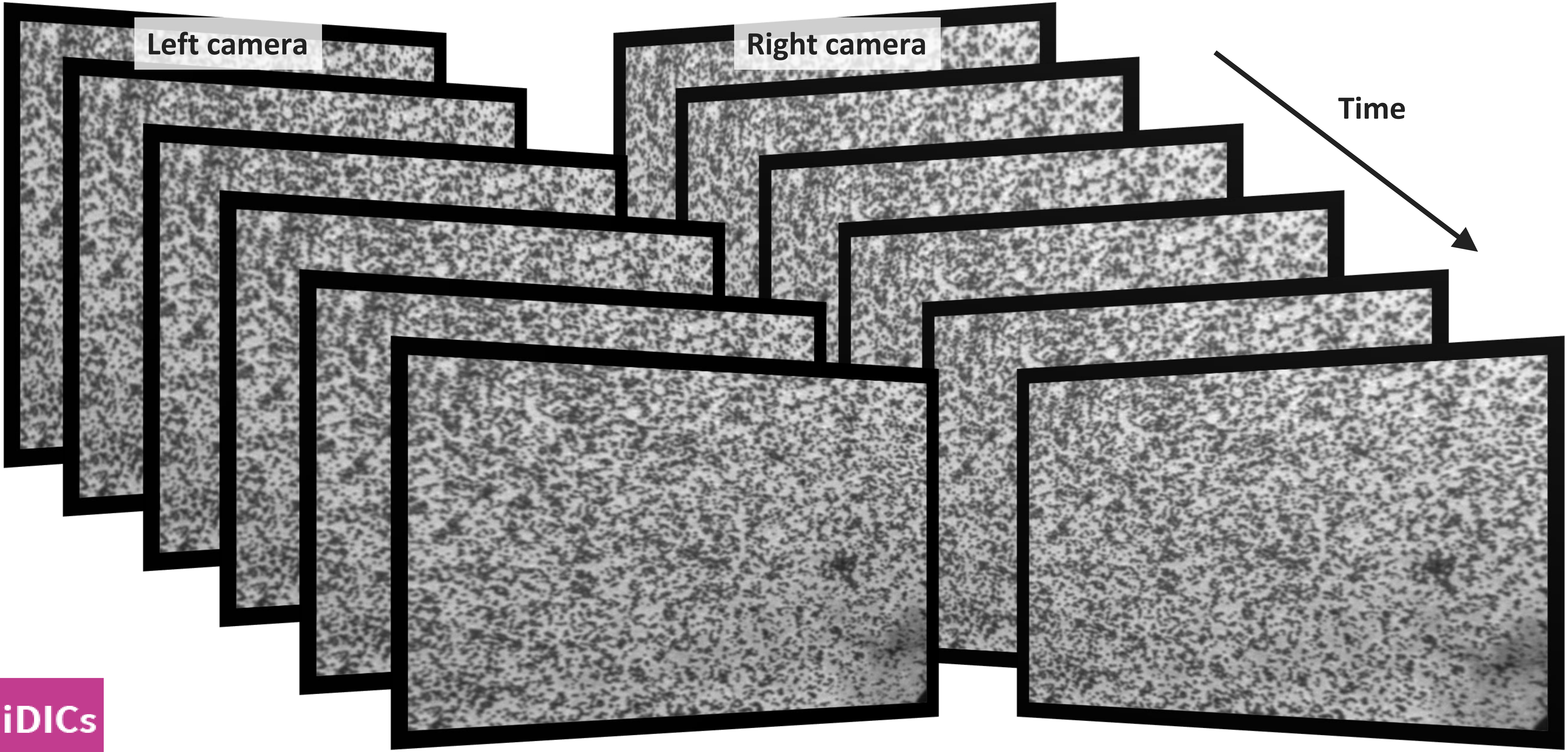
2. Correlation of the left and right cameras identifies the same point in each camera.



3. Cross-correlation and triangulation gives coordinates in 3D space.



Full-field, time-resolved deformation computed from stereo cameras capturing images throughout the mechanical test.



CHAPTER 2:
DESIGN OF DIC MEASUREMENTS

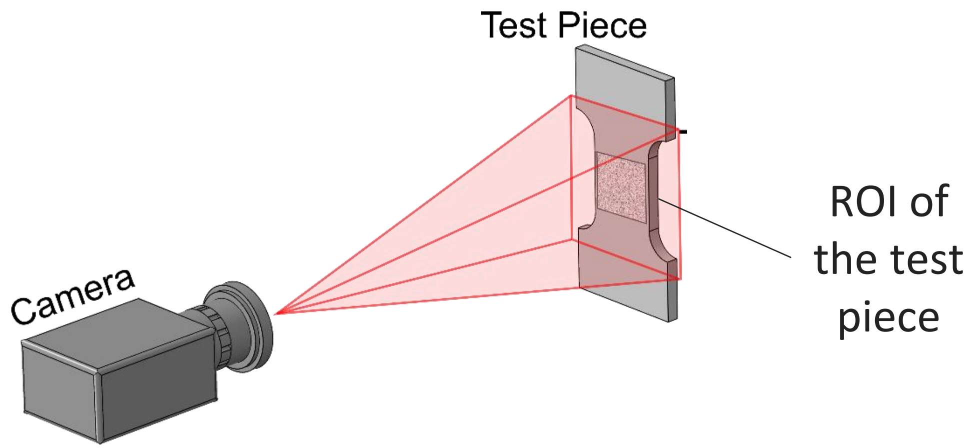
SEC. 2.1:
MEASUREMENT REQUIREMENTS

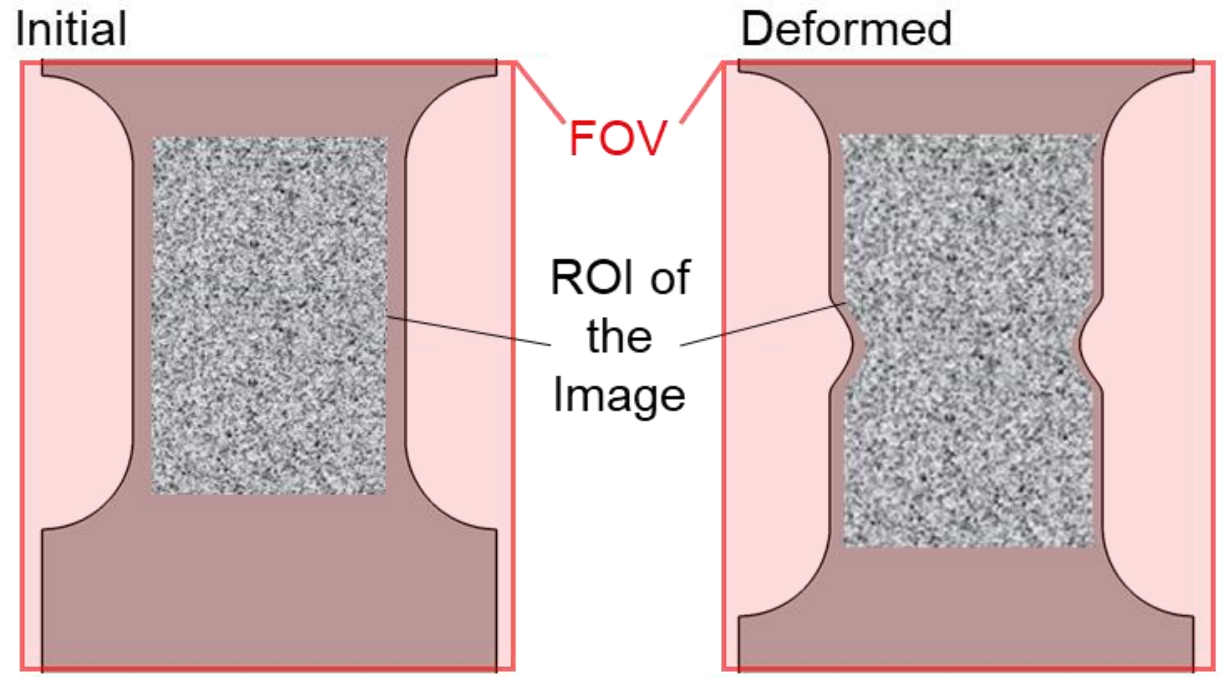
Quantity-of-Interest (QOI), Region-of-Interest (ROI), and Field-of-View (FOV)
Sec. 2.1.1 – Sec. 2.1.3

1. Determine the QOIs
   - Examples include: shape, displacement, velocity, acceleration, strain, strain-rate, etc.
   - Application specific:
     - Strain field near hole or necking region?
     - Displacements at grips?

2. Select the ROI of the test piece

3. Determine the required FOV, based on the ROI
   - Recommendation 2.1: ROI should fill FOV, accounting for anticipated motion



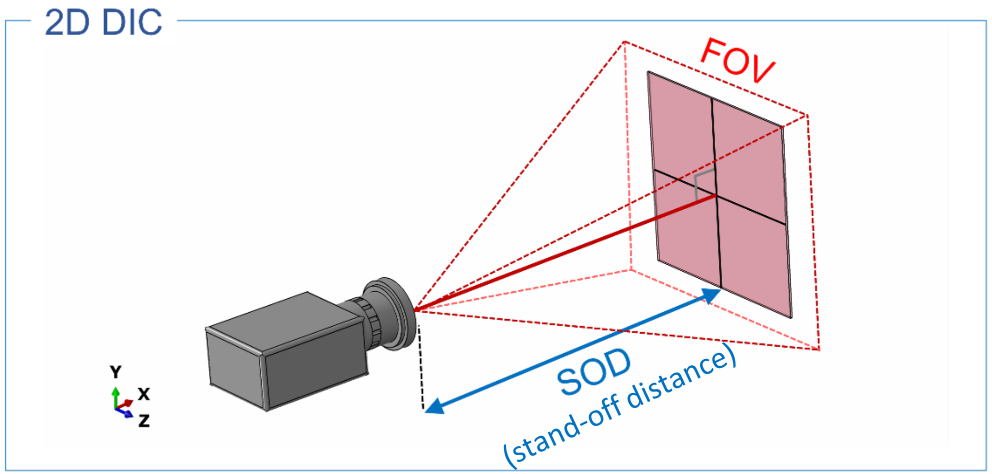


2D-DIC vs Stereo-DIC
Sec. 2.1.5

2D-DIC:

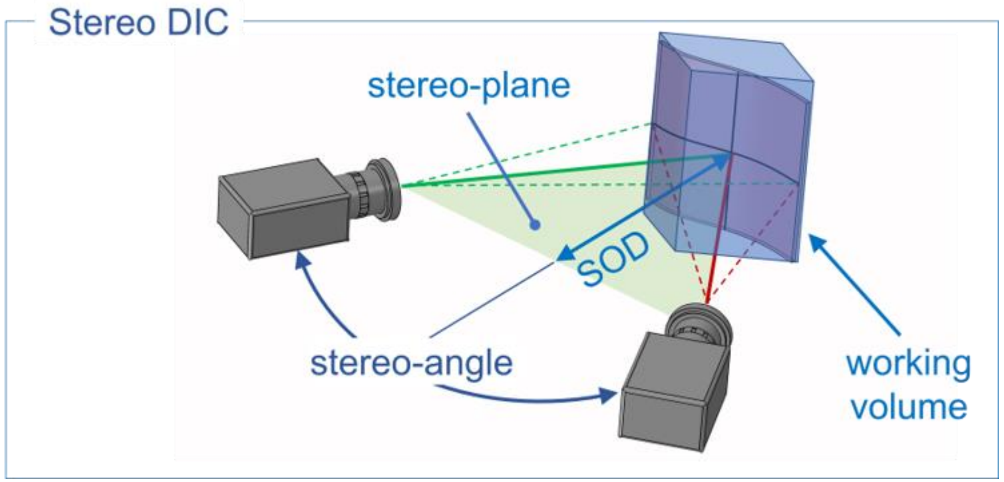
- One camera, perpendicular to a planar test piece
- Gives in-plane displacements and strains

- Caution 2.1: Test piece should be planar and perpendicular to camera, and remain so during the test



Stereo-DIC:

- Two cameras oriented at a stereo angle (typically 15-35 degrees)
- Gives 3D coordinates, displacements, strains on the surface of the test piece



Frame Rate and Exposure Time
Sec. 2.1.10 – 2.1.11

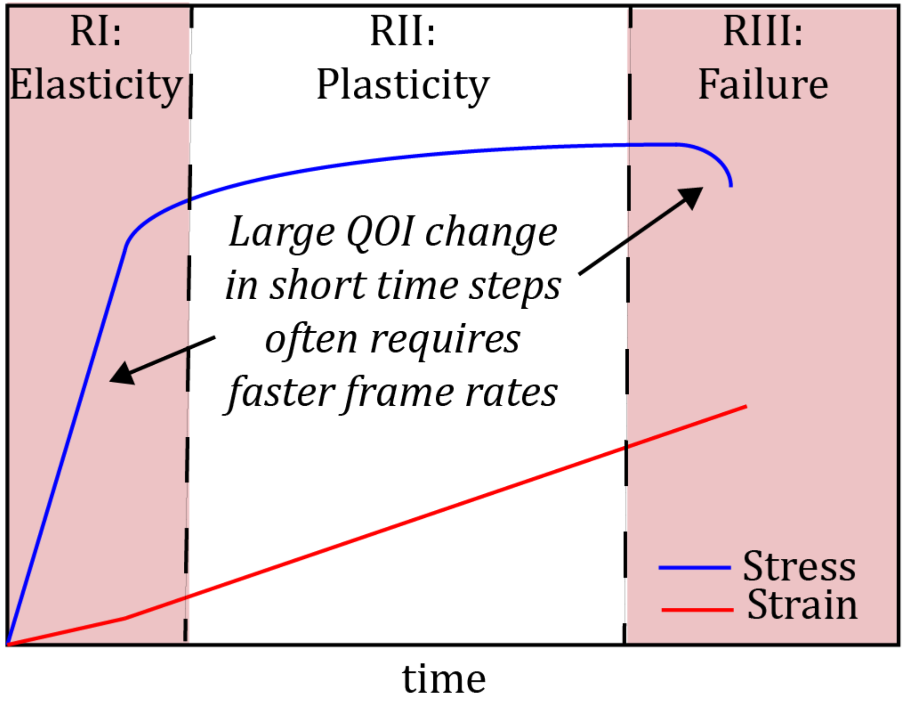
Frame Rate

- Optimal frame rate is application specific

Exposure Time

- Key point: prevent motion blur
- Tip 2.7: Maximum allowable test piece motion over the course of the exposure time is ~0.01 px (conservative) or up to 0.3 px (less conservative)

Example of Metal plasticity



CHAPTER 2:
DESIGN OF DIC MEASUREMENTS

SEC. 2.2:
EQUIPMENT AND HARDWARE

Camera and Lens selection
Sec. 2.2.1

- Tip 2.10: Experience is necessary to determine if a camera or lens is of sufficient quality; vendors evaluate equipment for you.
- Field-of-view, stand-off distance, and lens focal length are all intertwined.

Focal Length	Stand-Off Distance	Field-of-View
↑	Constant	↓
↑	↑	Constant
Constant	↑	↑

Constant stand-off distance

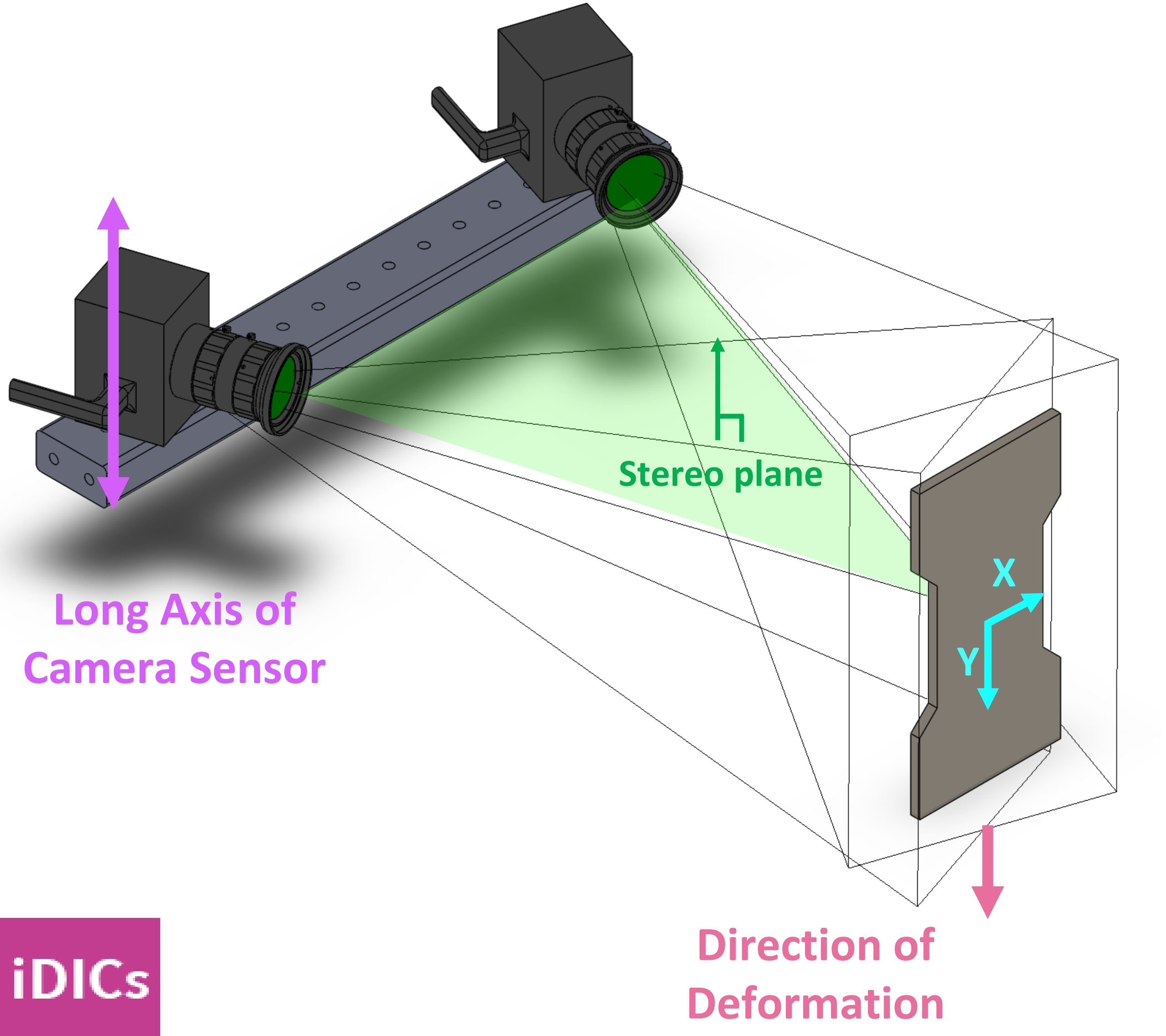
28 mm lens

50 mm lens

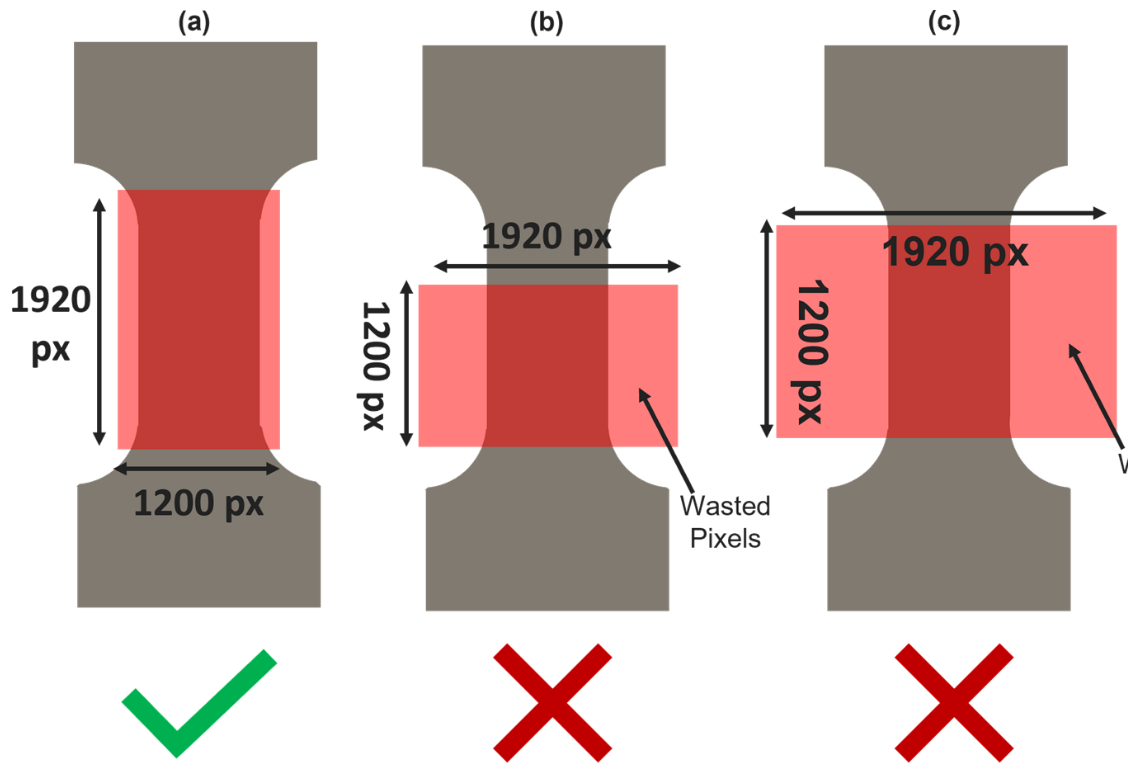
70 mm lens

210 mm lens

Recommended Camera Orientations
Recommendation 2.8, Figure 2.1

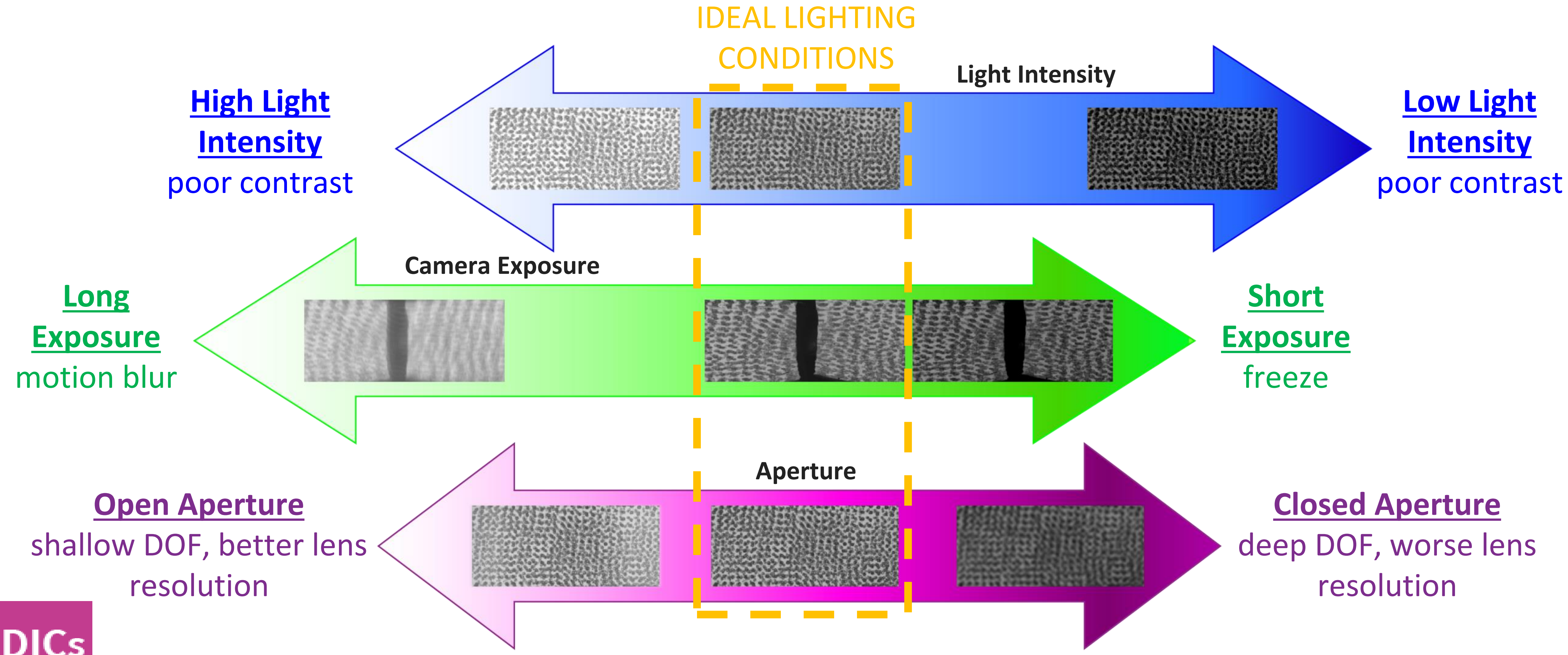


- Align the **long axis of your camera sensor** with the long axis of the test piece



Aperture, Lighting, Exposure, Gain and Contrast
Sec. 2.2.3 – Sec. 2.2.4

- **Recommendation 2.13: The better the image contrast is, the less noisy the DIC results are.**
  - For 8-bit cameras, minimum contrast is 50 grey-level counts or 20%.



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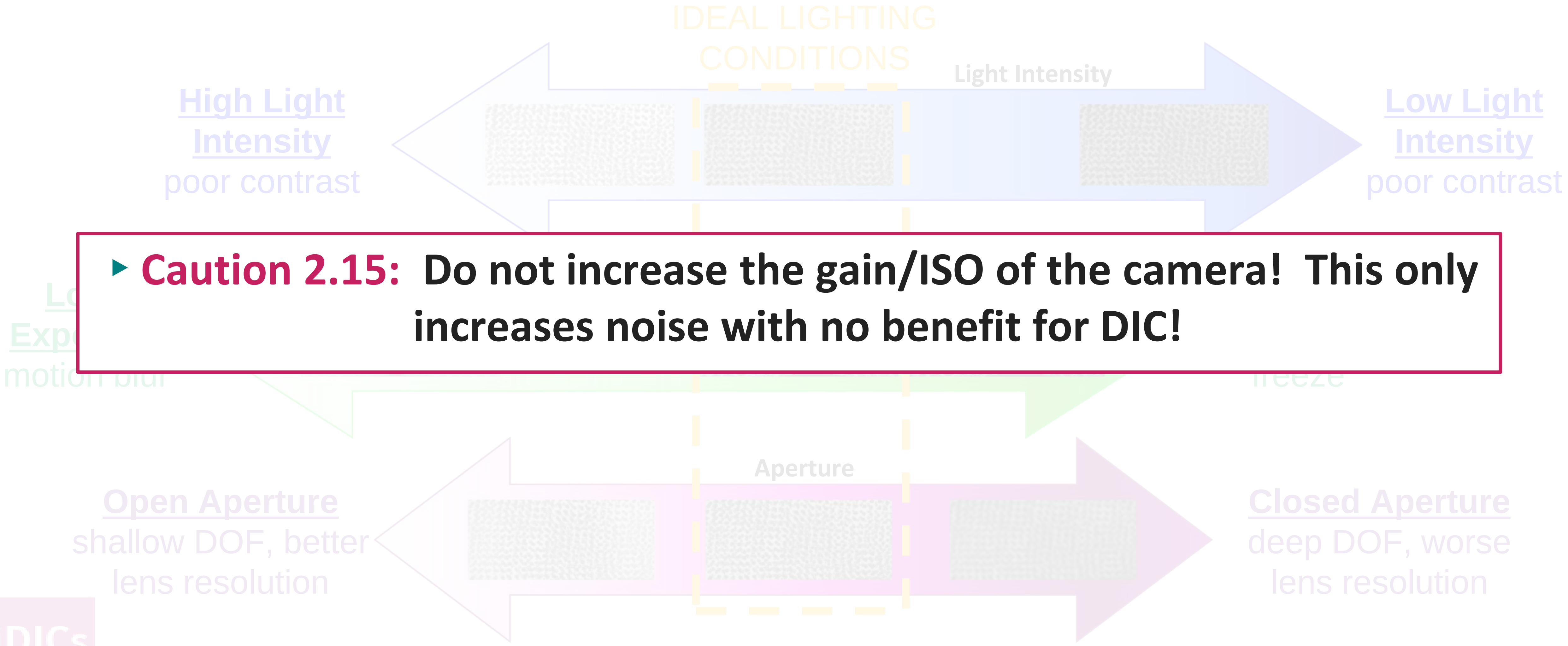


- **Caution 2.15: Do not increase the gain/ISO of the camera! This only increases noise with no benefit for DIC!**

CHAPTER 2:
DESIGN OF DIC MEASUREMENTS

SEC. 2.3:
DIC PATTERN

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

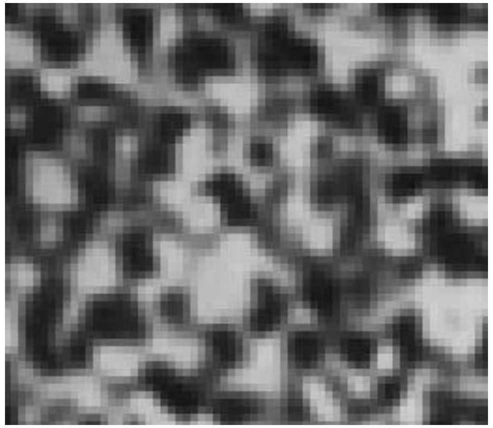
- **One fundamental assumption of DIC is that motion and deformation of the pattern that is imaged exactly replicates the underlying test piece motion and deformation.**

Two Types of Patterns:

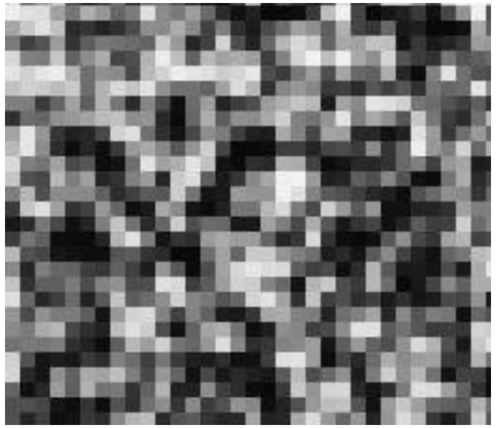
- *Natural patterns:* If the sample surface is heterogeneous, you may be able to image the test piece directly
- *Applied patterns:* Much more common

Key Pattern Characteristics:

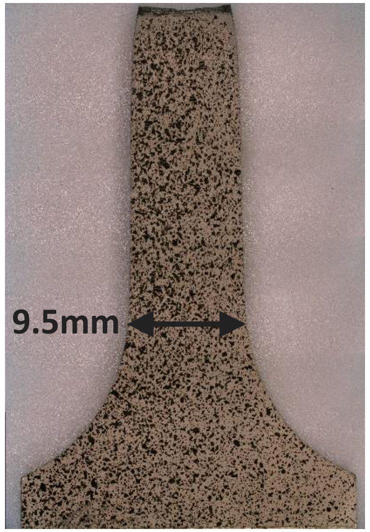
- *Size:* 3-5 pixels
  - Applies to both white and black features!
- *Density*: ~ 50% black and white
- *Quality/Bonding/Fidelity*: Pattern should not degrade during testing, should remain well-bonded to test piece, and deform conformally with the test piece
  - *Issues with patterns may appear in results as:*
    - Higher correlation residual / uncertainty
    - Missing data points (holes) / failure to correlate
    - Higher epipolar error
    - Non-physical data
    - **Or no obvious effect! → Carefully examine patterns**

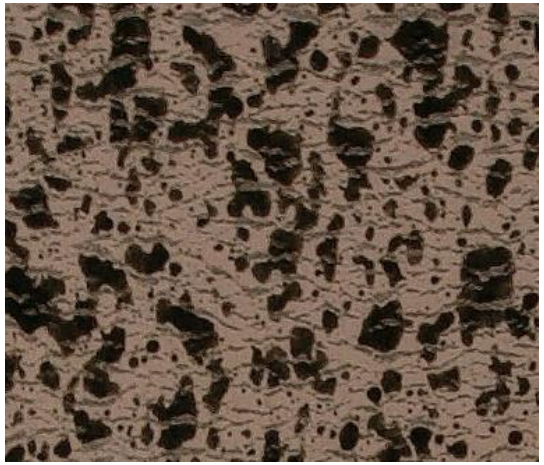


Appropriate size



Too small – aliased





Paint cracking and debonding at a small scale

SAND2020-9051 TR (slides)
SAND2020-9046 TR (videos)

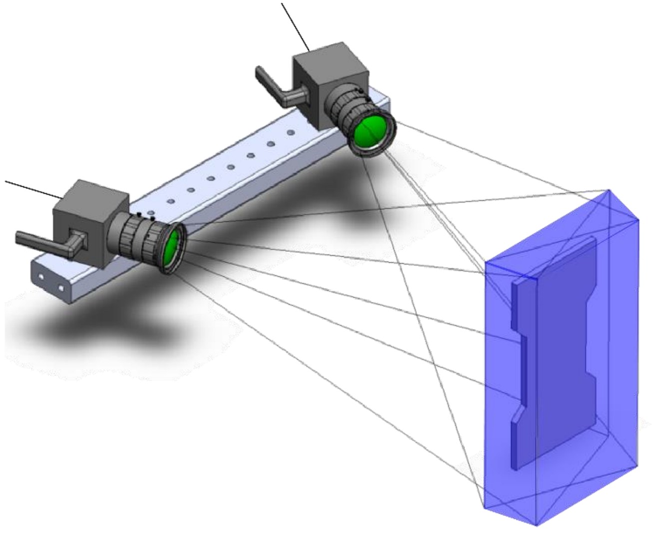
CHAPTER 3:
PREPARATION FOR THE MEASUREMENTS

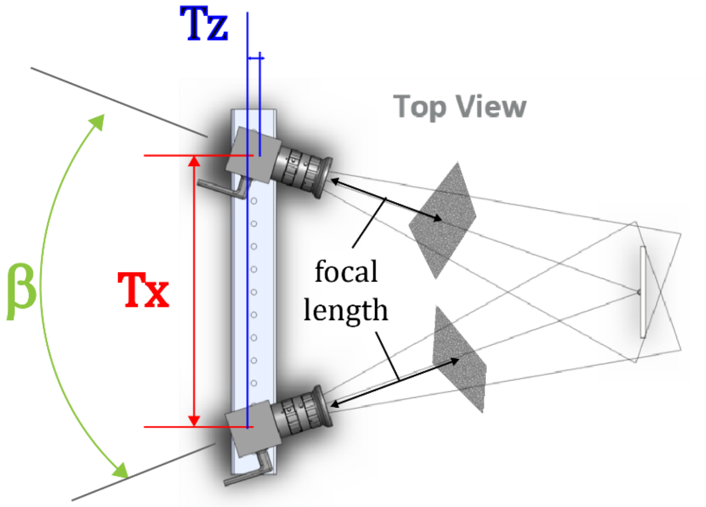
SEC. 3.2-3.3:
CALIBRATION

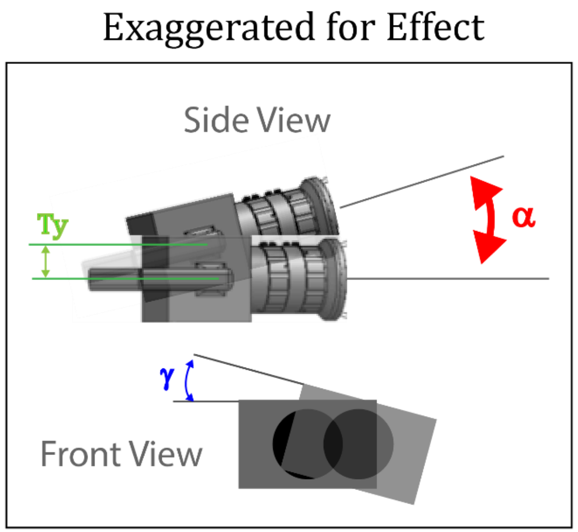
Purpose of Calibration – Stereo-DIC
Sec. 3.2.1

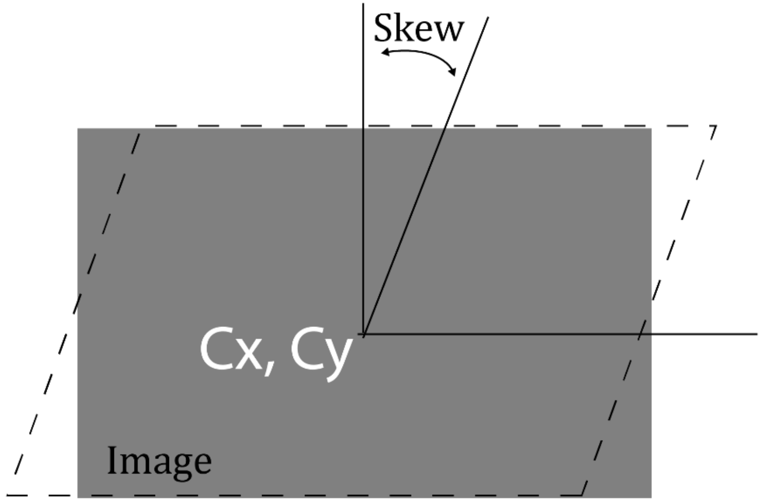
- *Intrinsic Parameters*
  - Focal length
  - Skew
  - Image Center (Cx, Cy)
  - Lens Distortions

- *Extrinsic Parameters*
  - Translations (X,Y,Z)
  - Rotations (α,β,γ)



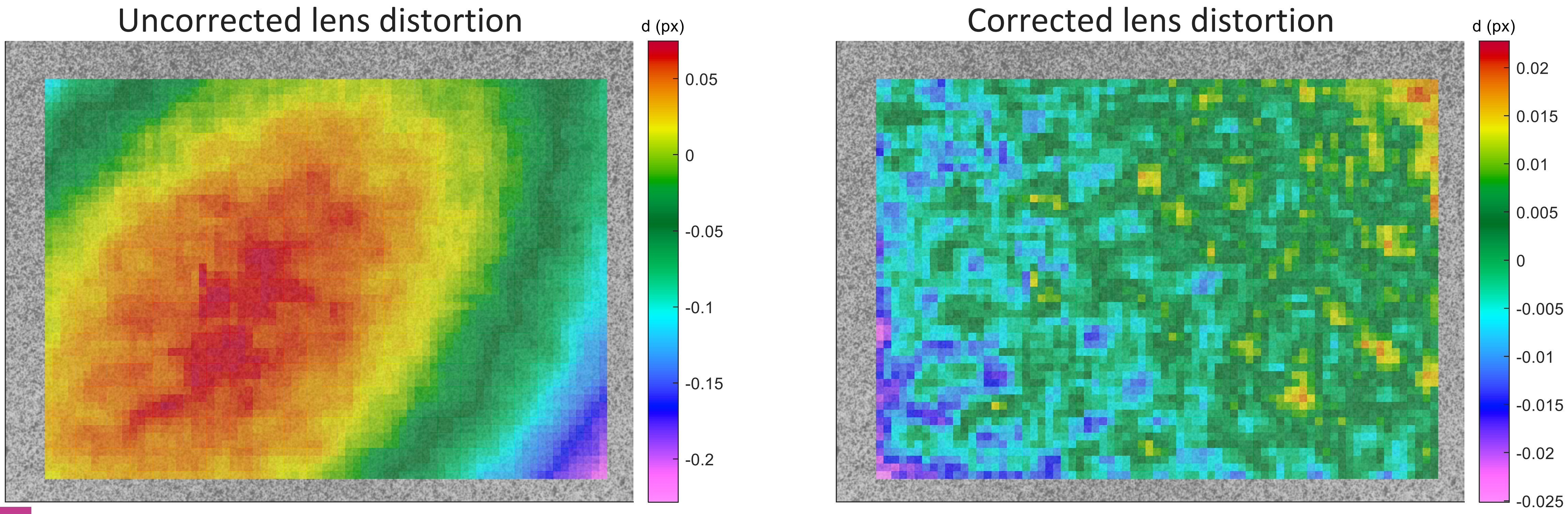






Purpose of Calibration – 2D-DIC
Sec. 3.2.1

- Caution 3.6 / Recommendation 3.5:
  - Calibration is still recommended for 2D-DIC, to correct for lens distortions.

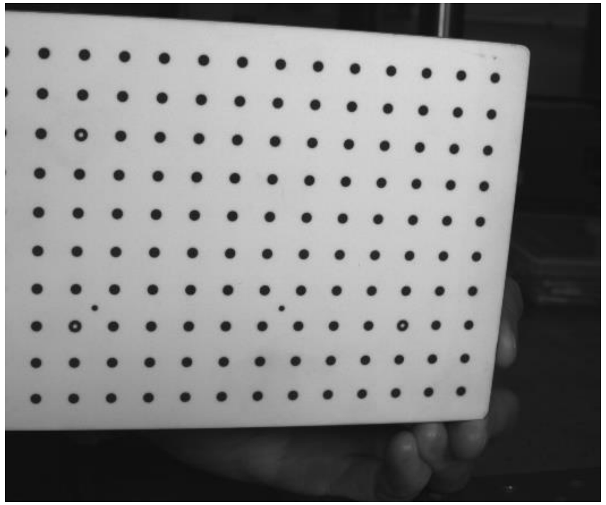
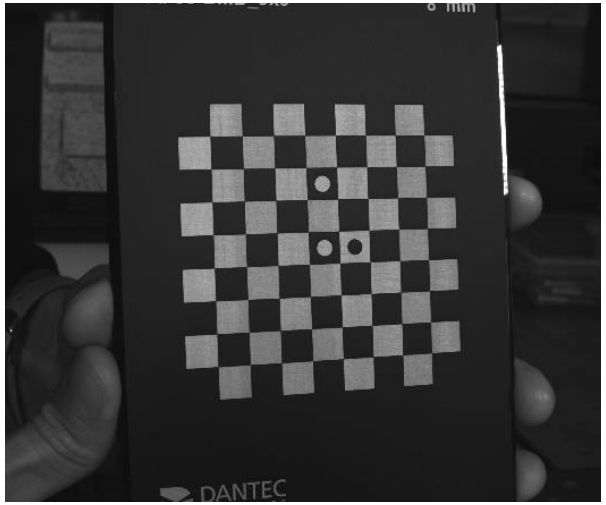


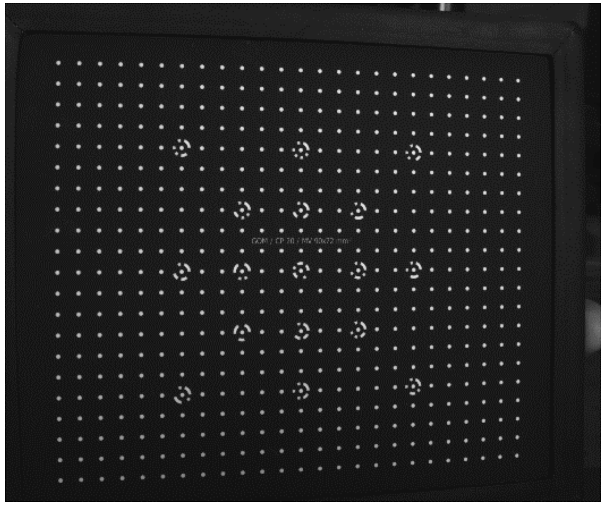
Select Calibration Target
Sec. 3.2.2.1

- Recommendation 3.6:
  - Target should be approximately the same size as the FOV or slightly smaller
  - Target shouldn't be smaller than ½ the size of the FOV

Calibration target examples from the Stereo DIC Challenge

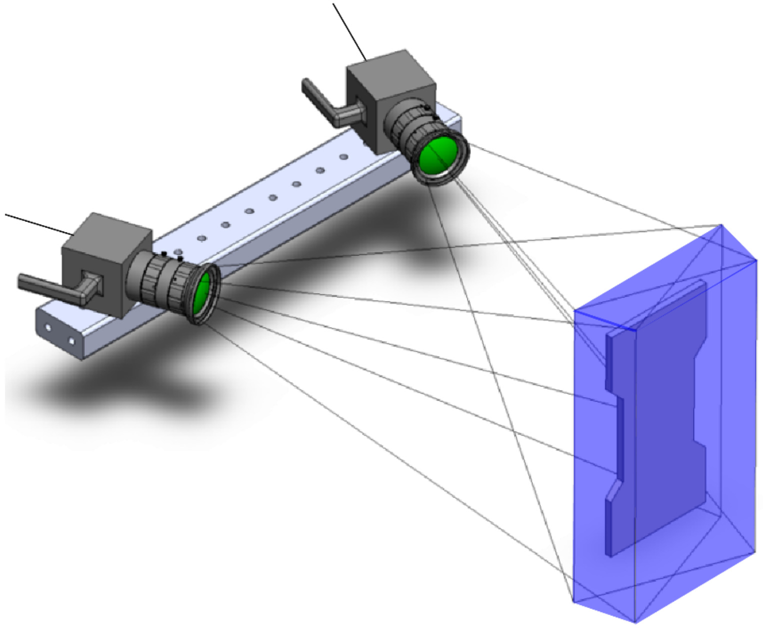
https://idics.org/challenge/

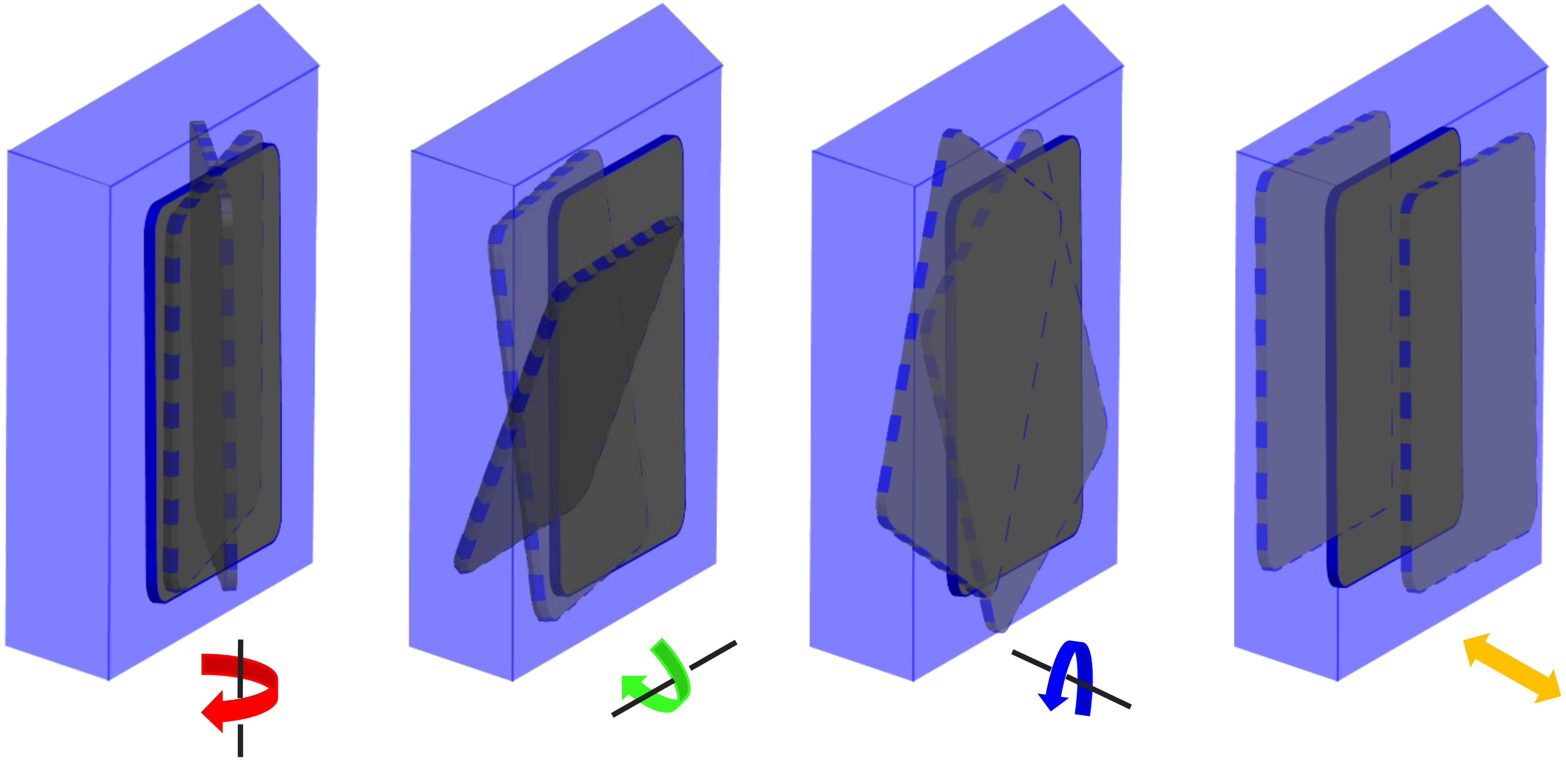



Acquire Calibration Images
Section 3.2.2.2-3.2.2.4

1. Clear working space
   - Recommendation 3.8:
     a) Move the test piece, not the stereo-rig, if possible
     b) Translate the stereo-rig
        - Caution 3.8: It is imperative that the stereo cameras are moved only as a rigid pair!
2. Adjust lighting and exposure
   - Caution 3.10: But not focus and aperture!
3. Acquire images that fill the field-of-view and depth-of-field



Volume to Calibrate



CHAPTER 5:
PROCESSING OF DIC IMAGES

SEC. 5.1: DIC SOFTWARE

SEC. 5.2: USER-DEFINED PARAMETERS

DIC Software
Sec. 5.1

- Both commercially and open source codes are available
- Speak with vendors at the conference

https://idics.org/resources/

Commercial DIC Software

Follow the links below to commercial DIC software vendors for more information

- Correlated Solutions
- Dantec Dynamics
- EikoSim
- gom
- Image Systems: DIC Elite
- LaVision
- MatchID

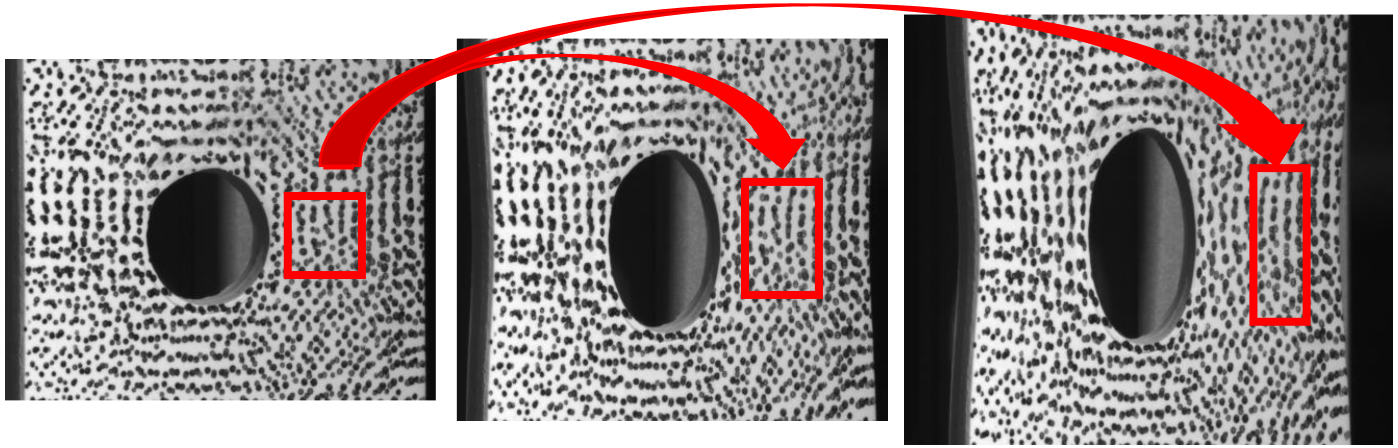
Research DIC Codes

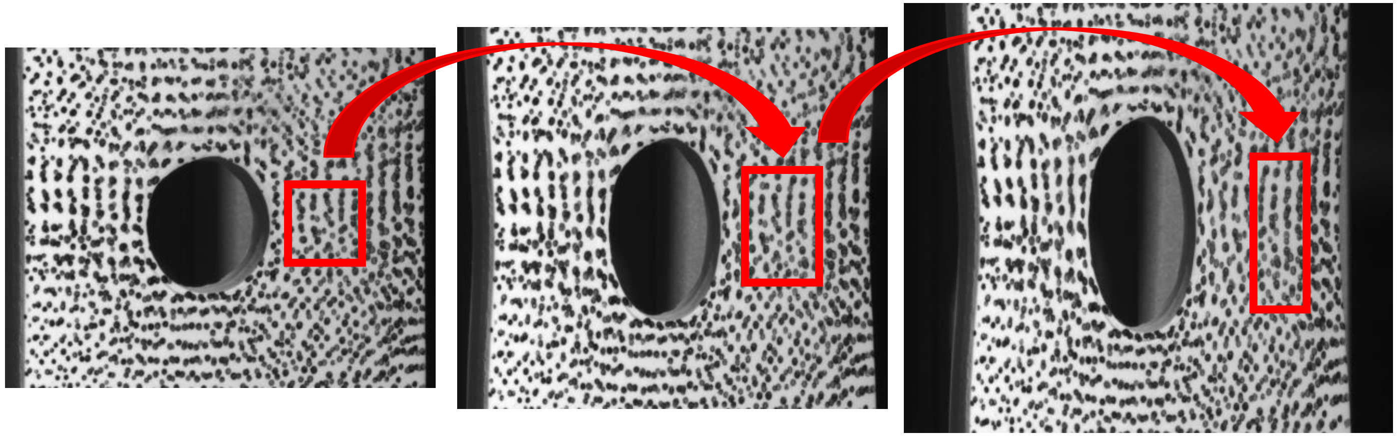
Non-commercial or open source DIC software

- AL-DIC and AL-DVC
- Digital Image Correlation Engine (DICe)
- Ncorr
- PReDIC
- UFreckles
- YADICS

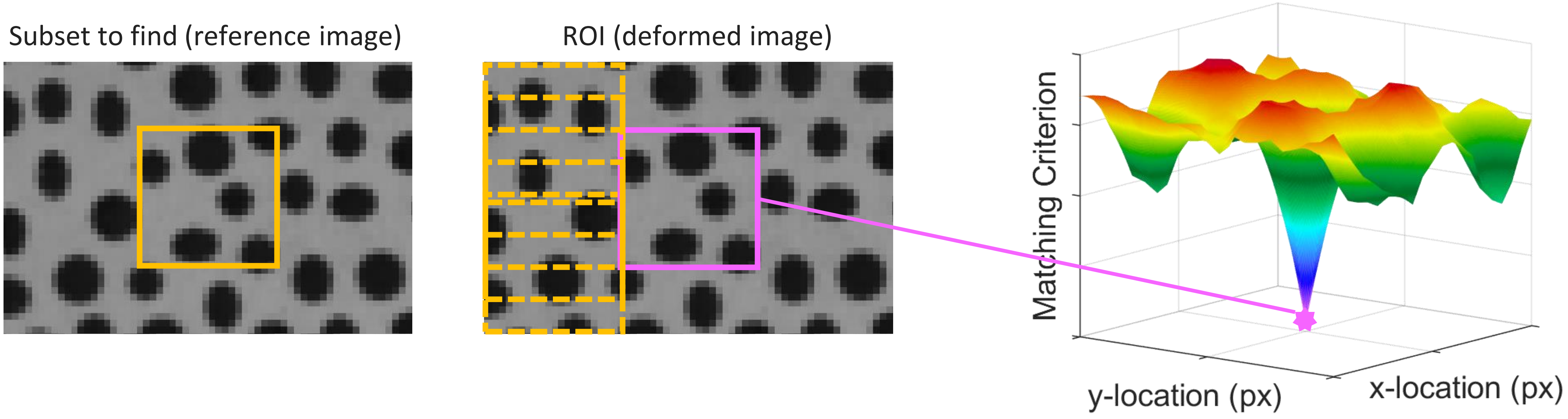
Reference Image
Sec. 5.2.1

- DIC tracks motion, in the Lagrangian sense, of a set of interrogation points, defined on a reference image:
  - **Standard Correlation: A single reference image**
    - Caution 5.1: Collect reference image prior to any displacement or force
  - **Incremental Correlation**
    - Each image is correlated to prior image
    - Advantage: Compensates for severe pattern warping with large strains
    - Disadvantage: Errors accumulate over image number





Matching criterion
Coming soon in Edition 2!



$$\chi^2 = \sum_i (G_i - F_i)^2$$

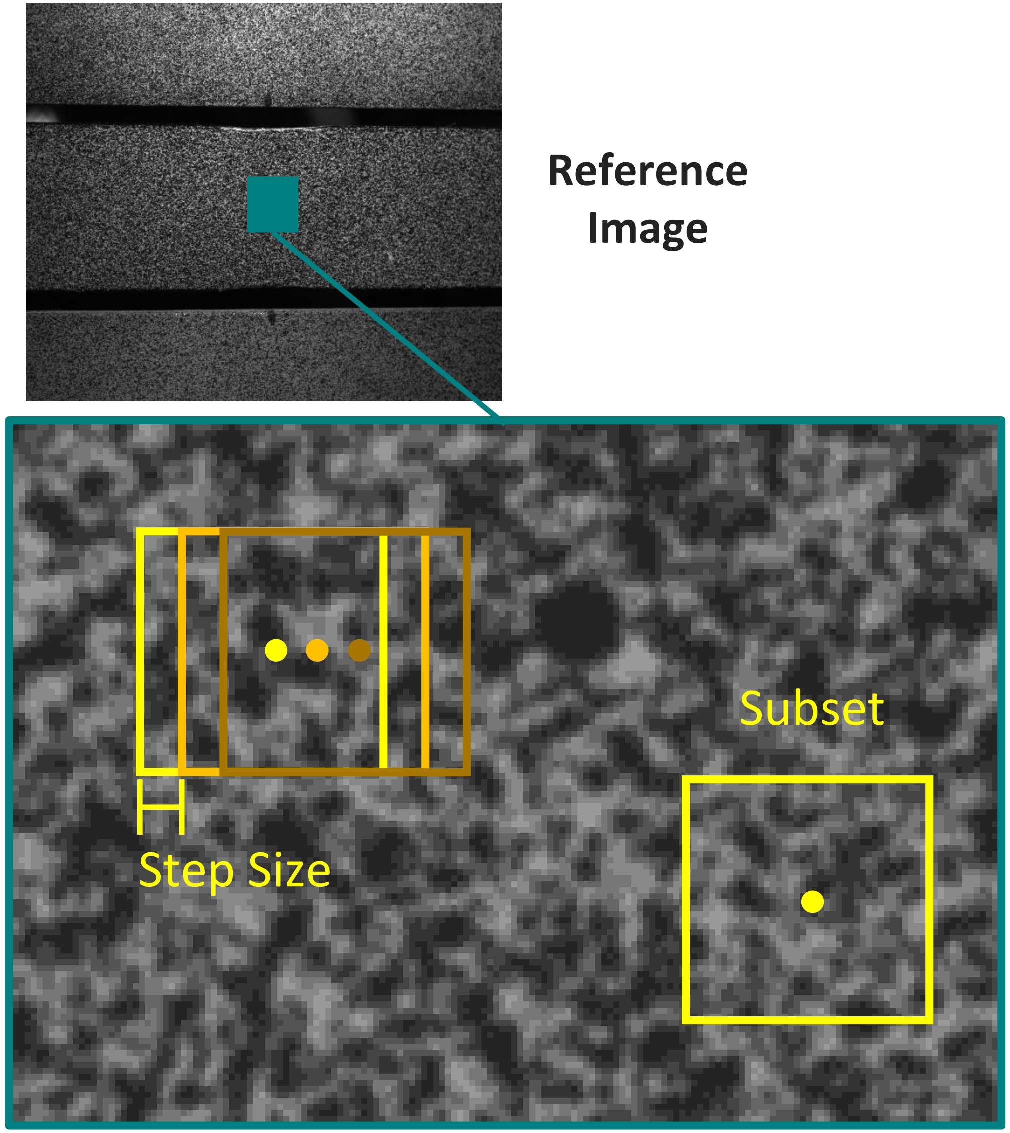
χ – is the value of the matching criterion
F – is the reference image
G – is the deformed image
i – is the pixel in the subset

Examples of Matching Criteria

1. Sum Squared Difference (SSD)
2. Normalized Sum Squared Difference (NSSD)
3. Zero Normalized Sum Squared Difference (ZNSSD)

Subset Size and Step Size
Sec. 5.2.5-5.2.6

- **Subset**: Portion of image used to calculate one 3D coordinate or displacement value
- **Subset Size**: Length of the subset in the reference image
- **Rule of thumb**:
  - Subset should contain a minimum of 3 DIC pattern features that are each 3-5 pixels in size
- **Step Size**: Spacing at which subset displacements are calculated
- **Rules of thumb:**
  - 1/3 to 1/2 of the subset size is recommended

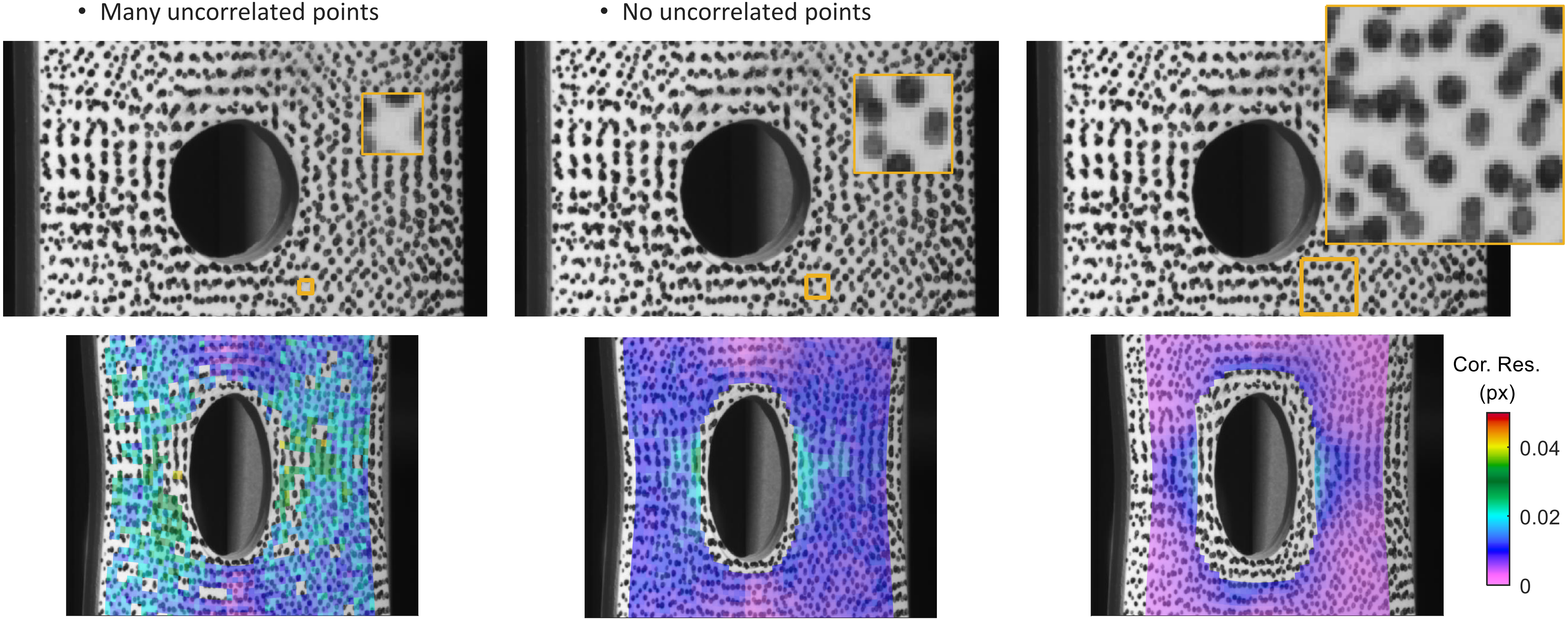


Correlation example: Subset

Subset size = 13 px
- Too small
- Insufficient number of features
- High correlation residual
- Many uncorrelated points

Subset size = 21 px
- Reasonable size
- Sufficient number of features
- Low correlation residual
- No uncorrelated points

Subset size = 51 px
- Too large
- Large border of missing data near edges of ROI
- Decreased spatial resolution



CHAPTER 5: PROCESSING OF DIC IMAGES

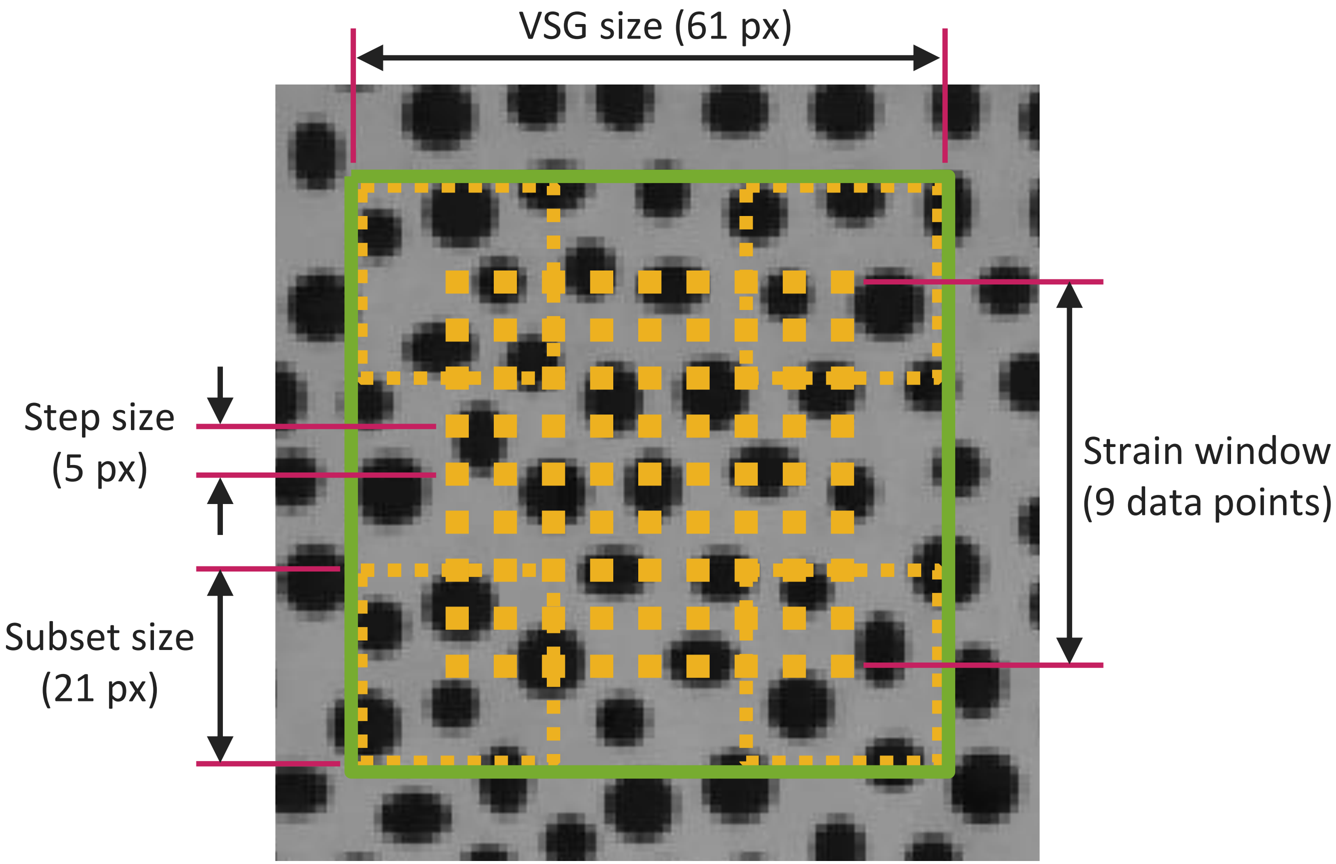
SEC. 5.3: STRAIN CALCULATIONS

Virtual Strain Gage (VSG) and Examples of Strain Calculation Methods Sec. 5.3.1 and Sec. 5.3.2

VSG size:

- Local region of the image that is used for strain calculation at a given location
- Analogous to, but not exactly, the size of a physical strain gage

$$L_{VSG} = (L_{window} - 1)L_{step} + L_{subset}$$



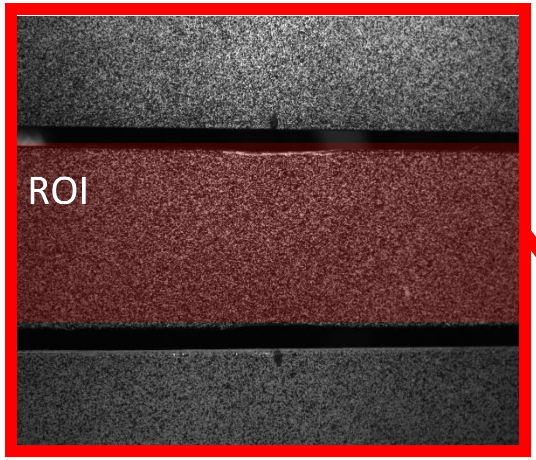
Strain computation methods:

- Many methods, such as:
  - Subset Shape Function
  - Finite Element Shape Function
  - Strain Shape Function
  - Spline Fit
- See software manual for details

iDICs

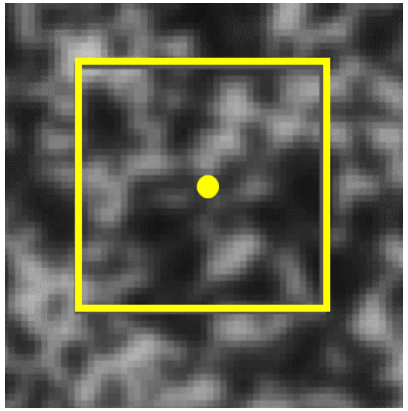
Virtual Strain Gage Study Example
Sec 5.3.1

Reference Image: Zero force

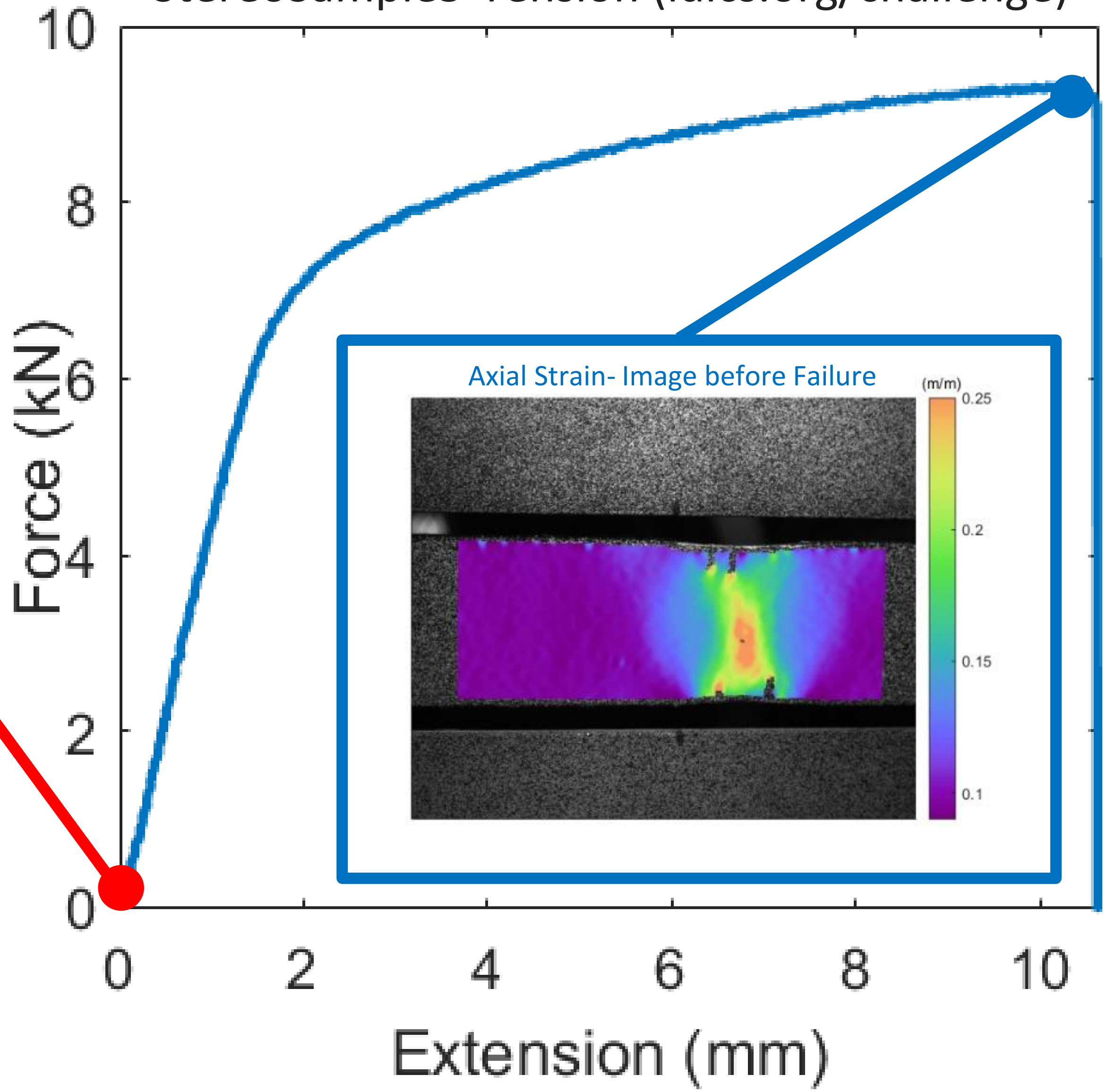


1. Select subset size and step size based on previously discussed metrics

Subset: 37 px
Step: 7 px



StereoSample5-Tension (idics.org/challenge)



Virtual Strain Gage Study Example
Sec 5.3.1

2. Select two images to correlate against reference image:
   a) an image after the reference image but zero force,
   b) the image of the highest strain *gradient*.

3. Analyze these images with different DIC settings, varying the VSG size
   - Tip 5.4: The dominant (but not only) variables that affect VSG size are subset size, step size, strain window/filter window, and strain shape function

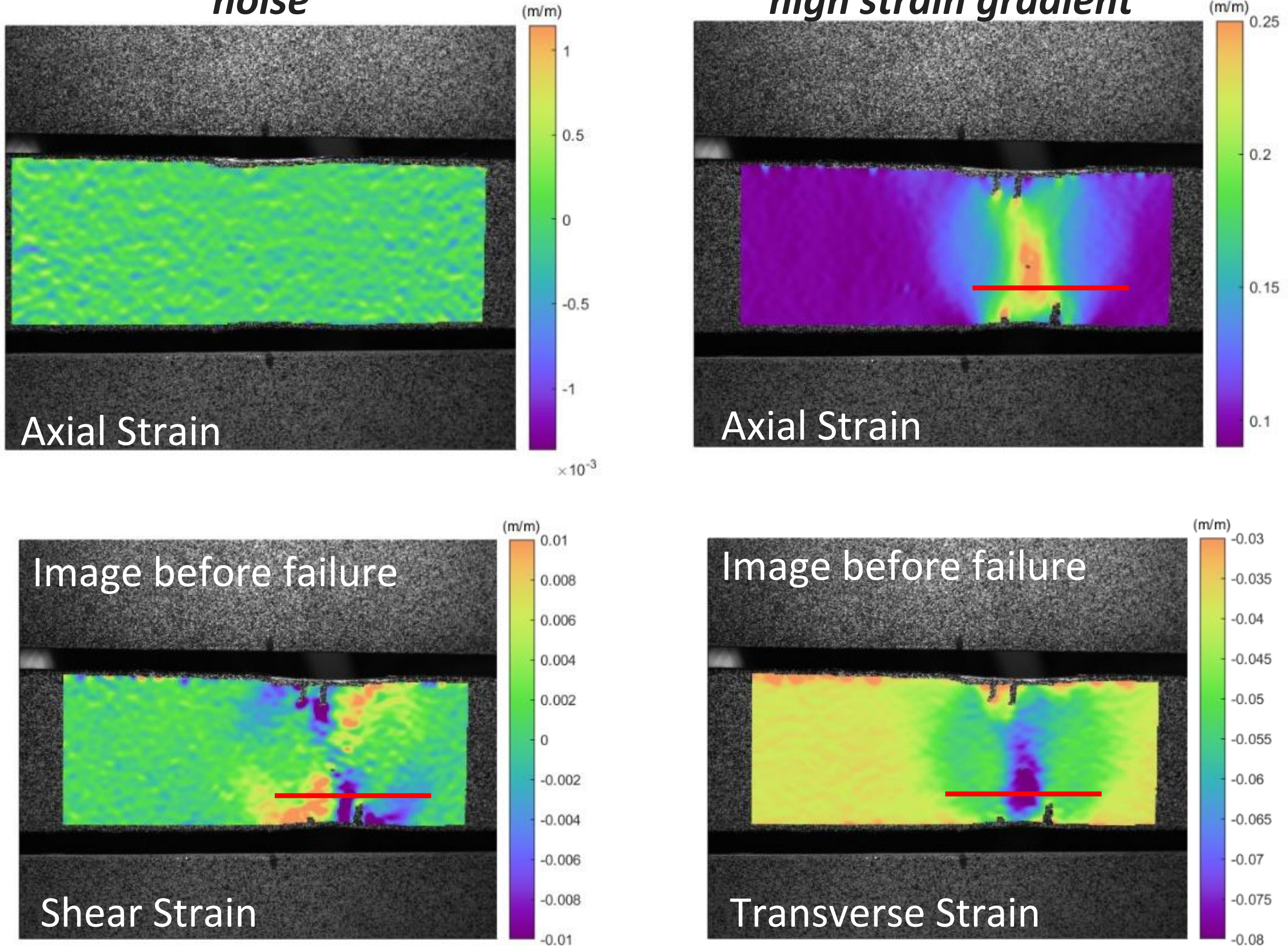
4. Extract a line cut through the region of highest strain gradient.

<u>Static Image</u>

noise

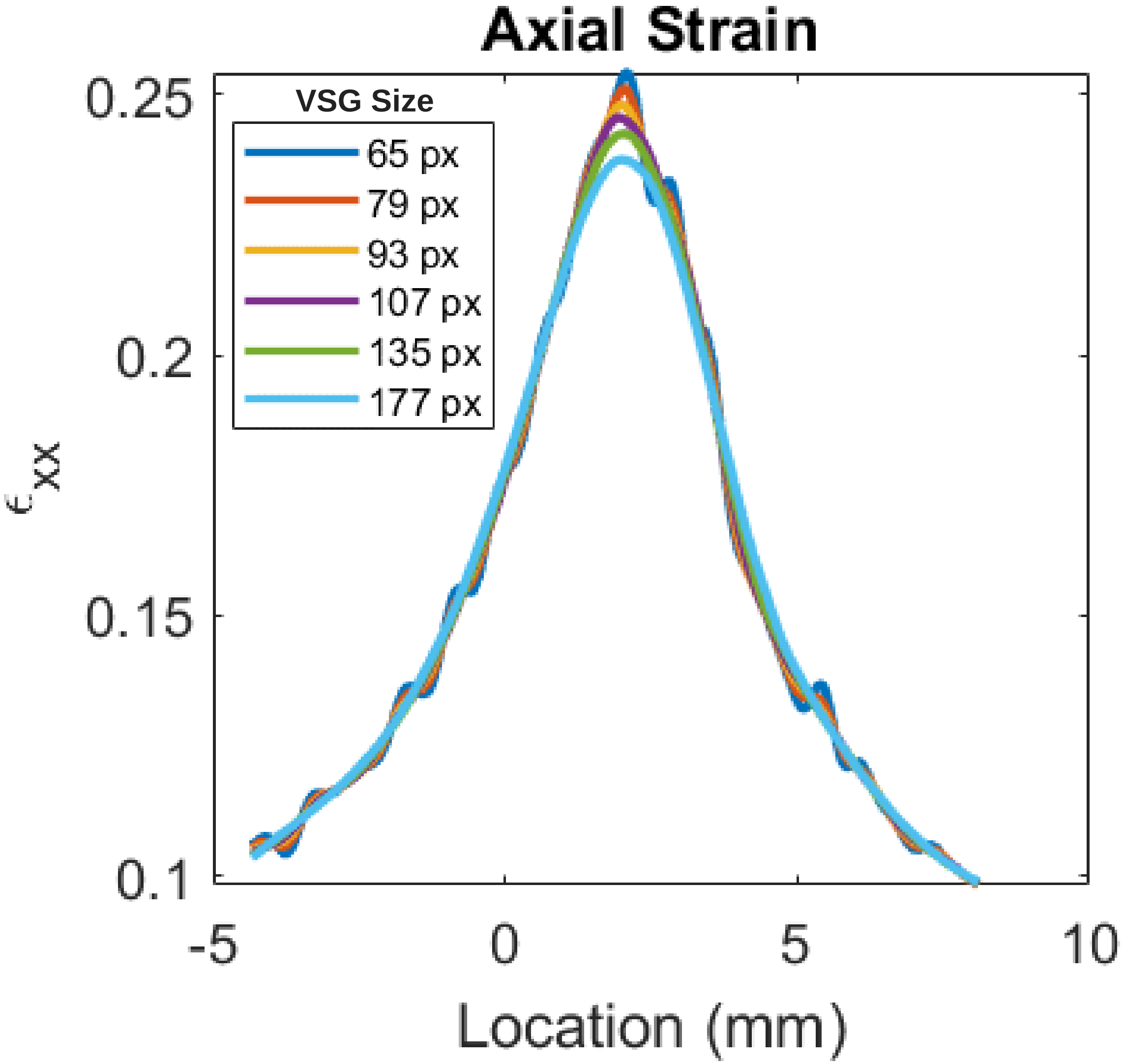
<u>Image before Failure</u>

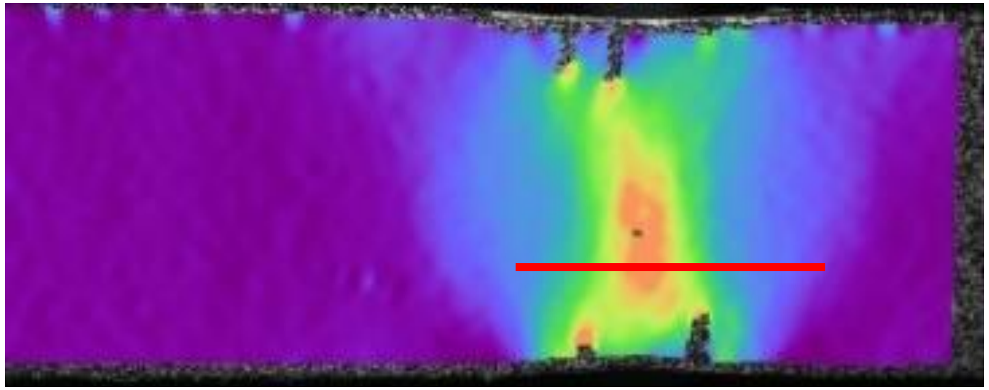
high strain gradient



Virtual Strain Gage Study Example
Sec 5.3.1

5. Assess convergence.





Virtual Strain Gage Study Example
Sec 5.3.1

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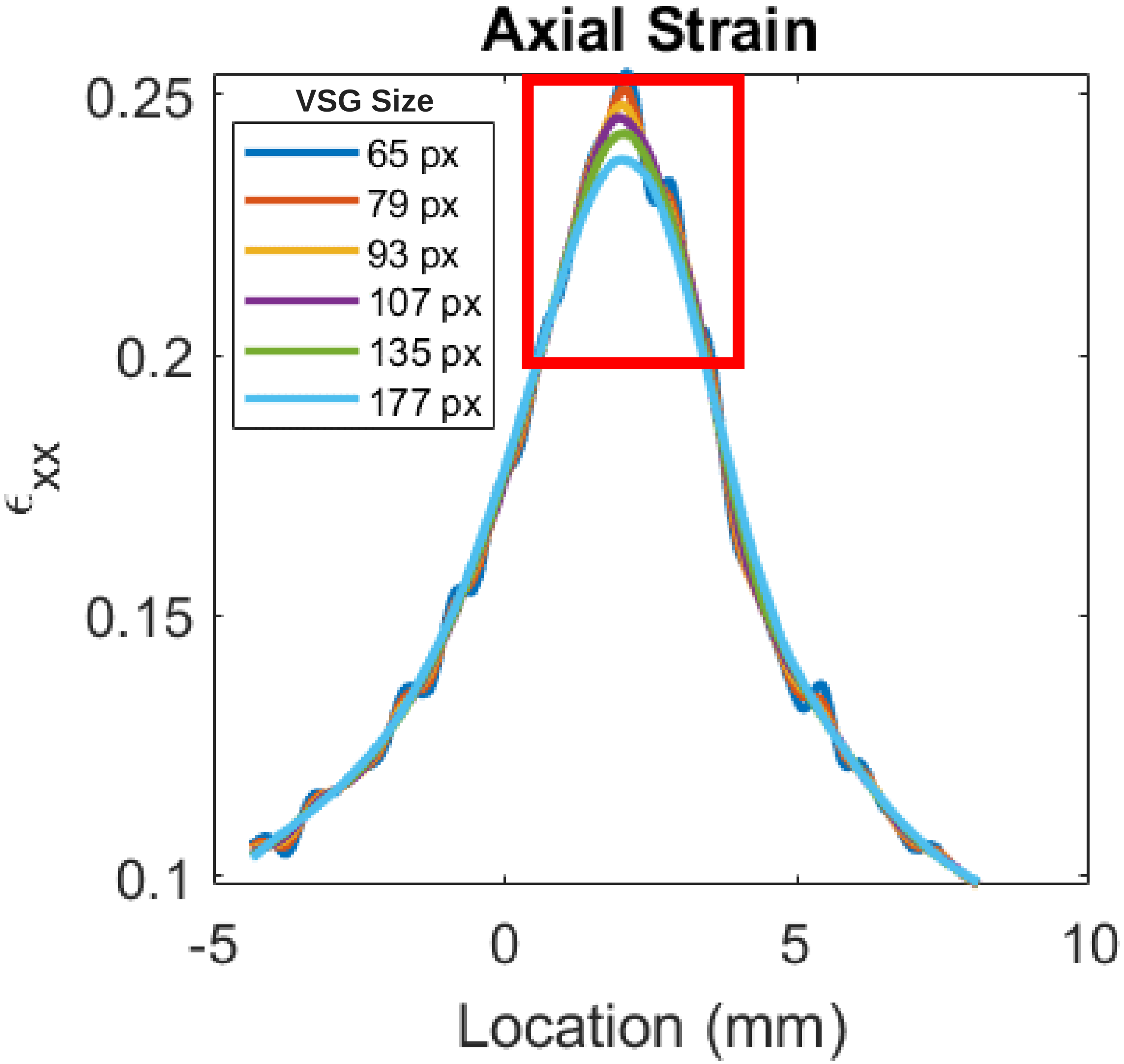
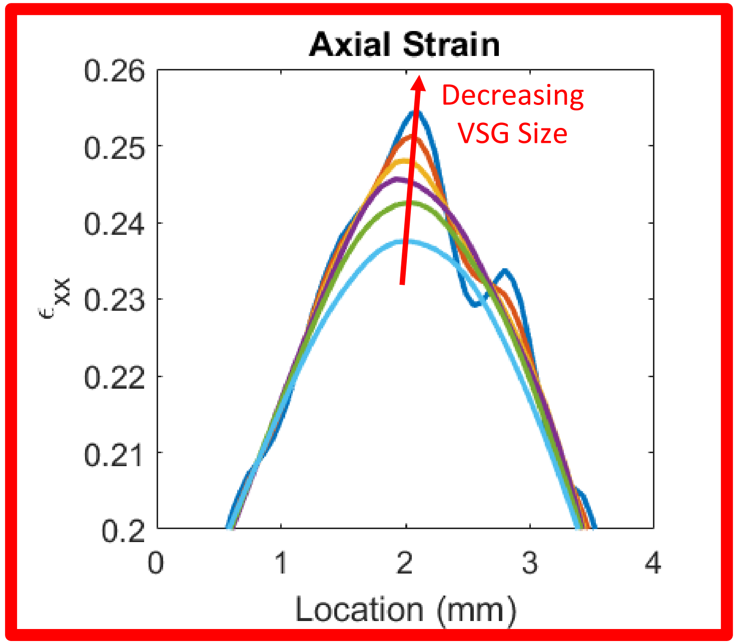


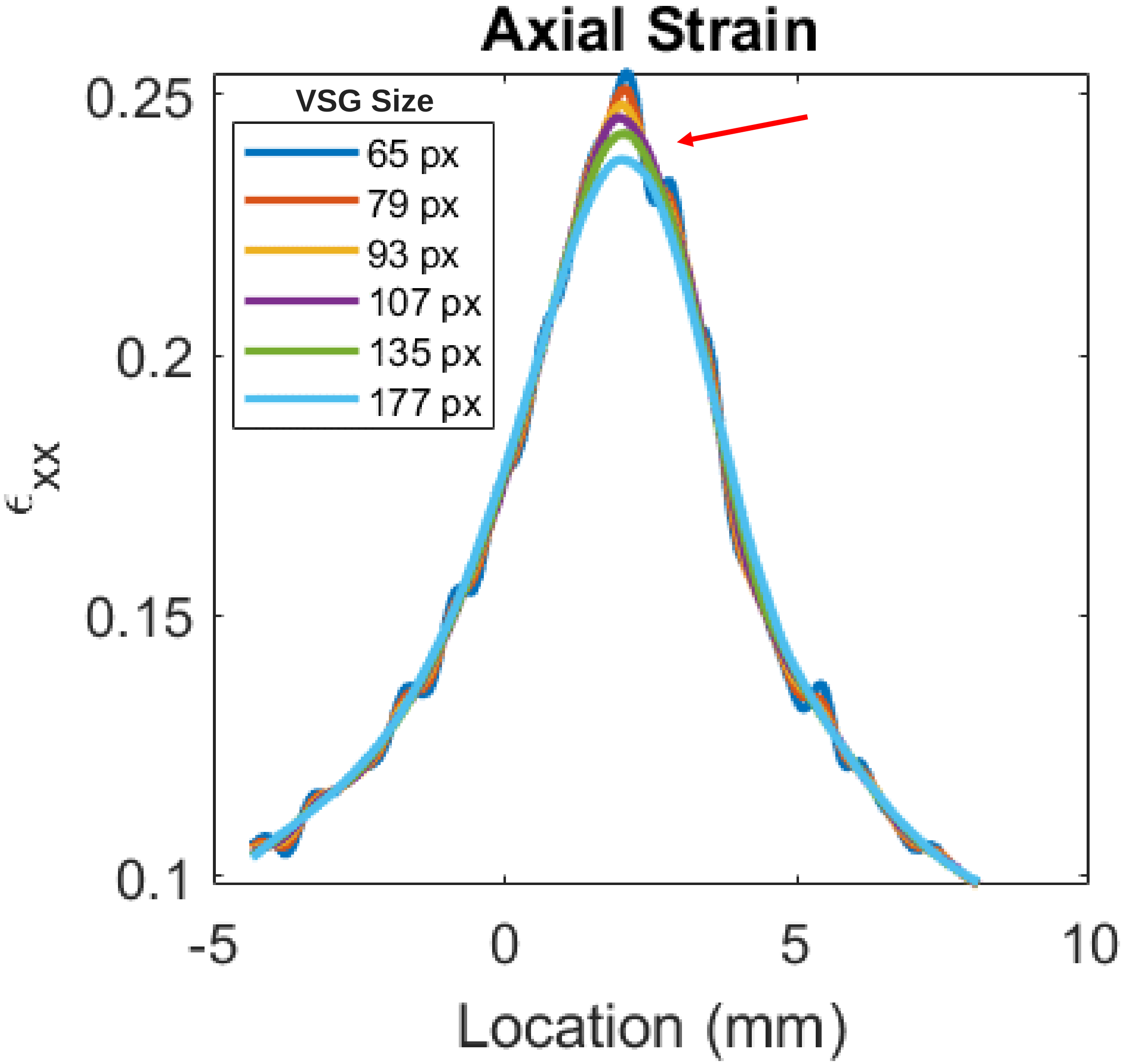


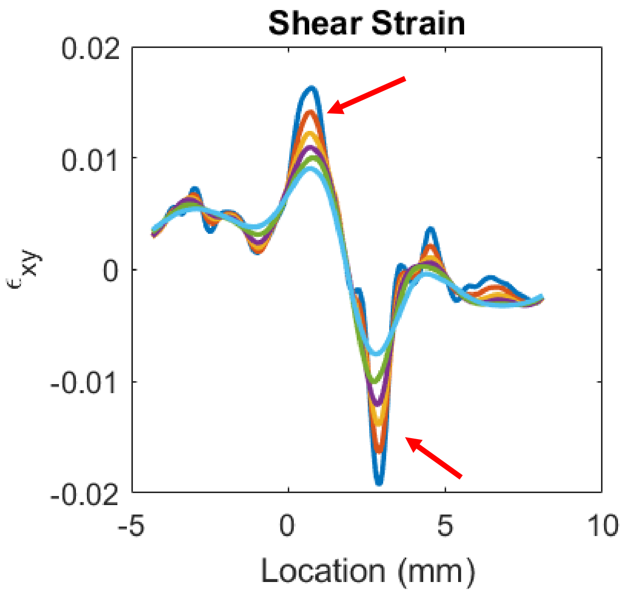
- If the maximum strain amplitude converges with smaller VSG, then the actual maximum strain amplitude has been captured.
- If the maximum strain amplitude never converges, the true value can not be known, but is instead equal to or greater than the reported strain measurements.

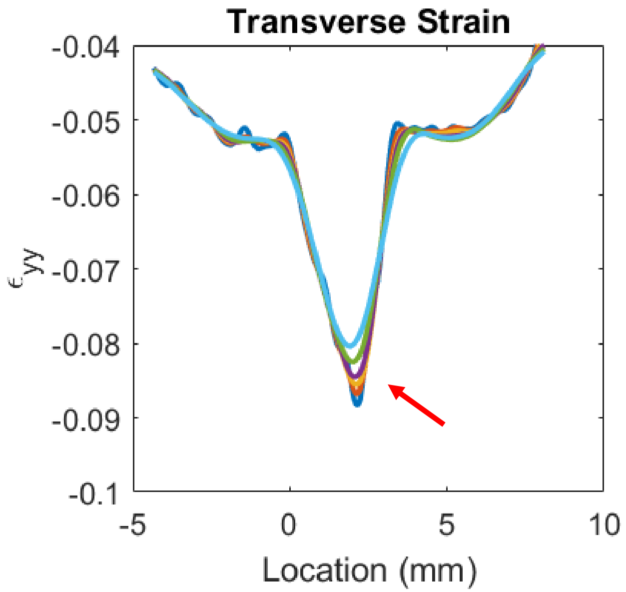
- *Tip 5.5: If strains do not converge, test can be repeated with smaller FOV/ higher magnification*

Virtual Strain Gage Study Example
Sec 5.3.1

5. Assess convergence.





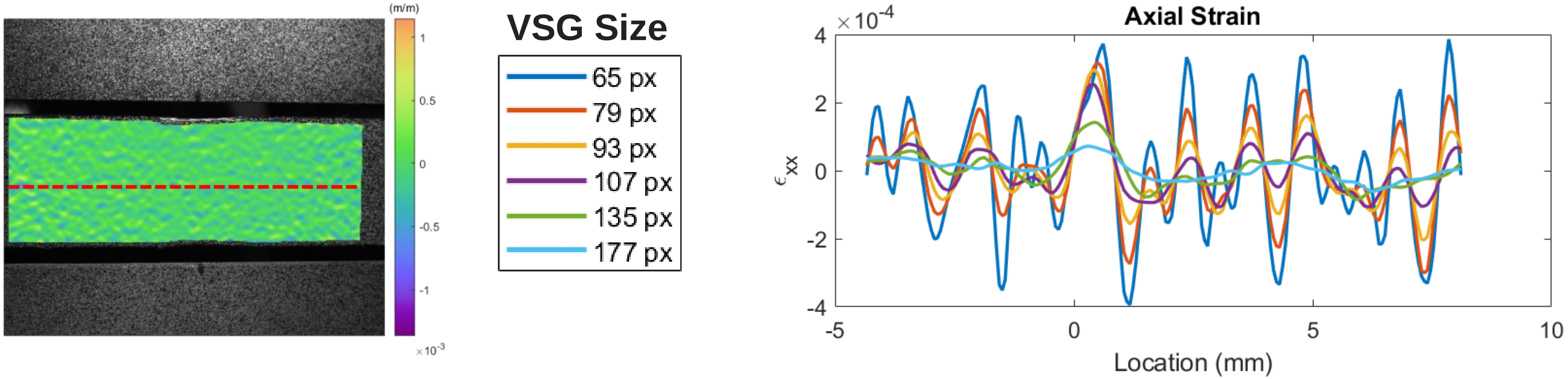


- *Tip 5.5: If strains do not converge, test can be repeated with smaller FOV/ higher magnification*

Virtual Strain Gage Study Example
Sec 5.3.1

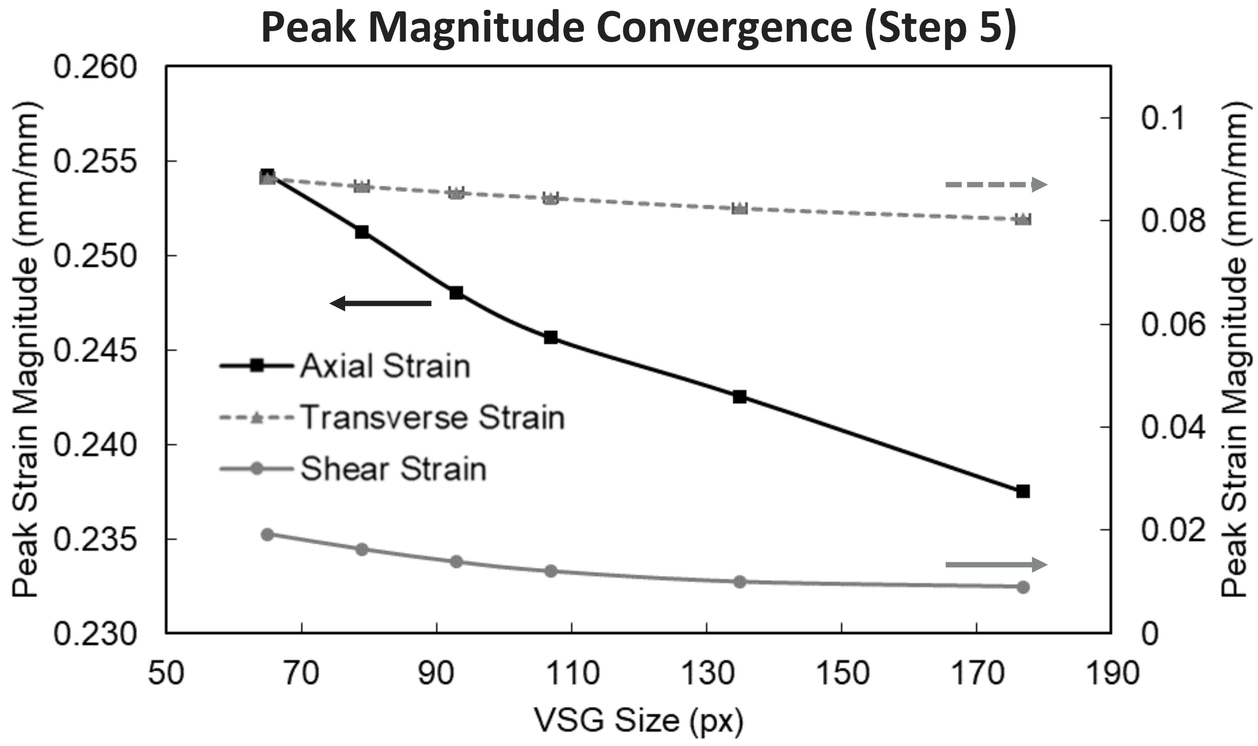
6. Quantify the noise.
   a) Series of static images
      - Evaluates camera noise, but not calibration parameters
      - Lower bound of noise floor
   b) Series of rigid-body motion images
      - More thorough evaluation of noise floor

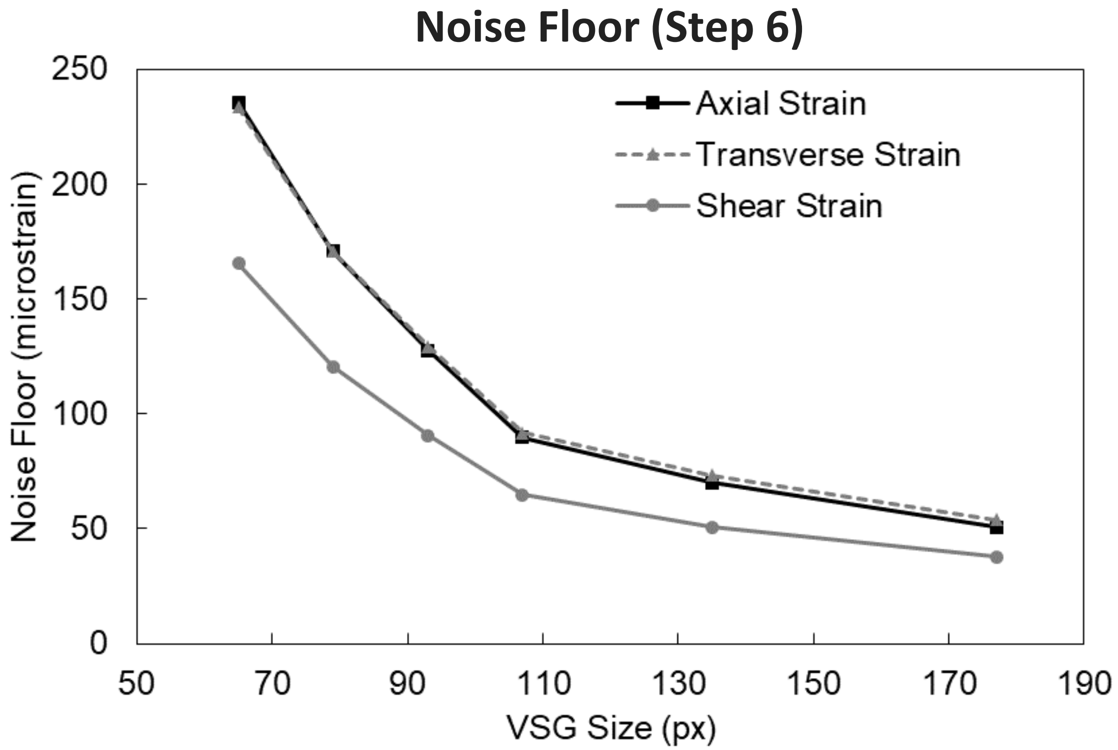
Strain should be zero.
All measured strains are errors.



Virtual Strain Gage Study Example
Sec 5.3.1

7. Ultimately, the right parameters are a function of the accuracy to noise ratio for a given QOI and are application dependent and a matter of expert judgement.





CHAPTER 6:
REPORTING REQUIREMENTS

Reporting Requirements

- Necessary for others to understand your measurements and repeat your measurements
- Build credibility for your experimental procedures and analysis

Table 1. DIC Hardware Parameters

Camera	<Manufacturer and Model>
Image Resolution	2448 x 2048 $pixels^2$
Lens	<Manufacturer and Mode, and Focal Length>
Aperture	f/8
Field-of-View	100 mm
Image Scale	24.5 pixels/mm
Stereo-Angle	25 degrees
Stand-off Distance	240 mm
Image Acquistion Rate	15 Hz
Patterning Technique*	Base coat of white spray paint with black ink stamped speckles
Pattern Feature Size (approximate)	5 pixels / 0.2 mm

*A more complete description of the patterning technique may be appropriate in the main text.

Reporting Requirements

Table 2. DIC Analysis Parameters

DIC Software	<Manufacturer, Version number>
Image Filtering	Gaussian filter with a 3x3 pixel kernel
Subset Size	21 pixels / 0.86 mm
Step Size	7 pixels / 0.29 mm
Subset Shape Function	Affine
Matching Criterion	Zero-normalized sum of square differences (ZNSSD)
Interpolant	Bi-cubic spline
Strain Window	15 data points
Virtual Strain Gauge Size*	119 pixels / 4.9 mm
Strain Formulation	Green-Lagrange
Post-Filtering of Strains**	Median temporal filter, span of 5 data points / 0.33 seconds
Displacement Noise-Floor***	0.01 pixels / 0.4 µm (in-plane); 0.03 pixels / 1.2 µm (out-of-plane)
Strain Noise-Floor***	250 µm/m

*The VSG size is computed from Eqn. 7.2 in the DIC Good Practices Guide [1]. Other estimations of the VSG size may be more appropriate, depending on the strain calculation method used in the DIC software.

**A more complete description of any pre- or post-filtering may be appropriate in the main text.

***A brief description of how the noise-floor was computed should be included in the main text.

Summary

- DIC is an extremely powerful tool that can be used to capture shapes, displacements, velocity, strains, strain-rates, and other kinematic QoIs.
- DIC is non-contact and independent of length-scale and time-scale. If you can take a picture of a high-contrast pattern, you can do DIC.
- Garbage in – garbage out! DIC requires careful attention to setup, test operation, and data processing.
- Reporting of DIC parameters gives us credibility as a community.
- The International DIC Society (iDICs) has many more resources available!

idics.org