Dipartimento Meccanica Matematica Management

MUR Dipartimento di Eccellenza 2018-2022 2023-2027

"Data Science Applications in Physics"

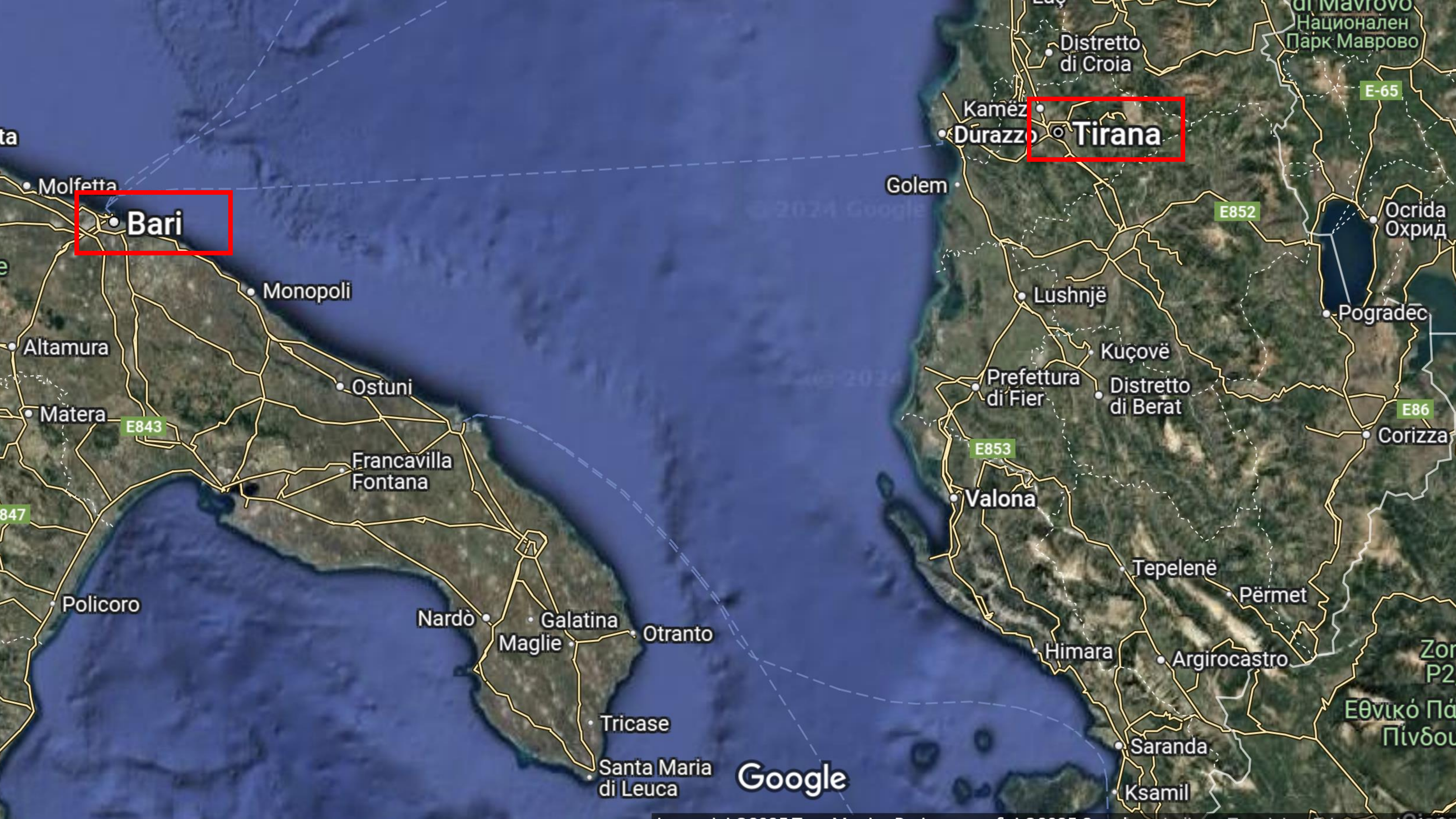
Winter School in Tirana 2025

Optical and Interferometric Methods for Material Characterization and Dimensional Analysis

Mon 27th January 2025

Giovanni Pappalettera

Faculty of Natural Sciences
Hall 413 B - Tirana



Distretto di Croia
Национален Парк Маврово
E-65
Kamëz
Durazzo
Tirana
Molfetta
Bari
Golem
E852
Ocrida Охрид
Monopoli
Lushnjë
Pogradec
Altamura
Kuçovë
Ostuni
Prefettura di Fier
Distretto di Berat
Matera
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E853
Francavilla Fontana
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Otranto
Maglie
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Argirocastro
Tricase
Saranda
Santa Maria di Leuca
Google
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Politecnico
di Bari
ENNIO CUSANO

POLITECNICO DI BARI IN NUMBERS

9.755 ENROLLED STUDENT WITH 2.980 WOMEN AND 132 FOREIGN STUDENTS

05 DEPARTMENTS

655 PROFESSORS and RESEARCHERS 184 WOMEN

265 NON TEACHING STAFF 126 WOMEN

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1990
POLITECNICO DI BARI

Dipartimento
Meccanica
Matematica
Management

MUR
Dipartimento
di Eccellenza
2018-2022
2023-2027

MECHANICS, MATHEMATICS and MANAGEMENT DEPARTMENT

SEAL of *EXCELLENCE DEPARTMENT*

2018-2022

2023-2027

A recognition given by the Italian Ministry of University and Research Selecting among 800 University Department

Best Ranking in the Industrial Area

Teaching Offer

Bachelor

- Mechanical Engineering
- Management Engineering
- Aerospace Systems Engineering(TA)
- Industrial and Naval Systems Engineering (TA)

Master

- Mechanical Engineering
- Management Engineering
- Energetic Engineering
- Mechanical Engineering

Post Lauream

- **PhD** Mechanical and Energetic Engineering (DRIME)
- **PhD** Management Engineering (DRIG)
- **PhD** Engineering and Aerospace Systems(DRISA)

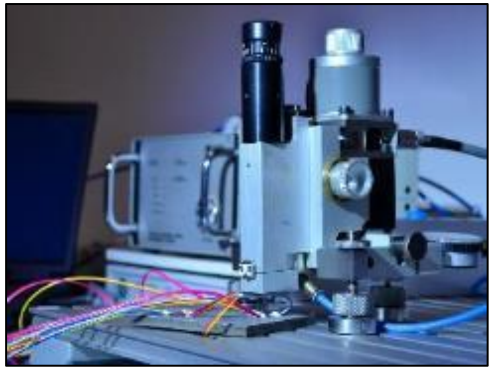
EXPERIMENTAL MECHANICS Lab.

Coordinator: Katia Casavola, ME, PhD, Full Professor – katia.casavola@poliba.it

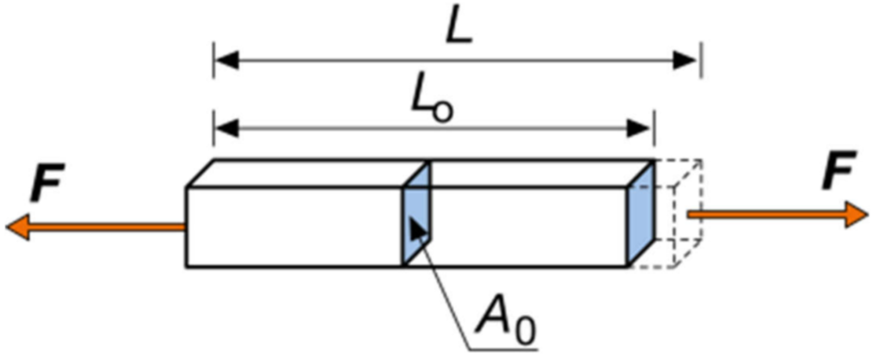
Staff: C. Barile, V. Moramarco, G. Pappalettera - Phd, Ass. Prof. / Researchers

Others: 1 researcher RTDA, 3 post doc, 3 PhD students, 1 technician

Founder of the Lab: Carmine Pappalettere – Prof. Emeritus

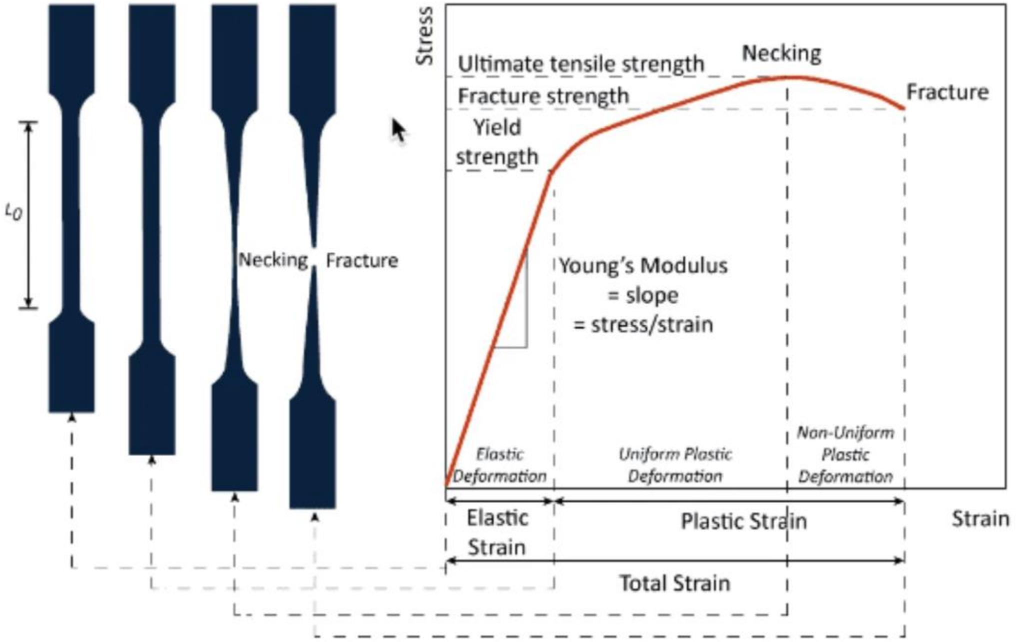


Stress and Strain



$$\sigma = \frac{F}{A}$$

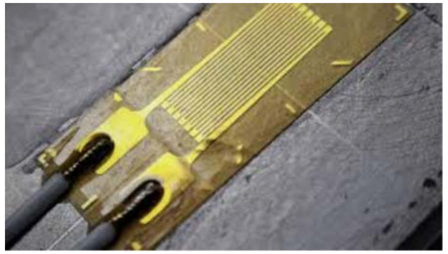
$$\varepsilon = \frac{\Delta L}{L_0}$$



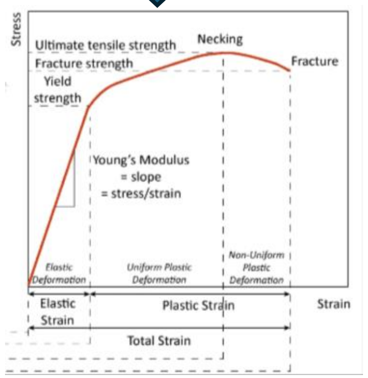
Stress

Strain

Apply Load



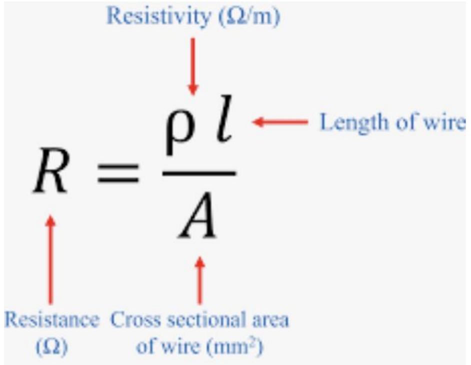
Measure Deformation

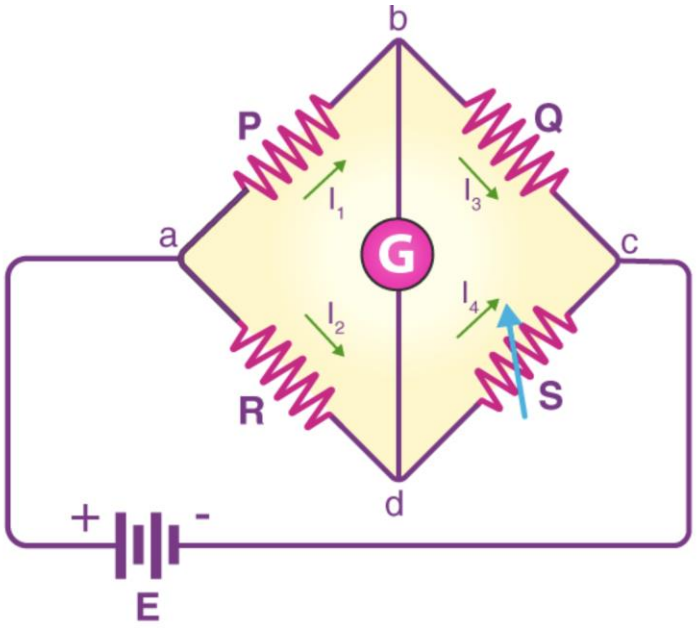


Get Stress/Strain Curve

Strain Measurement: Strain Gauge

Dimensional variation of the strain gauge change its resistivity

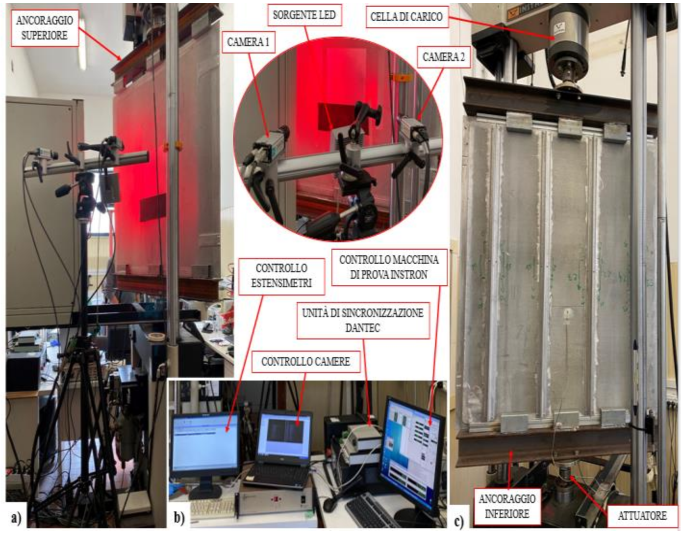




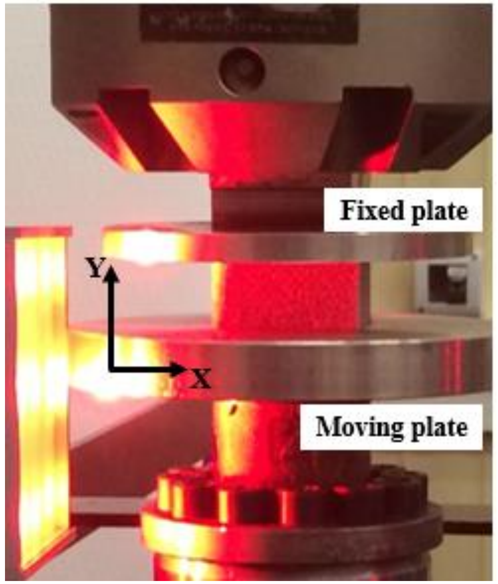
Wheatstone Bridge

$$\epsilon = \frac{l - l_0}{l_0}$$

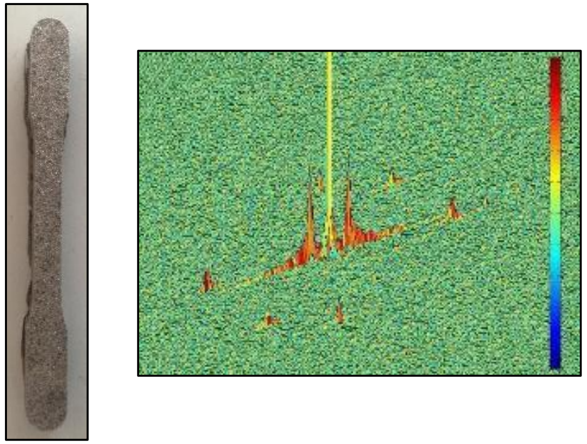
Strain Gauges limitations



Aluminum foam stringered panel

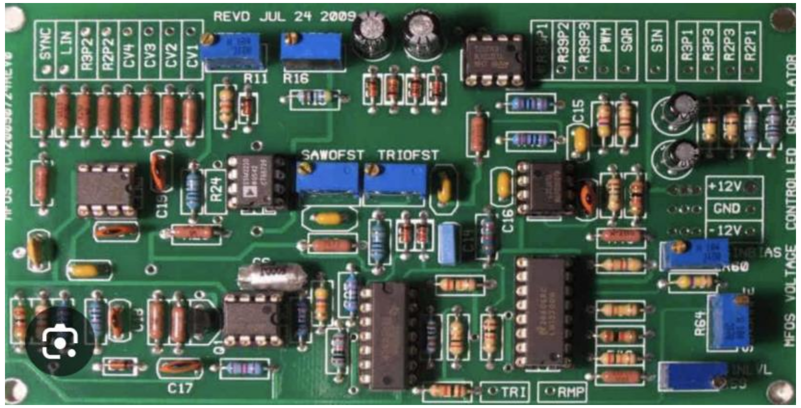


PU foam



Corrosion onset

CFRP Composite



PCB Board

Why optical Methods?

Every time we are looking for:

- No contact
- No destructive
- High resolution
- High sensitivity

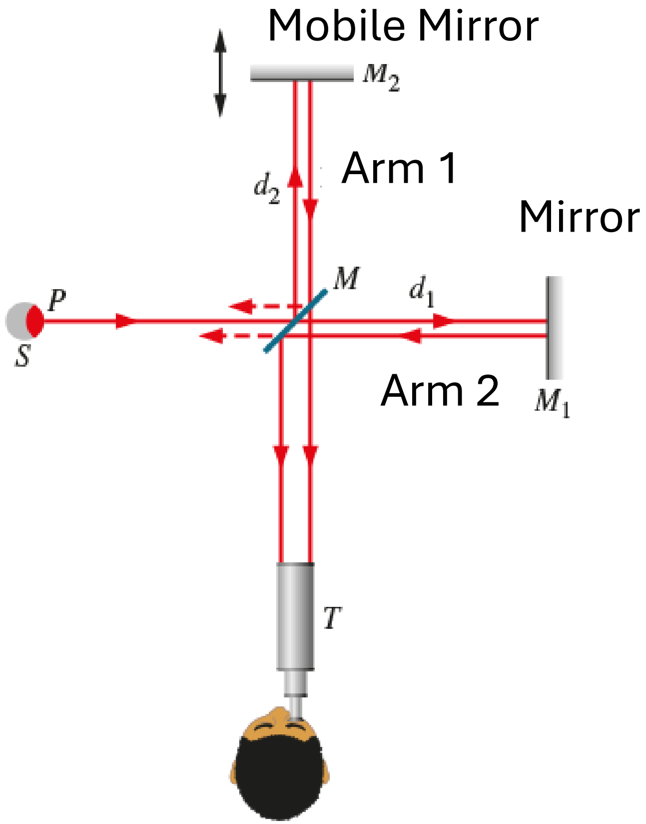
Which optical Methods?

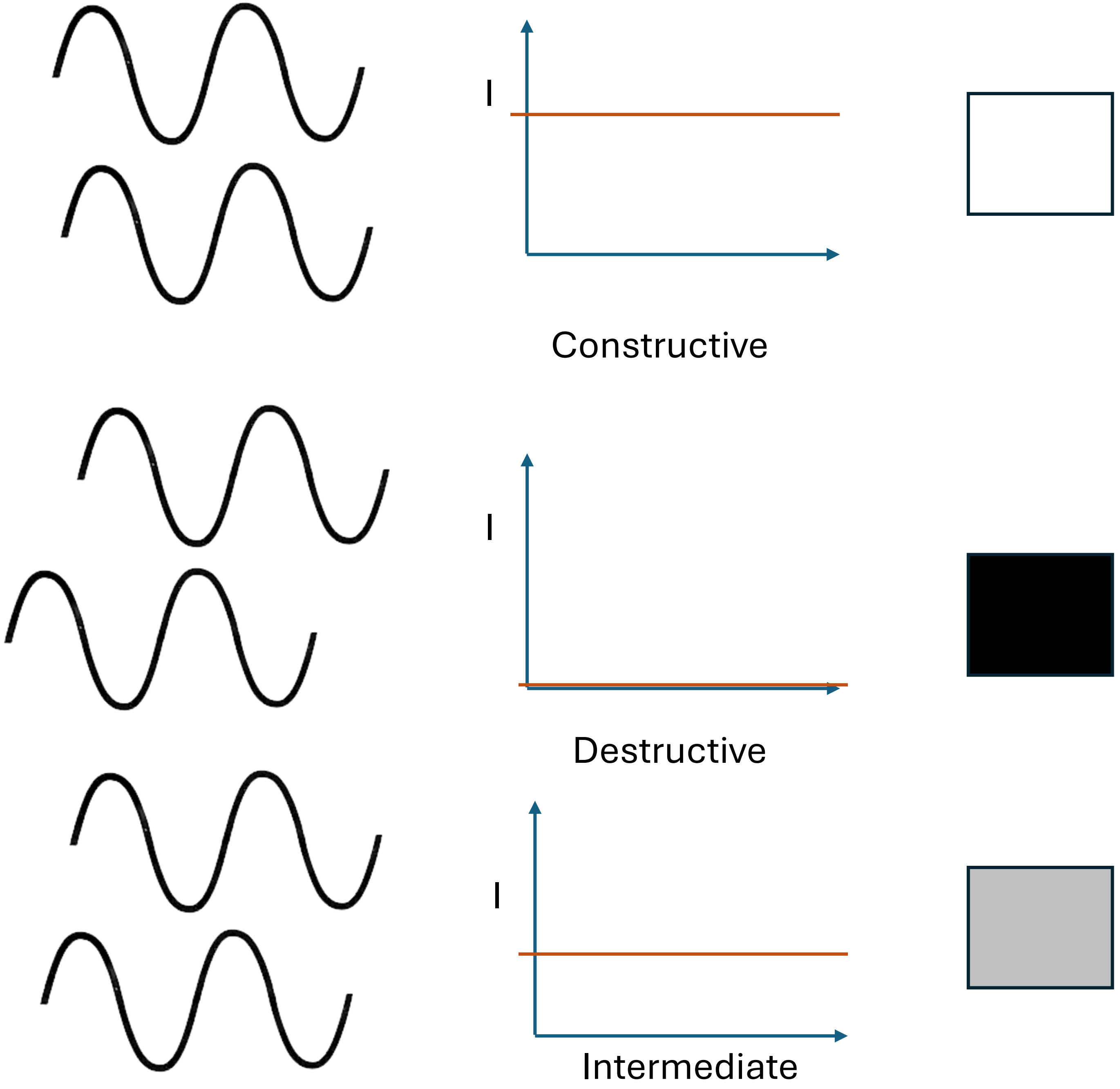
- **Speckle Interferometry**
- **Moirè Methods**
- **Fringe Projection Methods**
- Digital Holography
- Shearography
- Photoelasticity
- **DIC**
- .....

Interferometric Implementation

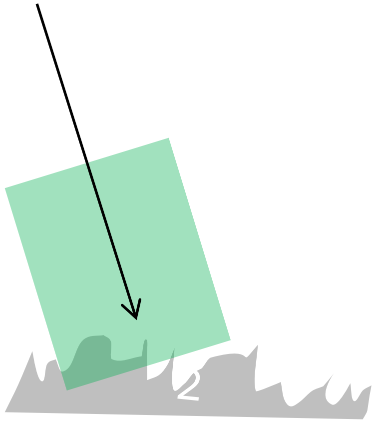
Non Interferometric Implementation

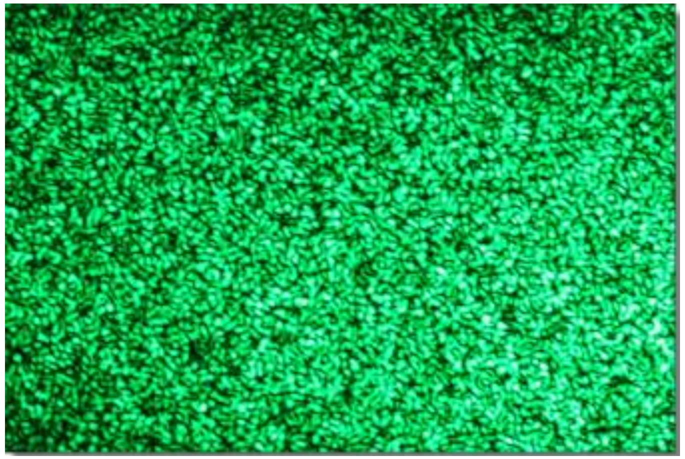
Interferometric Methods

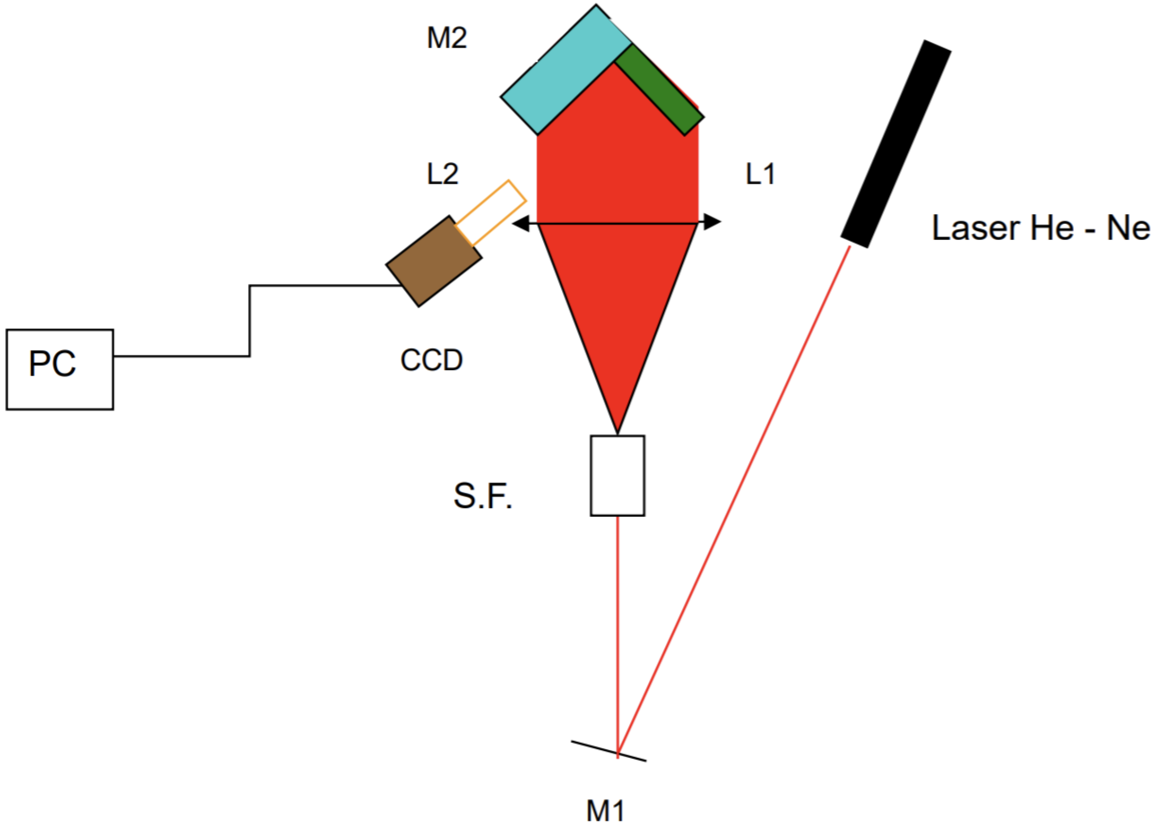


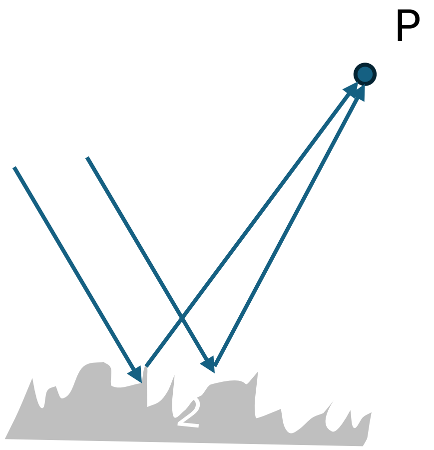


Speckle Methods



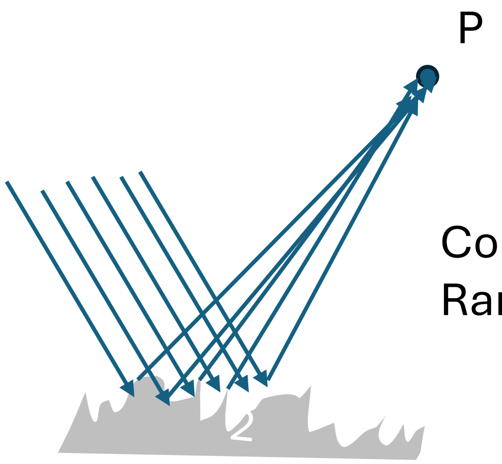






Intensity?

Constructive/Destructive



Intensity?

Constructive/Destructive
Randomly determined

Principle of Fringe Analysis

h ⟷ **Φ**

Basic idea is the relationship between phase in the pattern and the quantity to be measured

Fringes Generated by Laser Interference

$$w(x,y,t) = a(x,y)e^{i[\Phi(x,y)]},$$

This express the light wavefront at a given instant t

$$\Phi(x,y) = \frac{2\pi h(x,y)}{\lambda}$$

Phase can be express as a function of the travelled path h(x,y)

Principle of Fringe Analysis

Fringes Generated by Laser Interference

Let’s suppose now to have two wavefront and let’s call them reference and test

$$w_r(x,y) = a_r(x,y)e^{i[\Phi_r(x,y)]},$$

$$w_t(x,y) = a_t(x,y)e^{i[\Phi_t(x,y)]},$$

Let’s make them interfere on a surface

$$w(x,y) = w_r(x,y) + w_t(x,y).$$

Leading to an intensity

$$I(x,y,t) = |w_r(x,y) + w_t(x,y)|^2,$$

Principle of Fringe Analysis

$$I(x,y,t) = I'(x,y) + I''(x,y)\cos\left[\Phi_t(x,y) - \Phi_r(x,y)\right],$$

Where

$$I'(x,y) = a_r^2(x,y) + a_t^2(x,y)$$

$$I''(x,y) = 2a_r(x,y)a_t(x,y)$$

$$\cos\alpha \cdot \cos\beta = \frac{1}{2}\left[\cos(\alpha+\beta) + \cos(\alpha-\beta)\right]$$

$$\sin\alpha \cdot \cos\beta = \frac{1}{2}\left[\sin(\alpha+\beta) + \sin(\alpha-\beta)\right]$$

We can set

$$\phi(x,y) = \Phi_t(x,y) - \Phi_r(x,y),$$

We get the fundamental equation of the fringe analysis

$$I(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y)\right],$$

Principle of Fringe Analysis

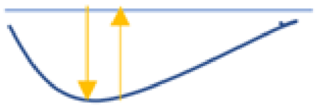
$$I(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y)\right],$$

Background

Contrast

Phase

$$h(x,y) = \frac{\phi(x,y)\lambda}{2\pi},$$



$$h(x,y) = \frac{\phi(x,y)\lambda}{4\pi}.$$

Principle of Fringe Analysis

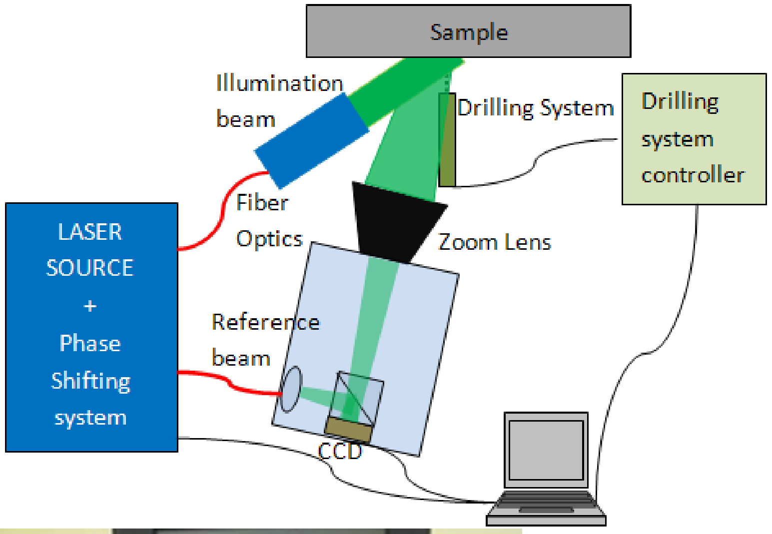
How I can extract the phase? **PHASE SHIFTING**

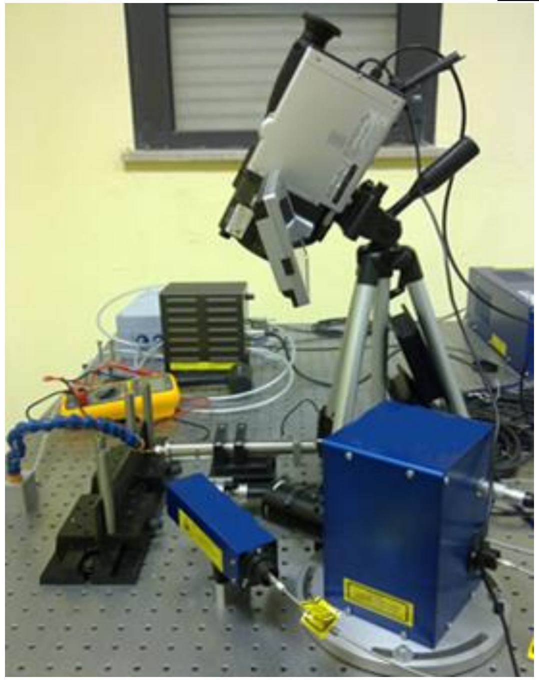
$$\begin{cases} I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) - \alpha], \\ I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y)], \\ I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \alpha]. \end{cases}$$

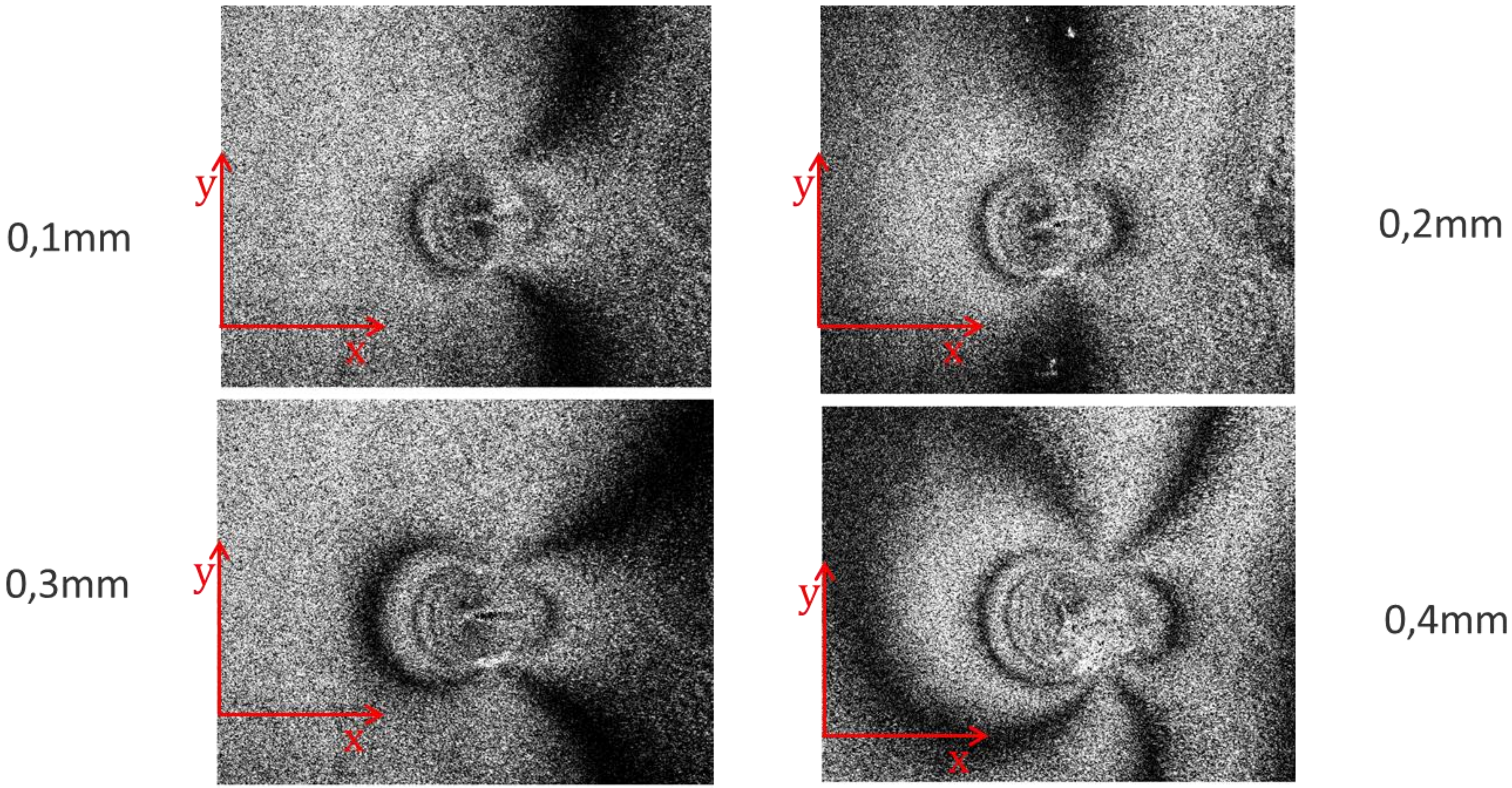
Three Step Phase Shifting

$$\phi(x,y) = \tan^{-1}\left[\frac{(1-\cos\alpha)(I_1 - I_3)}{\sin\alpha(2I_2 - I_1 - I_3)}\right]$$

Principle of Fringe Analysis: one application



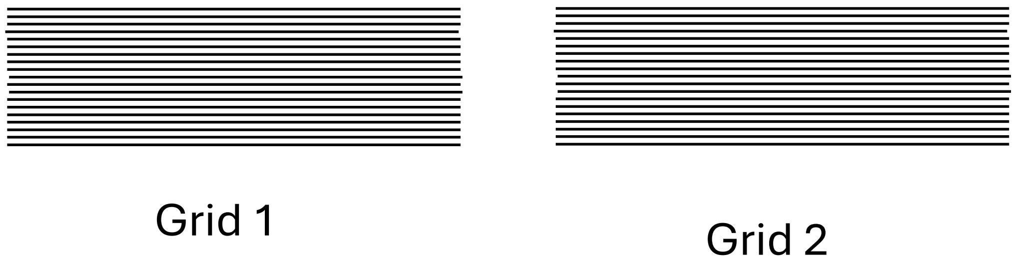


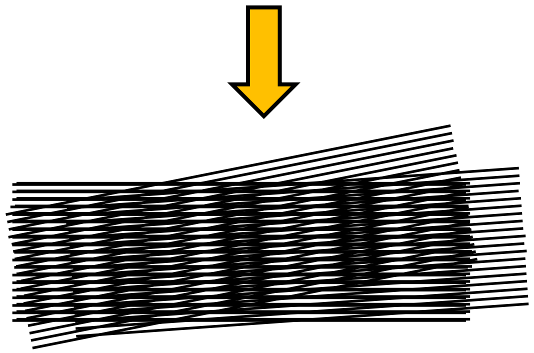


1 DPSS, λ=532 nm, P=25 mW laser source
1 CCD camera 640x480 ;
1 Electronically controlled cutter
1 Precision Translational stage
1 Compressed air cleaning system
1 PC

Speckle is a noise on the fringe pattern

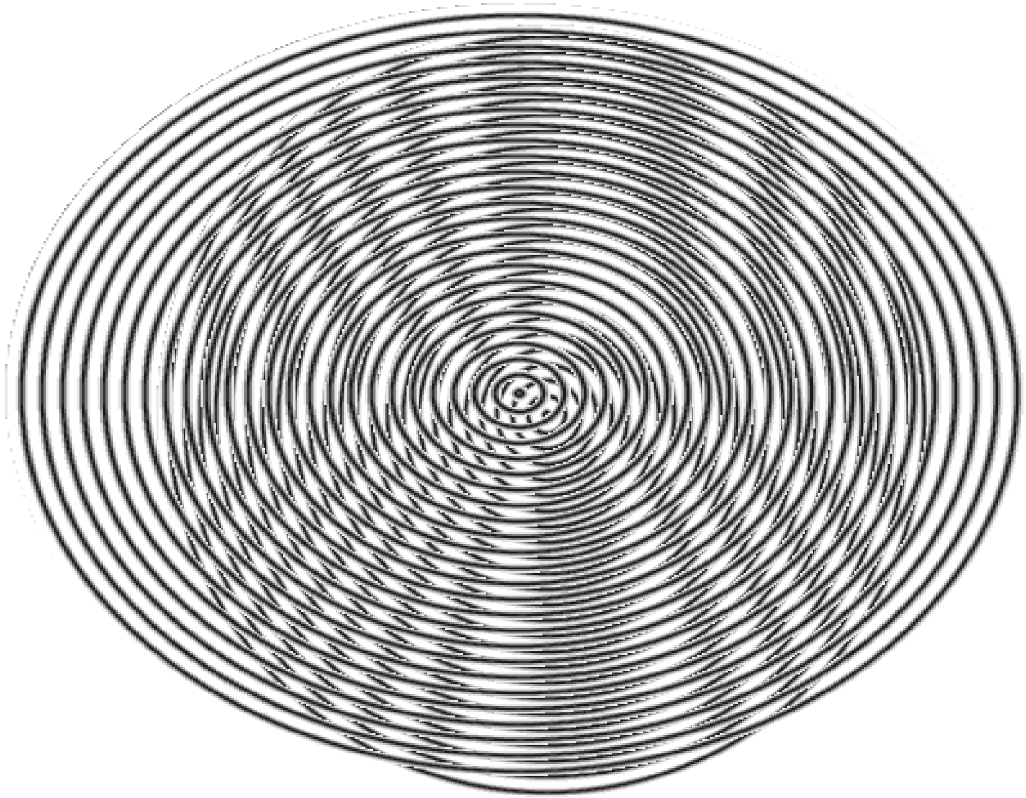
Moiré Principle

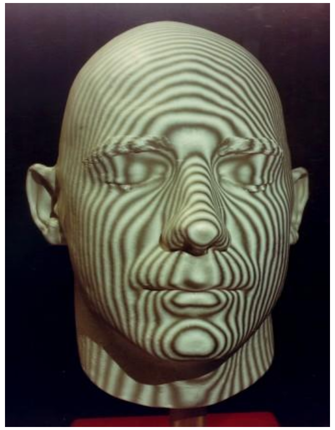


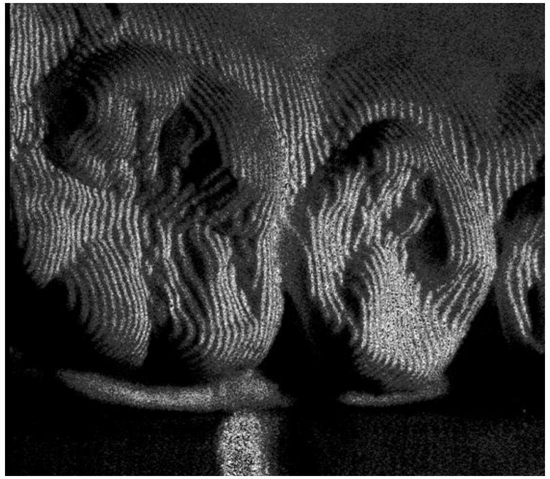


All the methods allowing to exploit this effect, overlapping even electronically these two grids are called moiré

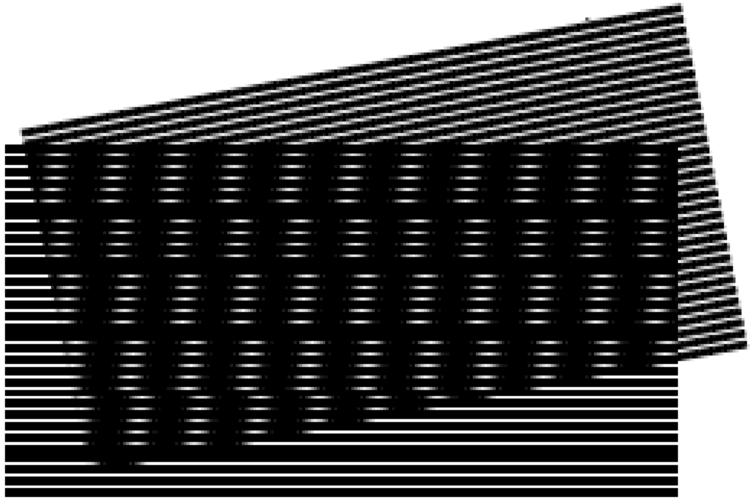
Moiré Principle

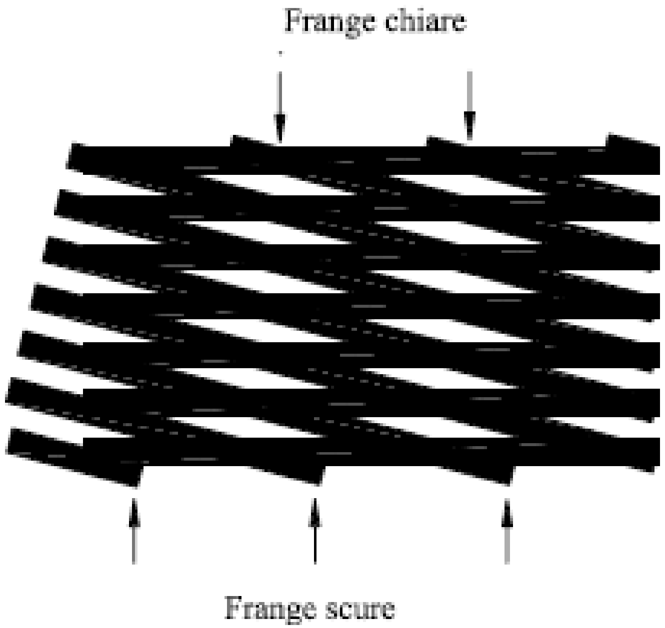






Moiré Method



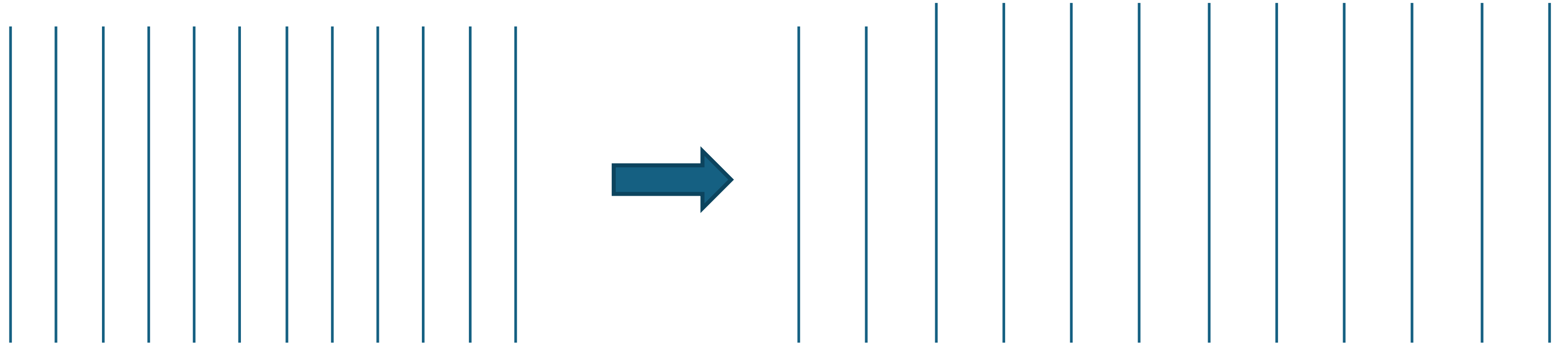


- Geometric Moiré
- Interferometric Moiré
- Reflection Moiré
- Shadow moiré

$u=pN_x$ $v=pN_y$ → In plane displacement

$w=KpN_z$ → Out of plane displacement

Moiré Method



p

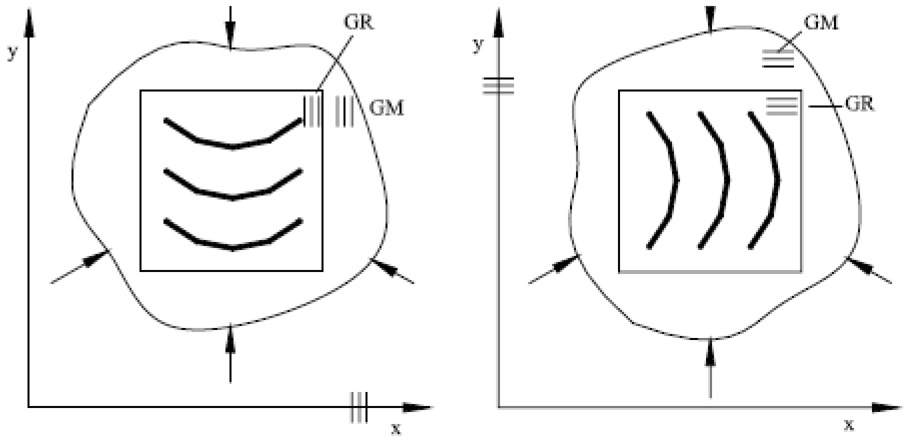
P’

p’=(dp)/(d±p)

d=moiré fringes distance

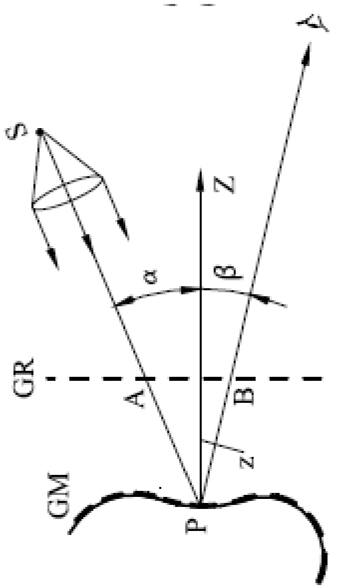
$$\varepsilon_x = \frac{\partial u}{\partial x},\ \varepsilon_y = \frac{\partial v}{\partial x},\ \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \quad \Rightarrow \quad \varepsilon_x = p\frac{\partial N_x}{\partial x},\ \varepsilon_y = p\frac{\partial N_y}{\partial y},\ \gamma_{xy} = p\left(\frac{\partial N_x}{\partial y} + \frac{\partial N_y}{\partial x}\right)$$

Moiré Method



$$\varepsilon_x = p\frac{\partial N_x}{\partial x},\quad \varepsilon_y = p\frac{\partial N_y}{\partial y},\quad \gamma_{xy} = p\left(\frac{\partial N_x}{\partial y} + \frac{\partial N_y}{\partial x}\right)$$

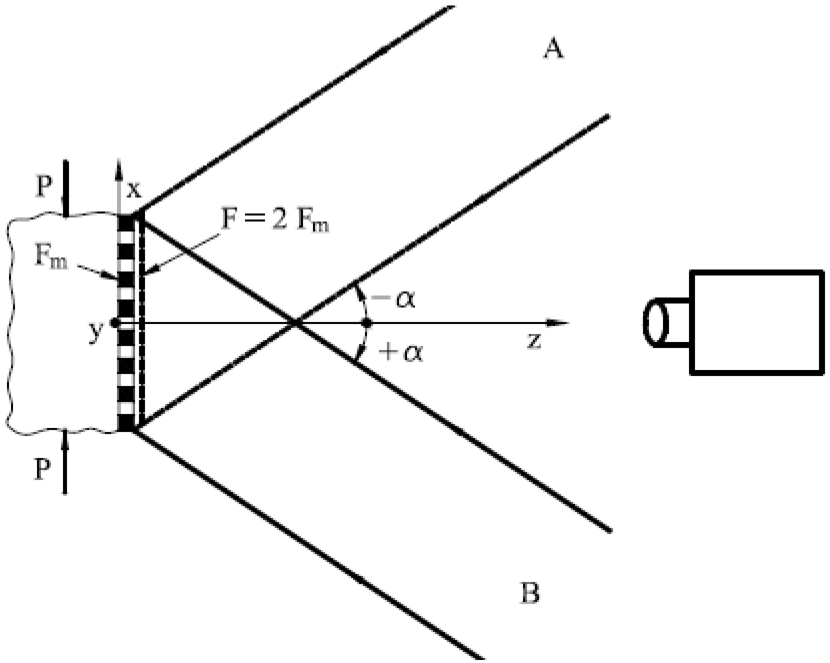
Plane moiré



$$z = \frac{p}{\tan\alpha + \tan\beta}N$$

Shadow Moiré

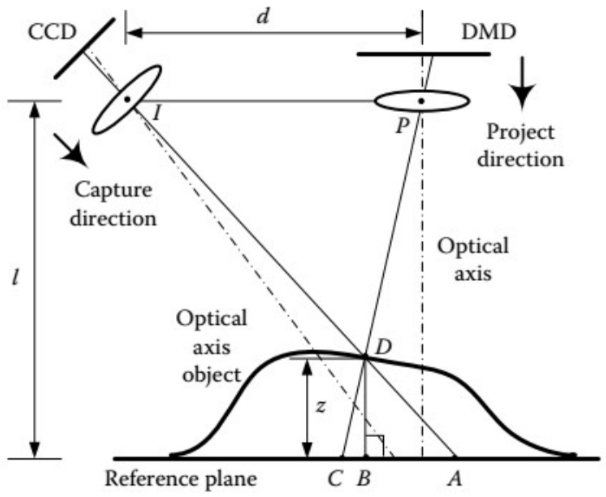
Moiré Method



Interferometric Moiré

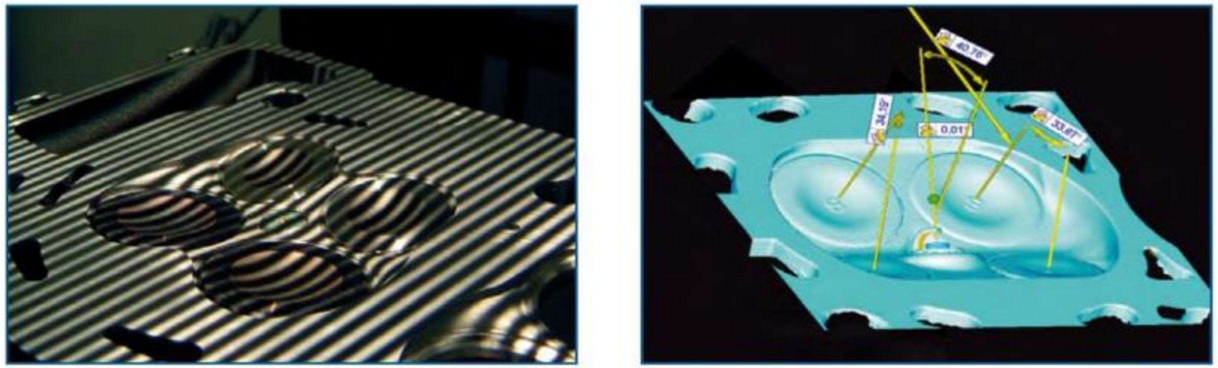
u=pNx

Fringe Projection Methods



$$\Phi_D = \Phi^r_C.$$

$$\Phi^r_A \leftarrow \Phi_D.$$



Acquisition of a motor combustion chamber by fringe (stripe) projection; analysis of the three-dimensional dataset (measuring area 100 x 100 mm)

If I subtract two phase map on the object and on the phase plane I get this:

$$\Delta\Phi_{DA} = \Phi_D - \Phi^r_A = \Phi^r_C - \Phi^r_A = \Delta\Phi^r_{AC}.$$

PID CAD Similar Triangles

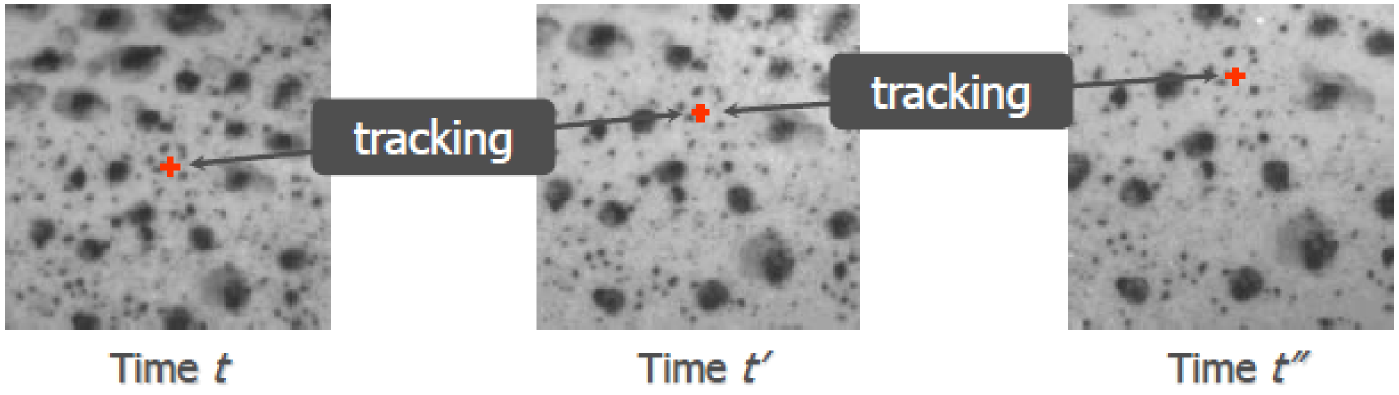
DB:AC=(l-z)/d → zd=ACl -ACz→z(d+AC)=ACl→z=ACl/(d+AC)

z=AC l /d

$$z(x,y) \propto \Delta\Phi^r_{AC} = \Phi_D - \Phi^r_A$$

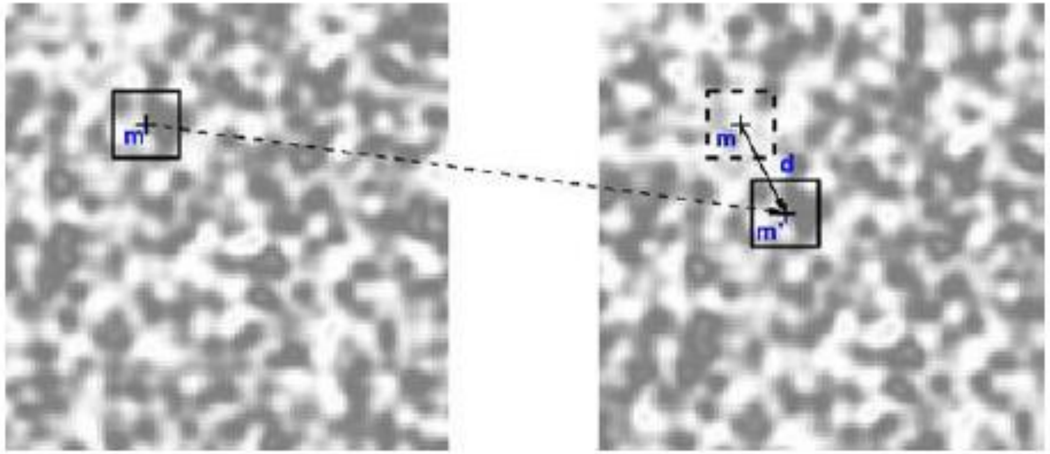
DIC

- 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**



DIC

- **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**

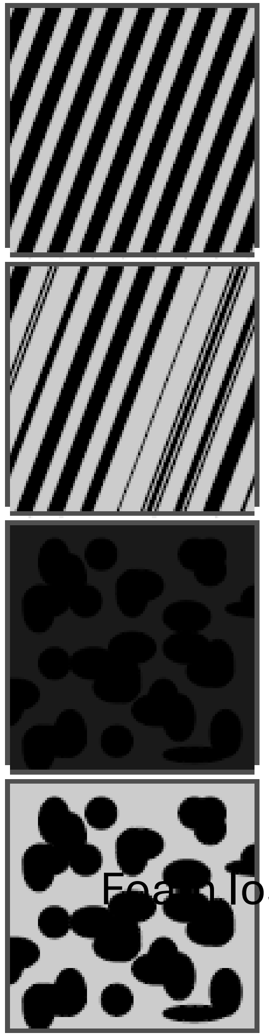


Time *t*

Time *t'*

DIC

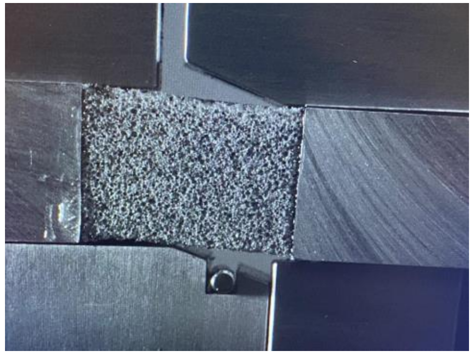
- The uniqueness of each signature is only guaranteed if the surface has a **non repetitive, isotropic, high contrast pattern**
- **Random textures** fulfill this constraint (speckle pattern)



Foam Iosipescu

Stress Concentration Airbus

Clear Aligners



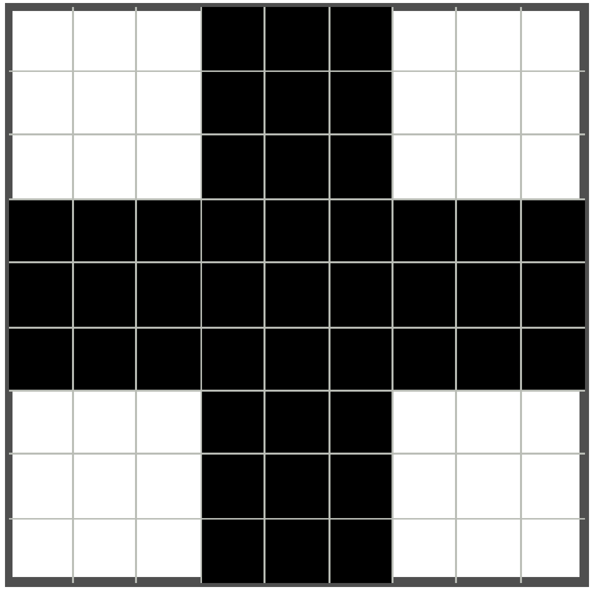
Iosipescu FOAM

DIC

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



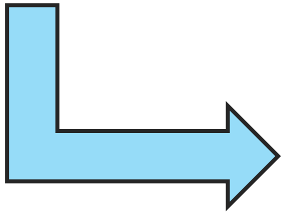
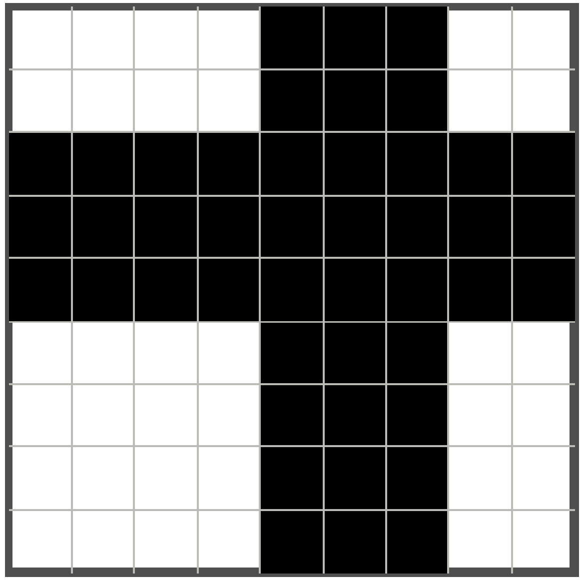


Image after motion, in memory

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



DIC

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

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

DIC

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

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

$$(100-0)^2+(0-0)^2+(0-0)^2+(0-0)^2+(100-0)^2+$$
$$(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+$$
$$(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+$$
$$(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+$$
$$(100-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(100-0)^2=18{,}000$$

Image before motion — (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 after motion — (u;v)=(-2;-2)

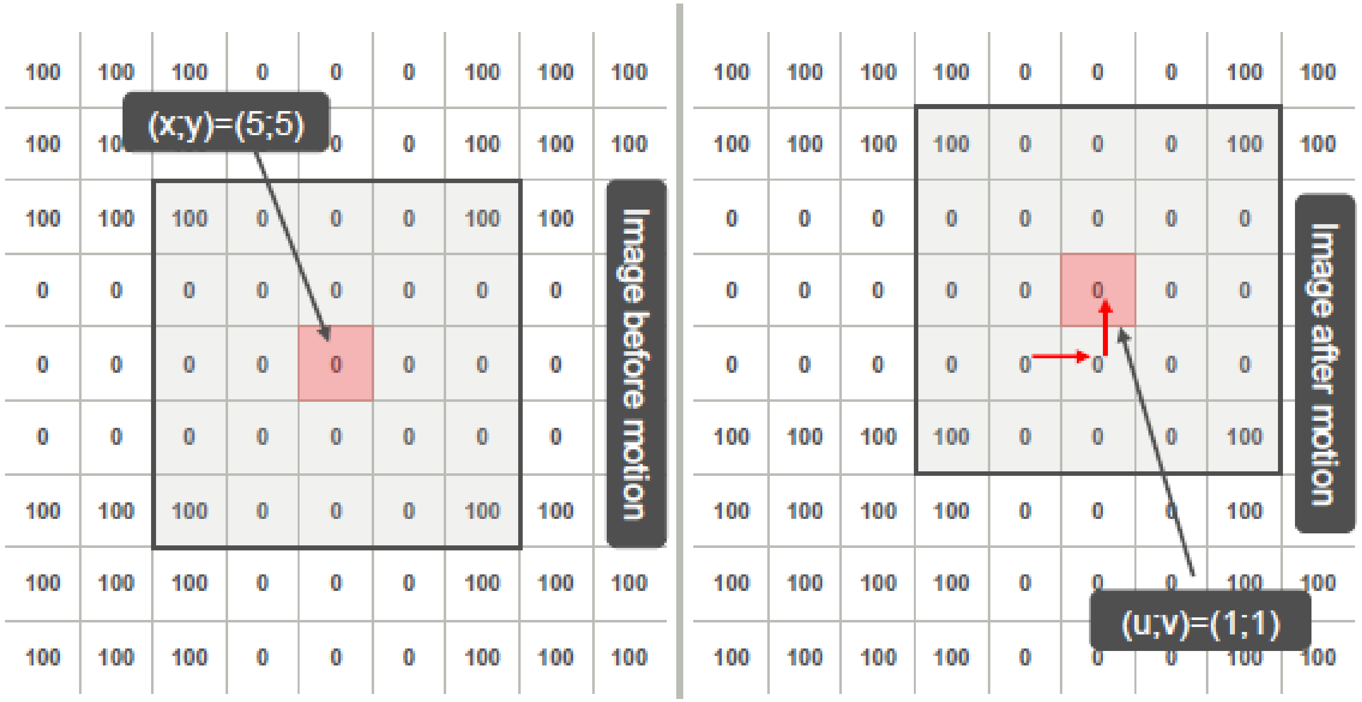
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
100	100	100	100	0	0	0	100	[illegible]
100	100	100	100	0	0	0	100	[illegible]
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

DIC

- 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)



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

Perfect Match!

DIC

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

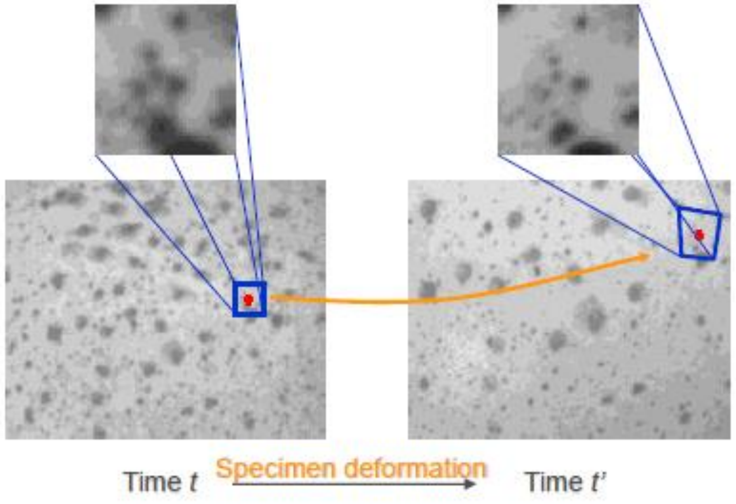
99	100	101	102	3	0	2	100	102
101	97	98	101	1	2	0	96	102
0	1	3	3	2	0	1	2	0
1	0	3	0	2	1	1	0	3
1	3	2	0	1	1	2	2	0
101	100	100	103	0	2	1	102	101
97	99	100	101	3	2	0	97	101
101	103	98	101	0	1	1	99	96
102	99	96	103	2	3	3	102	100

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

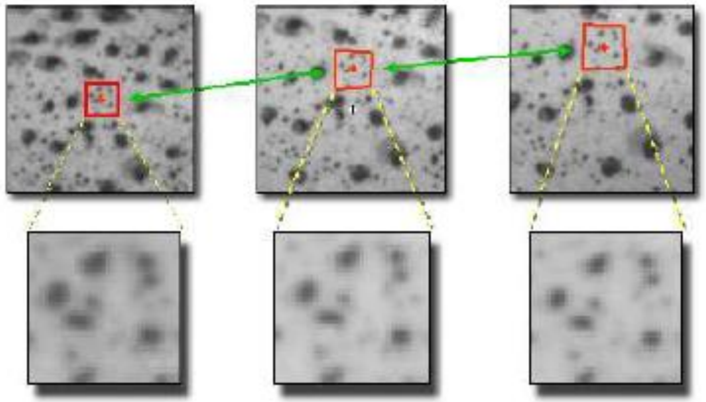
Best Match!

DIC

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

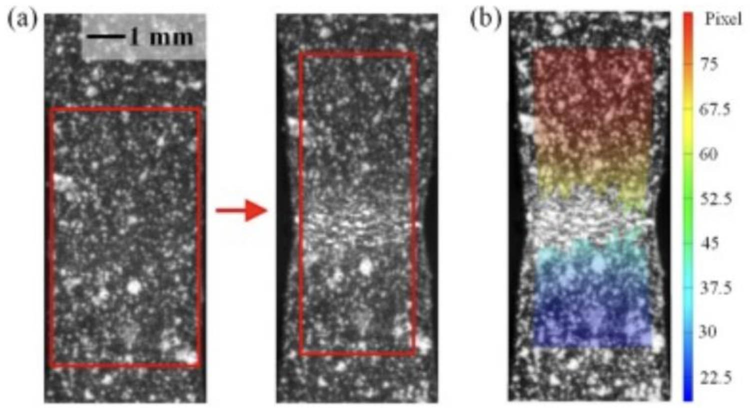


- Solution: model this displacement transformation (called **subset shape function**) and use it to define the deformed subset



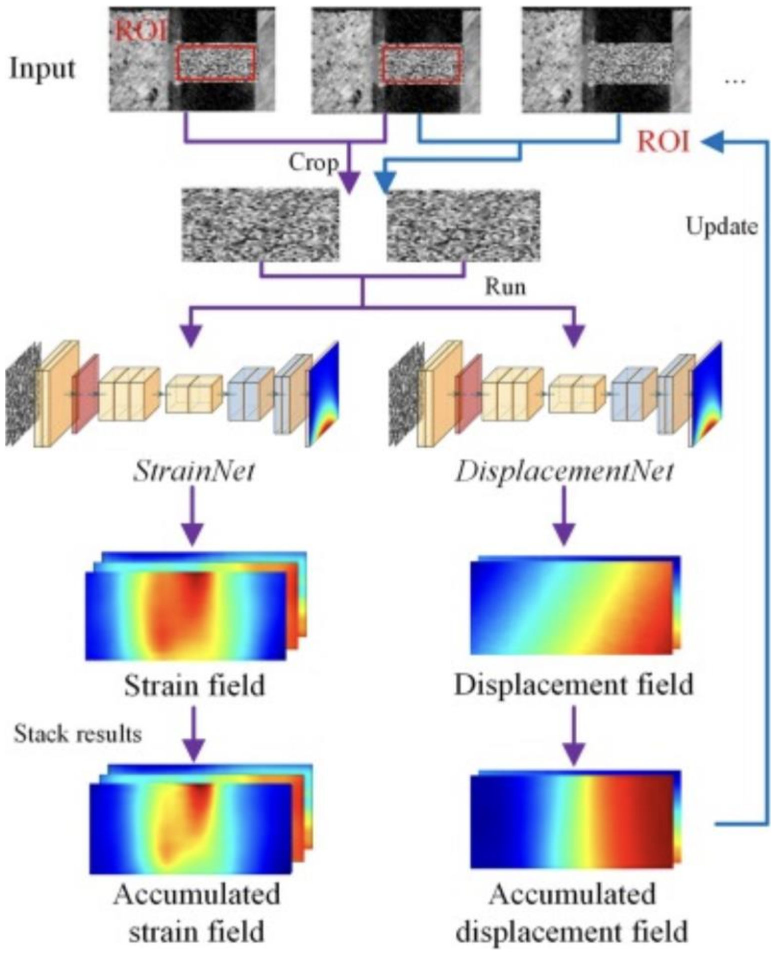
DIC current challenges and Machine Learning

- Improve Computational Time going toward real time evaluation
- Reduce error in calculating strain from displacement
- Manage with issue at high deformation up to paint breaking



Ru Yang, Yang Li, Danielle Zeng, Ping Guo, Deep DIC: Deep learning-based digital image correlation for end-to-end displacement and strain measurement. Journal of Materials Processing Technology, 302, 2022

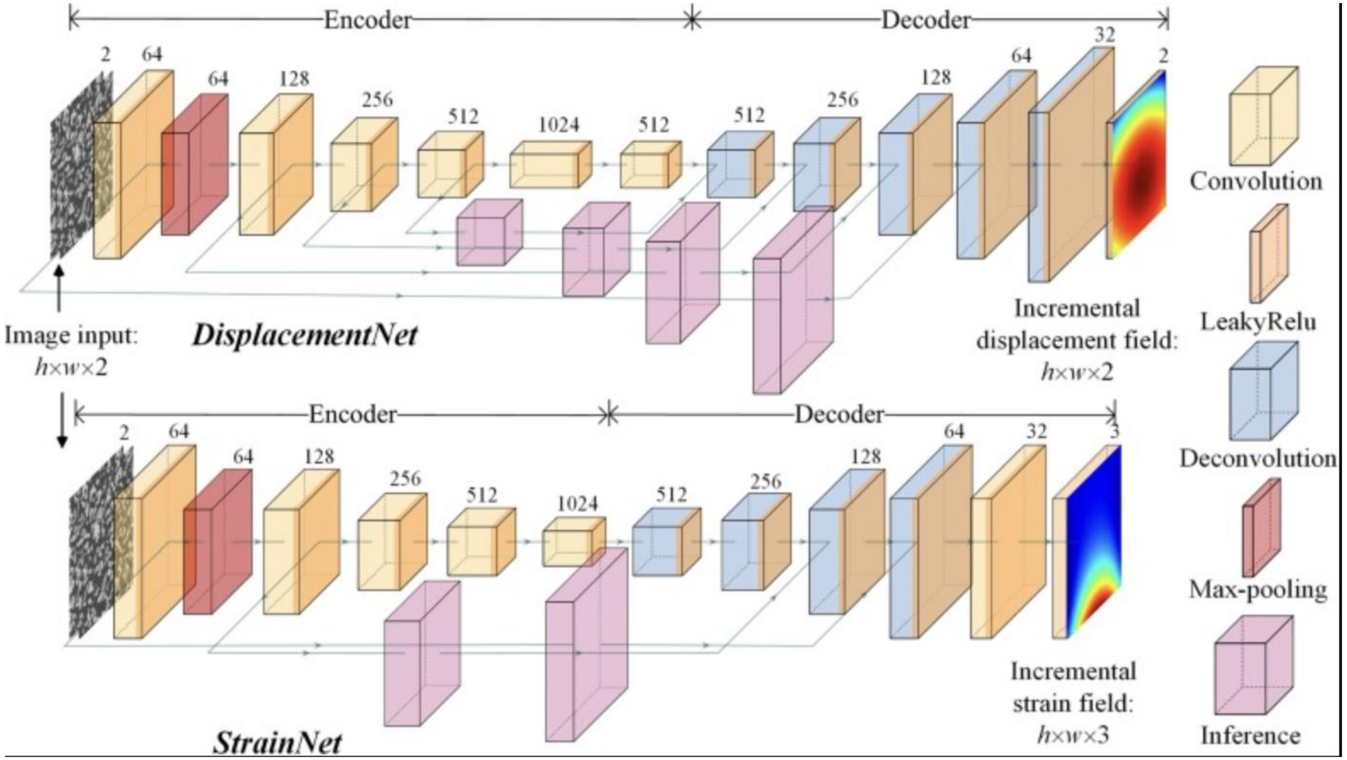
DIC current challenges and Machine Learning



Three ideas:

- Two separate net for Displacement and Strain
- Displacement and Strain Calculated in the incremental way
- Accumulated displacement is used to update the ROI

DIC current challenges and Machine Learning

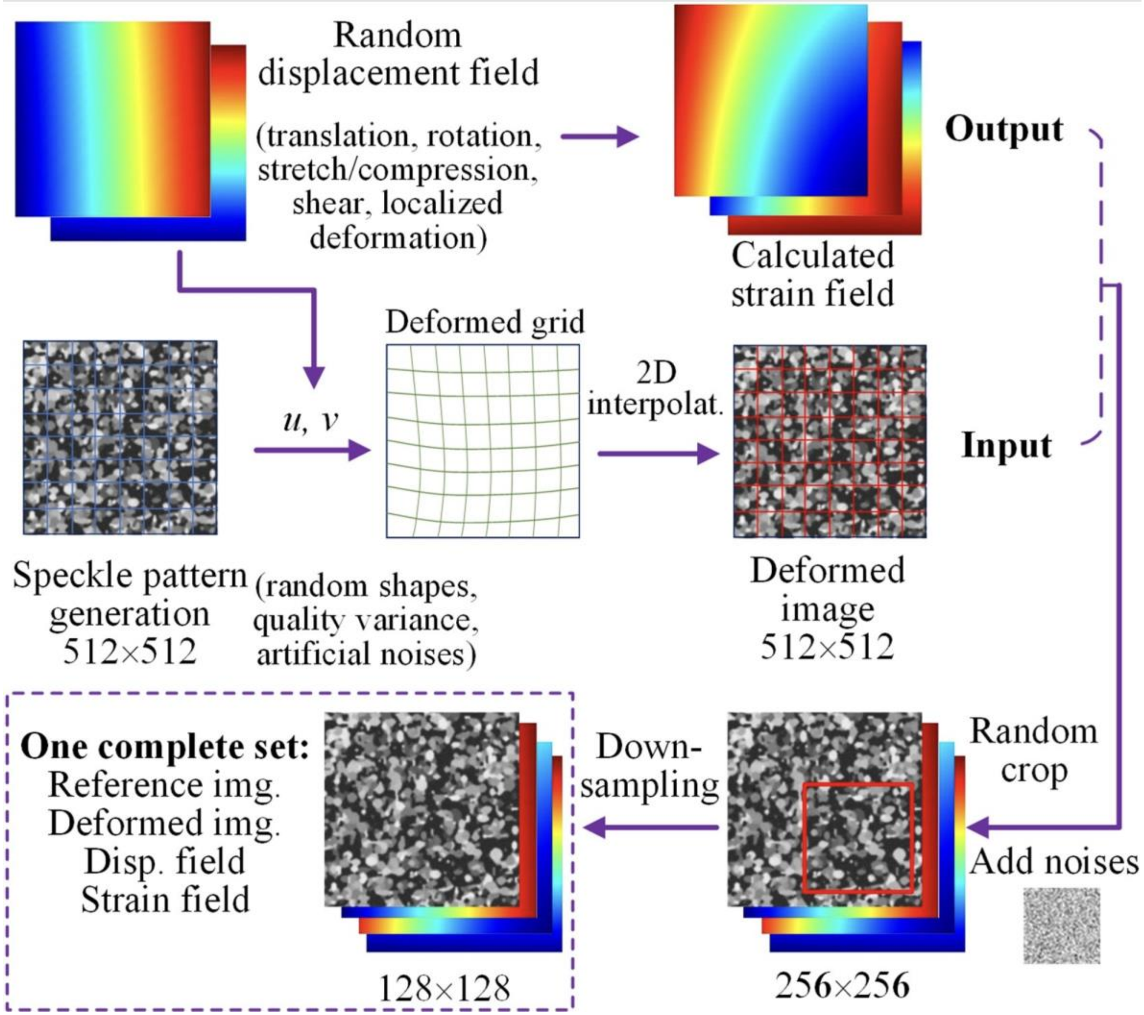


Using an encoder decoder architecture and Giving two input images (reference and calculation) you have:

Two displacement fields

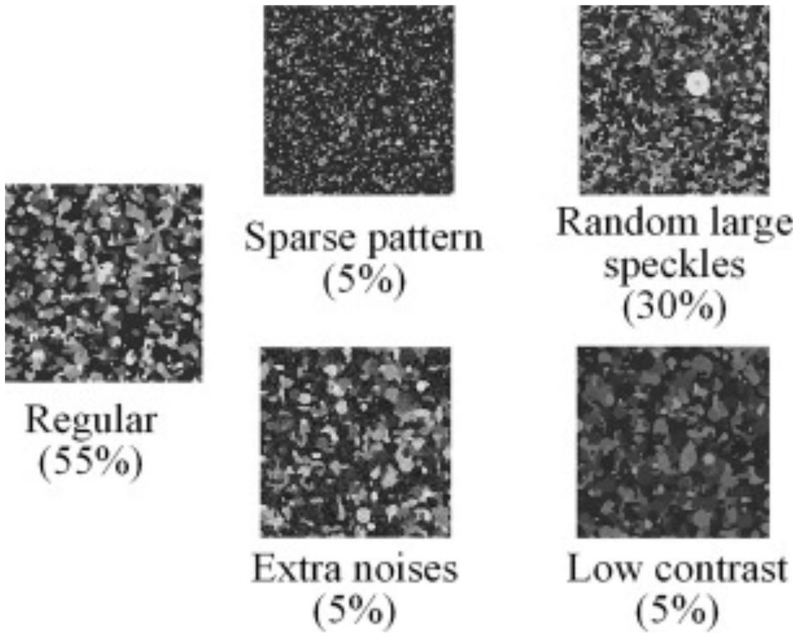
Three strain fields

DIC current challenges and Machine Learning

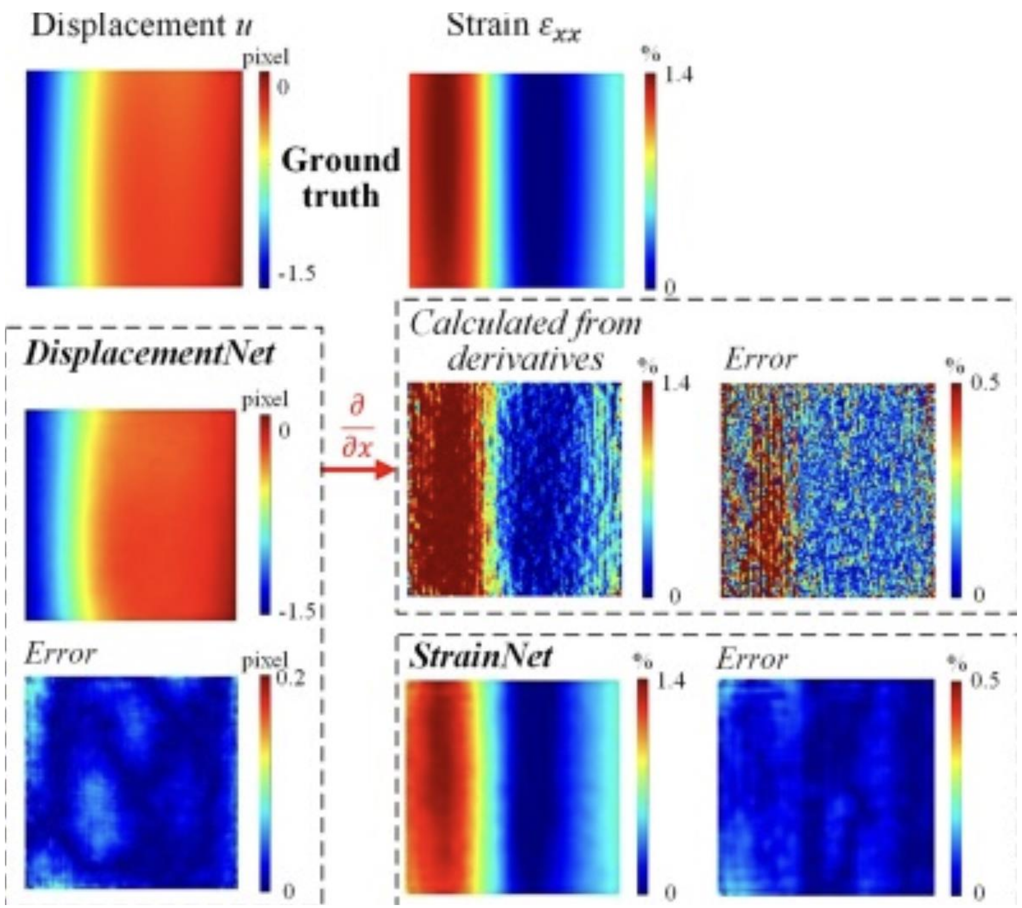


$$\begin{bmatrix}u\\v\end{bmatrix}=\underbrace{\begin{bmatrix}cos\theta & sin\theta\\ -sin\theta & cos\theta\end{bmatrix}}_{Rigidbodyrotation}\cdot\left(\underbrace{\begin{bmatrix}k_x-1&\gamma_x\\ \gamma_y & k_y-1\end{bmatrix}}_{\substack{Uniformstretch\\ andshear}}\cdot\begin{bmatrix}x\\y\end{bmatrix}+\underbrace{\begin{bmatrix}u_x^g\\u_y^g\end{bmatrix}}_{\substack{2DGaussian\\ deformation}}\right)+\underbrace{\begin{bmatrix}t_x\\t_y\end{bmatrix}}_{\substack{Rigidbody\\ translation}}$$

$$\begin{bmatrix}u_x^g\\u_y^g\end{bmatrix}=\sum_{j=1}^{N}\begin{bmatrix}A_x^j e^{-\frac{1}{2}\left(\frac{x-x_0^j}{\sigma_{x0}^j}\right)^2-\frac{1}{2}\left(\frac{y-y_0^j}{\sigma_{y0}^j}\right)^2}\\ A_y^j e^{-\frac{1}{2}\left(\frac{y-y_1^j}{\sigma_{y1}^j}\right)^2-\frac{1}{2}\left(\frac{x-x_1^j}{\sigma_{x1}^j}\right)^2}\end{bmatrix}, N=1or2$$



DIC current challenges and Machine Learning



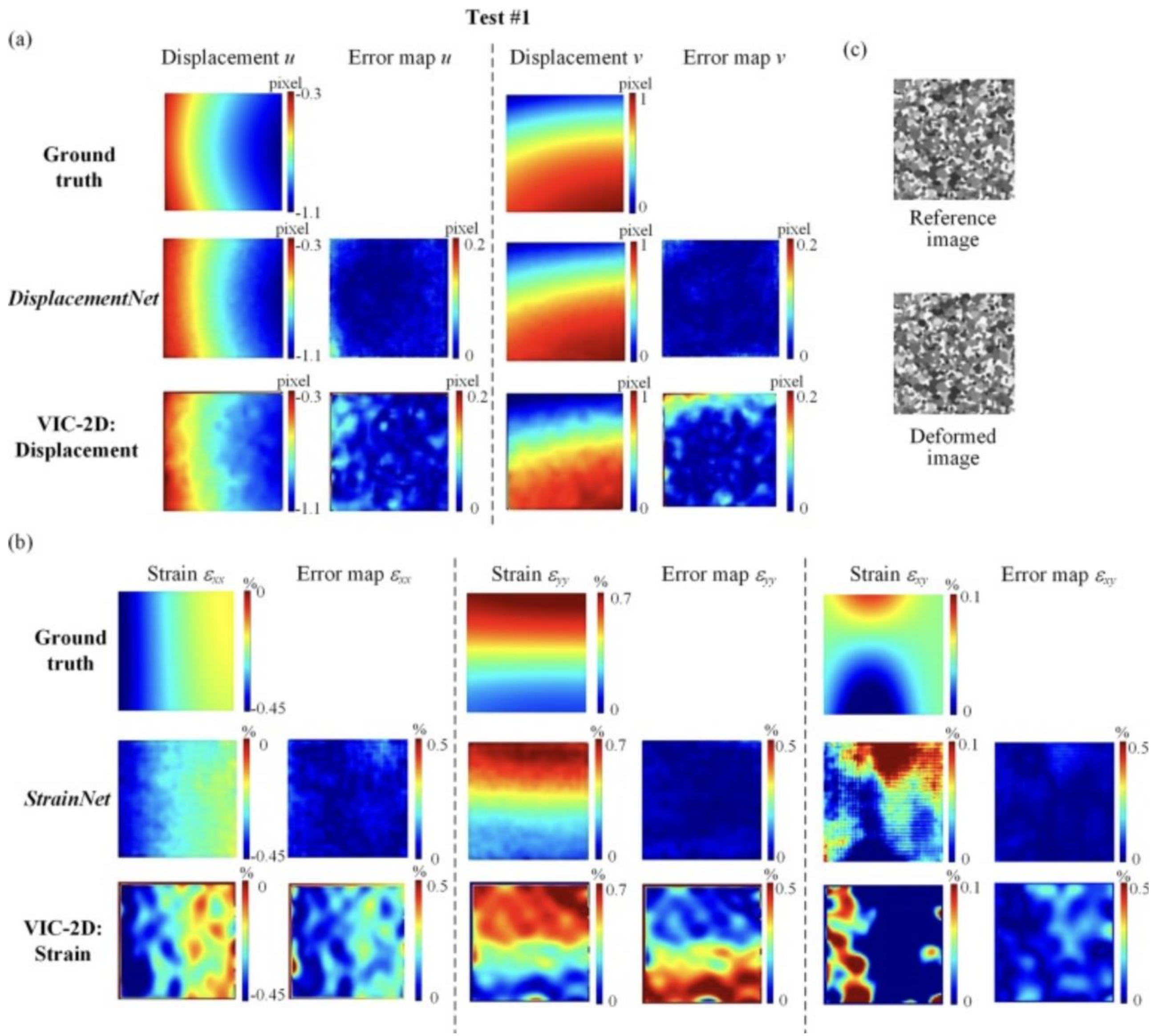
Calculated Strain Error
Max: 5.93%
Avg: 0.24 %

Strainnet Error
Max: 0.11 %
Avg: 0.018 %

Error in Strain Determination is reduced

But still not proved to manage large deformation at once

DIC current challenges and Machine Learning



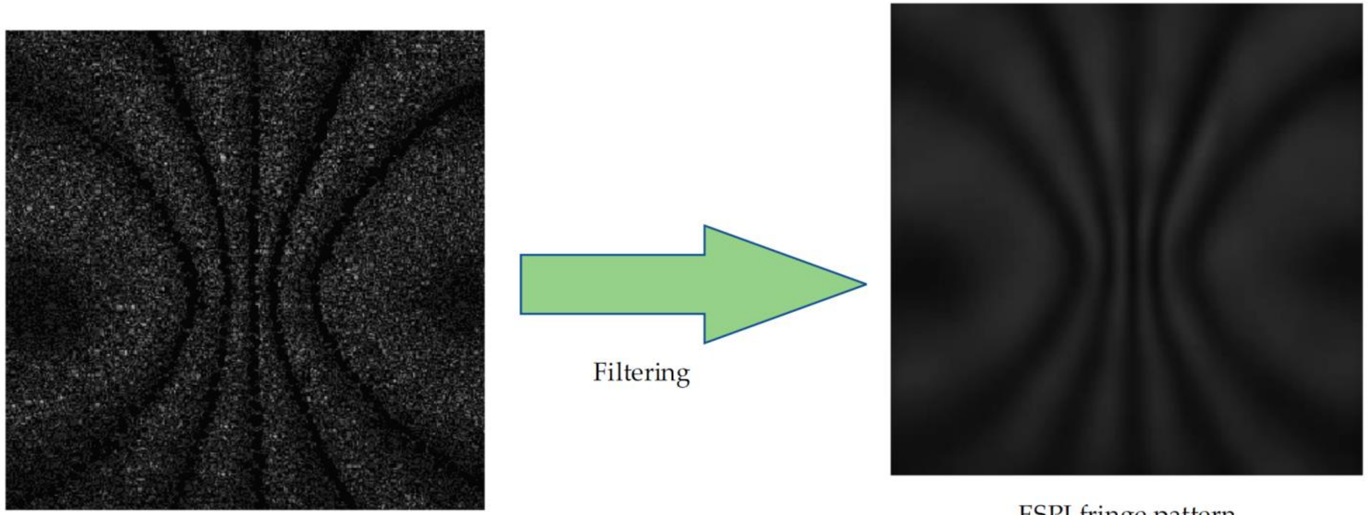
Higher accuracy both on displacement and Strain with respect to VIC-2D software

Other comparison can be done in terms of Calculation time
When applied to a sequence of 189 images
The net time for VIC 2D software was 27 s

Time for Deepnet was 2.35 s

https://github.com/RuYangNU/Deep-Dic-deep-learning-based-digital-image-correlation

ESPI current challenges and Machine Learning

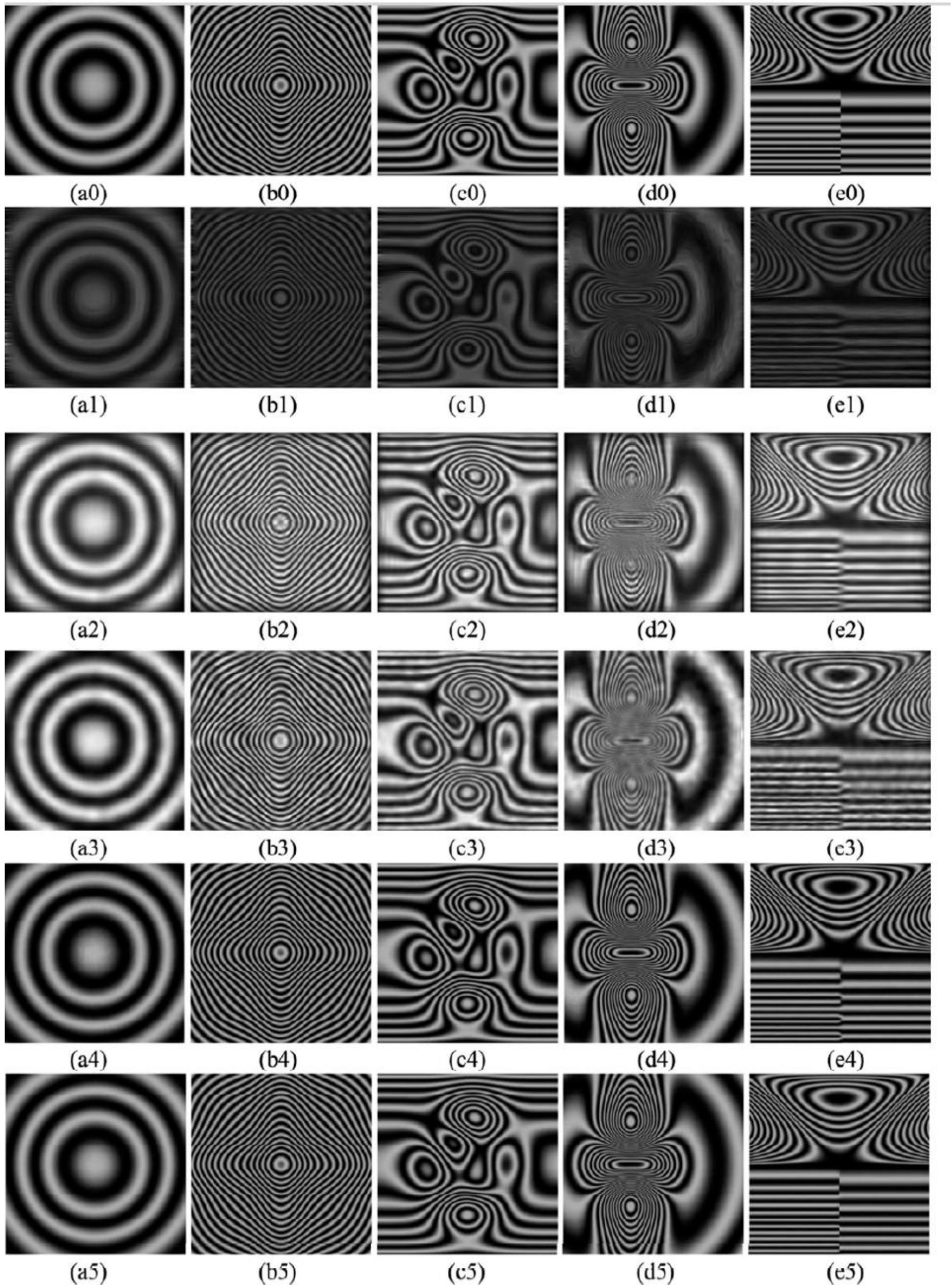


ESPI fringe pattern

ESPI fringe pattern
after filtering

- Denoising is a process which is slowing the measurement chain
- When dealing with complex fringe pattern Global optimum denoising can hyde some Local features
- Poor generalization

Wenbo Jiang, Tong Ren, Qianhua Fu Zeng, Deep Learning in the Phase Extraction of Electronic Speckle Pattern Interferometry. Electronics, 13(2), 2024



Ground Truth

SOOPDE

WFF

BL Hilbert L2

FDD NET

MDD NET

- Higher Contrast
- Higher Denoising
- Better shape Preservation

Xu, M.; Tang, C.; Hong, N.; Lei, Z. MDD-Net: A generalized network for speckle removal with structure protection and shape preservation for various kinds of ESPI fringe patterns. Opt. Lasers Eng. 2022, 154, 107017.

MUR
Dipartimento
di Eccellenza
2018-2022
2023-2027

Thank You For Your Attention!

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