Digital Image Correlation: Overview of Principles and Software

University of South Carolina

Correlated Solutions, Inc.

2D Image Correlation Fundamentals

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Outline

Introduction
- Purpose
- Basic Idea
- Principle
- Measuring Displacem.

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- Photometric Mapping
- Displacement Mapping
- Advanced Topics

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- Method

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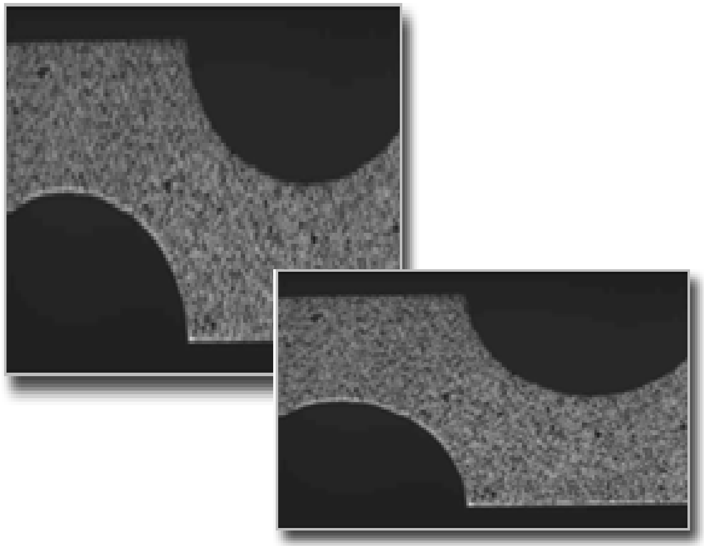
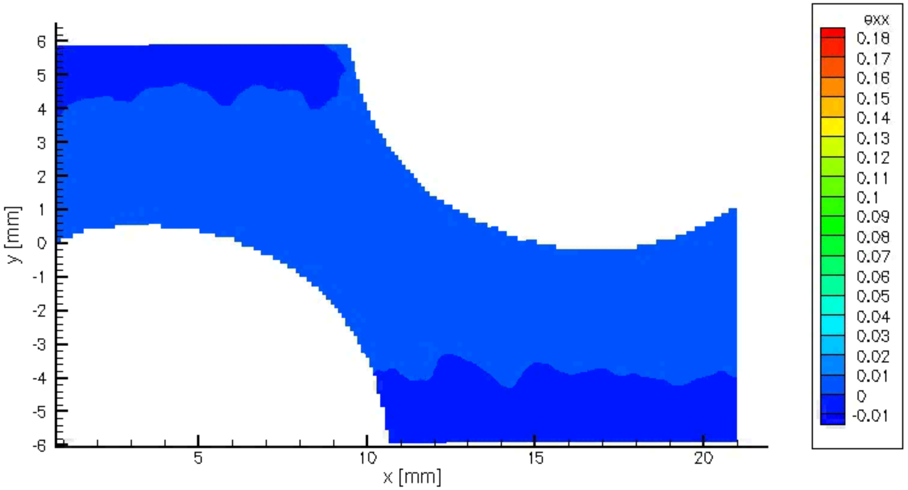
Deformation measurement



- Full-field measurement
- Non-intrusive
- Planar specimen only
- No out of plane motion



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- Large range of size scales (10^{-9} to 10^{2} m.)
- Large range of time scales (static to 200MHz)

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- Monocular (cyclopean) vision cannot determine the size of objects
- Consequence: a 200% isotropic deformation of an object produces the same image as if the object was moved to one-half its original distance from the visual sensor
- We **must** assume the object is **planar, parallel to and at a constant distance from the visual sensor** during the entire experiment

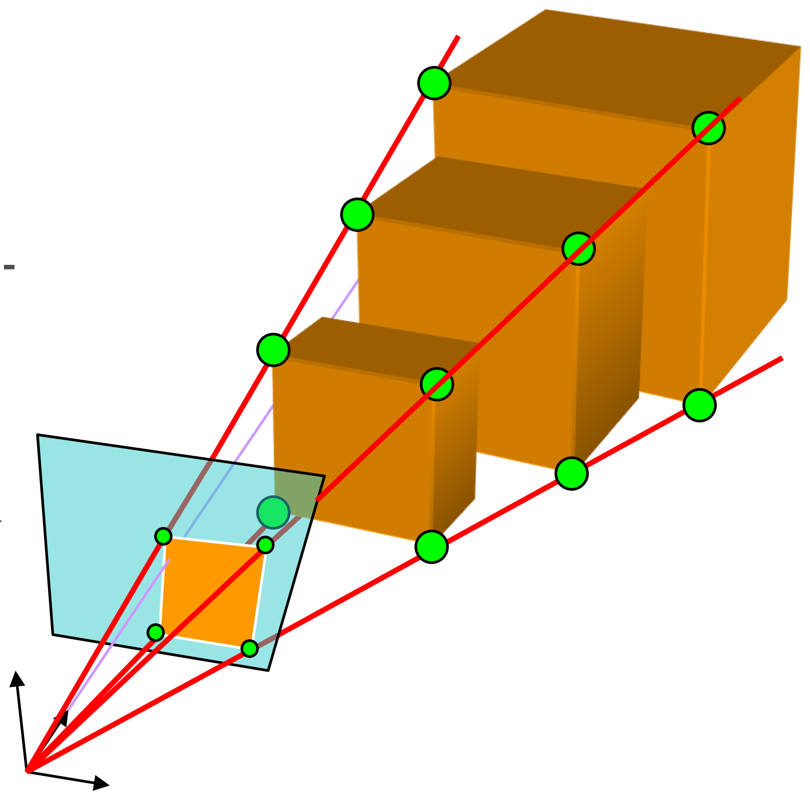

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Image Correlation Technique

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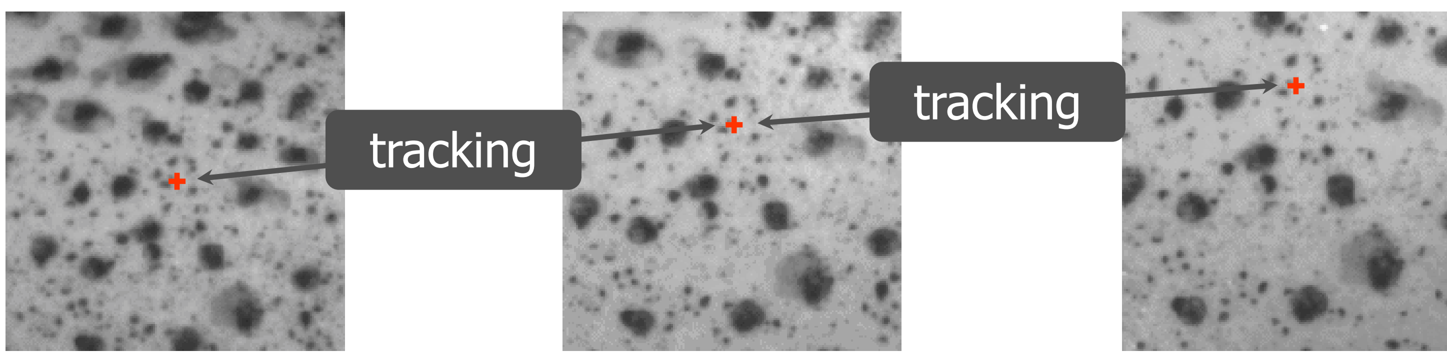
- How? Given a point and its signature in the undeformed image, **search/track** in deformed image for **the point** which has a **signature which maximizes a similarity function**



Time t | Time t' | Time t''

Image Correlation Technique

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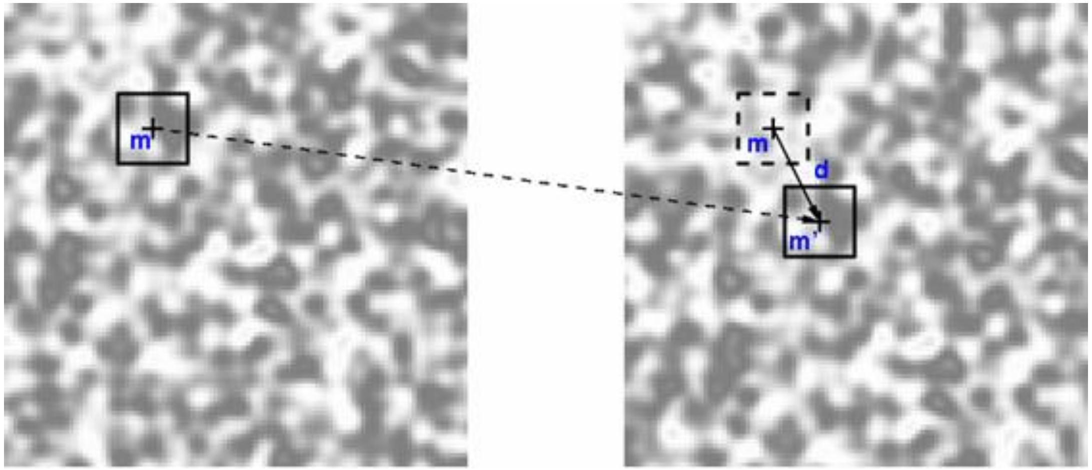
- **In practice**, a single value is not a unique signature of a point, hence **neighboring pixels are used**
- Such a collection of pixel values is called a **subset** or **window**



Time *t*   Time *t'*

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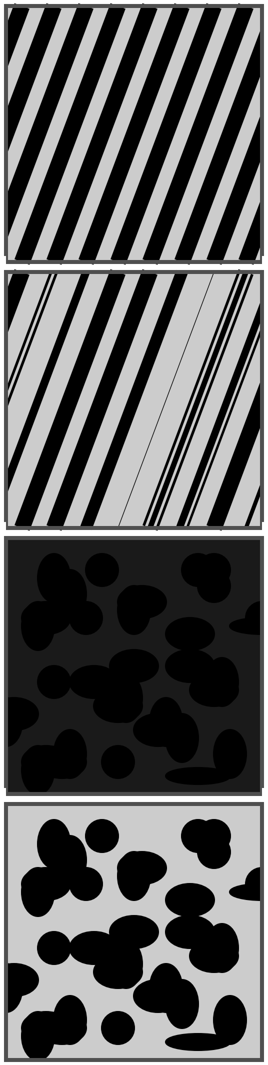
- The uniqueness of each signature is only guaranteed if the surface has a **non repetitive, isotropic, high contrast pattern**
- **Random textures** fulfill this constraint (speckle pattern)



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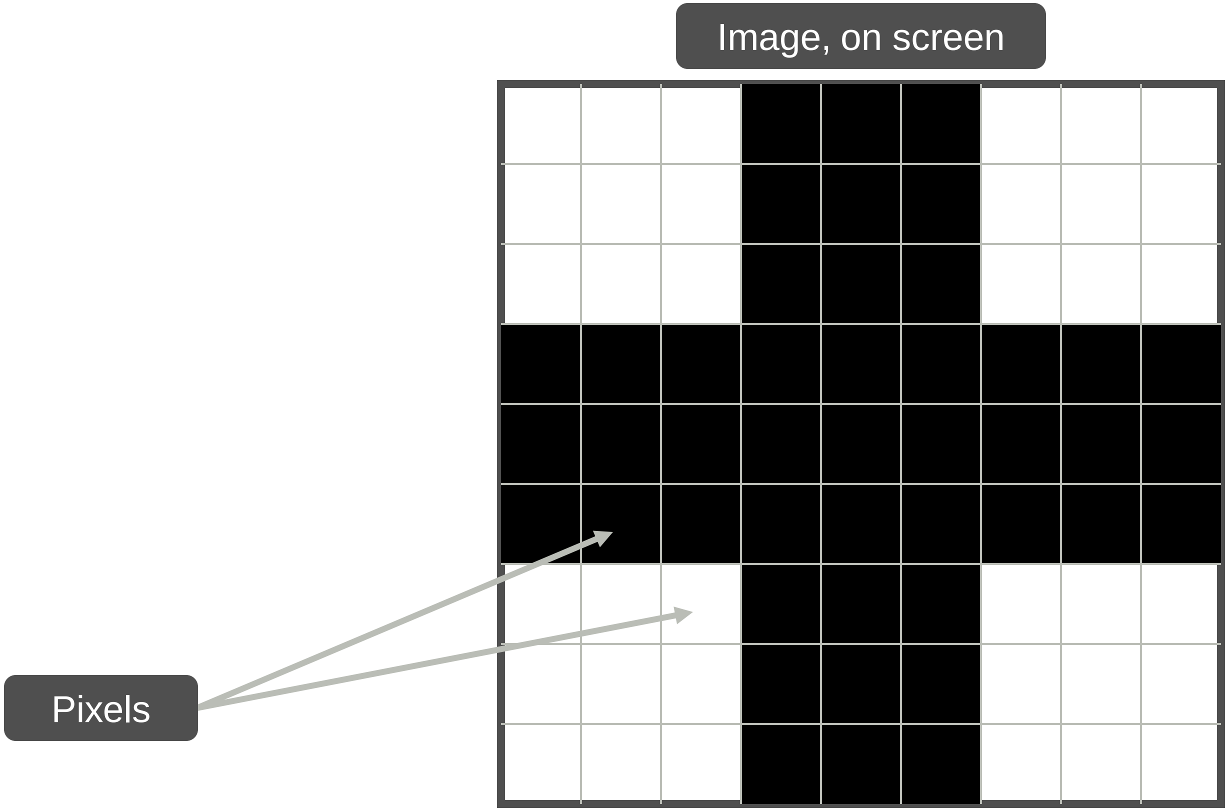
- Example
  - The camera acquires 9x9 pixel images
  - The specimen is marked with a cross-like pattern



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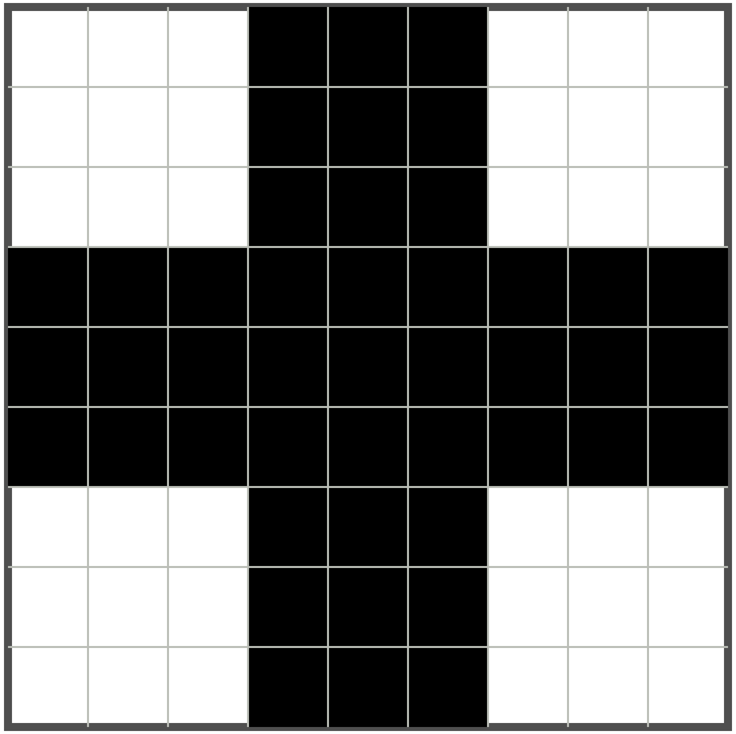
- Example
  - **White pixels** are gray level **100**
  - **Black pixels** are gray level **0**
- An image is a matrix of natural integers

Image, in memory

100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

Image, on screen



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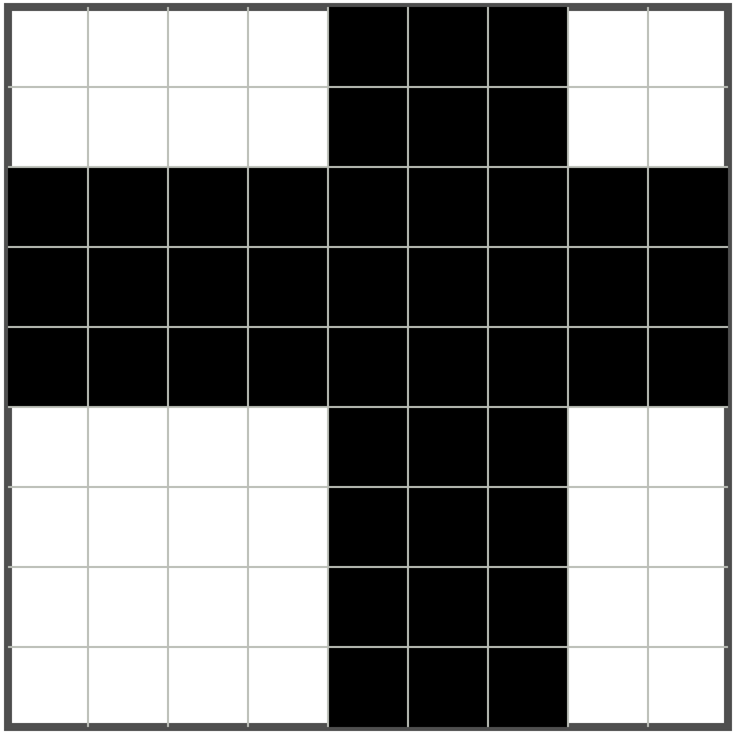
- ## Example
  - The **specimen moves** such that **its image moves 1 pixel up and right**

Image after motion, in memory

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

Image after motion, on screen



Principle

- **Example:** we define a 5x5 subset in the reference image (before motion)
- **Problem:** find where the subset moved (matching)

Image before motion

100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

Subset

Image after motion

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

?

Principle

- **Solution:** check possible matches at several locations and use a similarity score (correlation function) to grade them
- **Classic correlation function:** sum of squared differences (SSD) of the pixel values (smaller values = better similarity)

Pixel coord., reference image

Pixel value at (x+i; y+j)

Pixel value at (x+u+i; y+v+j)

$$C(\overline{x,y},\underline{u,v}) = \sum_{i,j=-n/2}^{n/2} \left(I(\overline{x+i,y+j}) - I^*(\overline{x+u+i,y+v+j})\right)^2$$

Image before motion

Image after motion

n: subset size (9 in our example)

Displacement (disparity)

Correlation function

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- Example: subset at **(x;y)=(5;5)**, displacement candidate **(u;v)=(-2;-2)**

$$C(5,5,-2,-2)=\sum_{i,j=-2}^{2}\left(I(5+i,6+j)-I^{*}(5-2+i,5-2+j)\right)^{2}$$

$$\begin{aligned}
&(100-0)^2+(0-0)^2+(0-0)^2+(0-0)^2+(100-0)^2+\\
&(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+\\
&(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+\\
&(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+\\
&(100-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(100-0)^2=18{,}000
\end{aligned}$$

(x;y)=(5;5)

100	100	100	0	0	0	100	100	100
100	[illegible]	[illegible]	[illegible]	0	0	100	100	100
100	100	100	0	0	0	100	100	[illegible]
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
100	100	100	0	0	0	100	100	[illegible]
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

Image before motion

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
100	100	100	100	0	0	0	100	[illegible]
100	100	100	100	0	0	0	100	[illegible]
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

Image after motion

(u;v)=(-2;-2)

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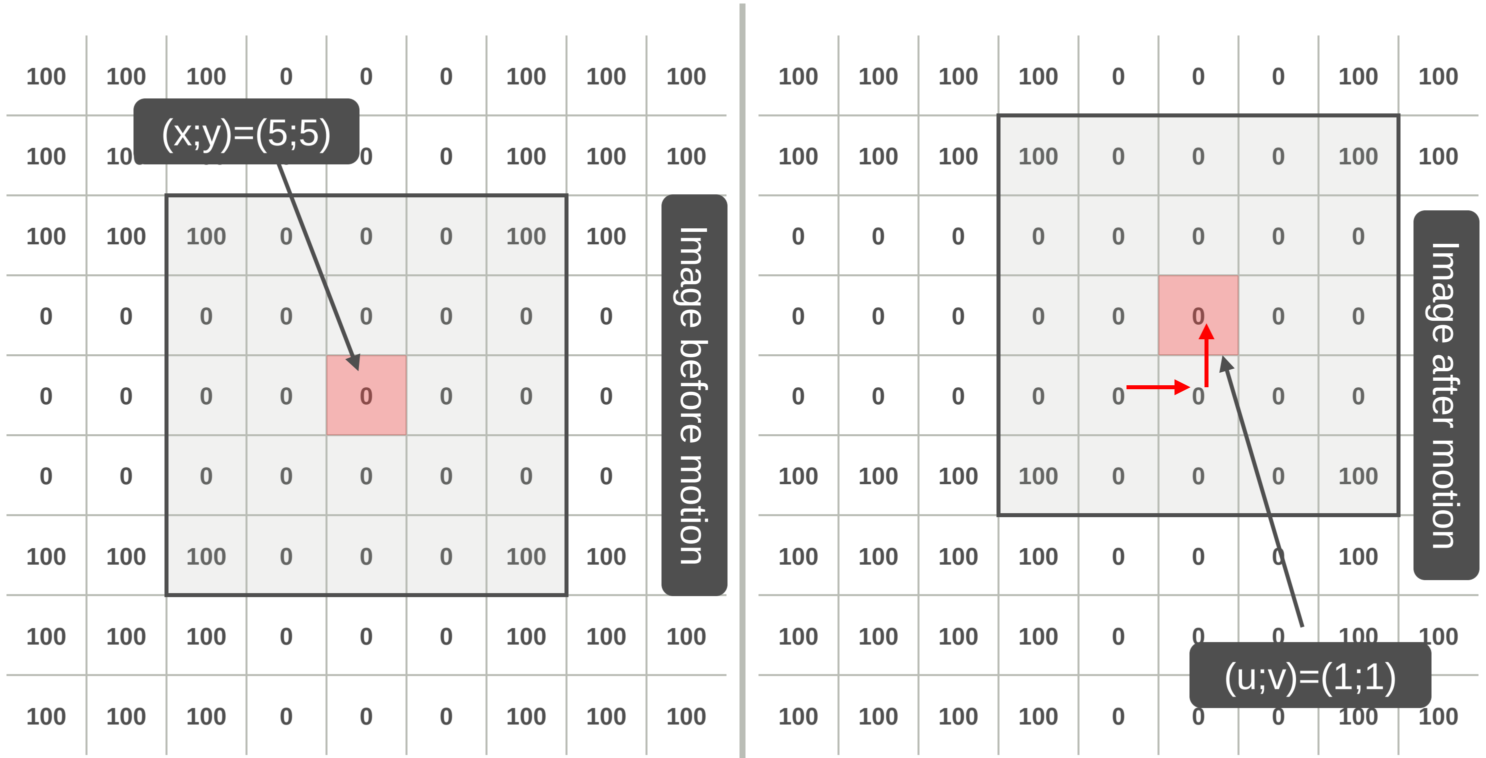
- Example: subset at **(x;y)=(5;5)**, displacement candidate **(u;v)=(1;1)**

$$C(5,5,1,1) = 0$$

- Better correlation score than candidate (u;v)=(-2;-2) [18,000]
  Indeed it is the smallest score achieveable (perfect match)



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- In reality, **images are corrupted** by some noise
- The SSD function will likely never be 0 for a perfect match

Image before motion

103	101	99	2	0	1	105	100	96
101	104	98	1	4	3	101	98	100
103	96	99	0	2	2	102	103	98
2	3	0	1	1	2	3	0	1
1	3	3	0	2	1	0	3	0
0	0	2	0	3	0	2	0	0
98	101	102	0	1	0	96	97	102
97	98	103	0	2	0	103	98	100
102	99	101	2	0	0	104	102	101

Image after motion

99	100	101	102	3	0	2	100	102
101	97	98	101	1	2	0	96	102
0	1	3	3	2	0	1	2	0
1	0	3	0	2	1	1	0	3
1	3	2	0	1	1	2	2	0
101	100	100	103	0	2	1	102	101
97	99	100	101	3	2	0	97	101
101	103	98	101	0	1	1	99	96
102	99	96	103	2	3	3	102	100

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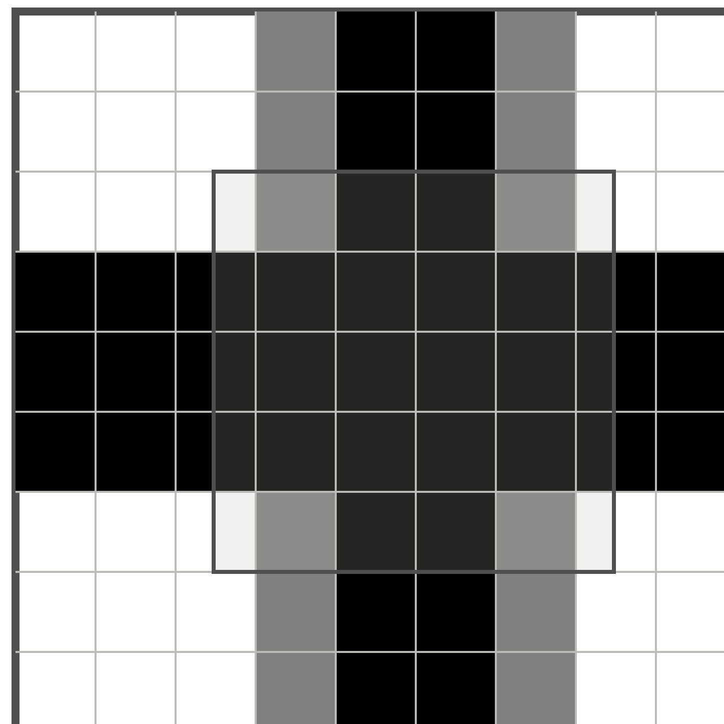
- **Example**
  - The **specimen moves** such that **its image moves 0.5 pixel to the right**
  - Need to interpolate the image at non-integer locations

103	101	99	52	0	1	55	100	96
101	104	98	51	4	3	51	98	100
103	96	99	49	2	2	52	103	98
2	3	0	1	1	2	3	0	1
1	3	3	0	2	1	0	3	0
0	0	2	0	3	0	2	0	0
98	101	102	52	1	0	46	97	102
97	98	103	51	2	0	53	98	100
102	99	101	48	0	0	54	102	101

Perfect match



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- During image acquisition:
  - Lighting conditions may change
  - Sensor integration time adjusted
  - Pattern may become lighter/darker when expanded/compressed

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- The photometric mapping is not guaranteed to be an identity, hence the DIC algorithm may have false matches
- Solution: model the photometric transformation and use it to design a robust correlation function

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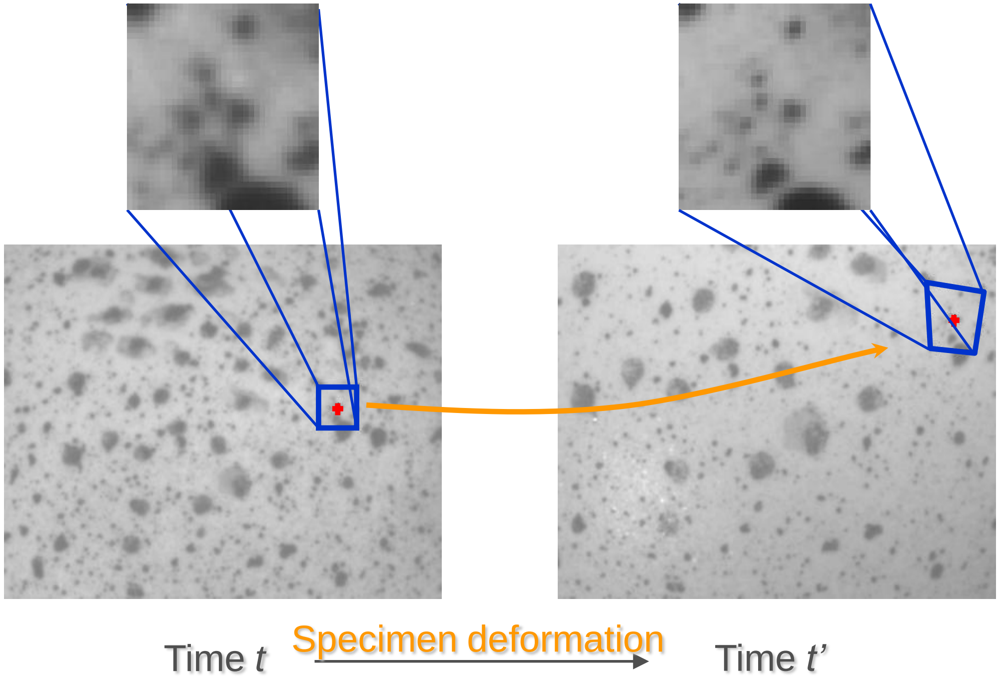
- General circumstances:
  - The subset in the deformed image has changed shape, e.g. a square initial subset is likely to be non-square



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- Solution: model this displacement transformation (called **subset shape function**) and use it to define the deformed subset

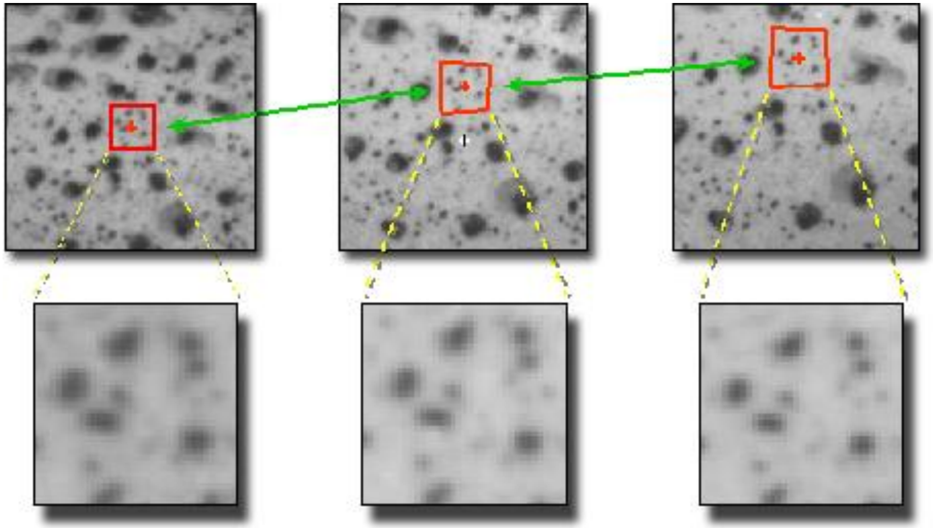

Image Interpolation

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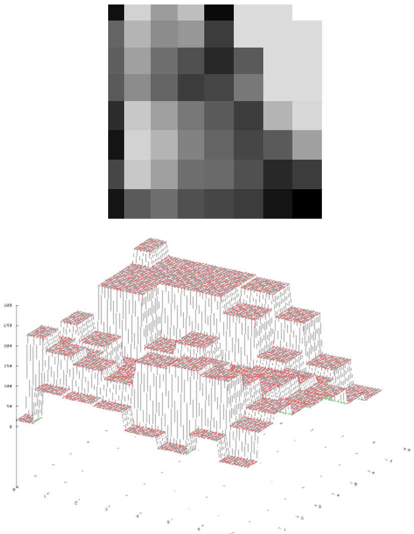
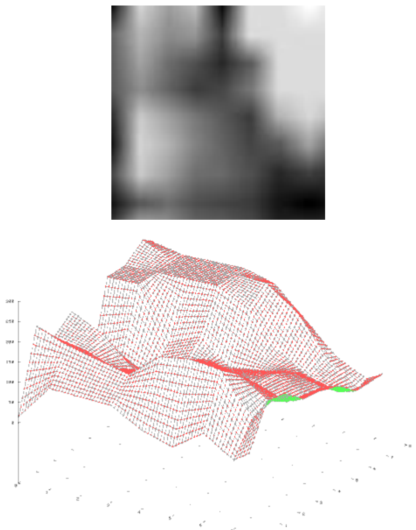
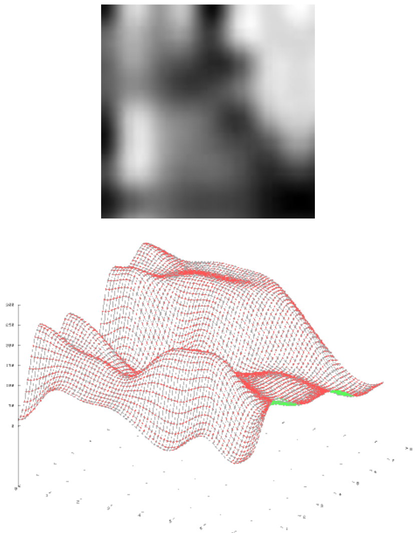
- Optimization algorithms require the criterion to be continuous over its parameter space
- Images are discrete, hence we need to reconstruct the continuous information by means of interpolation
- B-splines are a good choice for that purpose



Raw image



Bi-linear B-spline interp.



Bi-cubic B-spline interp.

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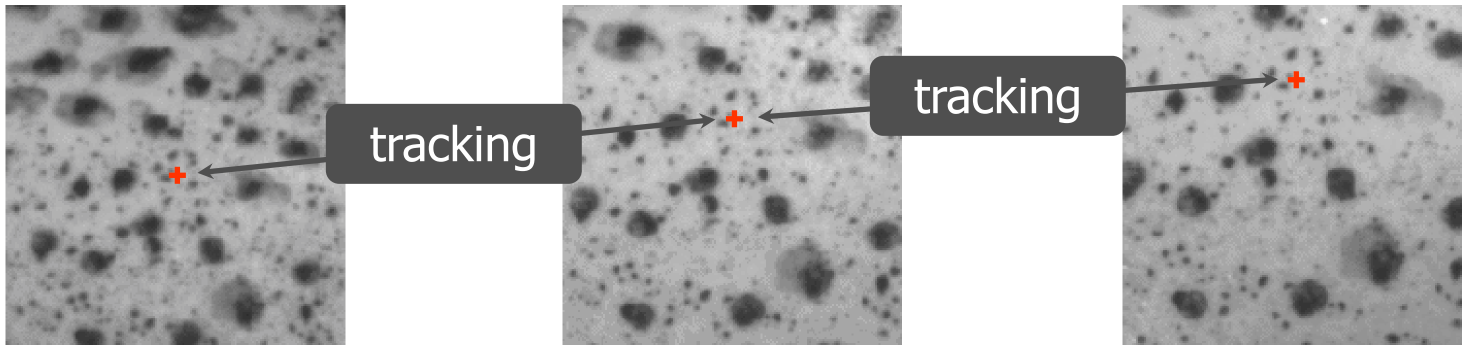

Time t Time t' Time t''

- Matching process
- Photometric mapping
- Shape function
- Implications

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- We thank **Prof. Jean-José Orteu** from **École des Mines d'Albi**, France, for providing us with multimedia content

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- We gratefully acknowledge the **University of South Carolina, Mechanical Engineering Dept.**, support for providing us with multimedia content

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Three-Dimensional Digital Image Correlation Overview

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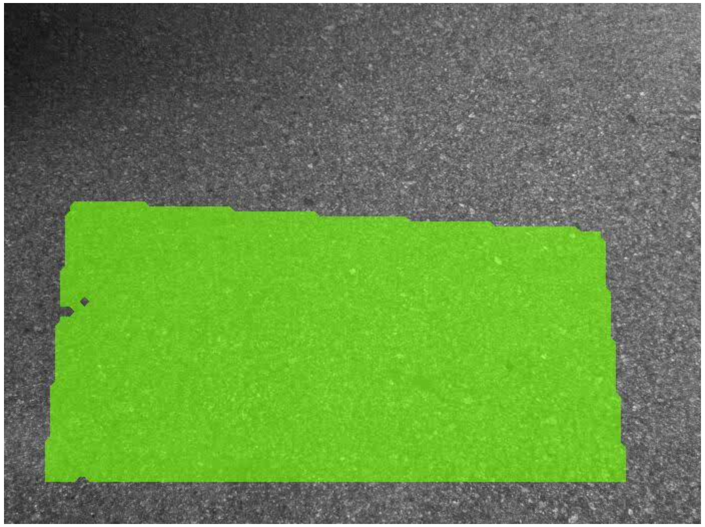
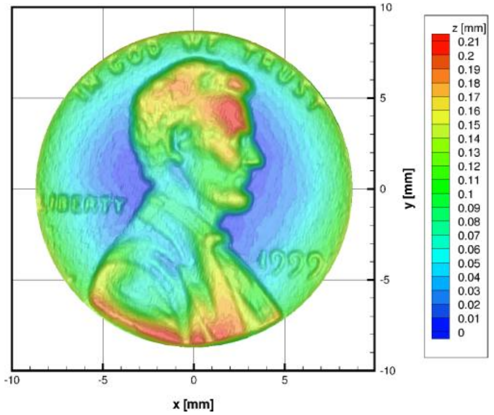
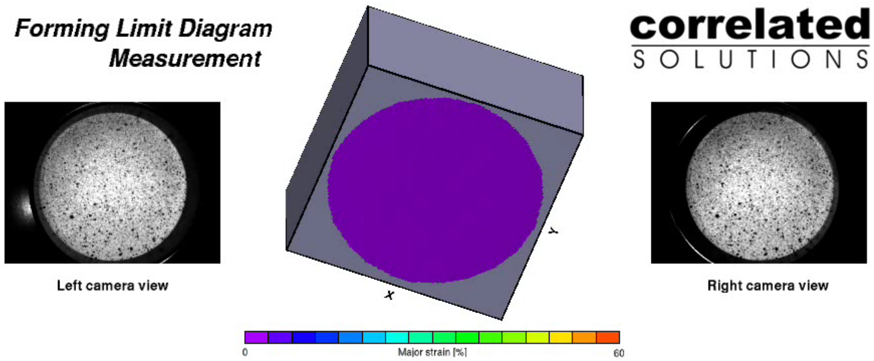
- 3-D shape
- Strain map
- Full-field measurement
- Non-intrusive
- **Any specimen shape**
- **Any motion**







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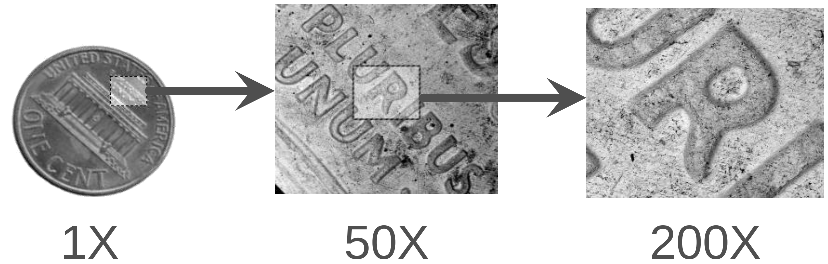
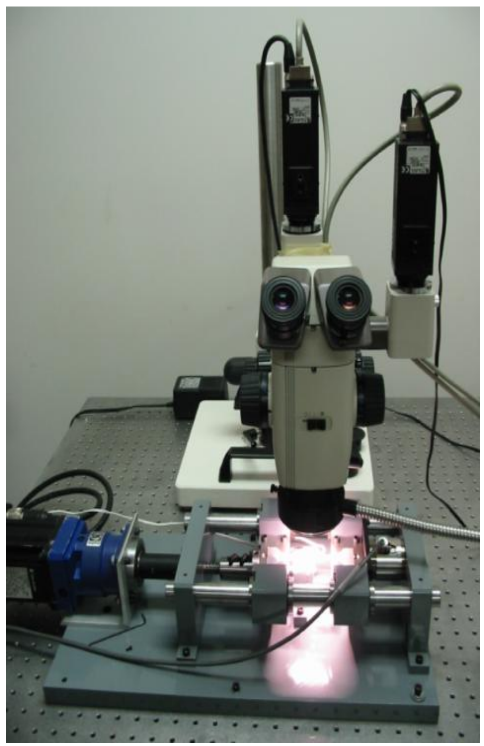
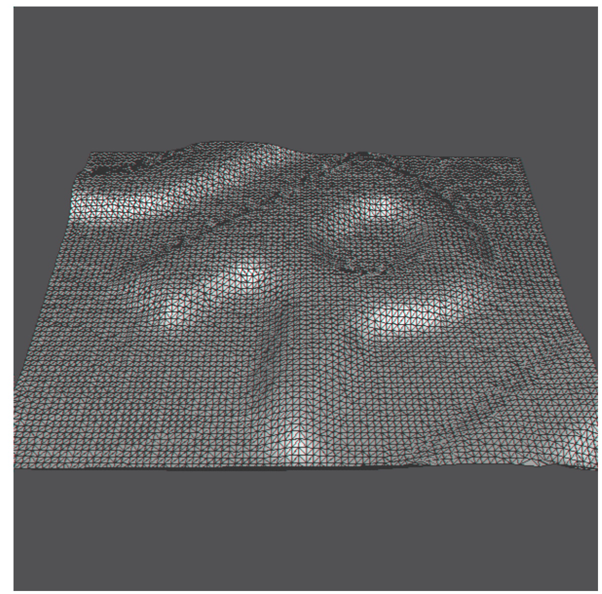
- Large range of size scales (10^{-9} to 10^{2} m.)







3-D shape of letter 'R' from "E PLURIBUS UNUM" on U.S. Penny coin using a Scanning Electron Microscope

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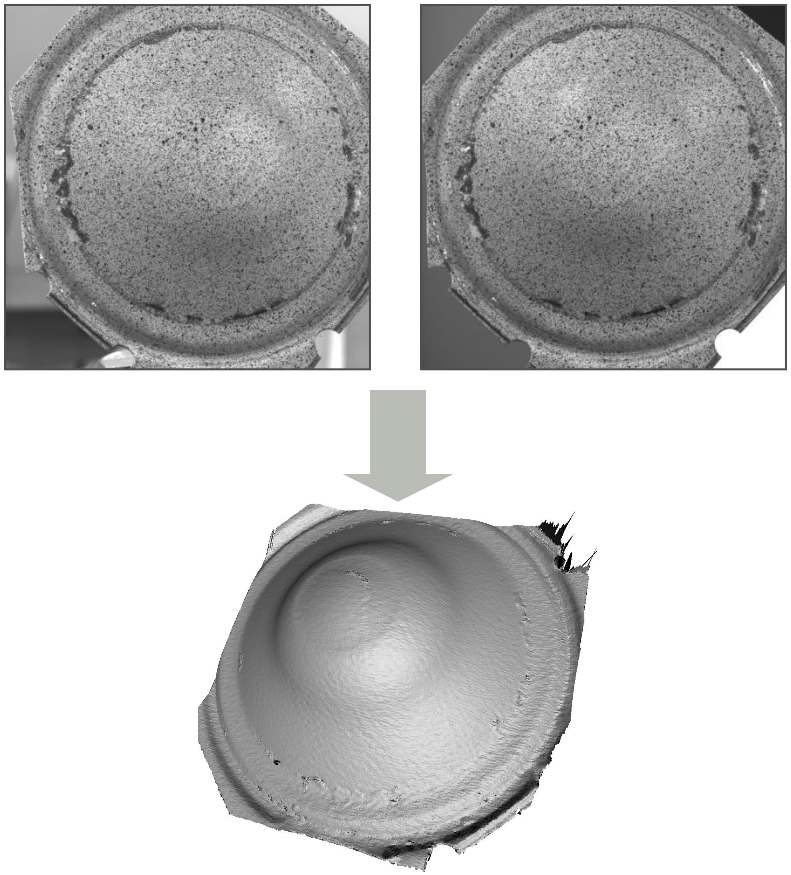
- Much like human vision, two imaging sensors provide enough information to perceive the environment in three-dimensions



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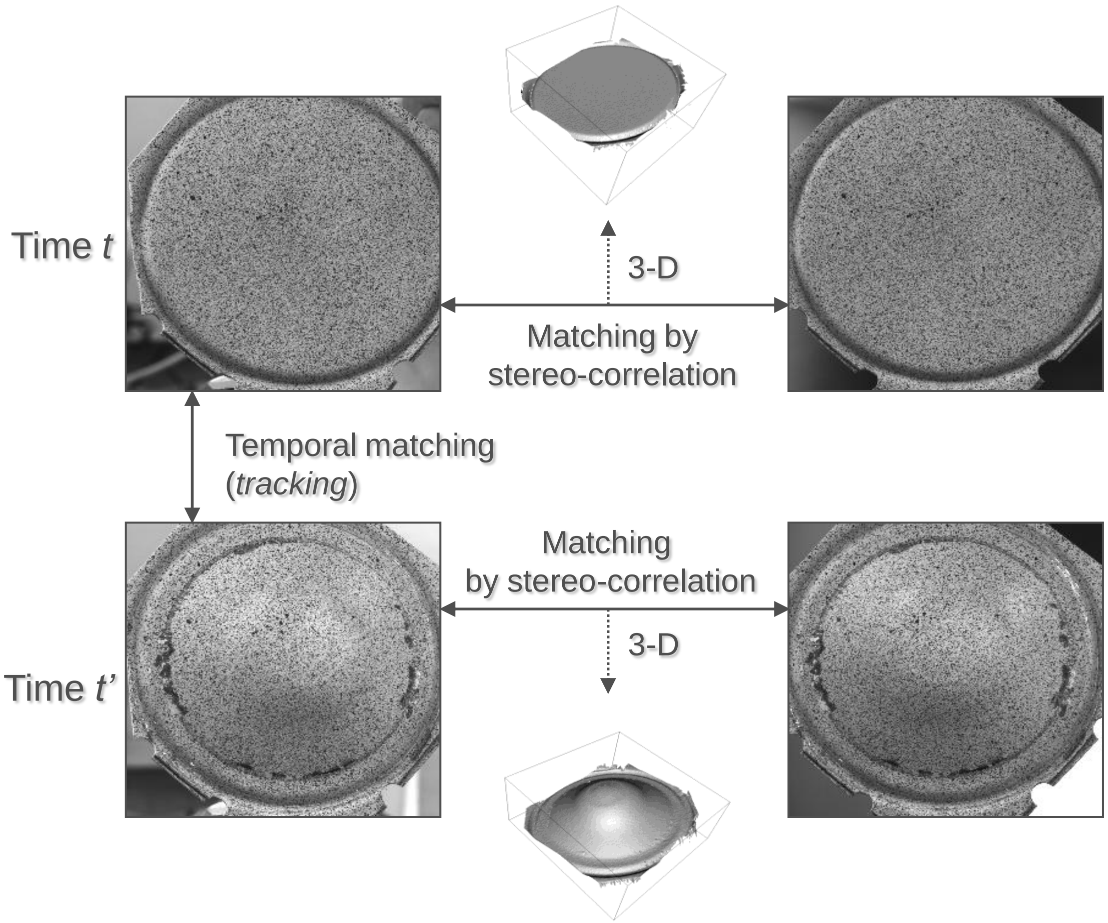
- **DIC for stereo-matching:** two 3-D shapes
- **DIC for tracking:** relates the two 3-D shapes through time



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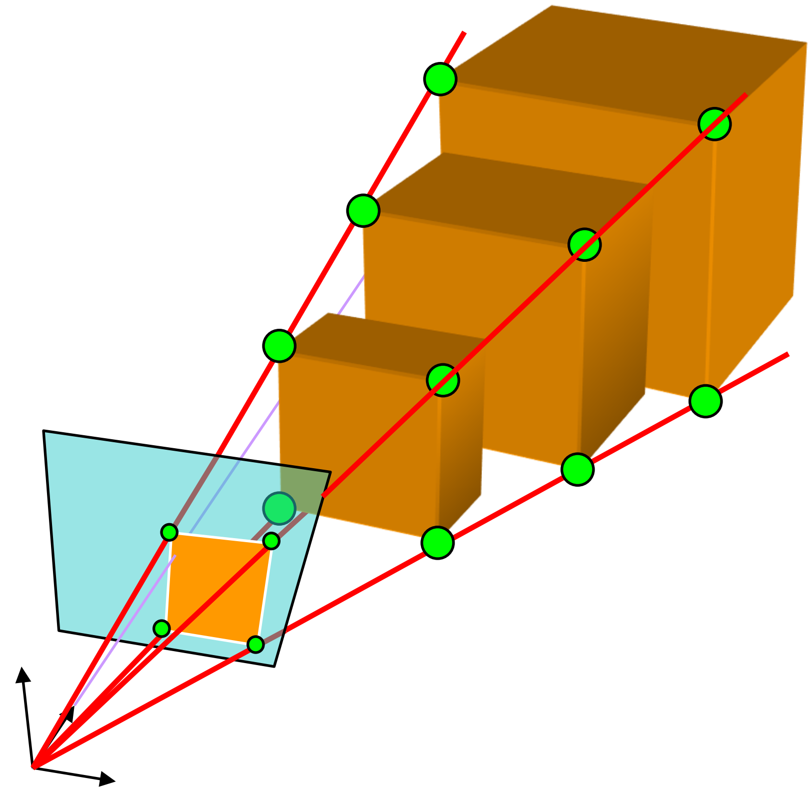
- Monocular (cyclopean) vision cannot resolve for the scale of objects



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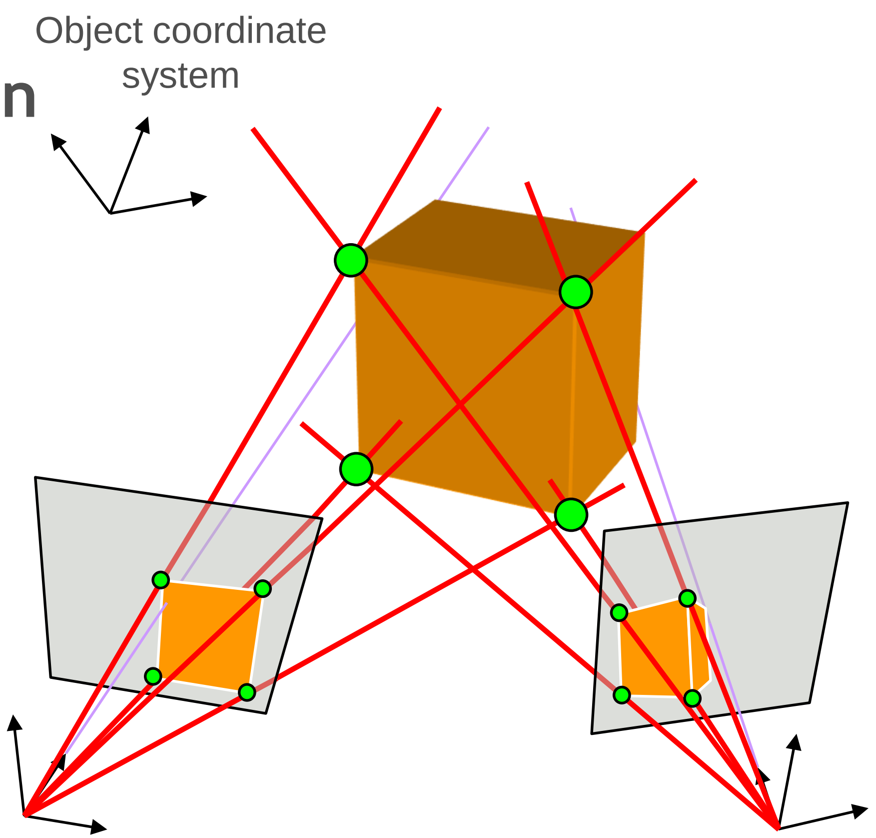
- Recovering the three-dimensional structure of the environment using two imaging sensors is called **stereo-triangulation**



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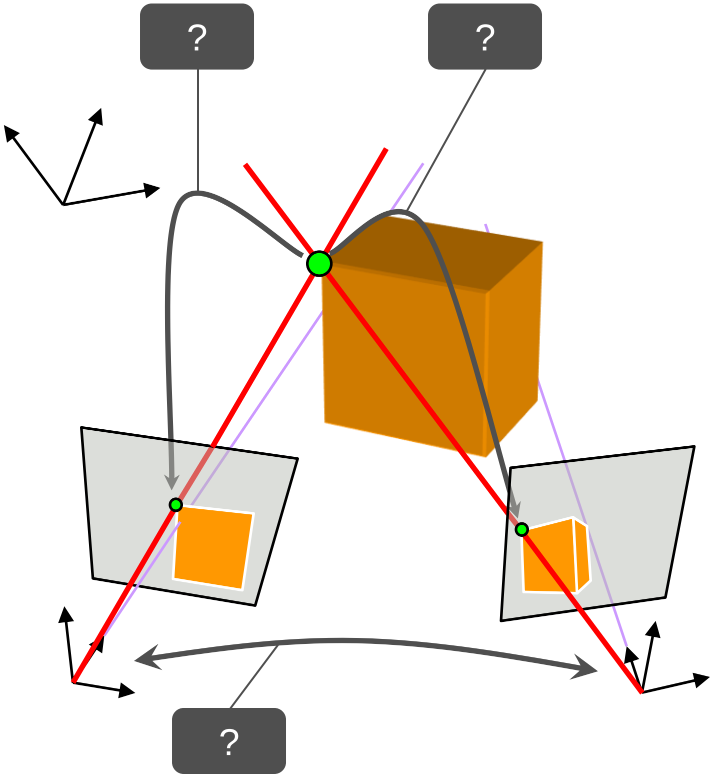
- Stereo-triangulation requires computing the intersection of two optical rays
- Feasible only if these rays are formulated in a common coordinate system
- We need to **model** and **calibrate** the stereo-rig



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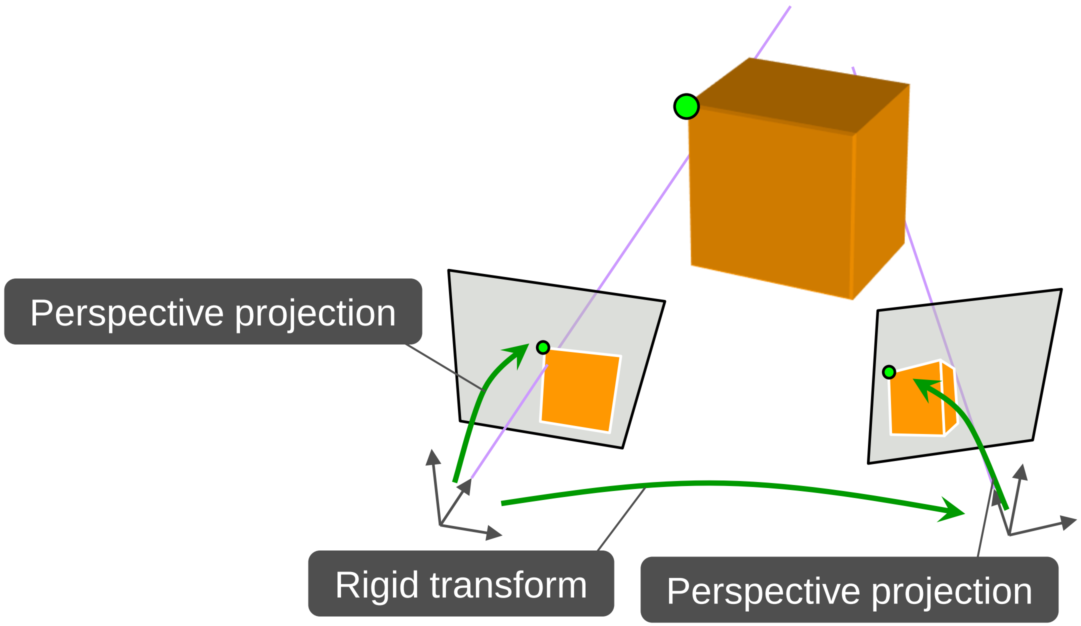

- Model: one **extrinsic** rigid transformation, two **intrinsic** perspective projections

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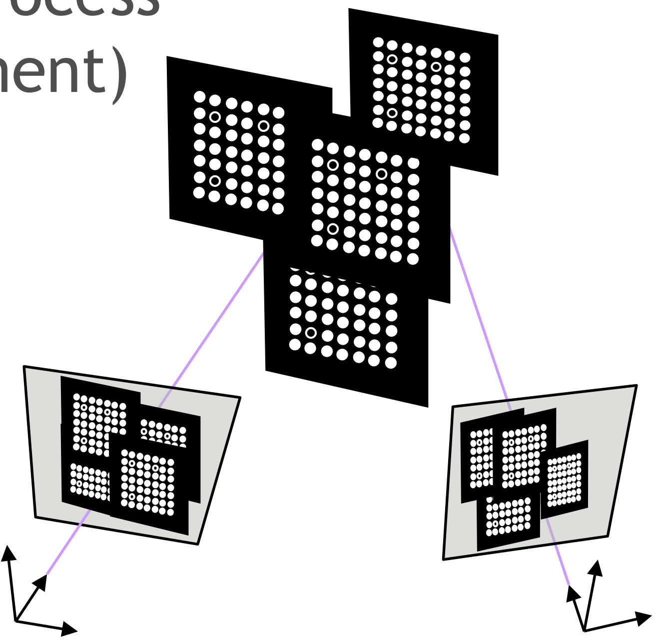
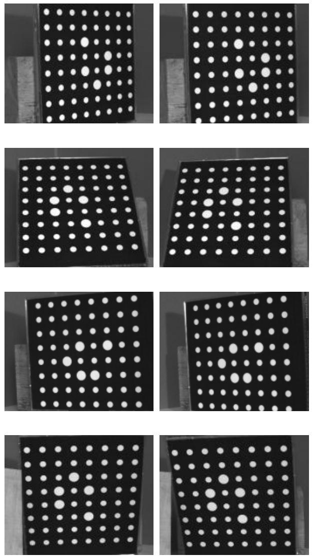
- Acquire pairs of images of a special target undergoing arbitrary motions
- Calibration is shape measurement process (bundle-adjustment)

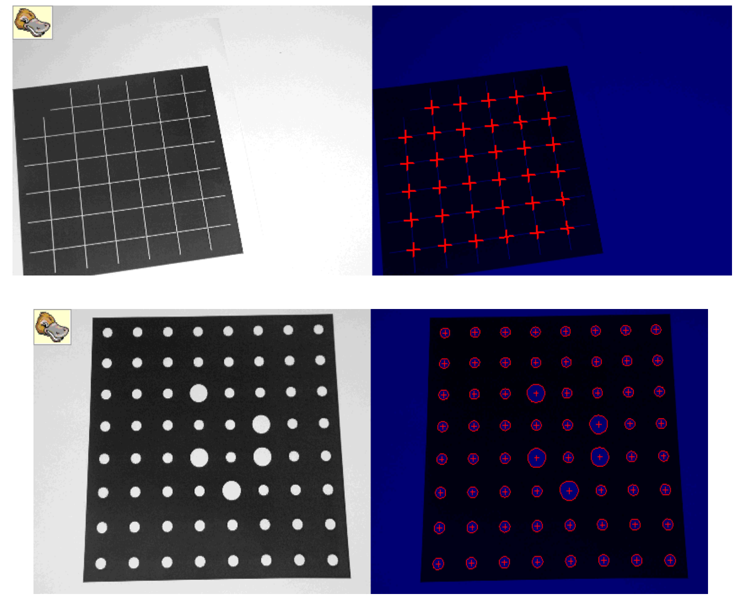




Parameter Estimation

- Dedicated pattern recognition algorithm

- Identification of the transfer function



Calibration target examples
Left: raw image, right: automatic pattern recognition

Transfer function

Parameter Estimation Techniques

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- Bundle Adjustment
  - No knowledge of calibration target required aside from a scale.
    - Shape of the target is measured during calibration.
    - Typically, a relatively flat target is used for initialization through a linear method.
  - Generally regarded as **the optimal** method to calibrate cameras.
  - Complex to implement due to large equation systems.
    - Require block matrix solvers to efficiently invert large equation systems.
  - Can provide confidence margins on all parameters estimated.

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- There are only two constraints required to accomplish calibration.

1. The calibration target must not deform between images.
2. A distance between two points on the target must be known.

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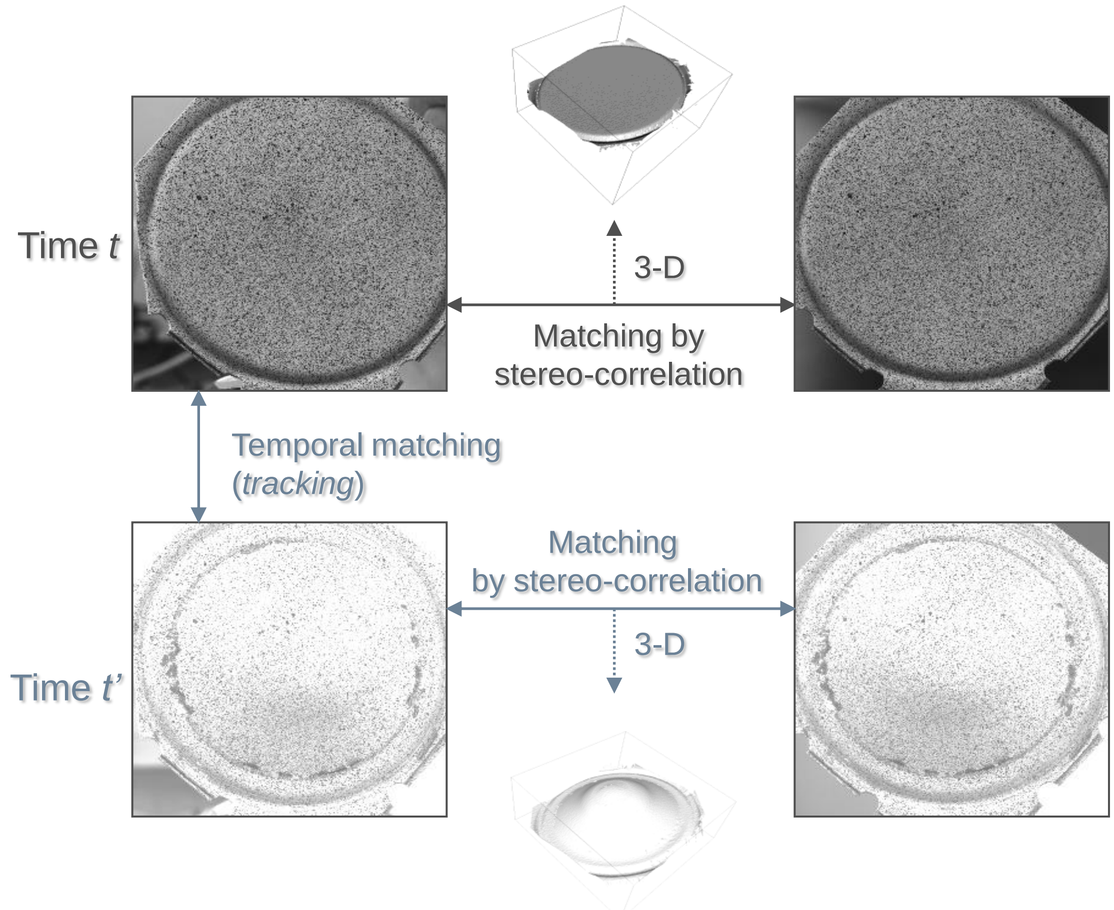
- 3-D Shape Measurement given a pair of images



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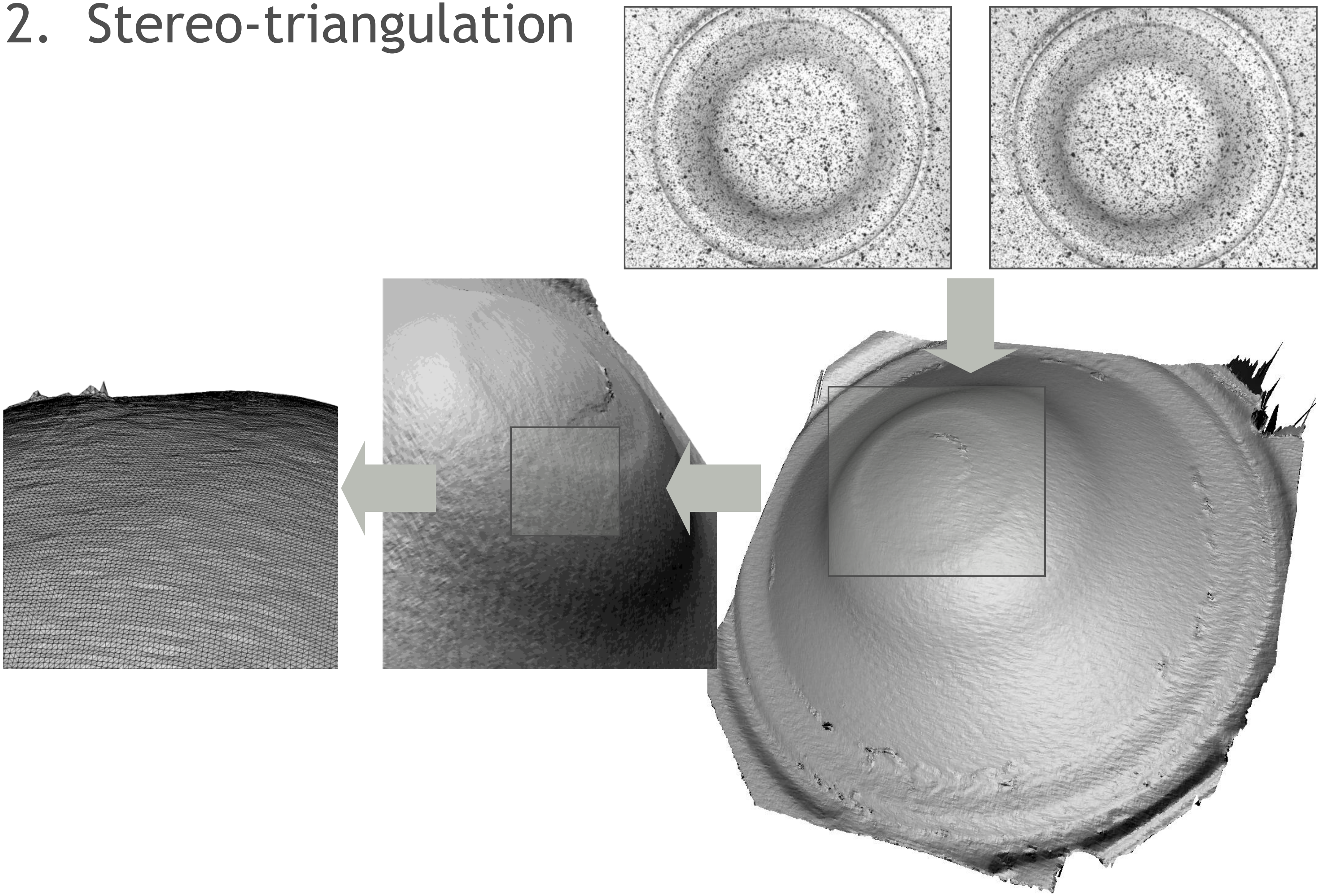
Two steps:

1. Stereo-correlation
2. Stereo-triangulation



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Tracking: Similar to 2-D DIC

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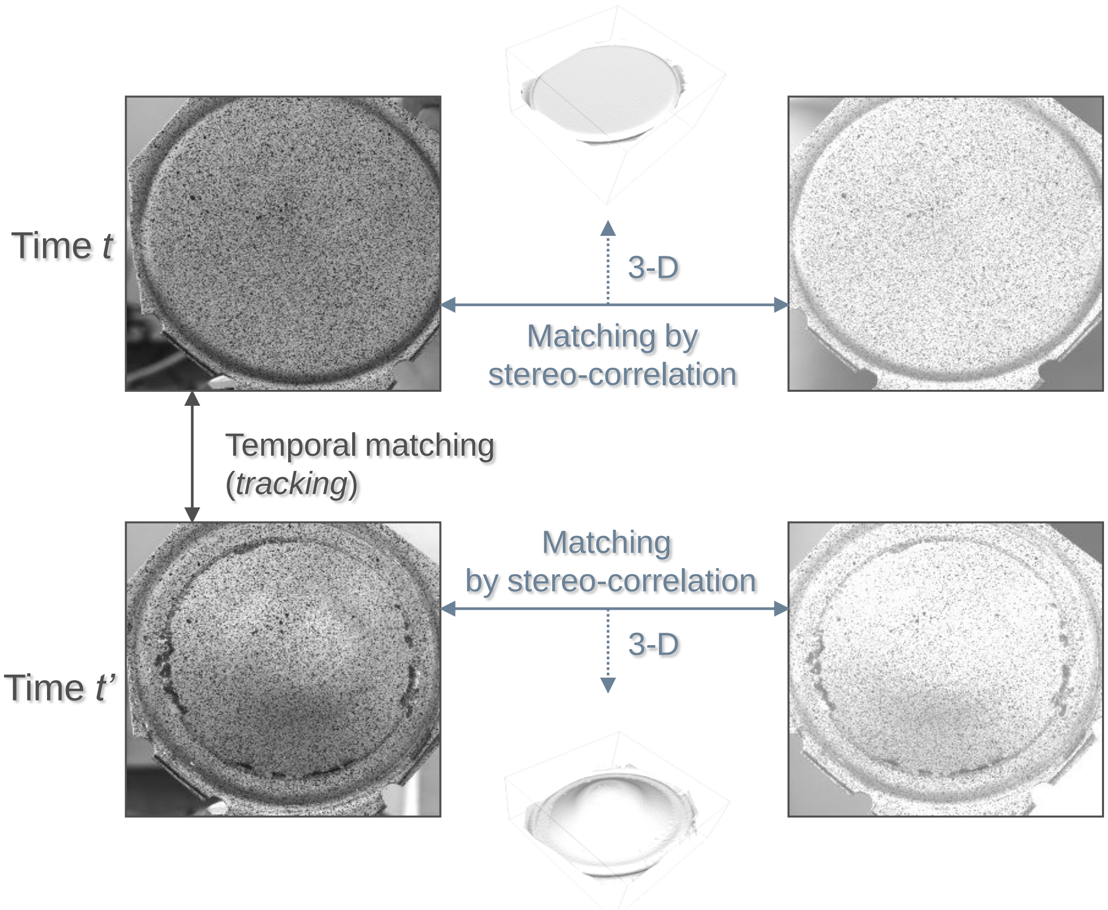
- Allow to relate 3-D shapes through time
- Algorithms similar to 2-D DIC



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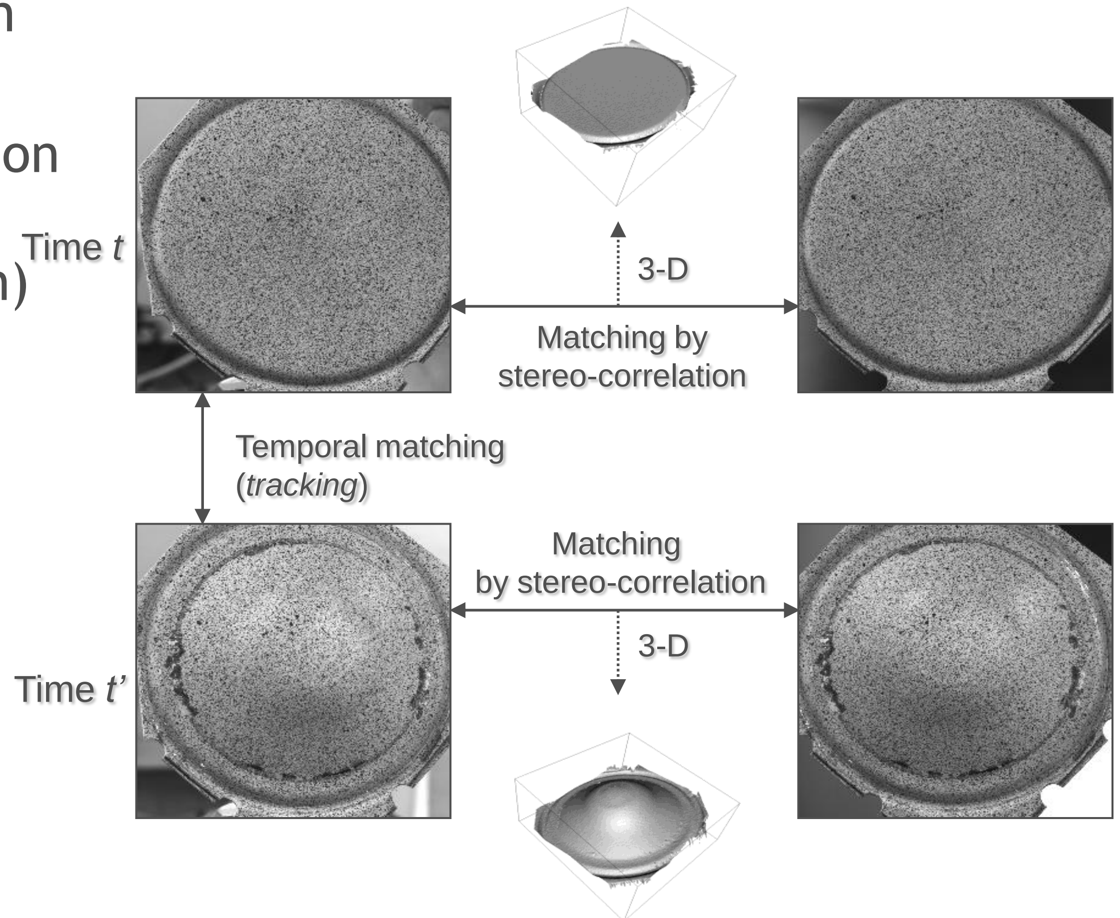
- The technology behind 3-D DIC
  - Stereo-correlation
  - Tracking by correlation
  - Stereo-triangulation (needs calibration)



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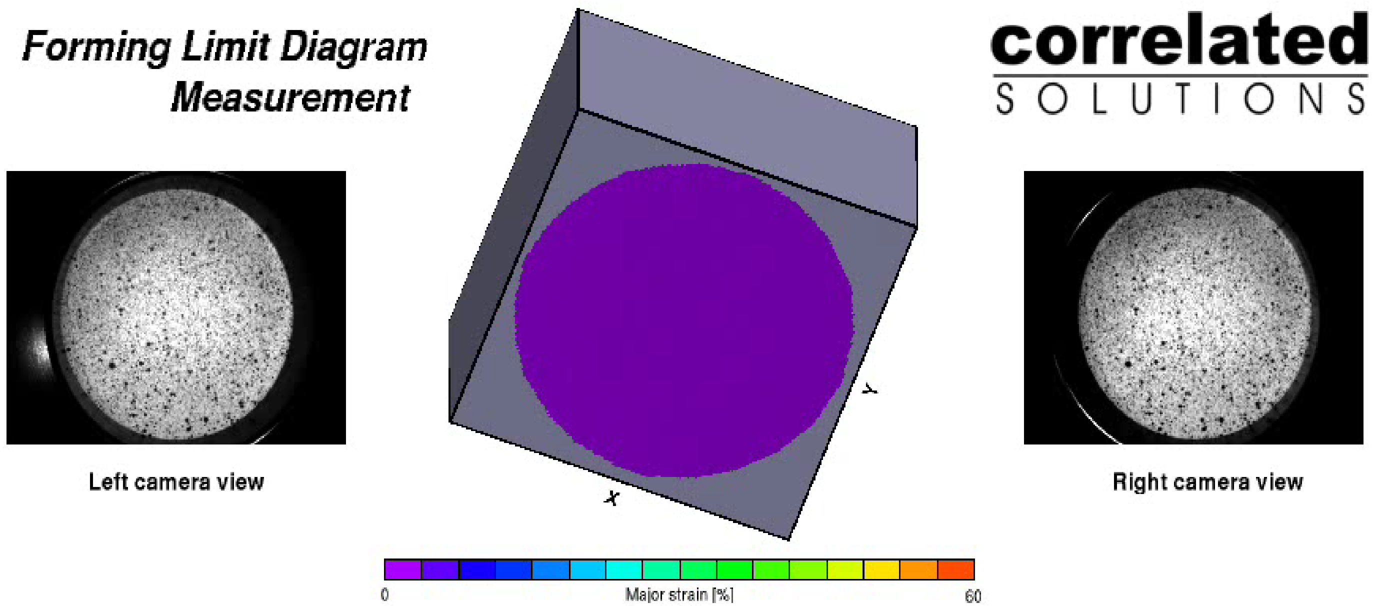
- Example



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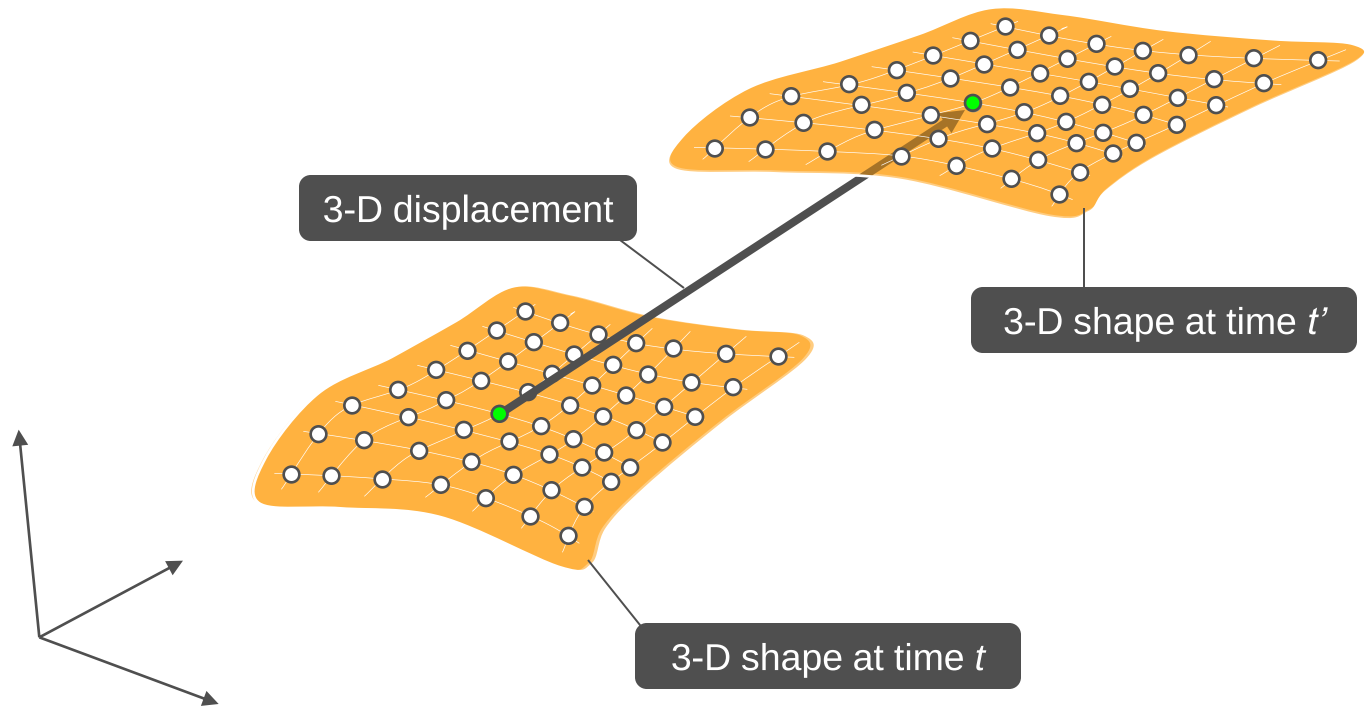
- Strains are computed from the measured displacements of object points (strains $\cong \nabla$ displacements)



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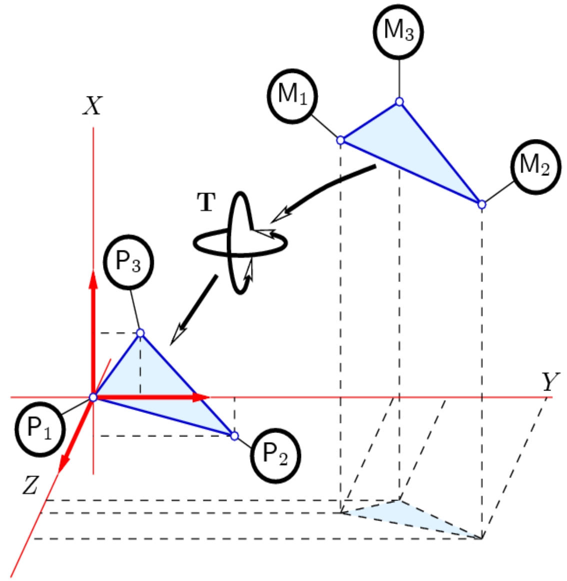
- Strains are only defined in the tangential plane of the surface.
- The DIC data can be converted to a triangular mesh.
- Since triangles are planar by definition, it is simple to compute the strain on each triangle.
- Same equations as found in FEM.



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Smoothing

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- The strains computed on each triangle are noisy, unless the triangles are fairly large.
- The strains are normally smoothed using low-pass filters.
- Low-pass filtering decreases spatial resolution.

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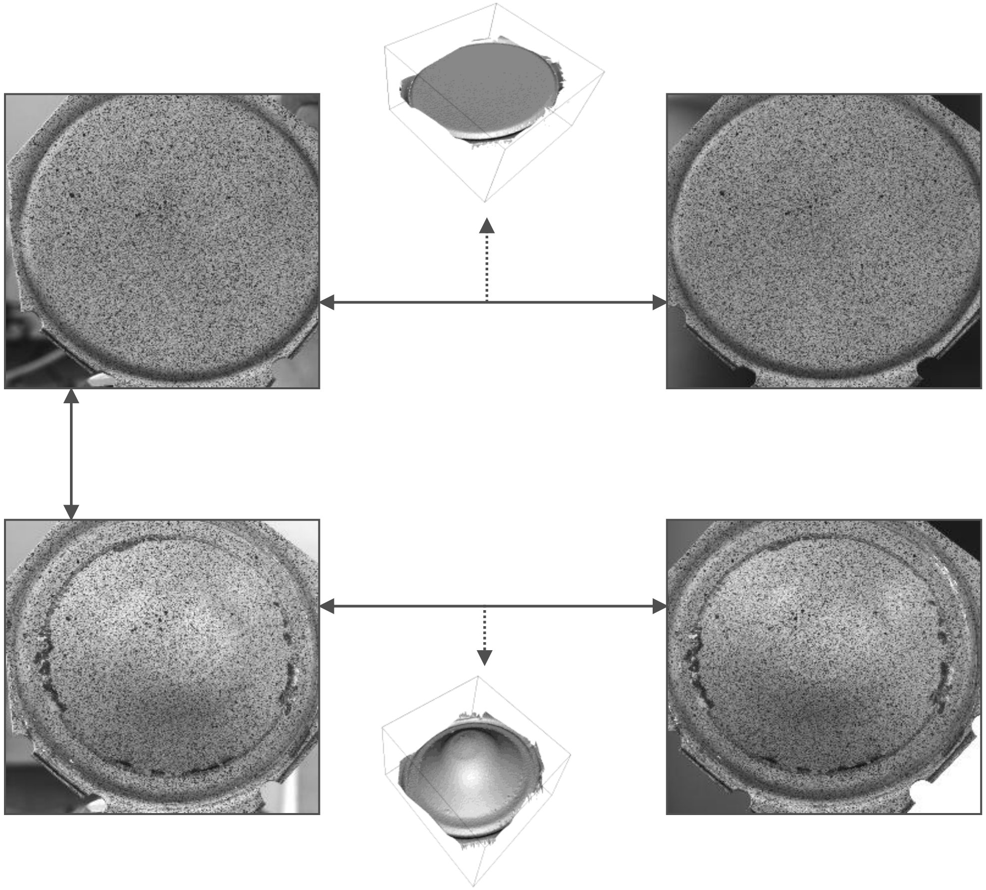
- Matching process – identical to 2D
- Combining matching with triangulation
- Combining triangulation with tracking



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- We thank **Prof. Jean-José Orteu** from **École des Mines d'Albi**, France, for providing us with multimedia content

- We gratefully acknowledge the **University of South Carolina, Mechanical Engineering Dept.**, support for providing us with multimedia content

Questions?

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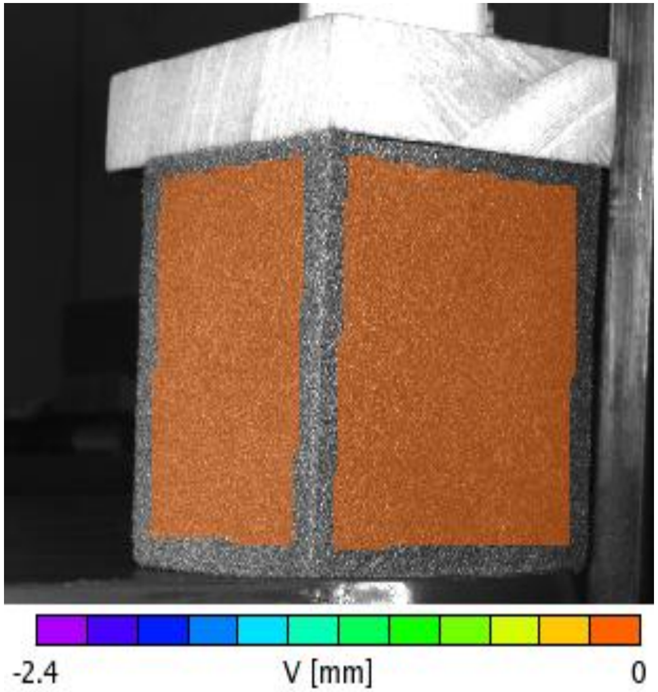

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3D Image Correlation Procedures and Practicalities

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- Cameras available for different time scales
  - Quasi-static (10-30 fps)
  - Medium speed (500 fps)
  - High-speed (50,000 fps)
  - Ultra-high speed (1,000,000 fps)
- Choose sensitive, monochrome cameras
- Pixel size
- CCD vs. CMOS

Camera Setup

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- Cameras must not move relative to each other
- Tolerable camera motion depends on magnification
- Example:
  - 1:1 magnification
  - 5 micron pixel size
  - Detectable motion 0.01 pixel
  - 50 nanometer relative camera motion is detectable!!!
- For high magnifications, a rigid camera setup is paramount

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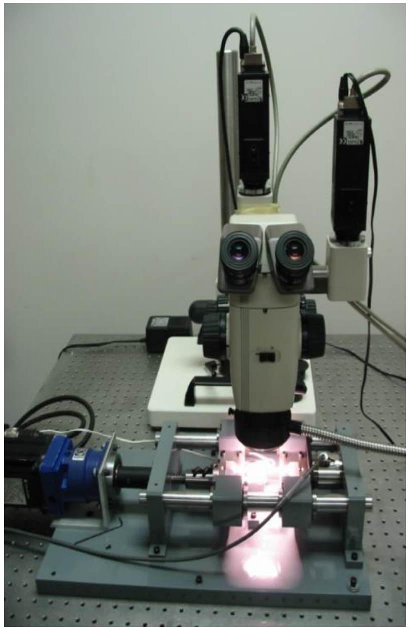
- Mount cameras on rigid support
- Tie down camera cables

- Use vibration isolation for high-magnification work



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Minimizing Bias & Noise

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- Bias: systematic deviations from the correct result
- Noise: random, zero-mean deviations from the correct result
- Noise and bias are present for location (in-plane, out-of-plane), displacement, and strain
- Bias can be reduced or eliminated with proper setup and parameters
- Noise is unavoidable, but can be minimized with careful setup

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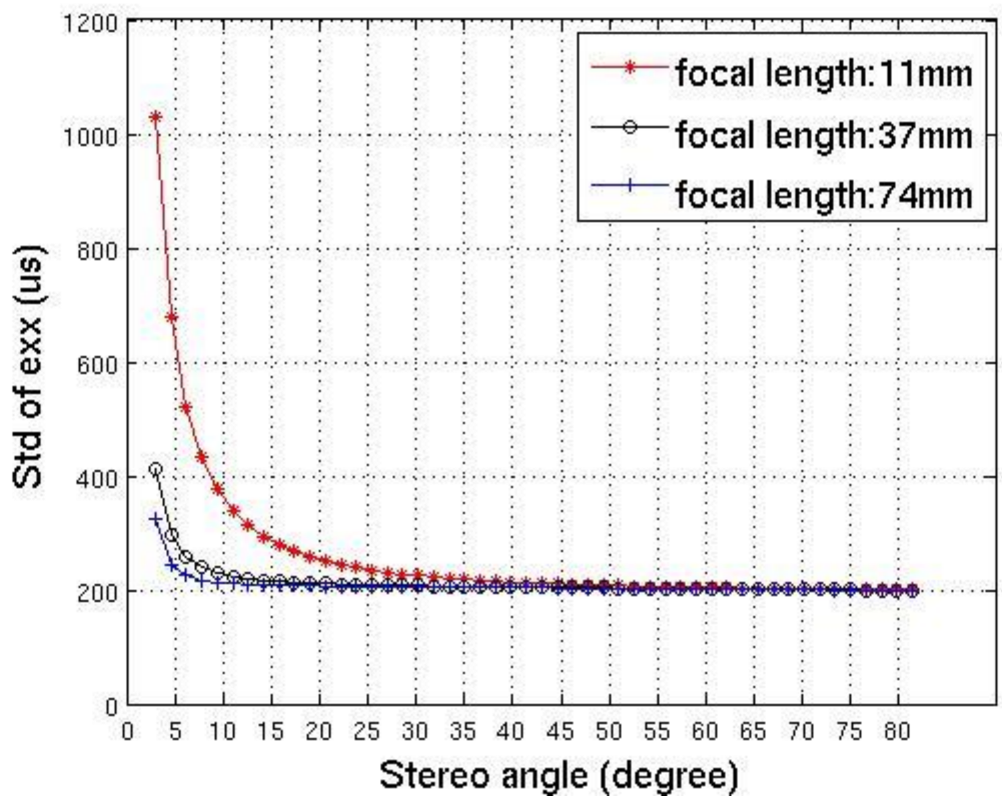
- Noise in displacement and strain is strongly dependent on stereo angle



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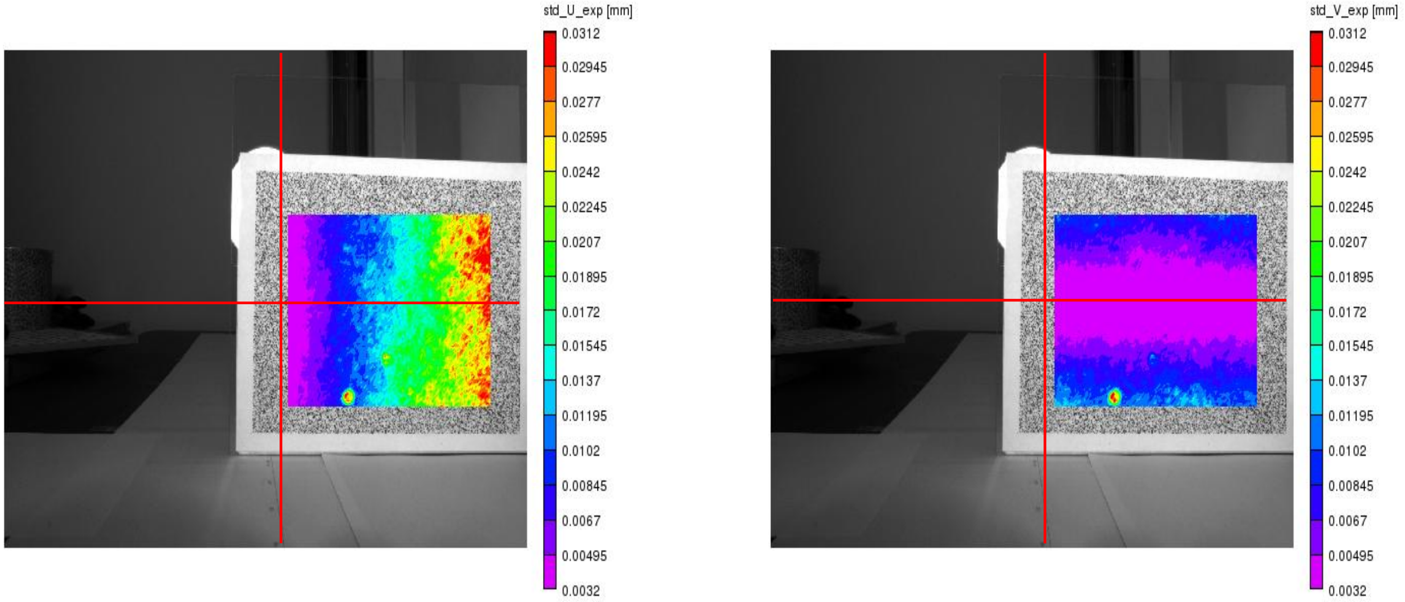
- Noise is lowest near the optical axis



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- For short lenses (8mm, 12mm), use a stereo angle of at least 25°
- With longer lenses (35mm, 70mm), use at least 10-15°
- If you must use small stereo angles, keep the AOI to the center of the images

Camera Synchronization

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- Stereo cameras must be synchronized
- Required accuracy depends on speed of event
- Synchronization accuracy should be small fraction of exposure time

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Focusing cameras

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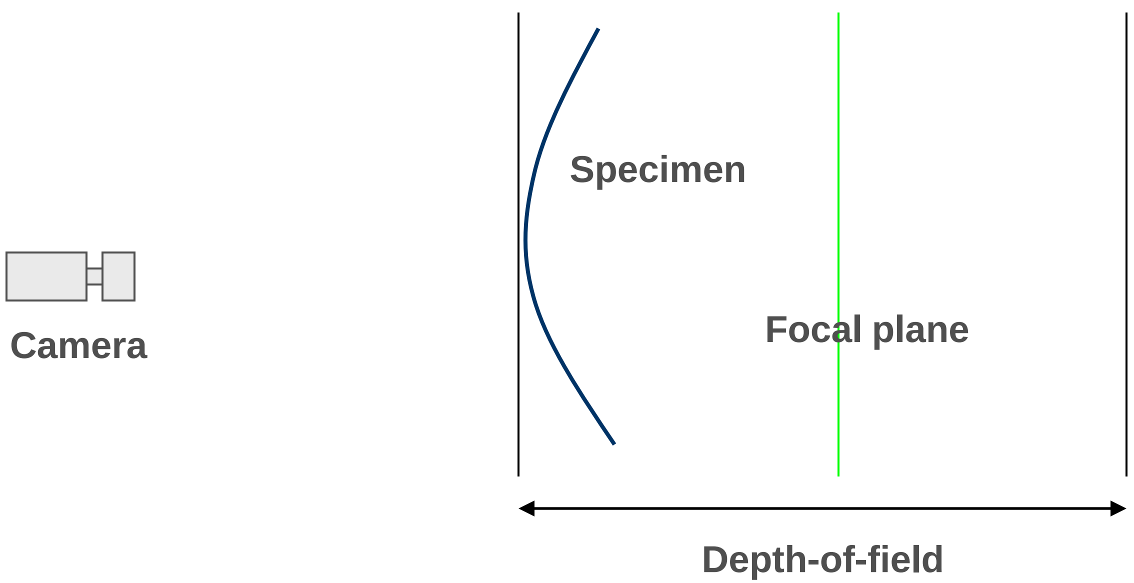
- The entire sample should be focused during the entire test
- It can be difficult to focus a camera correctly when the depth-of-field is large

Small aperture (high f-number):



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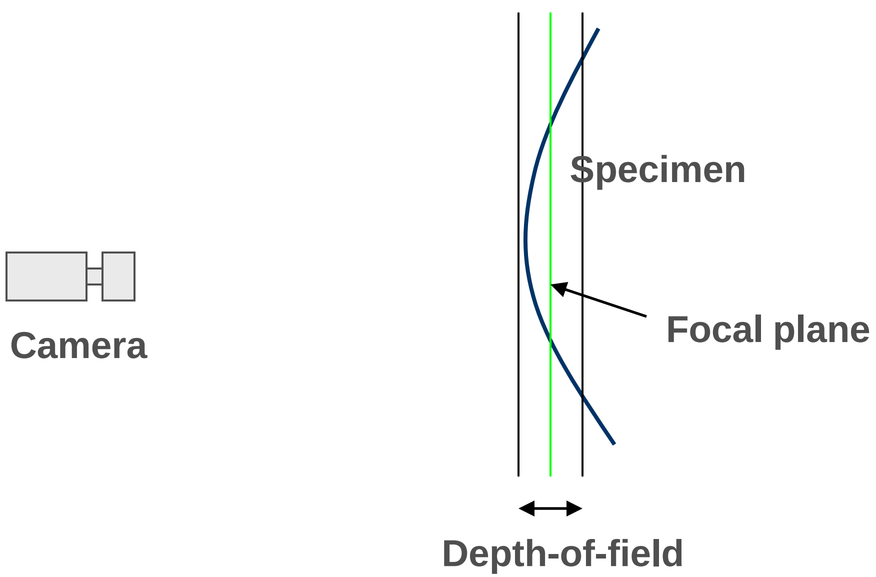
- It can be difficult to focus a camera correctly when the depth-of-field is large

Large aperture (small f-number):



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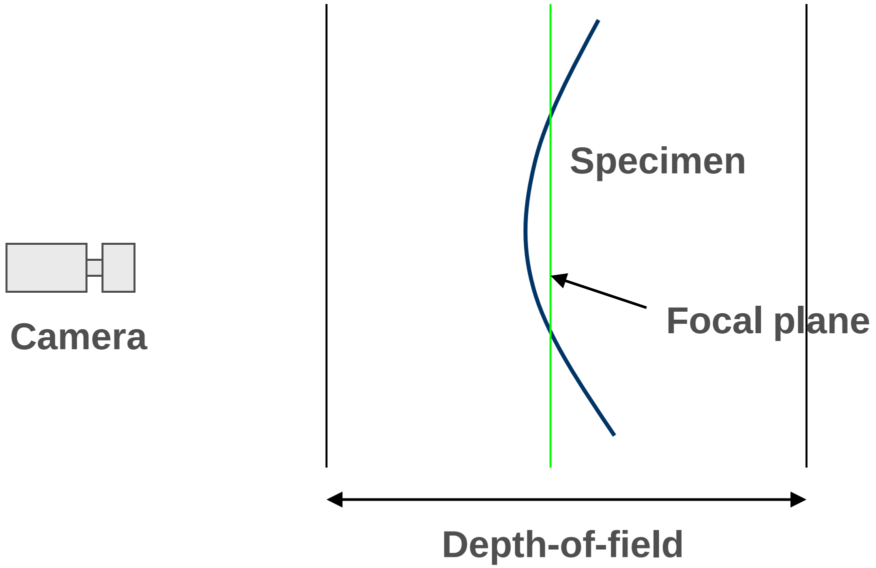
- Focus with open aperture
- Close aperture after focusing

After closing aperture:



Aperture, Exposure, Lighting

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- Use a short enough exposure to freeze
  - Calibration is frequently the bottleneck
- Apertures in the middle are best
  - DOF concerns
  - Diffraction limit & pixel size
- Difficult cases
  - Wet/shiny specimen
  - Metal & glare
  - Transparent/translucent
  - 3D and textures

Checking for Contaminations

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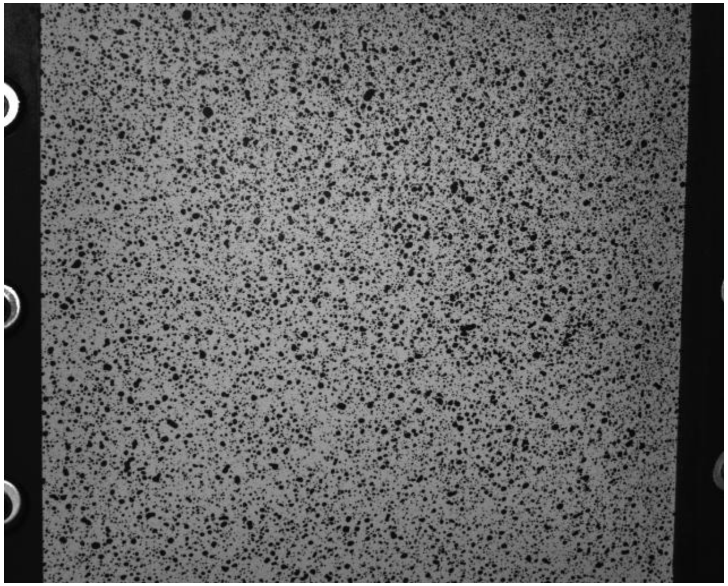
- Contaminations on sensor, IR filter or lens can lead to small local bias in data
- The image needs to be checked if contaminations are present



Contaminations cannot be spotted in speckle image

correlated SOLUTIONS

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- Contaminations can be seen by
  - Completely defocusing camera
  - Using a uniform gray background
- Move camera
  - If spot stays fixed, contamination present
- If contaminations are present, turn lens
  - If spot moves with lens rotation, contamination is on lens
  - If spot stays in place, spot is on sensor or IR filter
- Use compressed air to blow dust particles away
- Always use lens caps and camera covers to avoid contaminations in the first place

correlated SOLUTIONS

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- Select appropriate camera for speed requirement and resolution requirement
- Use sensitive, low-noise cameras
- Set cameras up on rigid supports and tie all cables down
- Use vibration isolation for high magnifications
- Focus at open aperture and close for test
- Always check for contaminations against uniform background or by blurring image

correlated SOLUTIONS

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- Uniform random pattern must be applied
- Large range of application methods:
  - Lithography and vapor deposition
  - Toner powder on paint
  - Spray painting
  - Toothbrush technique
  - Electrochemical etching
  - Screen printing
  - Adhesive-backed vinyl (e.g., 3M Controltac)
  - Stencils
  - …

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- Pattern must deform with sample
  - No slip for stick-on patterns
  - Dye sample for large deformations (100%-800%)
  - Must hold up to testing conditions (temperature, moisture, acceleration etc.)
- Pattern must not reinforce sample
  - Use dye penetrant developer for measurements on very thin metal foils

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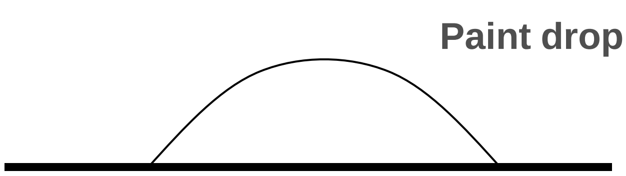
- It is absolutely critical to avoid specular reflections
  - If sensor is saturated, the signal is chopped off
  - Accurate matching no longer possible
  - Large artificial spikes in strain
- Use matte paints
- Whenever possible, use back lighting for transparent or semi-transparent samples
- Avoid thick paint drops
- Use diffuse lighting



Aliasing

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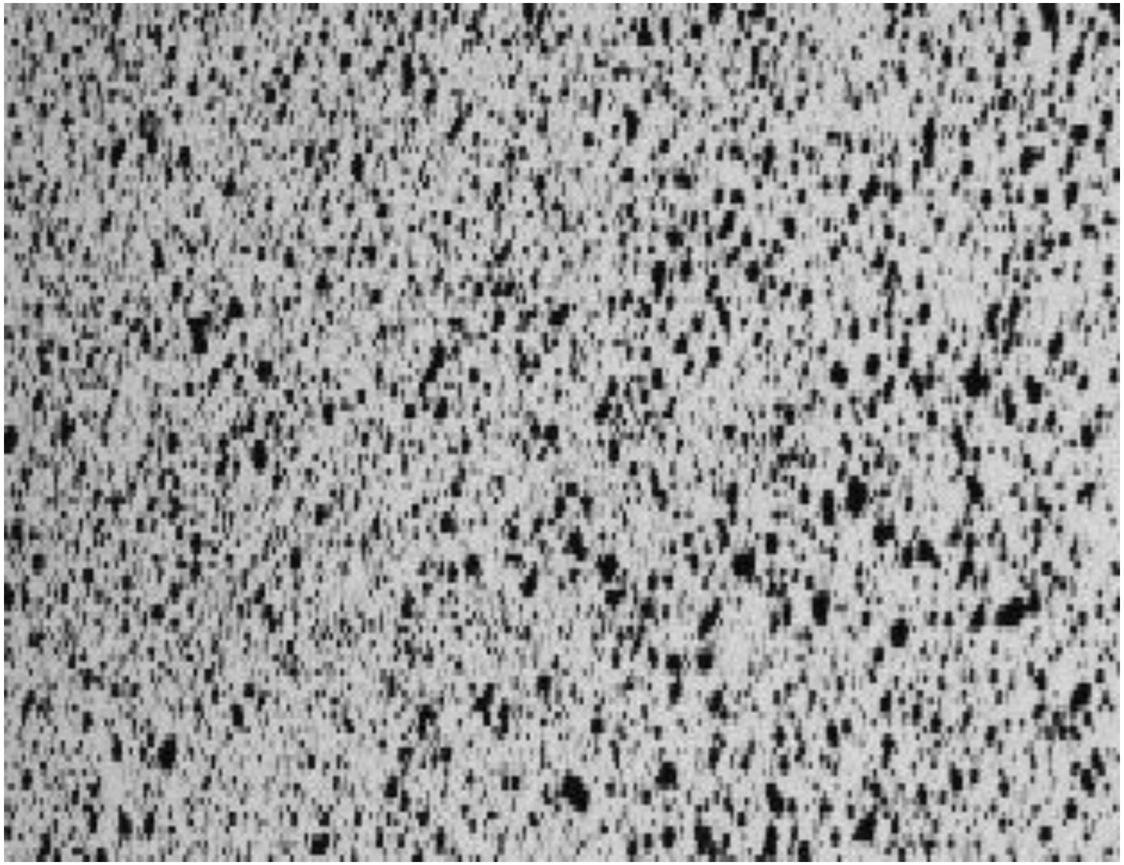

- Pattern elements are too fine, causing…

Aliasing

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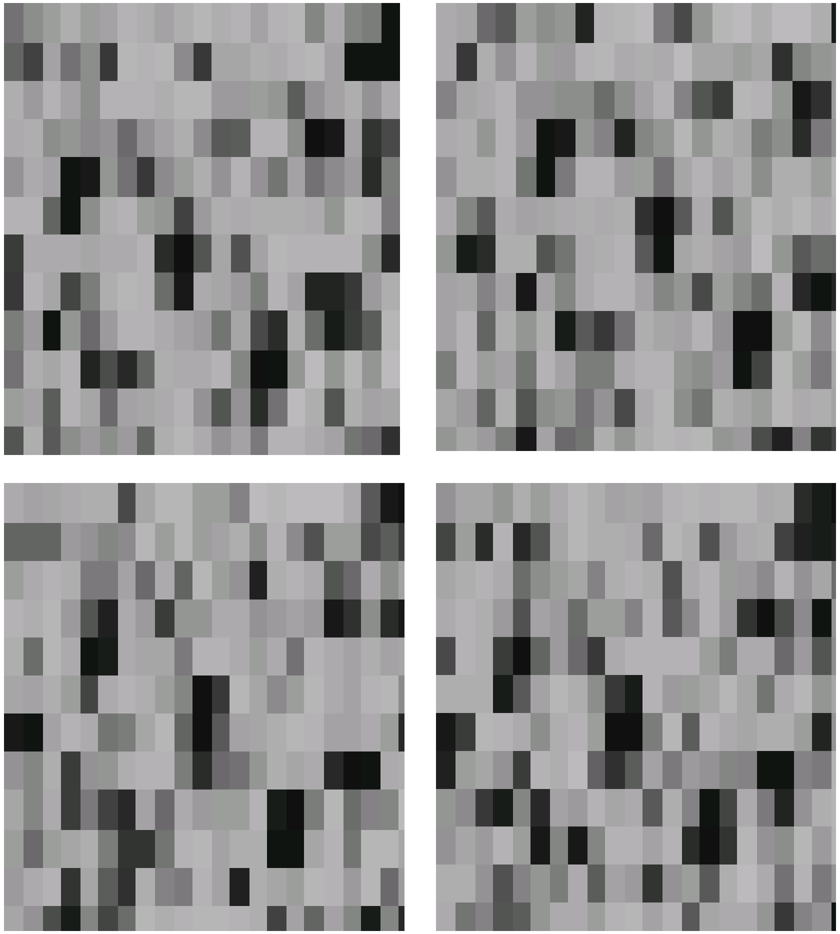

- Same patch!

What makes a good pattern?

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- Small speckles approximately 3-5 pixels in size
  - Permits analysis with small subset
  - High spatial resolution
- No preferred orientation
- Uniform (check histogram)
- Matte
- No big paint blobs or uncovered areas

correlated SOLUTIONS

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- Pattern must deform with sample and not reinforce specimen
- Pattern must not degrade (too much) during test
- A wide variety of application methods exist
- Pattern should be uniform
- Specular reflection must be avoided
- Dense speckle pattern is desirable to achieve maximum spatial resolution

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correlated SOLUTIONS

Camera and System Calibration

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- The internal camera parameters have to be calibrated (focal length, image center, distortions, skew)
- The relative orientation of the stereo cameras has to be known for triangulation
- Typically, all parameters are calibrated at the same time using a calibration target

correlated SOLUTIONS

Calibration as Shape Measurement

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Camera calibration is a shape measurement of the calibration target!!!

correlated SOLUTIONS

Calibration Target

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Does one need a precision calibration target to calibrate a stereo system?

- Internal camera parameters can be calibrated from a completely arbitrary calibration target (only constraint: target must be rigid)
- Rotation and direction vector between cameras can also be calibrated from arbitrary target
- Scale of translation vector can only be recovered from known distance on target

Calibration Target

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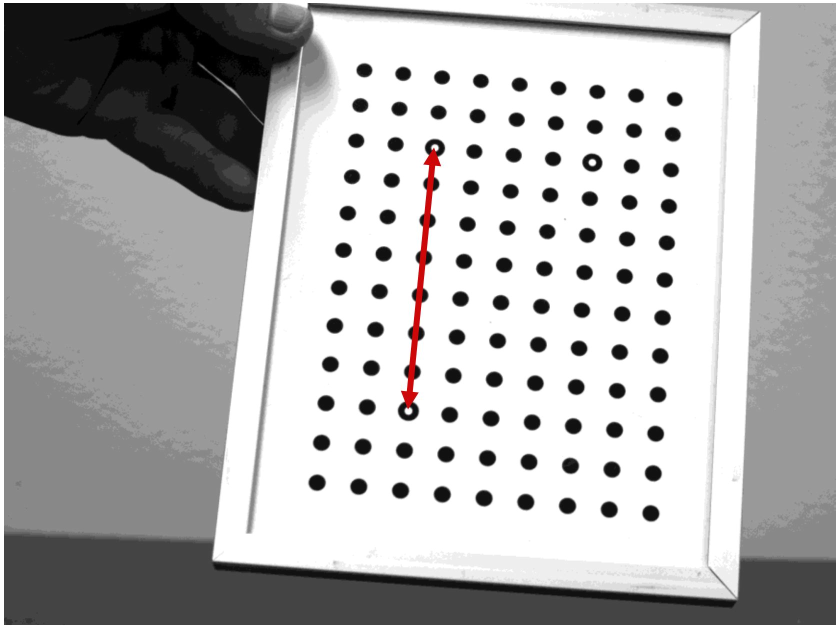
- Target does not need to be precisely flat or have a known shape to accurately calibrate a stereo system
- A distance between two fiducial points has to be known accurately to recover the absolute scale



correlated SOLUTIONS

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- Typically, a fairly flat calibration target is used (simple linear solutions to the calibration problem exist for planar targets)
- Multiple views of the target (15) are acquired
- A bundle adjustment procedure determines shape of target and calibration parameters

What orientations of the target make a good calibration sequence?

Importance of Rotations

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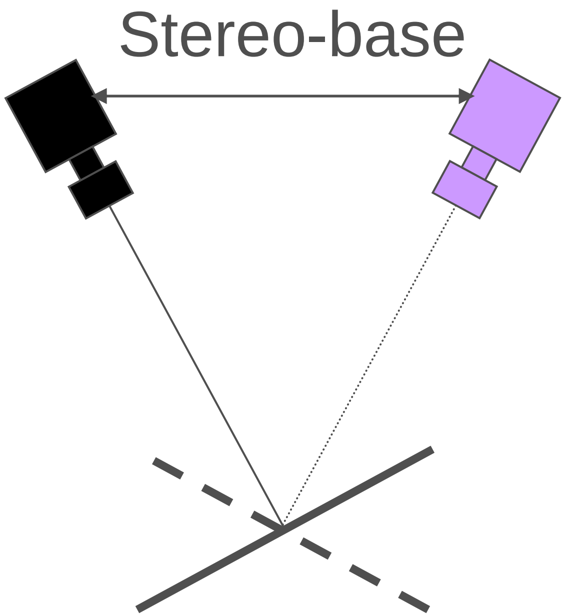
- Calibration equivalent to shape measurement
- Reliable shape measurement only possible for large stereo-baseline
- Rotations serve to increase baseline



Calibration Procedure

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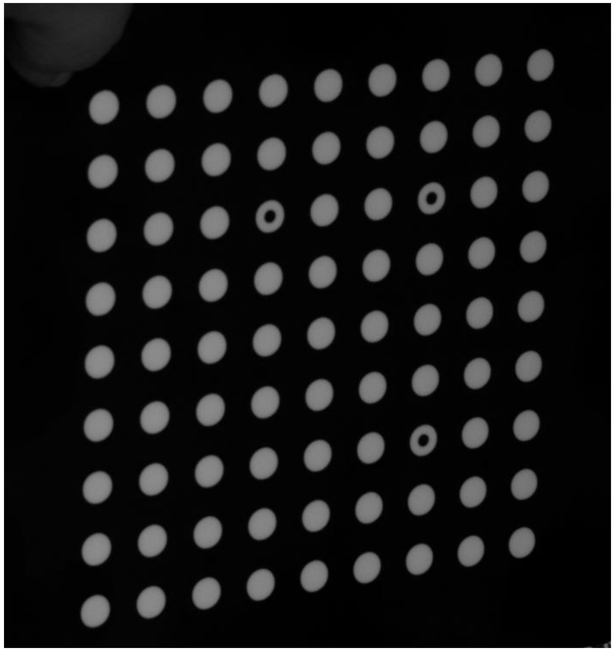
- Coded targets are used for automatic extraction
  - Coded markers must be visible in all views
- Avoid glare
- Use short exposure times to freeze target motion (rule of thumb: 1/focal length seconds)



Calibrating Image Distortions

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- Distortions are described by high-order polynomials in the distance from the image center
  - Distortions are normally small in central image area
  - Distortions rapidly increase at image boundaries
- It is critical that the calibration grid covers the entire image, particularly close to the boundaries, to accurately calibrate lens distortions
- Short focal-length (and inexpensive) lenses require higher-order polynomials and can only be calibrated with a large number of images

High-Magnification Calibration

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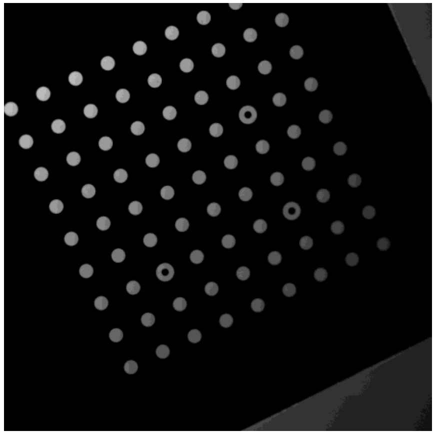
- For high magnifications, glass grids are used
  - Background lighting
  - Positioning



- Strong tilt becomes very difficult at smaller FOV's
  - "High-magnification" options
- DOF concerns
  - Calibrating in front may be impossible

correlated SOLUTIONS

High-Speed Calibration

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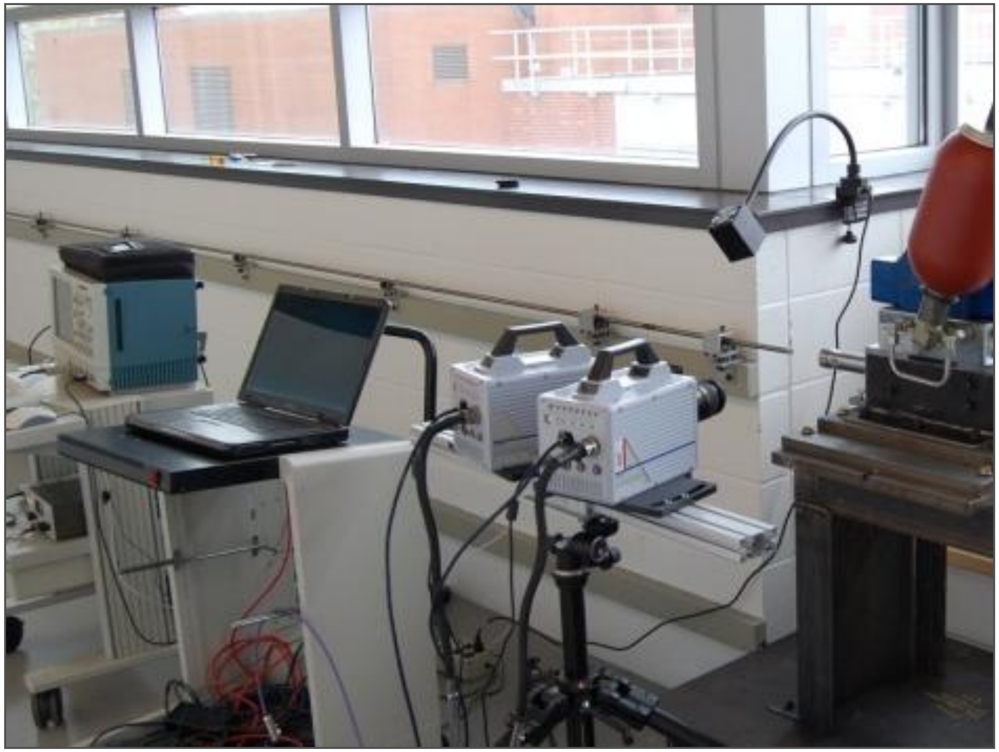
- Full resolution calibration
  - Crop adjustment
- DOF concerns
  - Calibrating in front may be impossible



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- Calibration for camera parameters and relative orientation is required
- Calibration is a shape measurement of the target
  - Target can be arbitrarily shaped and unknown
  - A length scale on the target has to be known
  - Large rotations of the target are required for accurate calibration
- Distortions require that target fills entire image
- Short or inexpensive lenses require a large number of images to calibrate distortions
- High-magnification
- High-speed

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- B/W cameras with sufficient frame rate to capture the event
- Rigid setup, well focused and clean optics/sensor
- Synchronized cameras
- Uniform, dense speckle patterns with no specular reflections
- Sufficient number of calibration images in suitable orientations
- Good experimental techniques!

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Questions?