Directional DIC with automatic feature selection

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ILLIMITED LAB

Topics to discuss

Motivation

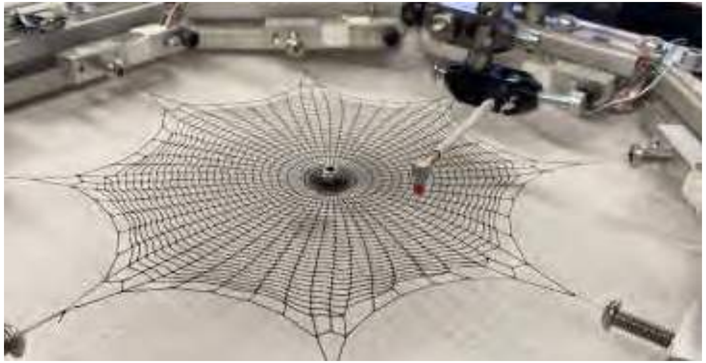
Theoretical background

Directional DIC

Next steps

Why optical methods

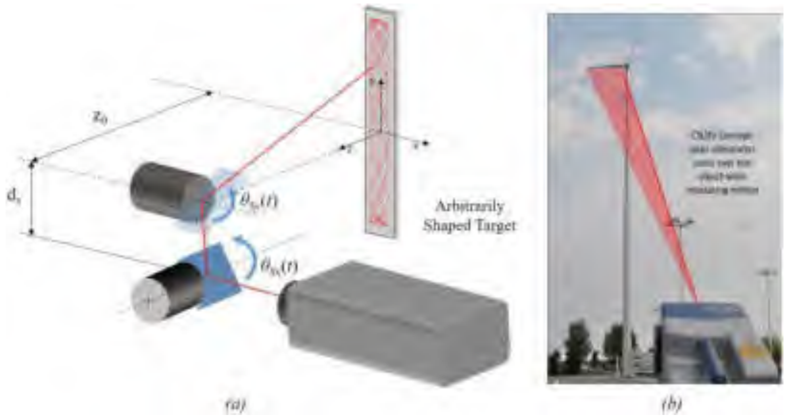
Non-contact



Why optical methods

Full field

Accelerometer	No
Strain Gauge	No
Laser Doppler Vibrometry	Yes (kinda)
High Speed Cameras	**Yes**

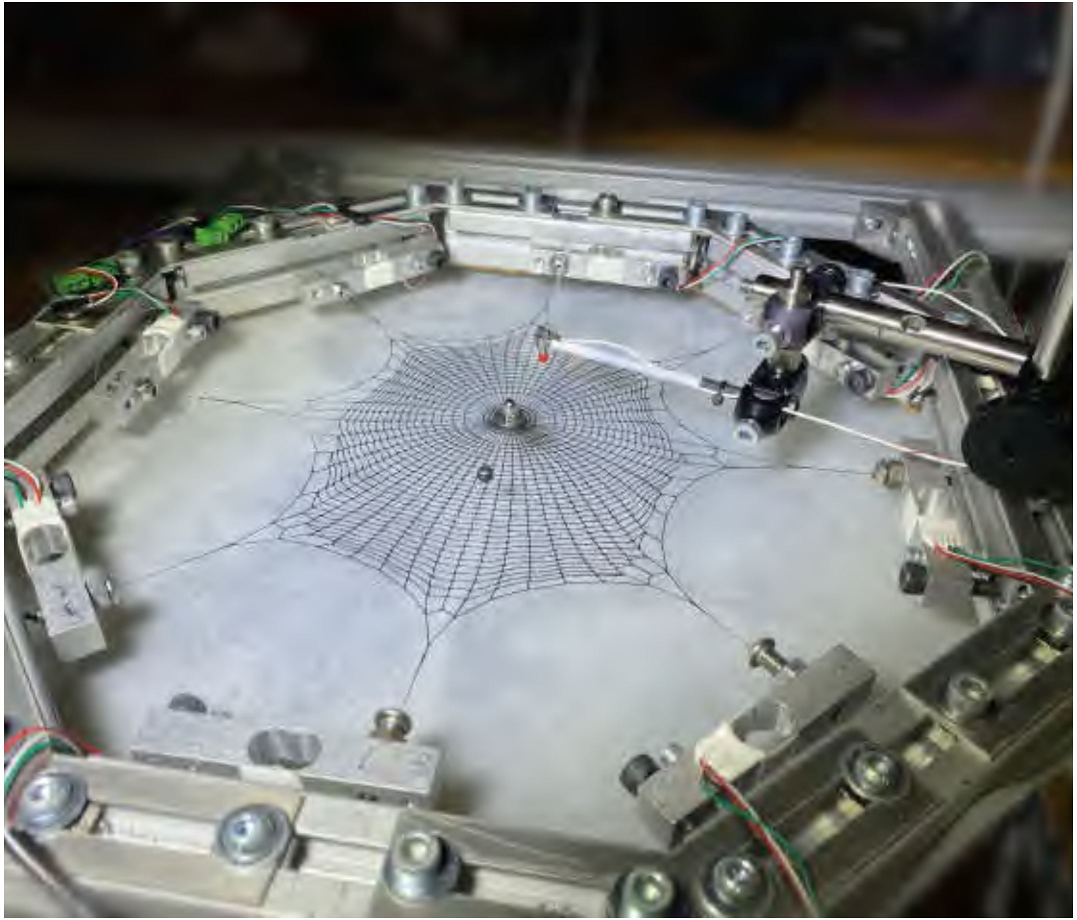


Optical methods | **Challenges**

What if no speckle patterns can be applied?

Identify naturally occurring features

Automatically select the best tracking points



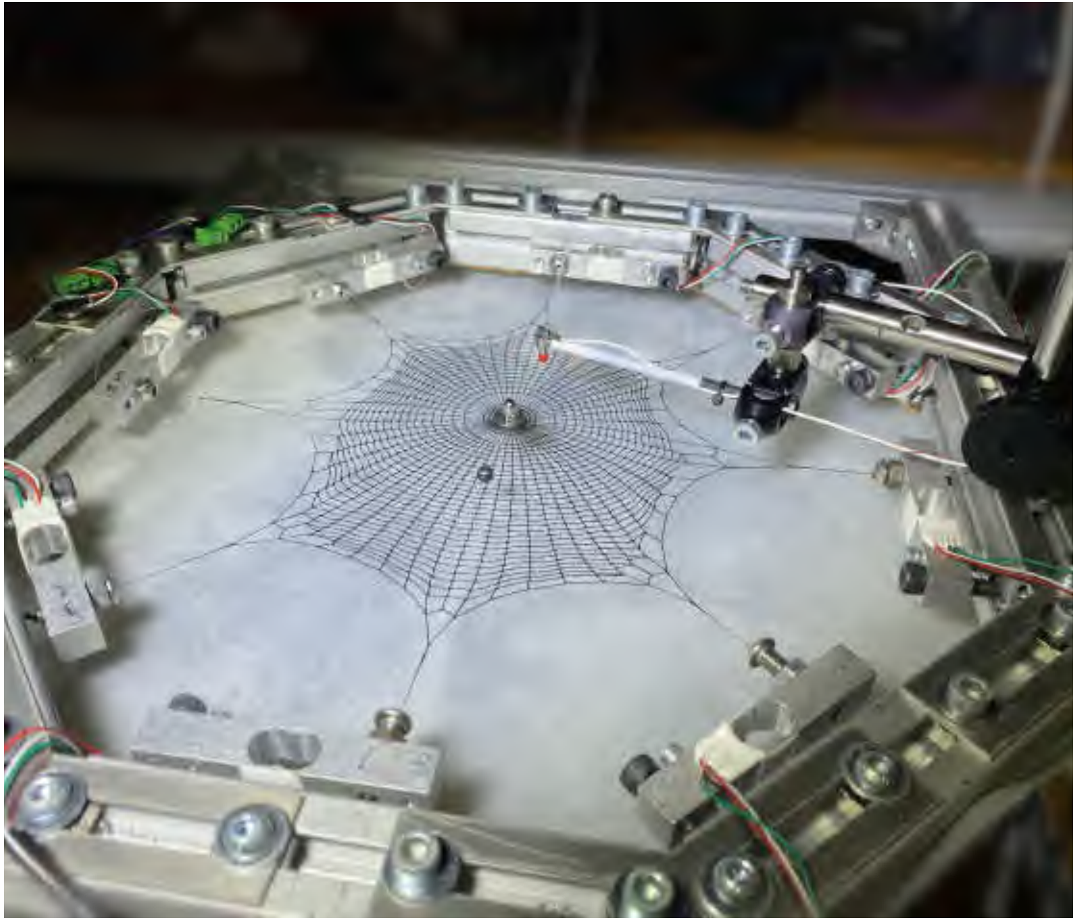
Optical methods | **Challenges**

What if no speckle patterns can be applied?

Identify naturally occurring features

Automatically select the best tracking points

- Aerodynamic structures
- Civil structures
- MEMS devices



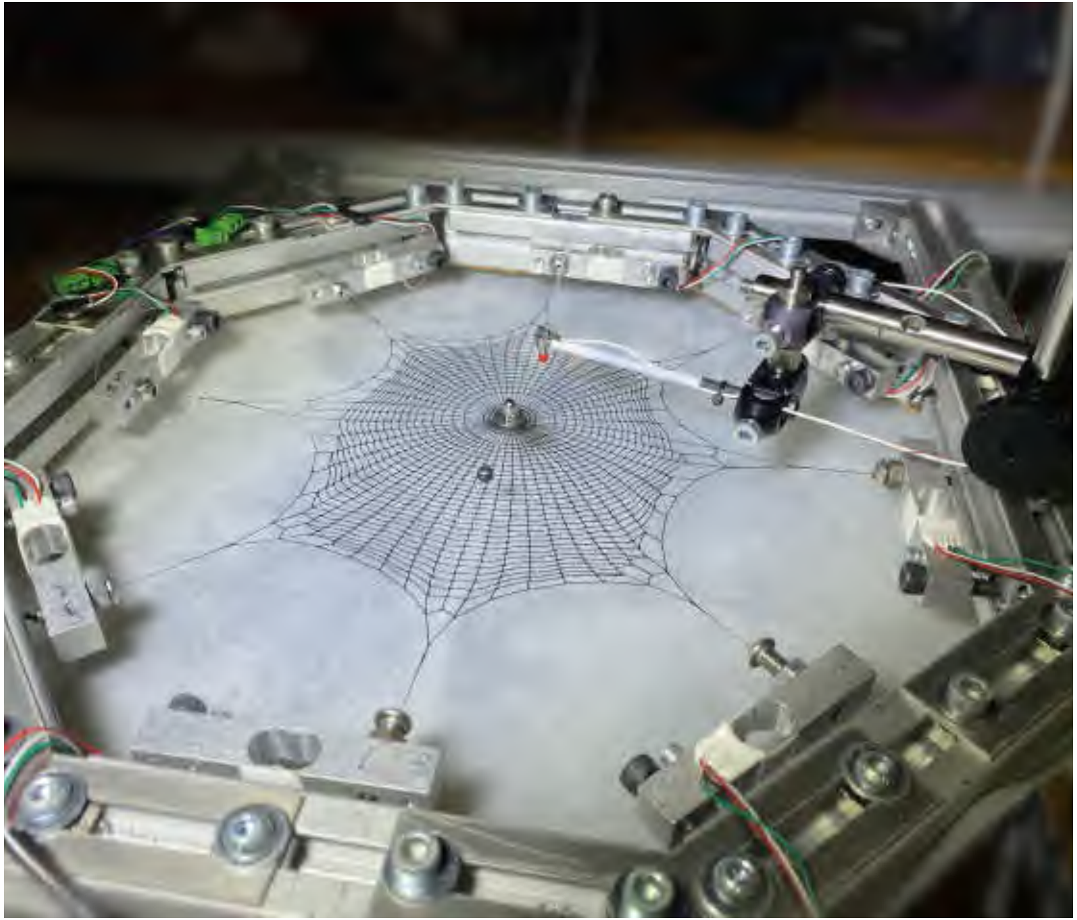
Optical methods | **Challenges**

What if no speckle patterns can be applied?

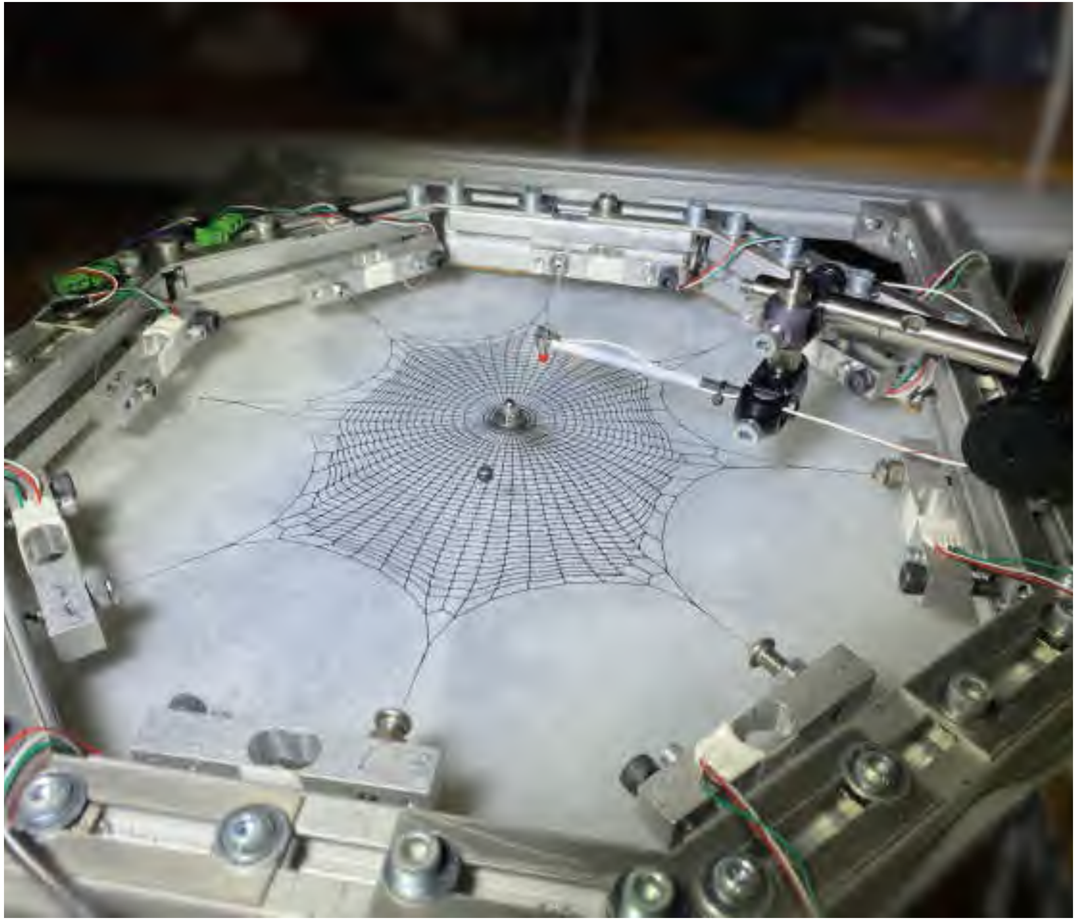
Identify naturally occurring features

Automatically select the best tracking points

Use each video as effective as possible!

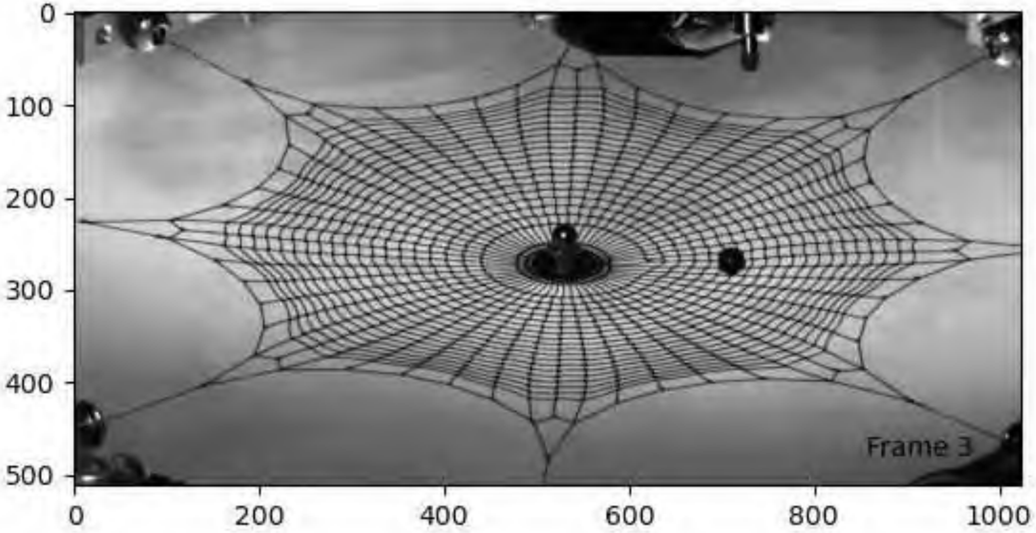


Directional DIC with automatic feature selection

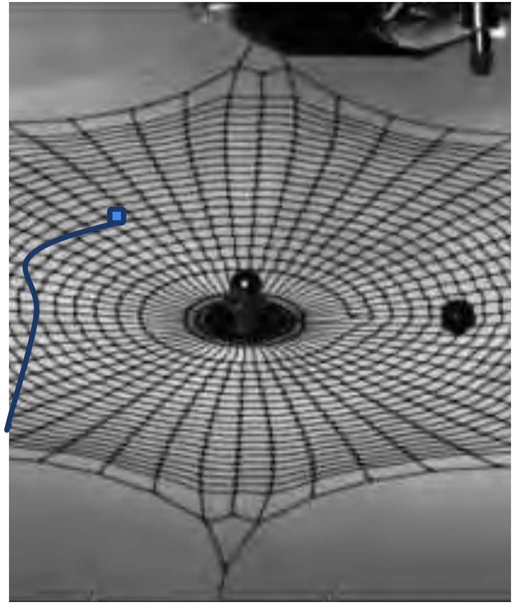


Testing a spider web-like structure | **Challenges**

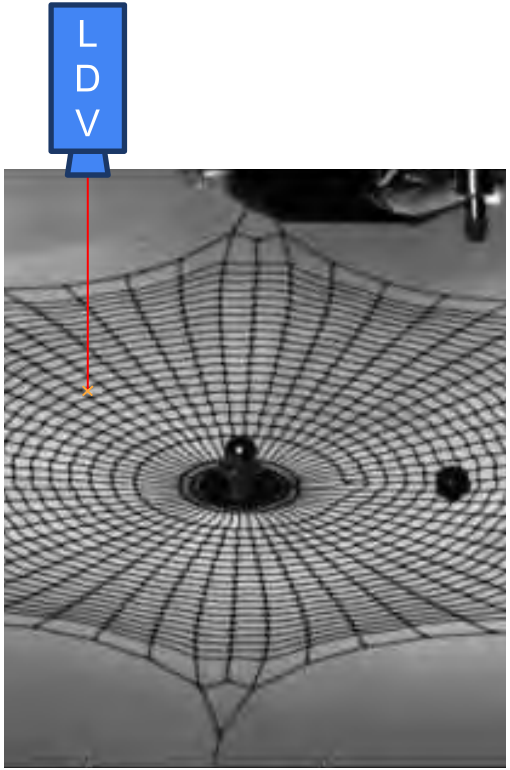
- Low mass
- Large displacements
- Thin elements



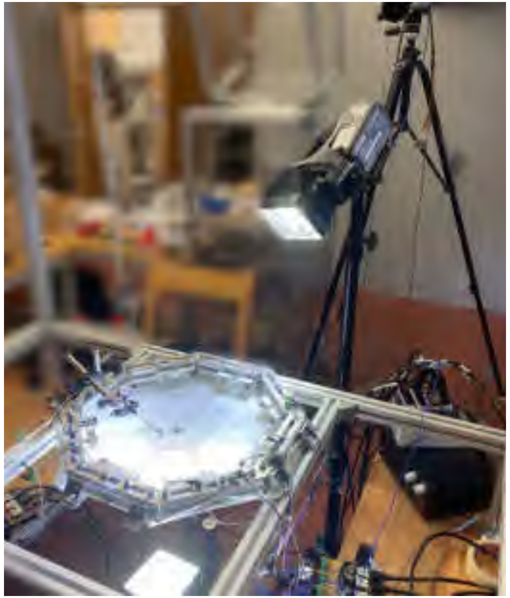
Challenges | **Experimental**



Contact

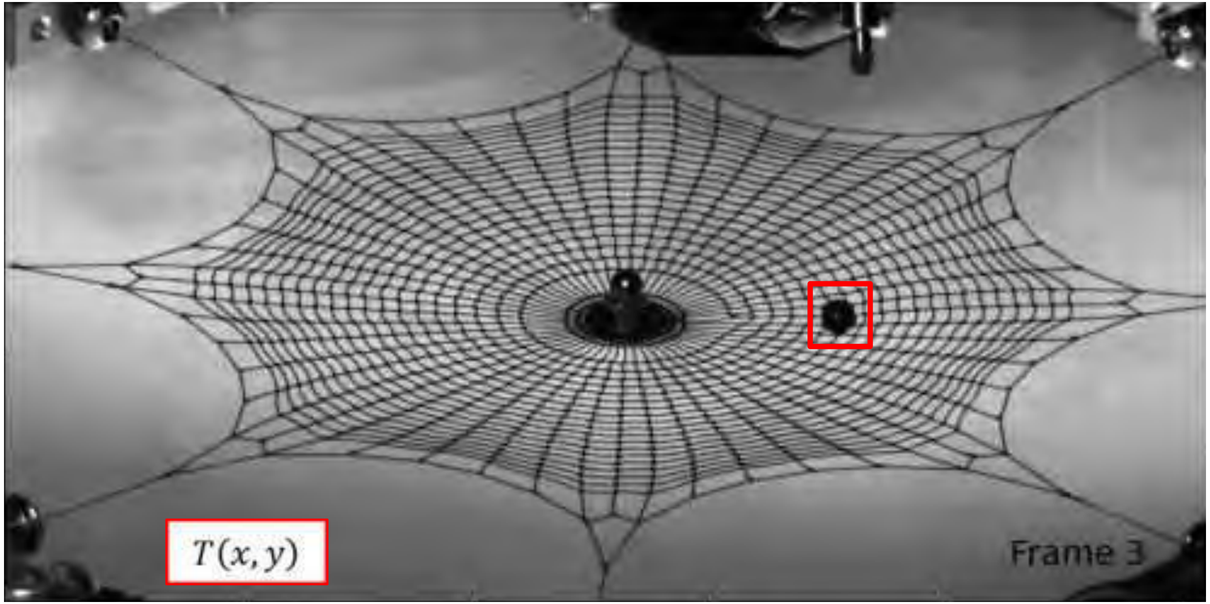


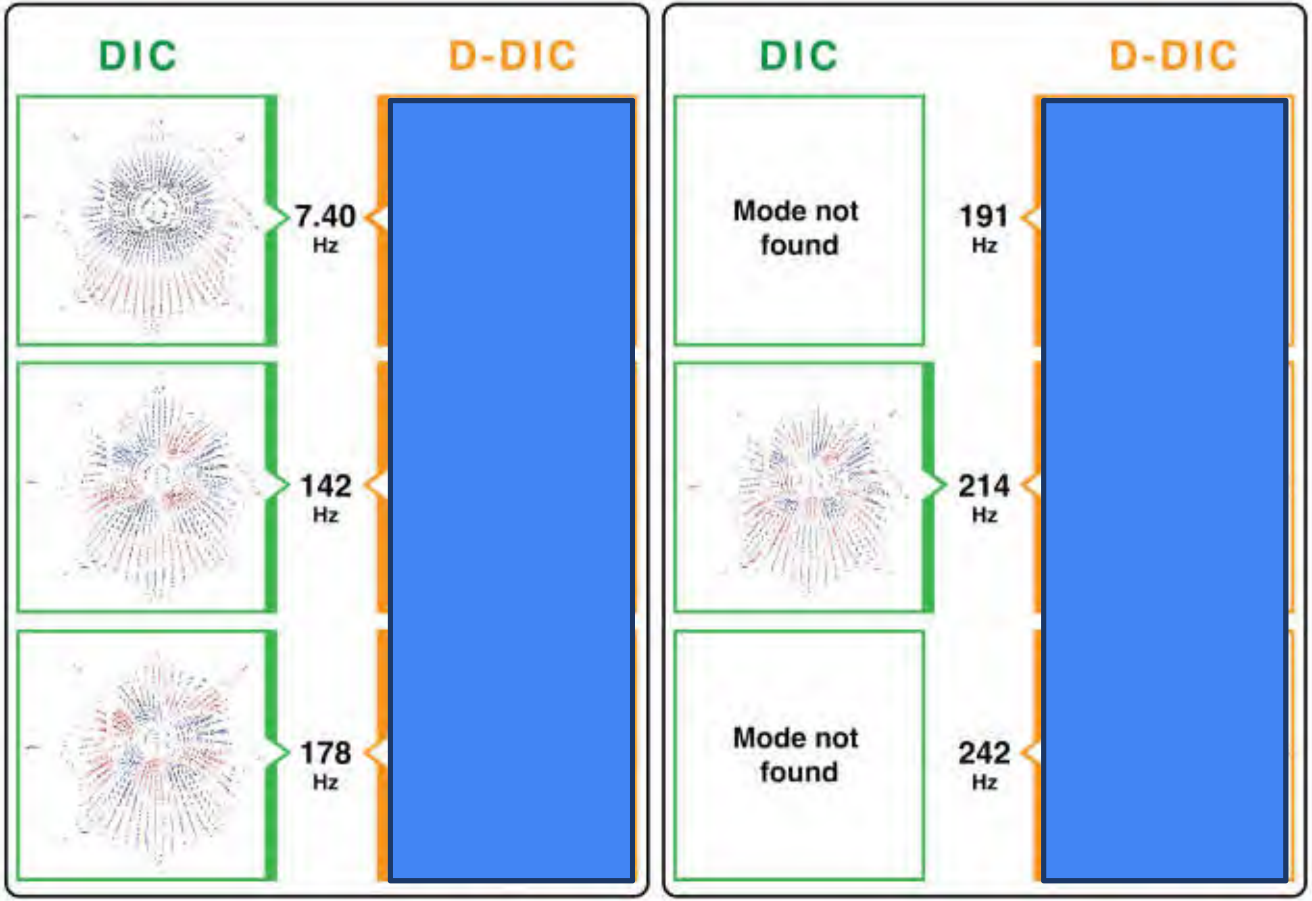
LDV



Optical

Image alignment technique for displacement measurements

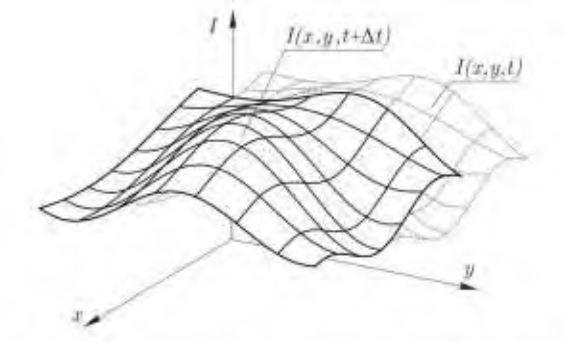



DIC
D-DIC
7.40 Hz
142 Hz
178 Hz
DIC
D-DIC
Mode not found
191 Hz
214 Hz
Mode not found
242 Hz

$T(x,y)$: Denoised Template image
$I(x,y)$: A frame in video

Denoise:

$T(x, y)$: Denoised Template image
$I(x, y)$: A frame in video

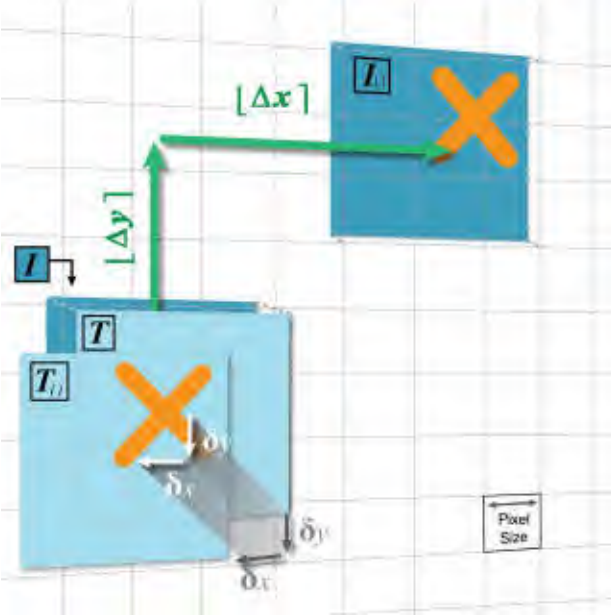


Enable large displacements (multi-pixel)

$\lfloor \Delta x \rceil$: Nearest integer

Split global displacements:
$\Delta x = \lfloor \Delta x \rceil + \{\Delta x\}$, and
$\Delta y = \lfloor \Delta y \rceil + \{\Delta y\}$.

DIC



Solving for δx and δy.

$$\min_{\delta x, \delta y} \left[T_{\{\}}(x - \delta x, y - \delta y) - I_{\lfloor \rfloor}(x, y) \right]^2.$$

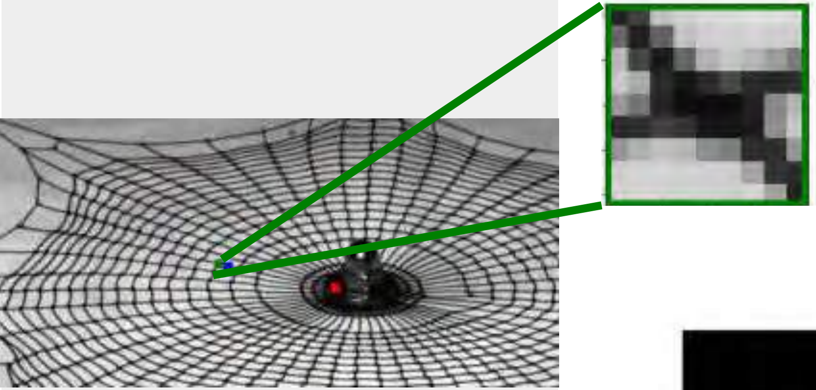
Take the first order Taylor series expansion

$$\min_{\delta x, \delta y} \left[T_{\{\}}(x, y) + \frac{\partial T_{\{\}}}{\partial x} \delta x + \frac{\partial T_{\{\}}}{\partial y} \delta y - I_{\lfloor \rfloor}(x, y) \right]^2$$

Flip spatial derivatives

Requires evaluating $\frac{\partial T_{\{\}}}{\partial \boldsymbol{x}}$ each iteration for each frame

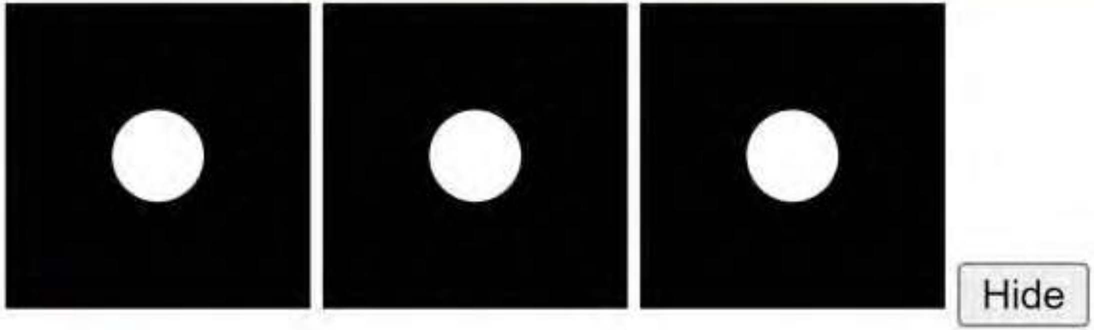
$\partial T_{\{\}}$ $\partial I_{[\,]}$



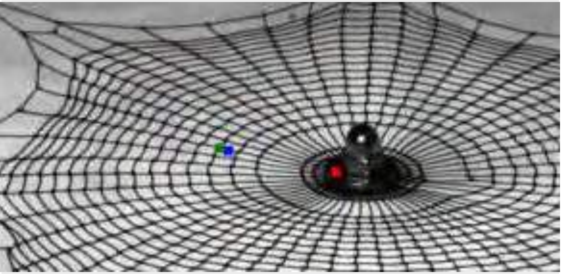
$$[T_p]_{q\times q}$$

DIC | **The aperture problem**

Can we track all locations?



We need a gradient in two orthogonal directions



DIC | **Expected tracking performance**

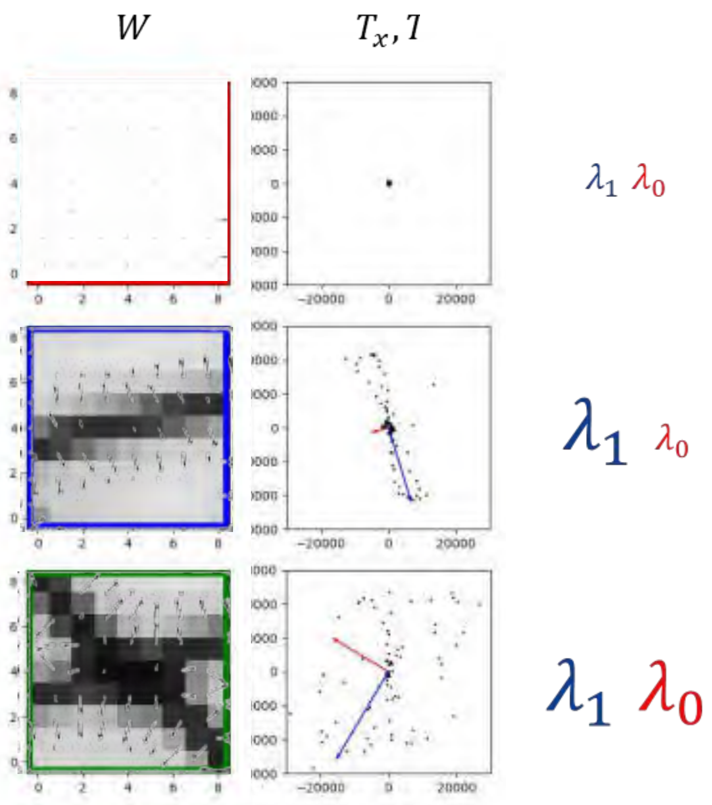
$$\begin{bmatrix}\delta x\\ \delta y\end{bmatrix} = H^{-1}\sum_{p}\begin{bmatrix}\frac{\partial T}{\partial x}\\ \frac{\partial T}{\partial y}\end{bmatrix}\left[T_{\{\}} - I_{[\,]}\right]$$

with

High sensitivity when H is big

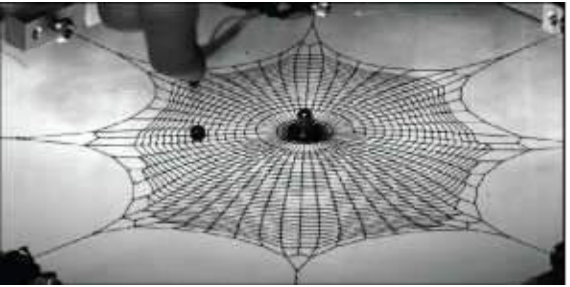
High stability when H is easily invertible:

Focus on pixel subsets with high eigenvalues



Automatic feature selection | approach

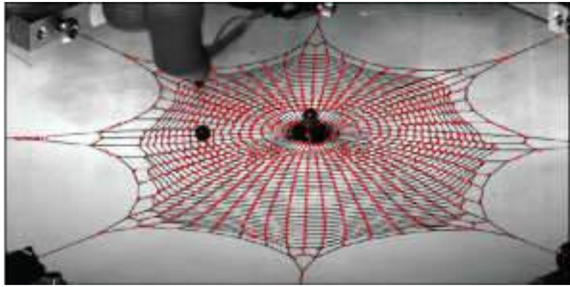
$T(x, y)$



Denoise T

$S(x, y)$

Apply λ_0 as a filter across T



Choose features with an algorithm

DIC | **Automatic feature selection algorithms (1/3)**

Descending order of score in S, excluding overlapping windows

Algorithm 1: Select by descending score excluding overlapping windows, based on [49, 50]

Input: Score image S, window size w, number of features n

Output: f: a List of n feature locations

```
w = w // 2;
Sort the pixel locations in S in descending order of score;
initialize an empty list f;
for pixel location (x, y) in the ordered list do
    if any pixel locations (x − w − 1 : x + w, y − w − 1 : y + w) is in f then
        Continue to the next pixel location;
    end
    Add the pixel locations (x, y) to f;
    if The number of features in f equals n then
        Exit the loop;
    end
end
```


[49] Tomasi, C., and Kanade, T., "Shape and motion from image streams: a factorization method," *Proceedings of the National Academy of Sciences*, Vol. 90, 1991, pp. 9795–9802. https://doi.org/10.1073/pnas.90.21.9795, URL https://pnas.org/doi/full/10.1073/pnas.90.21.9795

[50] Shi, J., and Tomasi, "Good features to track," IEEE Comput. Soc. Press, 1994, pp. 593–600. https://doi.org/10.1109/CVPR.1994.323794

DIC | **Automatic feature selection algorithms (2/3)**

Local maxima

Algorithm 2: Select at local maxima, based on [48, 51]

Input: Score image S, window size w, number of features n

Output: f: a list of n feature locations

1. Apply a maximum filter of size w to the score image S to obtain S^{f}, the filtered score image;
2. Identify local maxima in S by finding locations where $S^{f}(x, y) = S(x, y)$;
3. Sort the local maxima in descending order based on their scores in S;
4. Select the first n locations from the sorted list as the feature locations f;

[48] Moravec, H. P., "Rover Visual Obstacle Avoidance," *International Joint Conference on Artificial Intelligence*, 1981. URL https://api.semanticscholar.org/CorpusID:18232715.

[51] Harris, C., and Stephens, M., "A Combined Corner and Edge Detector," Alvey Vision Club, 1988, pp. 23.1–23.6. https://doi.org/10.5244/C.2.23, URL http://www.bmva.org/bmvc/1988/avc-88-023.html.

DIC | **Automatic feature selection algorithms (3/3)**

Adaptive Non-Maximal Suppression (ANMS)

For more evenly spread out features

Algorithm 3: ANMS algorithm, based on [52]

Input: List of potential feature locations f^0, score image S, number of features n, robustifying factor c

Output: f: List of n feature locations

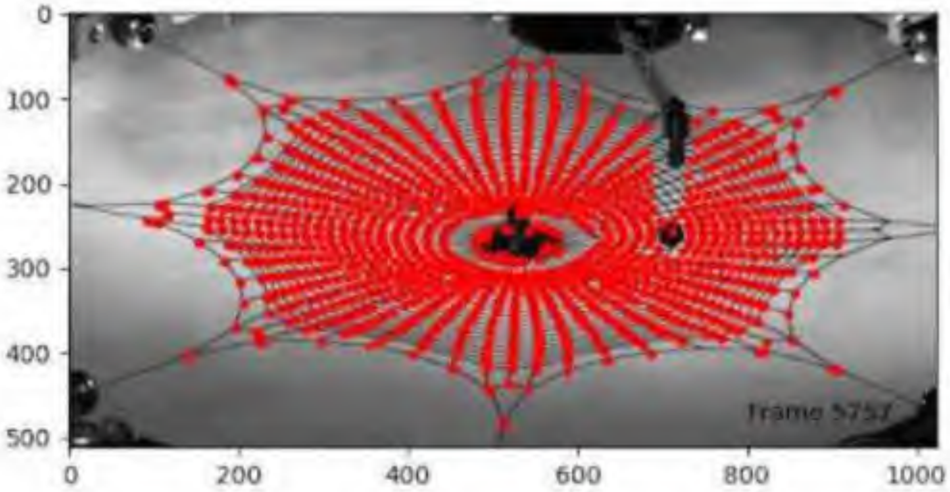
Sort the potential feature locations f^0 in descending order based on their scores in S;
Initialize an array R with ∞ for each f_i^0 in f^0;
for *each potential feature location* f_i^0 *in* f^0 **do**
    for *each potential feature location* f_j^0 *in* $f_{1:i-1}^0$ **do**
        if $c \cdot S(f_j^0) > S(f_i^0)$ **then**
            Compute the distance $r = \|f_i^0 - f_j^0\|_2$;
            if $r < R_i$ **then**
                $R_i = r$;
            end
        end
    end
end
Select the locations in f^0 corresponding to the largest n values in R as f;

[52] Brown, M., Szeliski, R., and Winder, S., "Multi-Image Matching Using Multi-Scale Oriented Patches," IEEE, 2005, pp. 510–517. https://doi.org/10.1109/CVPR.2005.235, URL http://ieeexplore.ieee.org/document/1467310/.

Demo | **Identify displacements**

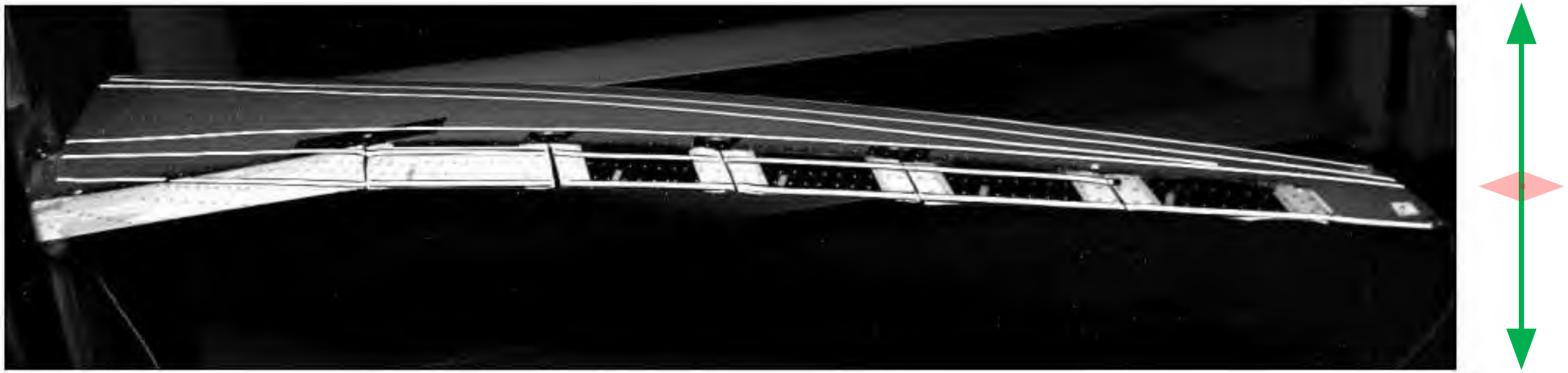
Open Source package: PyIDI
https://github.com/ladisk/pyidi

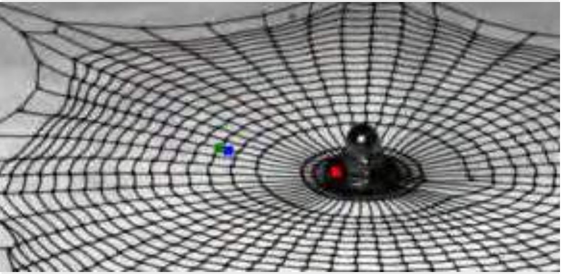
But can we do better?...



Directional DIC | **Uni-directional displacement**

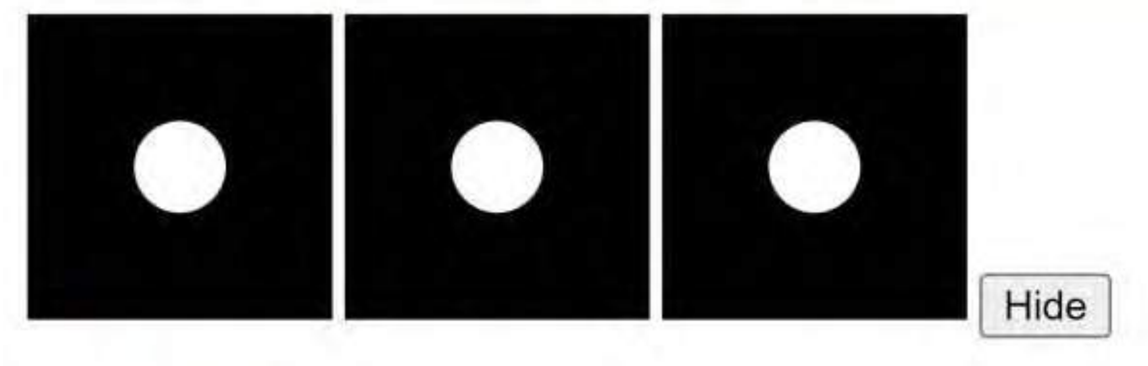
In structural vibration, displacement is *often* locally unidirectional





D-DIC | **The aperture problem**

Can we track all locations?



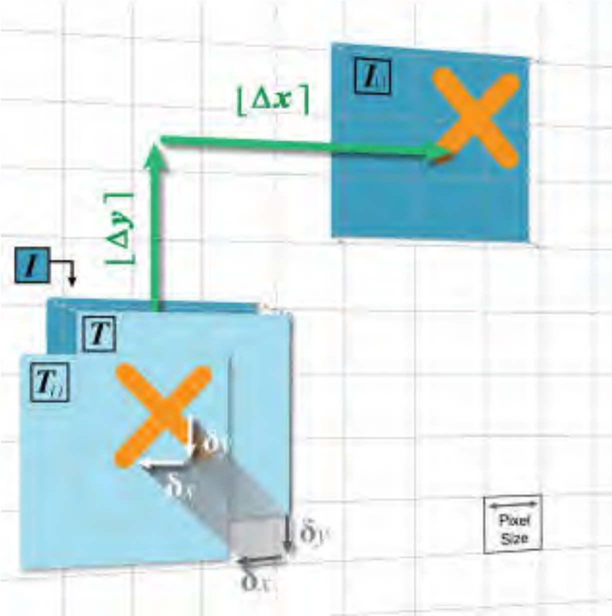
~~We need a gradient in two orthogonal directions~~

Masmeijer, T., Zaletelj, K., Slavič, J., and Habtour, E., "Directional DIC with automatic feature selection."
Under review: Mechanical Systems and Signal Processing

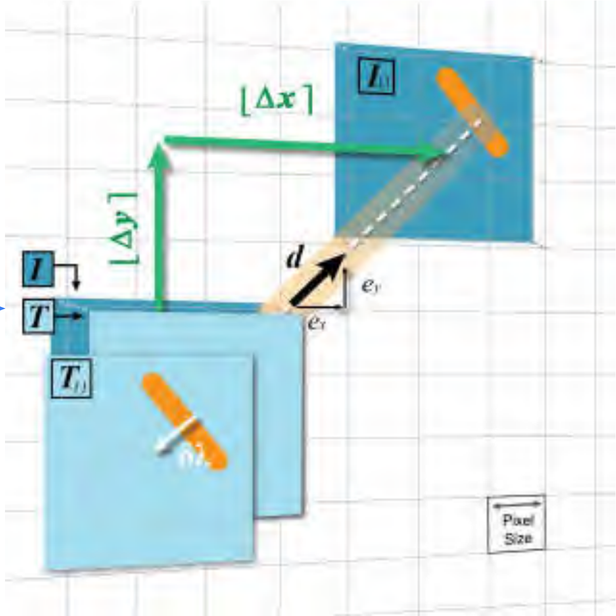
D-DIC | **Directional DIC**

$\boldsymbol{d} = [e_x; e_y]$, with $|\boldsymbol{d}| = 1$

Conventional DIC



Directional DIC



D-DIC | **Directional DIC**

Updated solving procedure

Conventional DIC

$$\begin{bmatrix} \delta x \\ \delta y \end{bmatrix} = H^{-1} \sum_p \begin{bmatrix} \frac{\partial I_{\lfloor\rfloor}}{\partial x} \\ \frac{\partial I_{\lfloor\rfloor}}{\partial y} \end{bmatrix} [T_{\{\}} - I_{\lfloor\rfloor}]$$

with

$$H = \sum_p \begin{bmatrix} \left(\frac{\partial I_{\lfloor\rfloor}}{\partial x}\right)^2 & \frac{\partial I_{\lfloor\rfloor}}{\partial x}\frac{\partial I_{\lfloor\rfloor}}{\partial y} \\ \frac{\partial I_{\lfloor\rfloor}}{\partial x}\frac{\partial I_{\lfloor\rfloor}}{\partial y} & \left(\frac{\partial I_{\lfloor\rfloor}}{\partial y}\right)^2 \end{bmatrix}$$

Update until convergence
$\{\Delta x\} \leftarrow \{\Delta x\} + \delta x$, and
$\{\Delta y\} \leftarrow \{\Delta y\} + \delta y$.

Directional DIC

$$\delta\lambda = \frac{1}{\sum_p \left(e_x \frac{\partial I}{\partial x} + e_y \frac{\partial I}{\partial y}\right)^2} \sum_p \left(e_x \frac{\partial I}{\partial x} + e_y \frac{\partial I}{\partial y}\right) (I_{\lfloor\rfloor} - T_{\{\}})$$

Update until convergence
$\{\Delta x\} \leftarrow \{\Delta x\} + \delta\lambda e_x$, and
$\{\Delta y\} \leftarrow \{\Delta y\} + \delta\lambda e_y$.

D-DIC | **Directional DIC**

Updated parameter for quantifying expected tracking performance

Conventional DIC

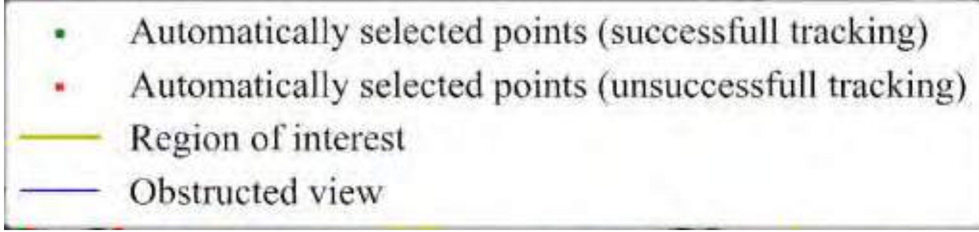
$$\lambda_0 = \min(\text{eig}(H))$$

→

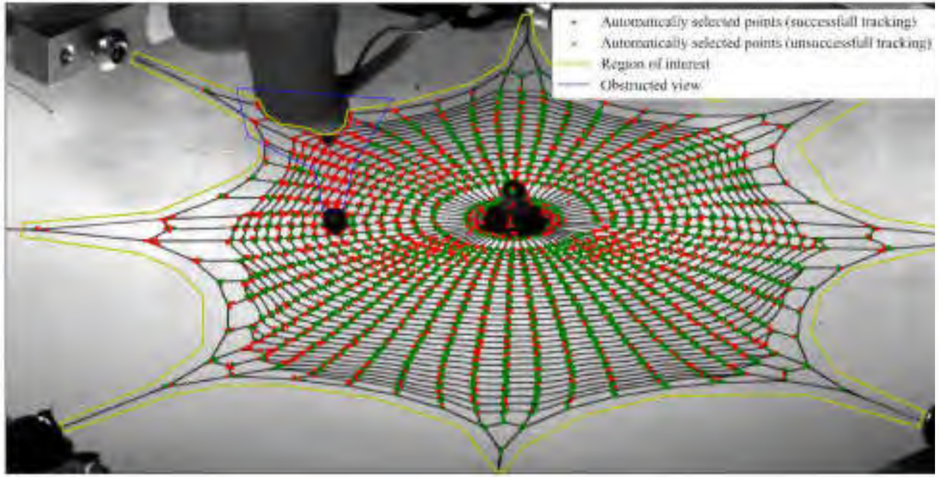
Directional DIC

$$\lambda_\text{d} = \sum_p \left| e_x \frac{\partial T}{\partial x} + e_y \frac{\partial T}{\partial y} \right|$$

DIC vs. D-DIC | **Small subsets [3 × 3] pixels**

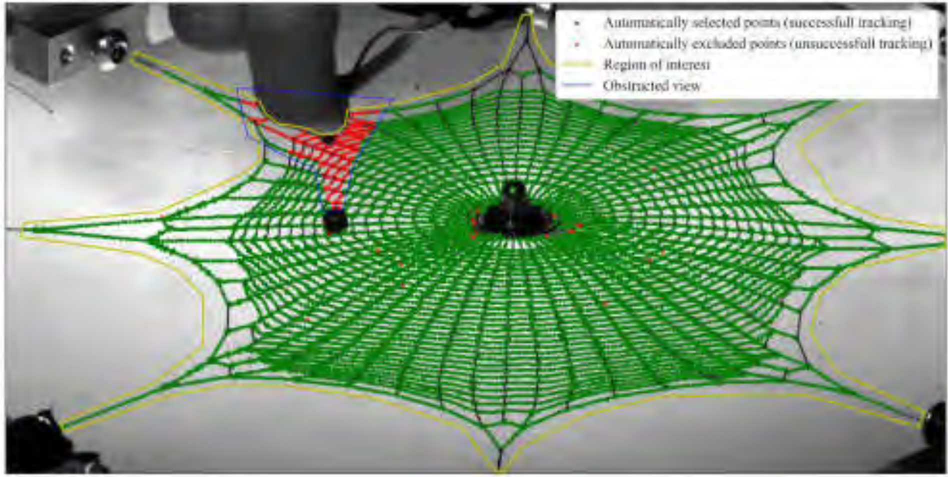


Conventional DIC



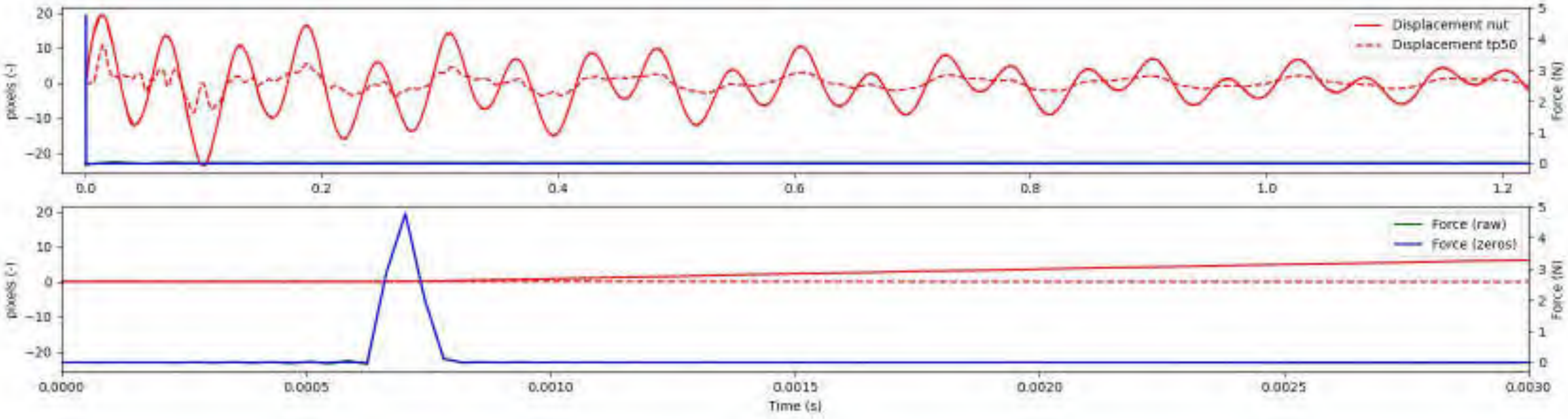
3040/4846

Directional DIC



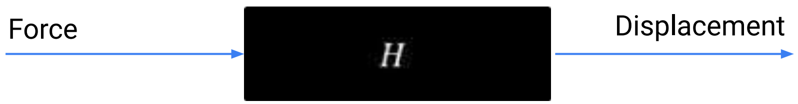
10,014/10,035

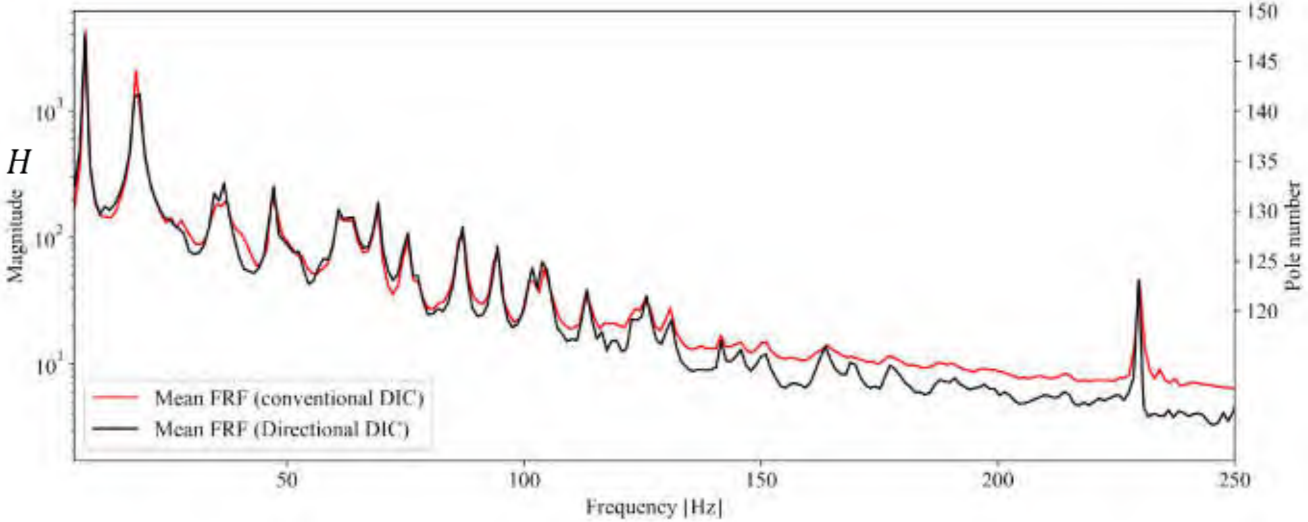
Sample signal



For subsets of 9×9 pixels

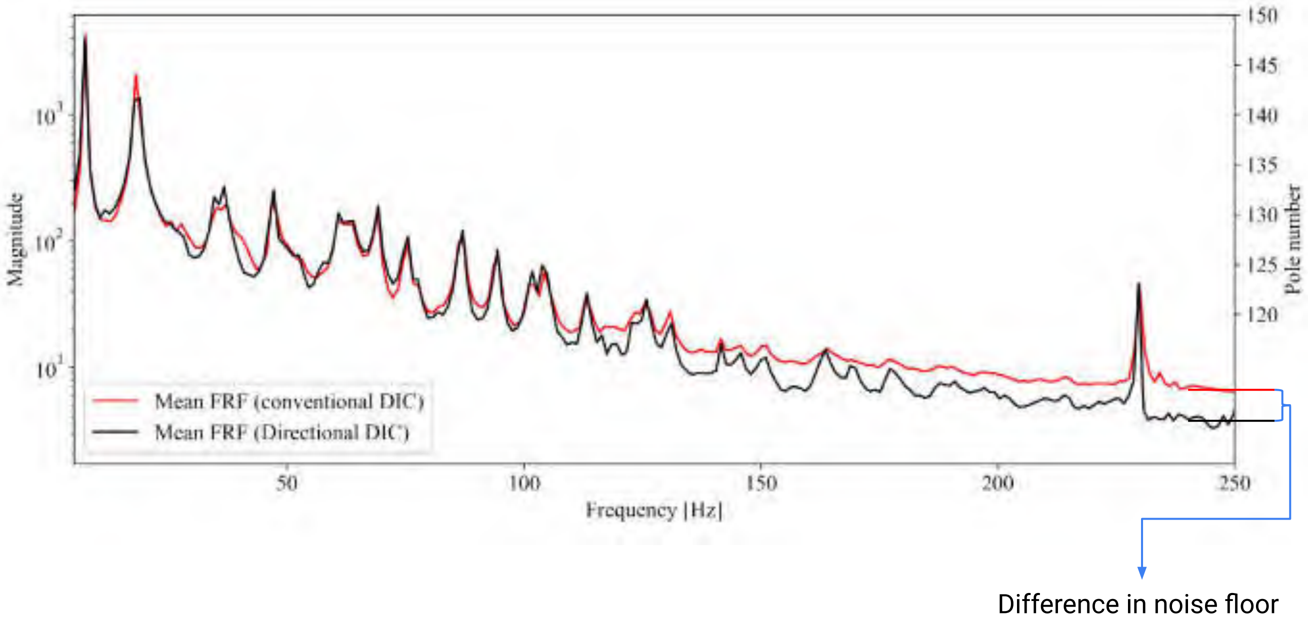
1,521 vs. 5,340 successful points





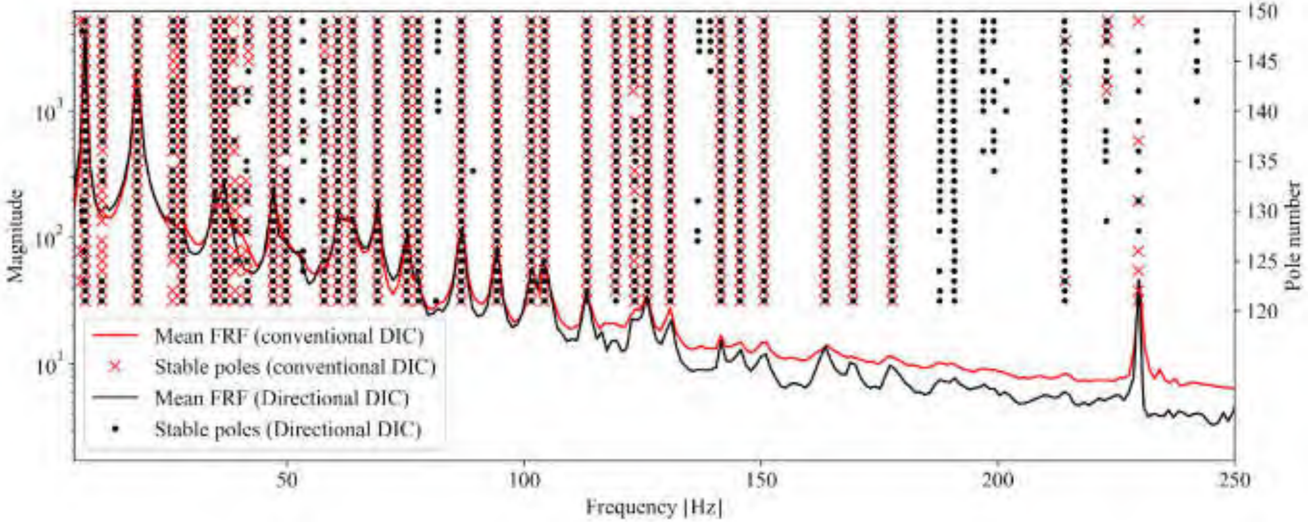
For subsets of 9×9 pixels

1,521 vs. 5,340 successful points



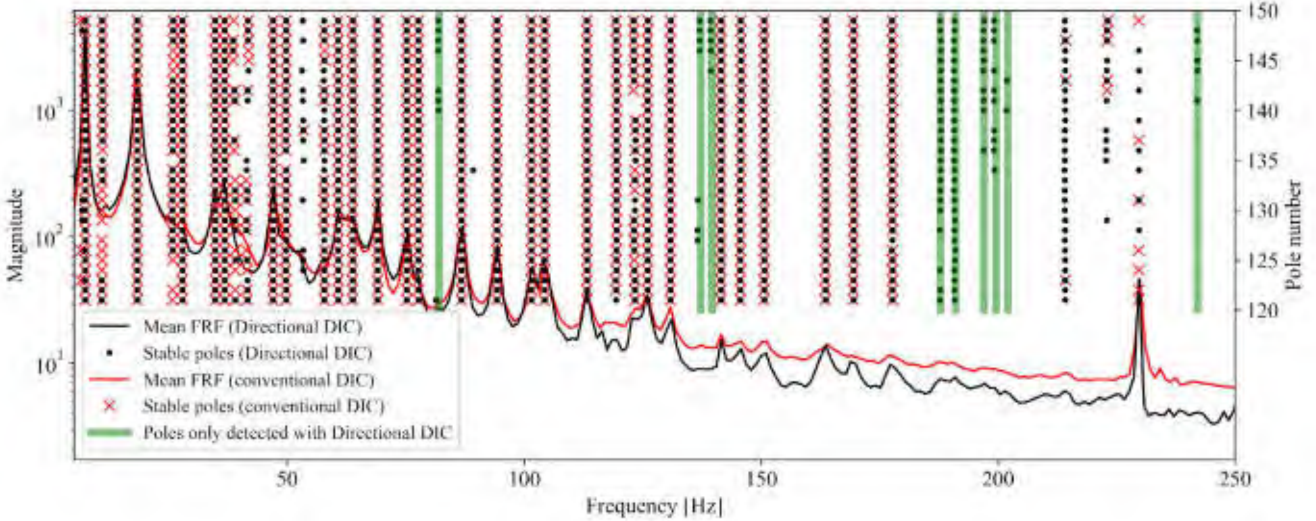
For subsets of 9×9 pixels

- Lower noise floor with D-DIC



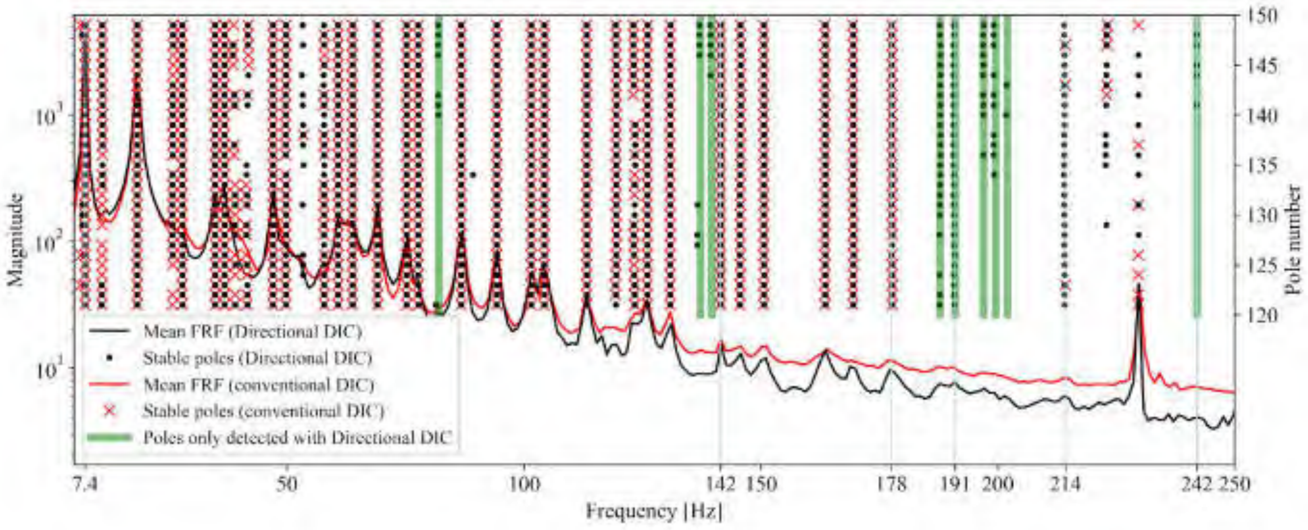
For subsets of 9×9 pixels

- Lower noise floor with D-DIC



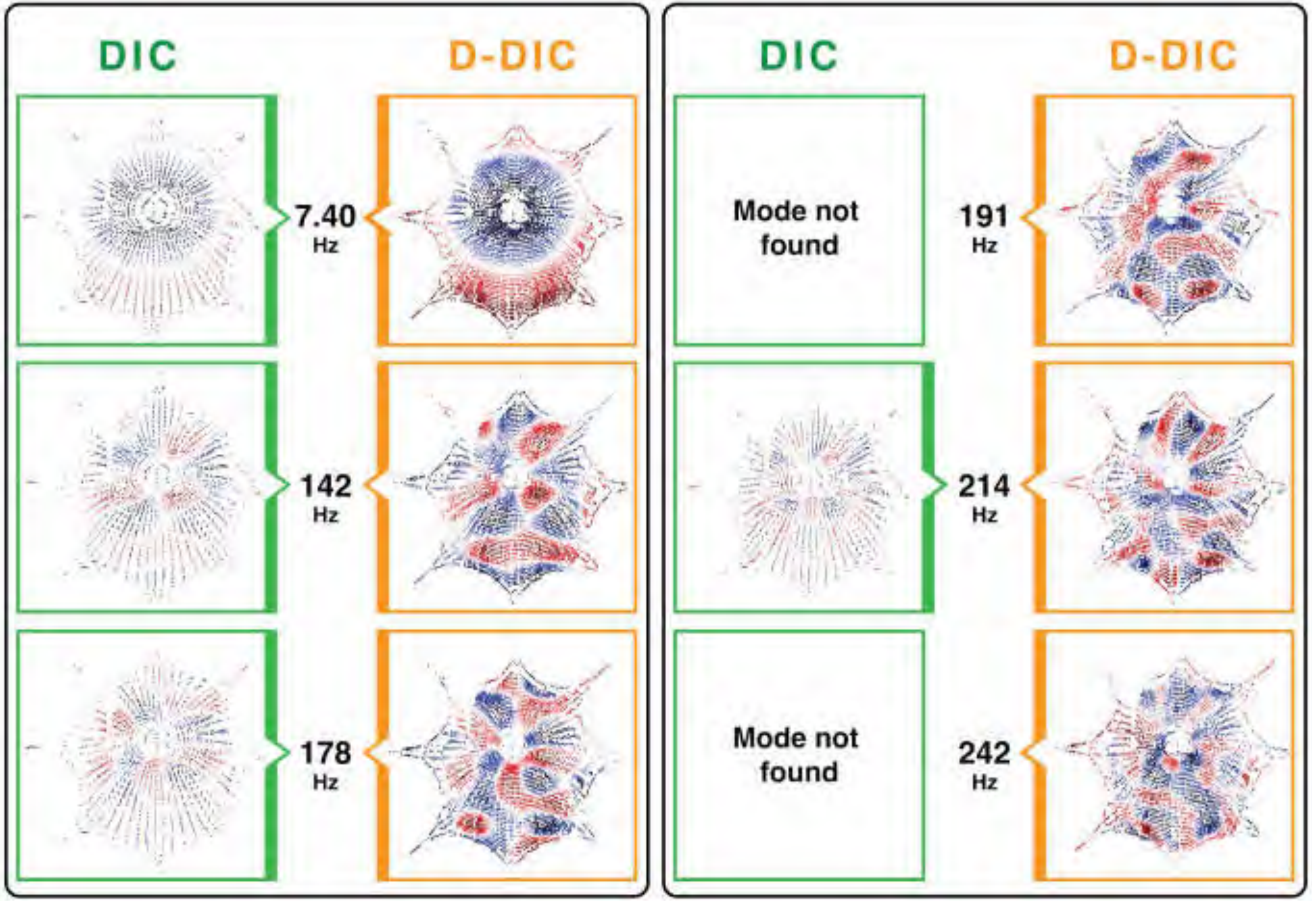
For subsets of 9×9 pixels

- Lower noise floor with D-DIC



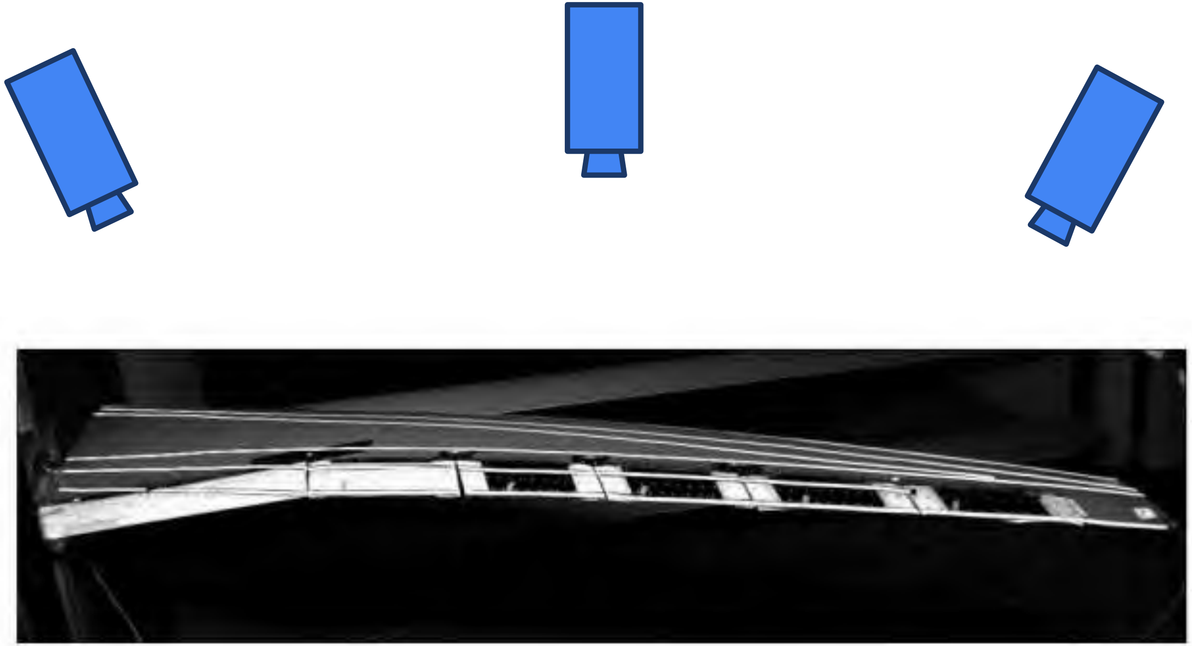
For subsets of 9×9 pixels

- Lower noise floor with D-DIC



3D D-DIC

Tests conducted. Planned for IMAC 2025



A better parameter to quantify expected performance

Motion perpendicular to $\boldsymbol{d}$ decreases accuracy and robustness of D-DIC, especially when a feature has a high gradient perpendicular to $\boldsymbol{d}$.

Such features can potentially be suppressed, for example with:

$$\lambda_{\mathrm{d}*} = \sum_{p} \left| e_x \frac{\partial T}{\partial x} + e_y \frac{\partial T}{\partial y} \right| - c \cdot \left| e_x \frac{\partial T}{\partial y} + e_y \frac{\partial T}{\partial x} \right|$$

e.g. with $c = 0.1$

University of Ljubljana

Collaboration with Ladisk at the University of Ljubljana

Funding with
Boeing International Research Fellowship

Illimited Lab – University of Washington

Used OpenSource packages:

Data acquisition	LDAQ	https://github.com/ladisk/LDAQ
Displacement identification	PyIDI	https://github.com/ladisk/pyidi
Modal characterization	PyEMA	https://github.com/ladisk/pyEMA

Simplified Optical Flow

1-DOF displacement identifier

- Assumes motion is in direction of ∇I

$$|\nabla I|\ \Delta s = I(x_j, y_k, t) - I(x_j, y_k, t + \Delta t)$$

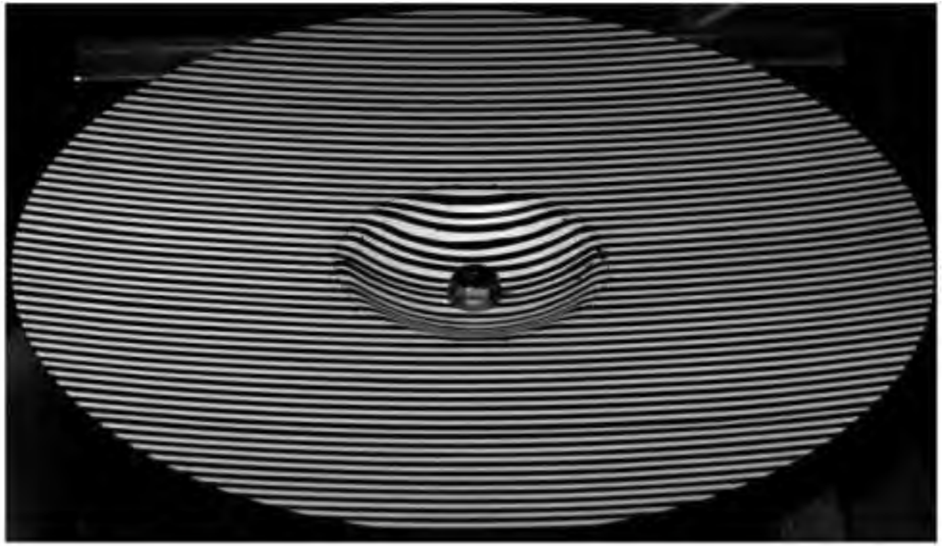
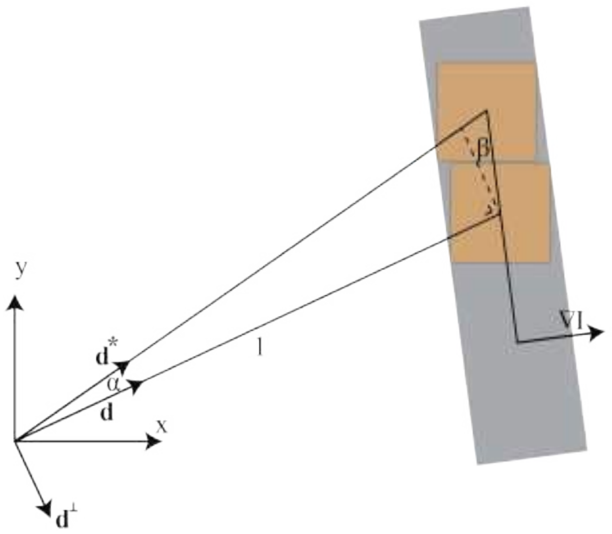


Figure 16: A frame from the full-field cymbal experiment

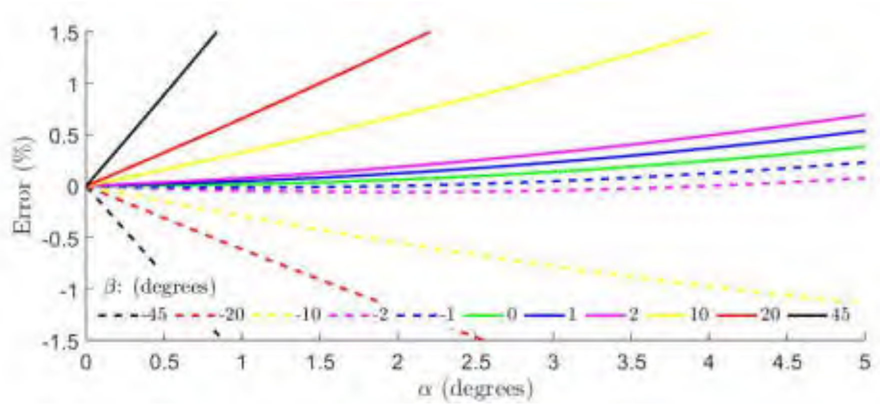
Assumption of uni-directionality

$\mathbf{d}^*$: Real motion direction
$\mathbf{d}$: Assumed motion direction

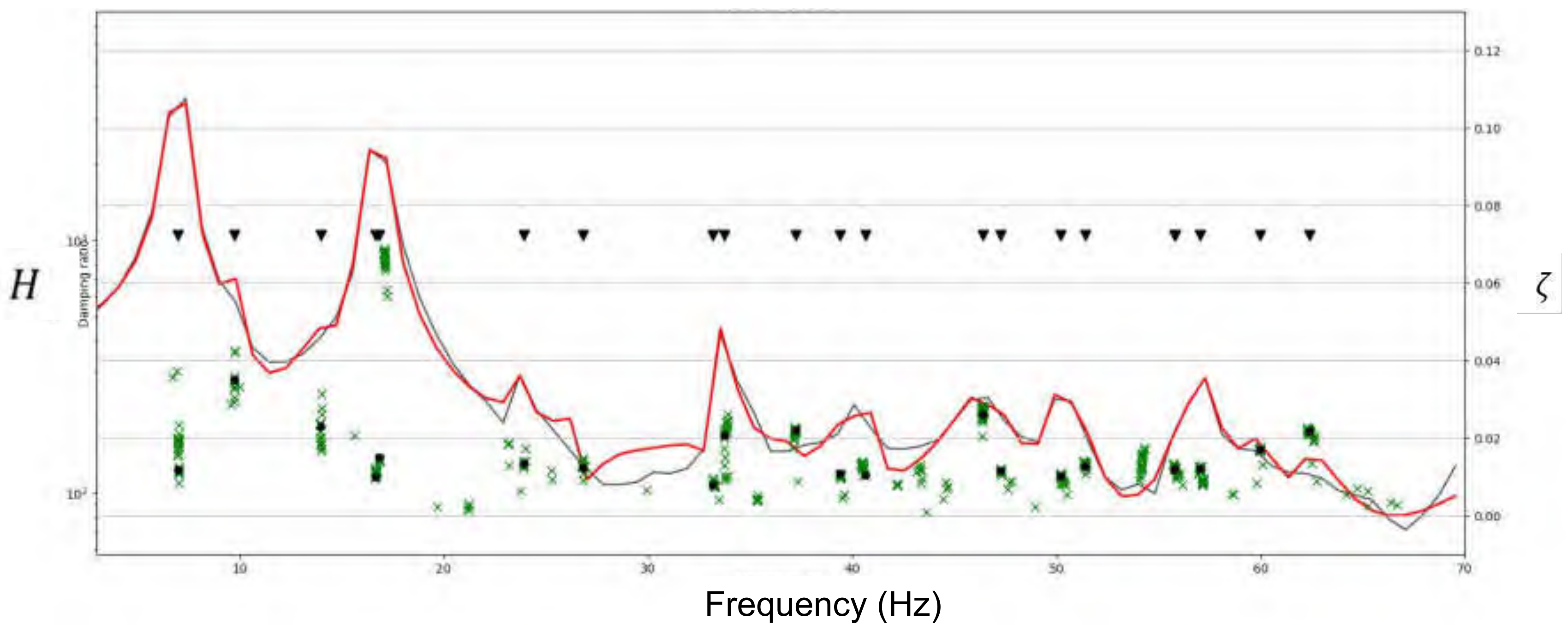


For individual pixel

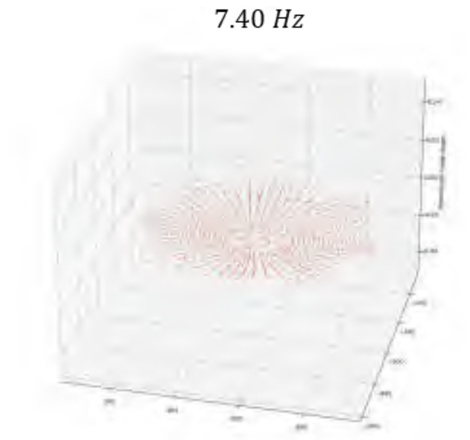
$$\text{error} = \left(\frac{\cos(\beta)}{\cos(\beta+\alpha)} - 1\right) \cdot 100\%$$



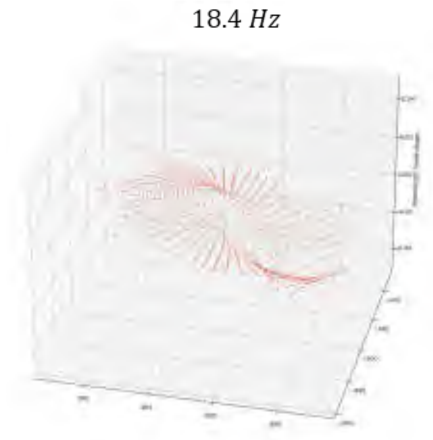
Future work | **Internal Resonances**



Future work | **Internal Resonances**

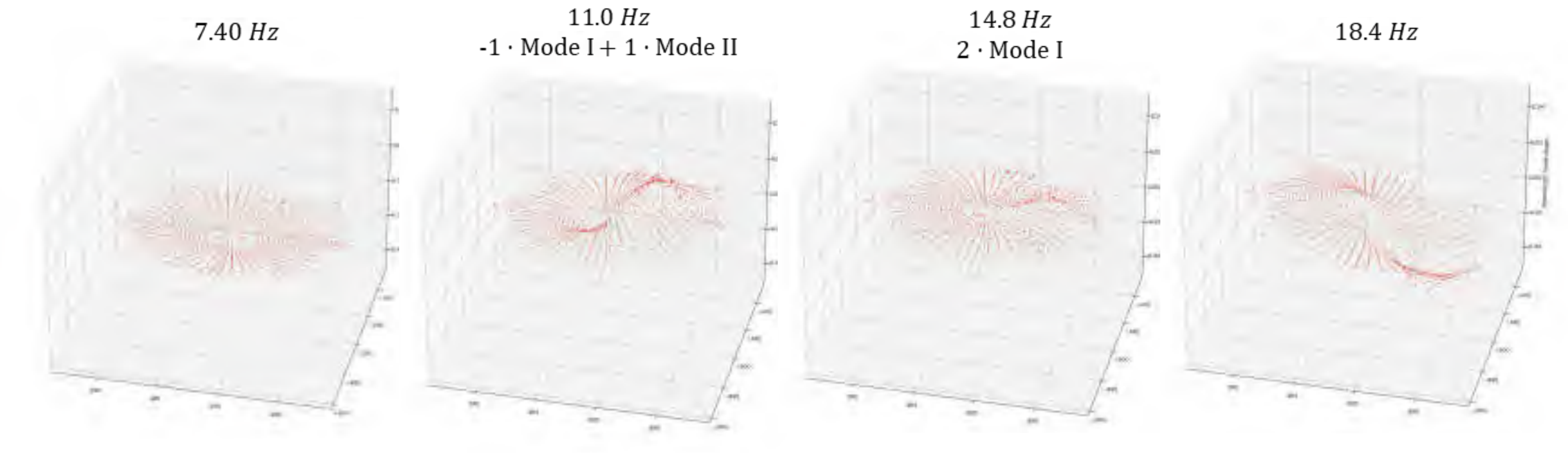


Mode I



Mode II

Future work | **Internal Resonances**



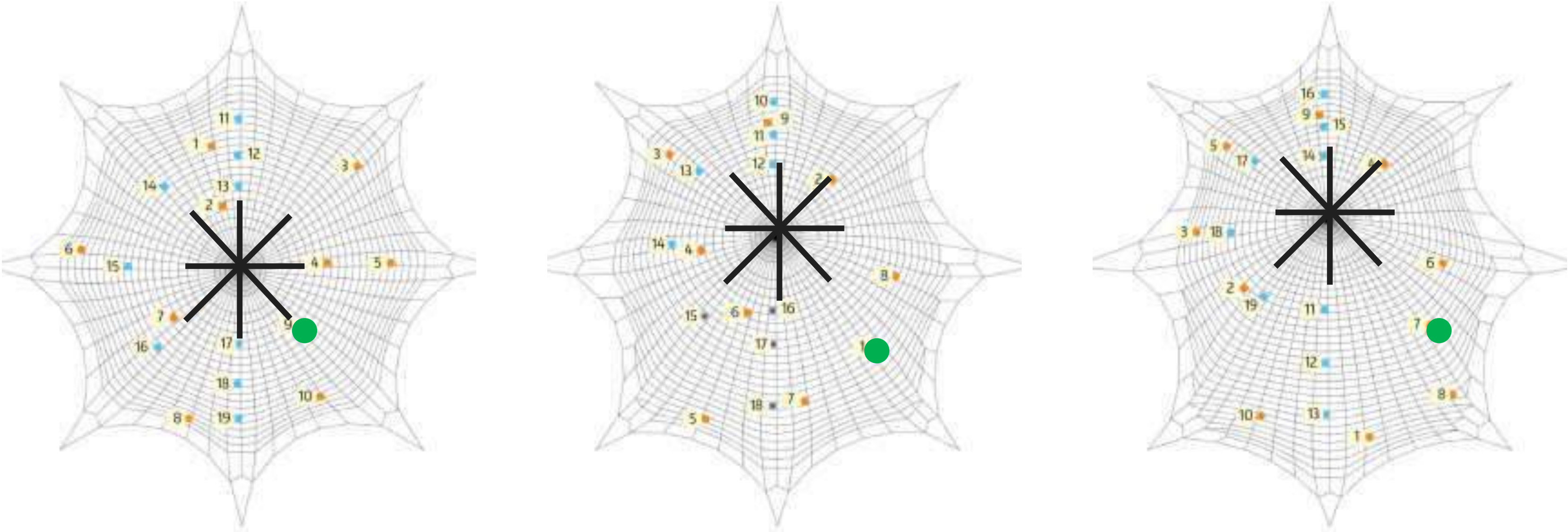
Mode I

Mixed modes

Mode II

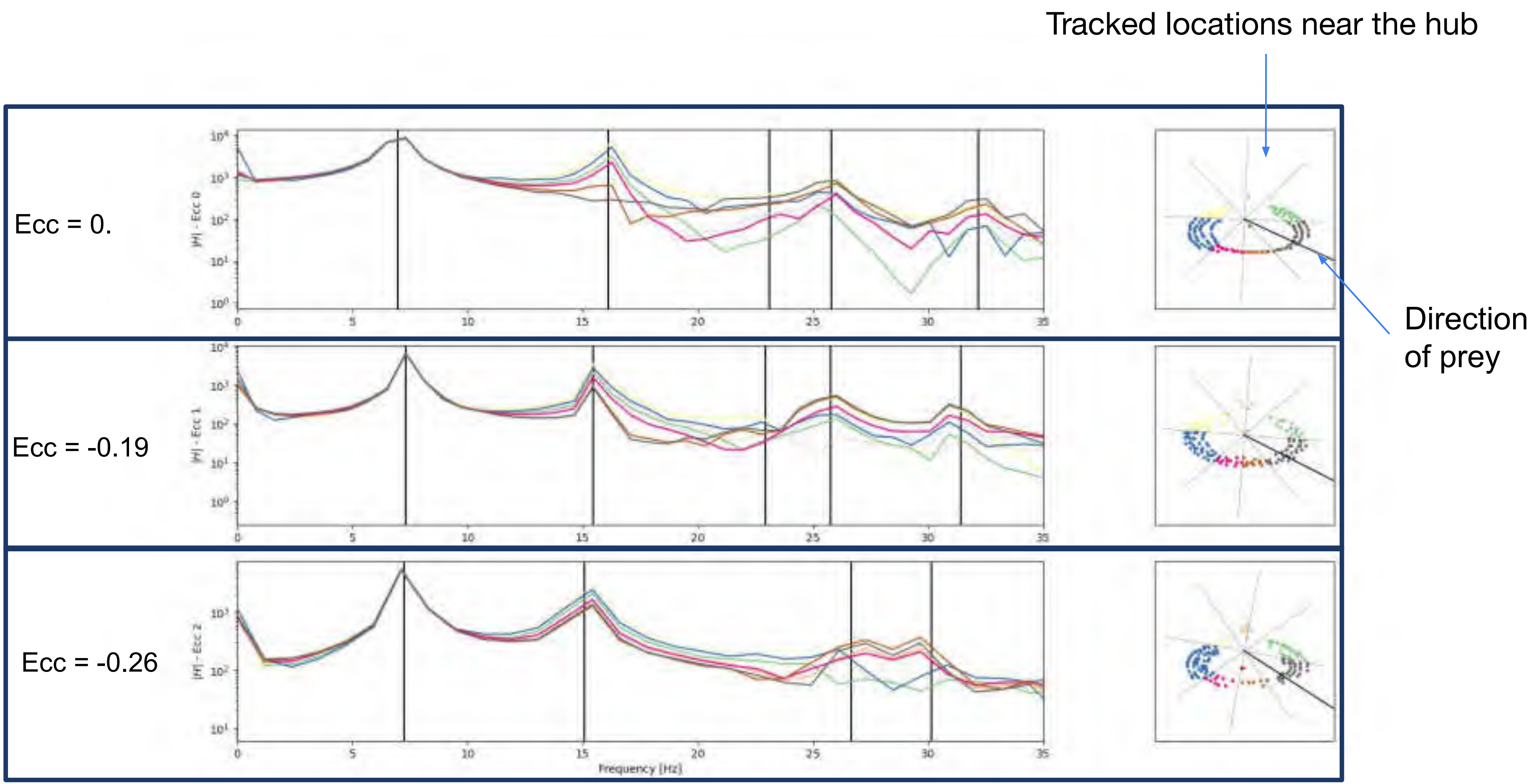
$$k\omega = \sum_{j=1}^{N} n_j \Omega_j, \;\; j = 1, \ldots, N, \qquad k = 1,2, \ldots, \qquad n_j = 0, \pm 1, \pm 2, \ldots$$

FRF | **Comparing designs**



Single impact location
Split results per leg section

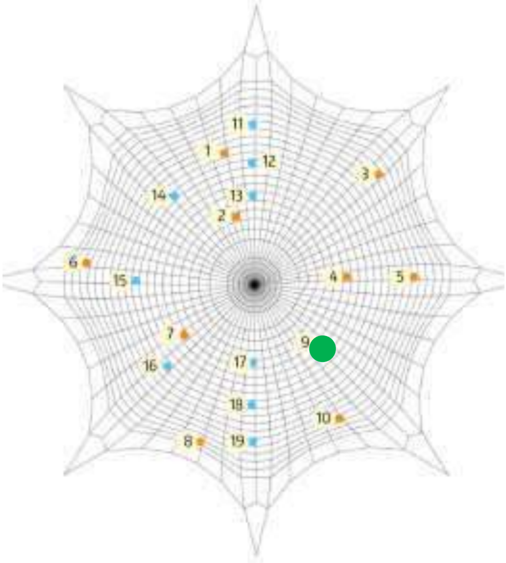
Tracked locations near the hub
Direction of prey
Ecc = 0.
Ecc = -0.19
Ecc = -0.26
|H| - Ecc 0
|H| - Ecc 1
|H| - Ecc 2
Frequency [Hz]

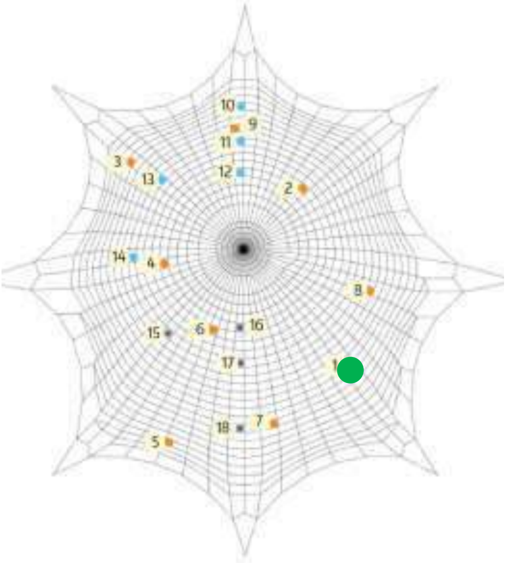


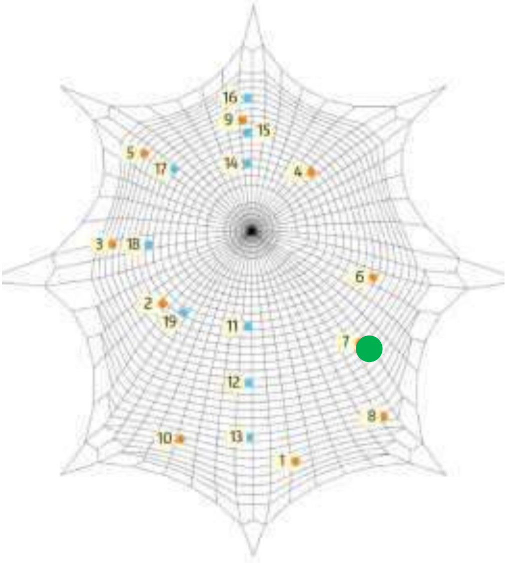
Experimental | **Progress of analysis**

● Analyzed

• • Not analyzed



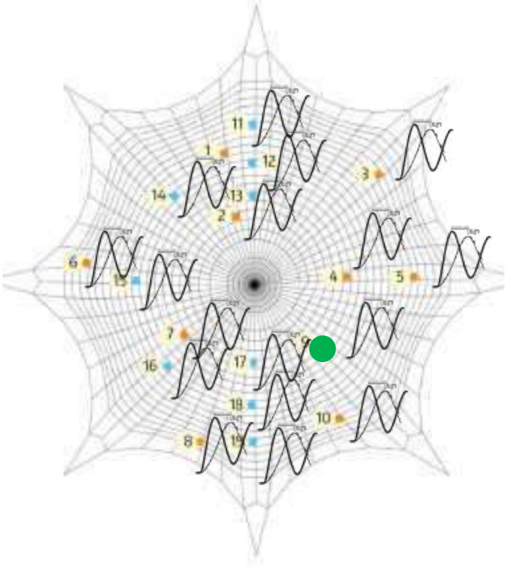




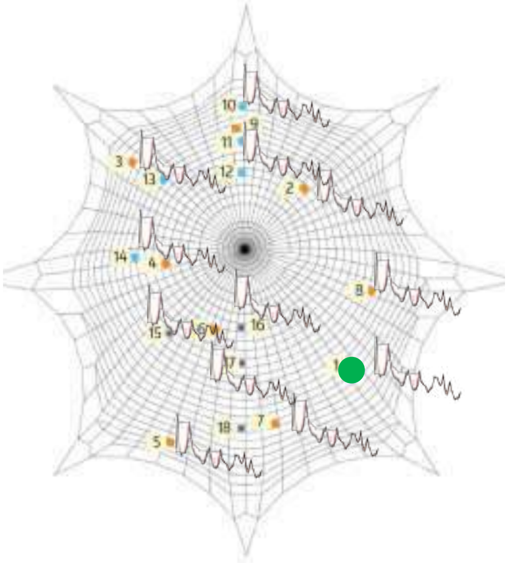
Tested

Untested

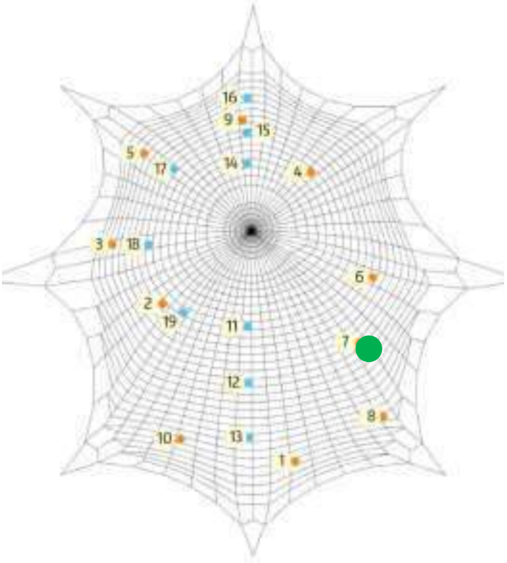
Next steps | **Identify signaling cues**



Time domain



Frequency domain



Conclusions

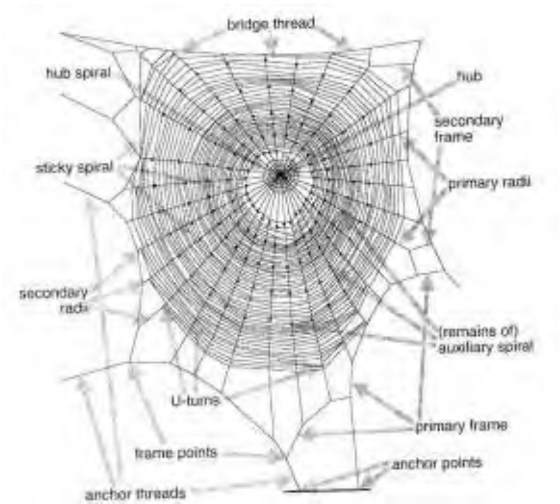
- Internal resonances
- Measured dynamics will vary at leg positions
- Dynamics change as design changes

Careful in further analysis
- Frequency resolution is low
- After mode II comparing designs becomes challenging

Numerical | Next steps

What do we now know
- The signaling capabilities are indeed dependent on design
- Eccentricity increases differences

But
- Every spider web is unique



Zschokke, S. (1999). Nomenclature of the orb-web. *Journal of Arachnology*, *27*(2), 542–546.

WITT, P. N., RAWLINGS, J. O., & REED, C. F. (1972). Ontogeny of Web-building Behavior in Two Orb-weaving Spiders. *American Zoologist*, *12*(3), 445–454.

Numerical | Next steps

What do we now know

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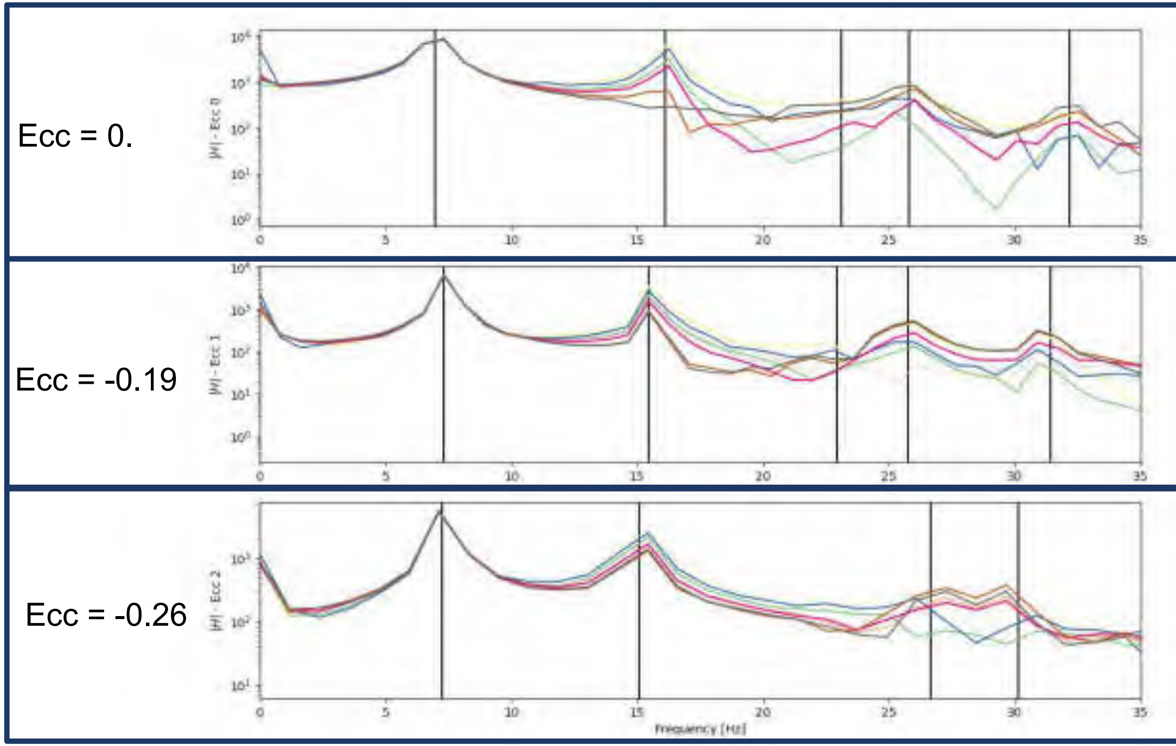
But

- Every spider web is unique
- Dynamics change as design changes



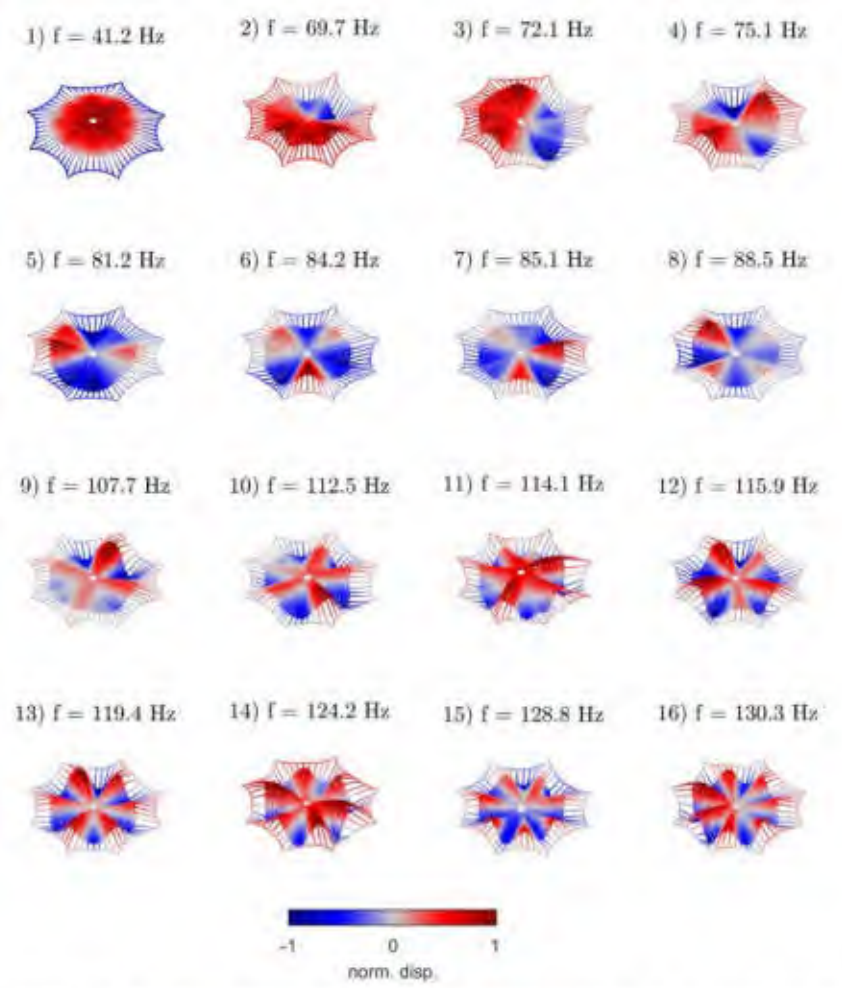
Numerical | Next steps

What do we now know

- The signaling capabilities are indeed dependent on design
- Eccentricity seems to improve signaling

But

- Every spider web is unique
- Dynamics change as design changes
- A spider can not be fully aware of the intrinsic dynamics of a web



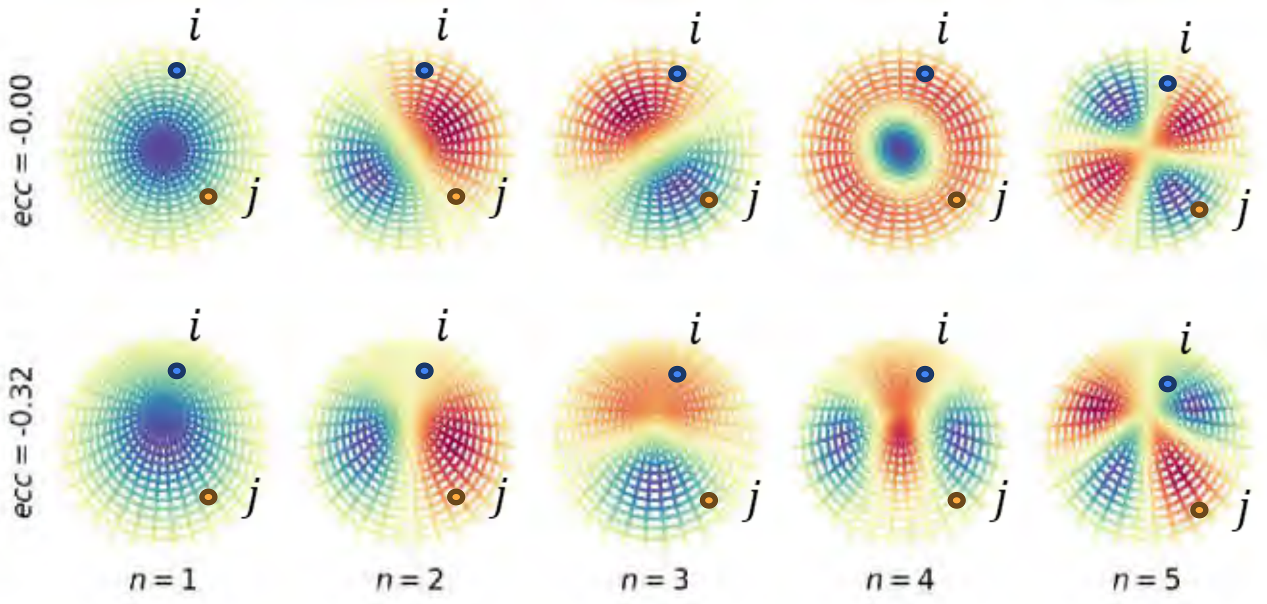
Lott et al. 2022

Two points in the web are correlated according to

$$G_{ij} = \phi_{in}\phi_{nj}^T$$

Signal is unique!

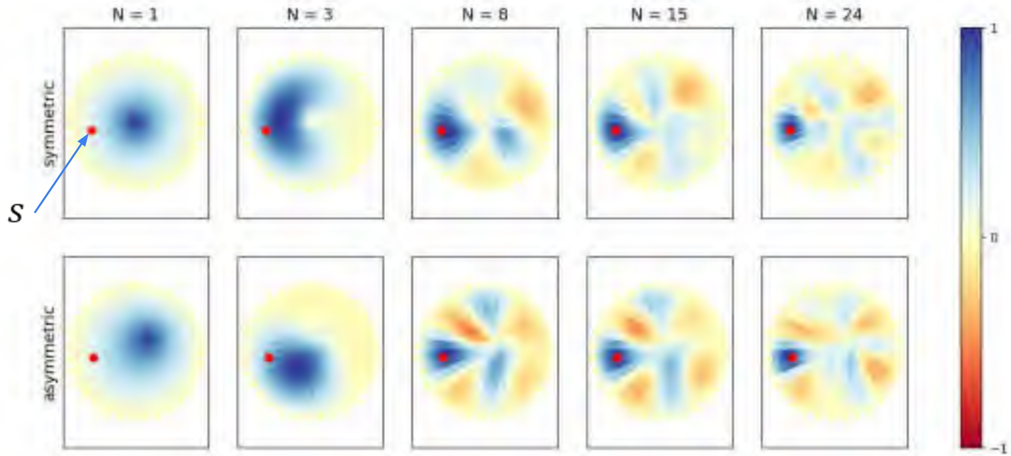
$$\phi_{iN}\phi_{Nj}^T = \delta_{ij}$$



Numerical | **Uniqueness of response**

$$G_{sj} = \phi_{sN}\phi_{Nj}^{T}$$

Ideal figure looks like 1 at the source location and 0 everywhere else



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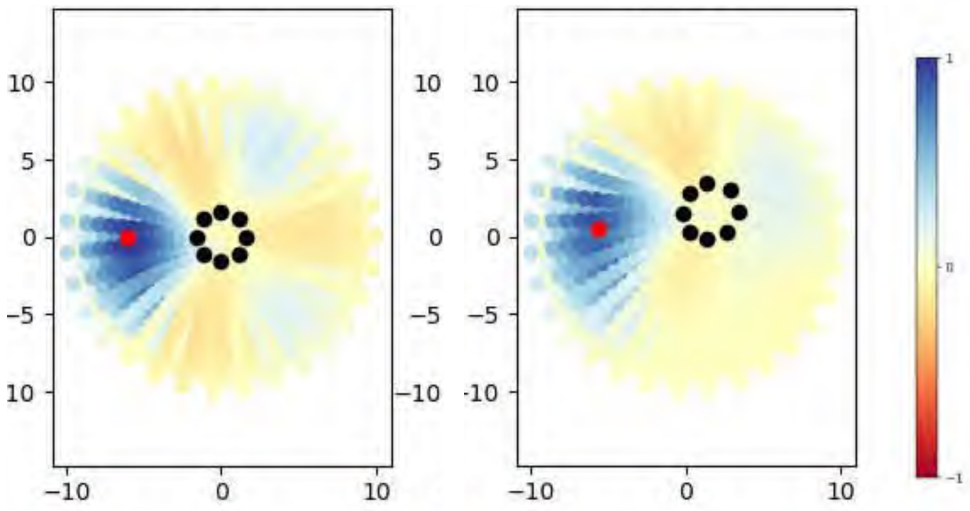

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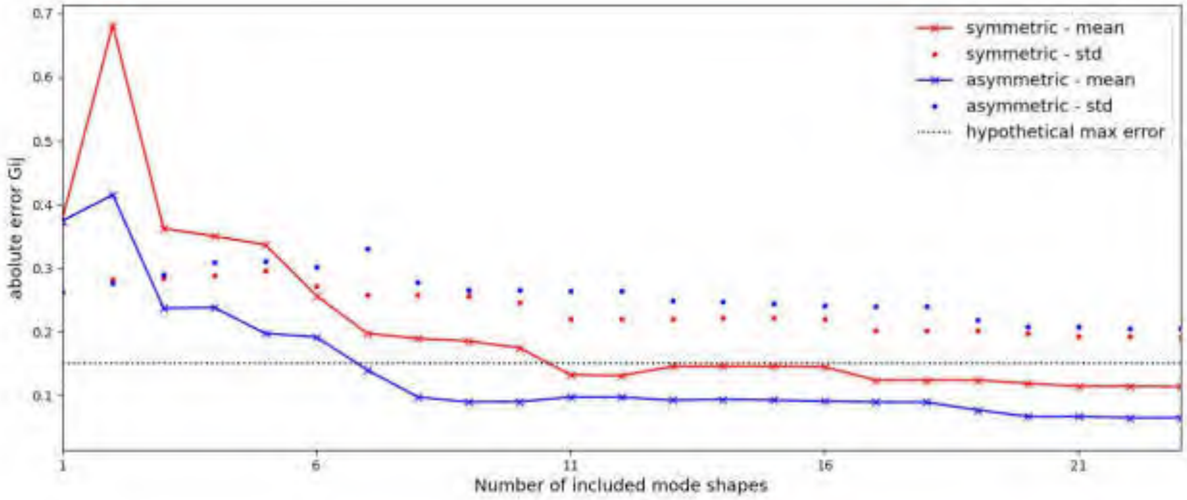
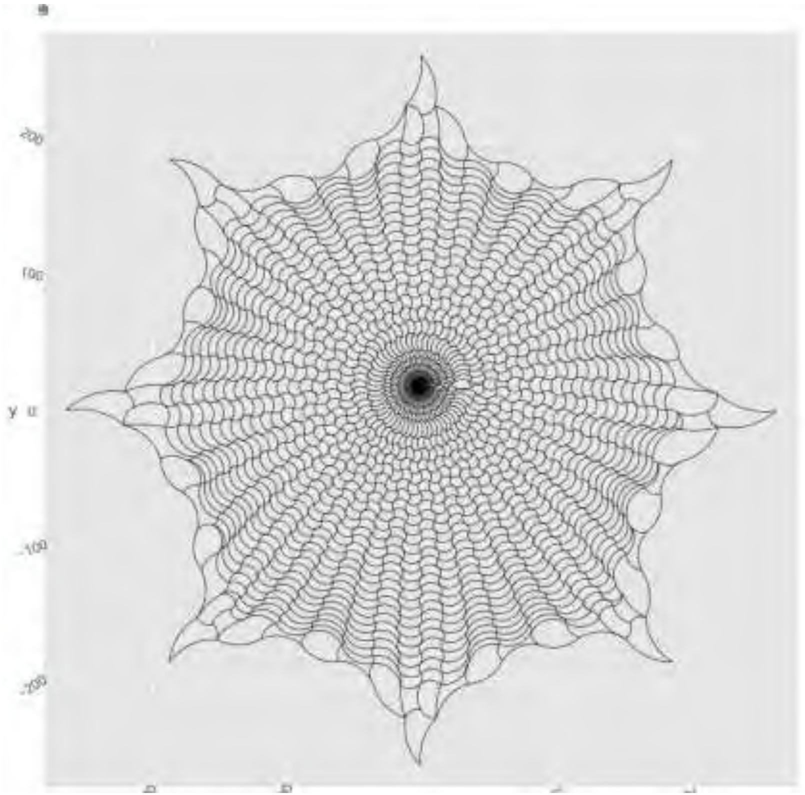


Numerical | Next steps

Only include modes robust to small design changes

Printing networks with variable tension gradients using single layer FDM printing



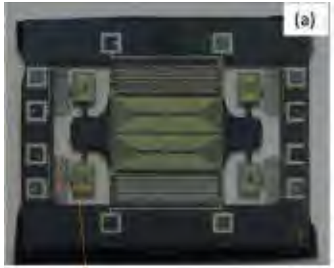
D-DIC | **Motivation**

When edge like features must be tracked

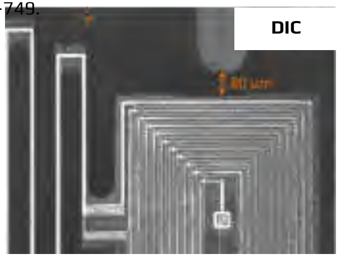
λ_d is less strict than λ_0

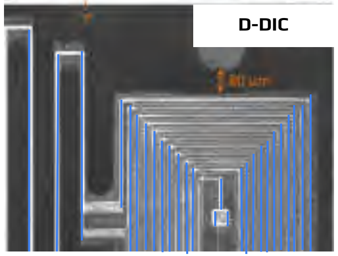
Applying orthogonal gradients is challenging when:

- Structures are lightweight and flexible



Liu, H., Qian, Y., Wang, N., & Lee, C. (2014). An In-Plane Approximated Nonlinear MEMS Electromagnetic Energy Harvester. *Journal of Microelectromechanical Systems*, *23*(3), 740–749.





D-DIC | **Motivation**

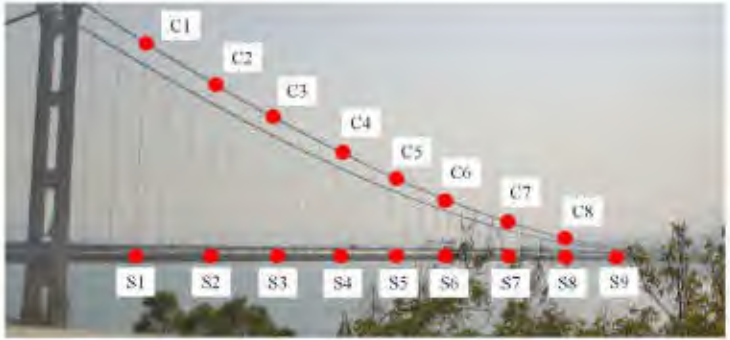
When edge like features must be tracked

λ_d is less strict than λ_0

Applying orthogonal gradients is challenging when:

- Structures are lightweight and flexible
- Structure very big

Wang, Y., Hu, W., Teng, J., & Xia, Y. (2024). Full-field displacement measurement of long-span bridges using one camera and robust self-adaptive complex pyramid. *Mechanical Systems and Signal Processing*, *215*, 111451



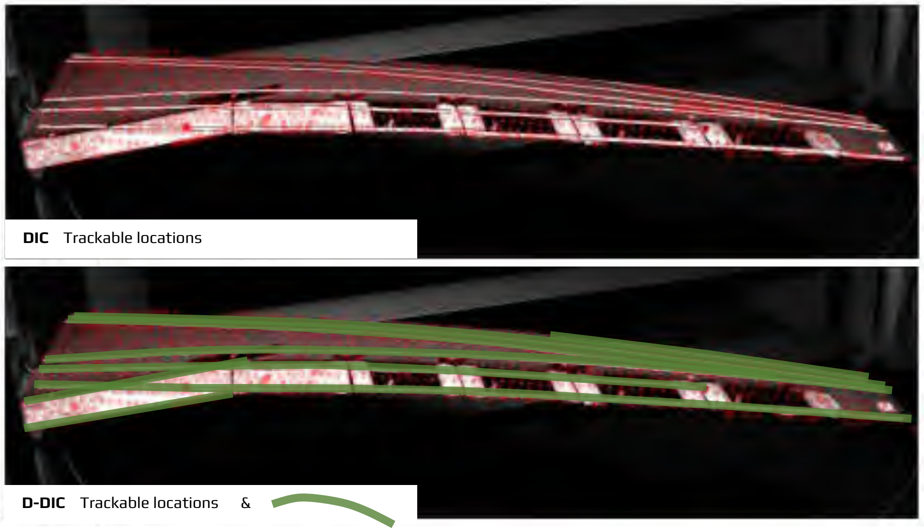
D-DIC | **Motivation**

When edge like features must be tracked

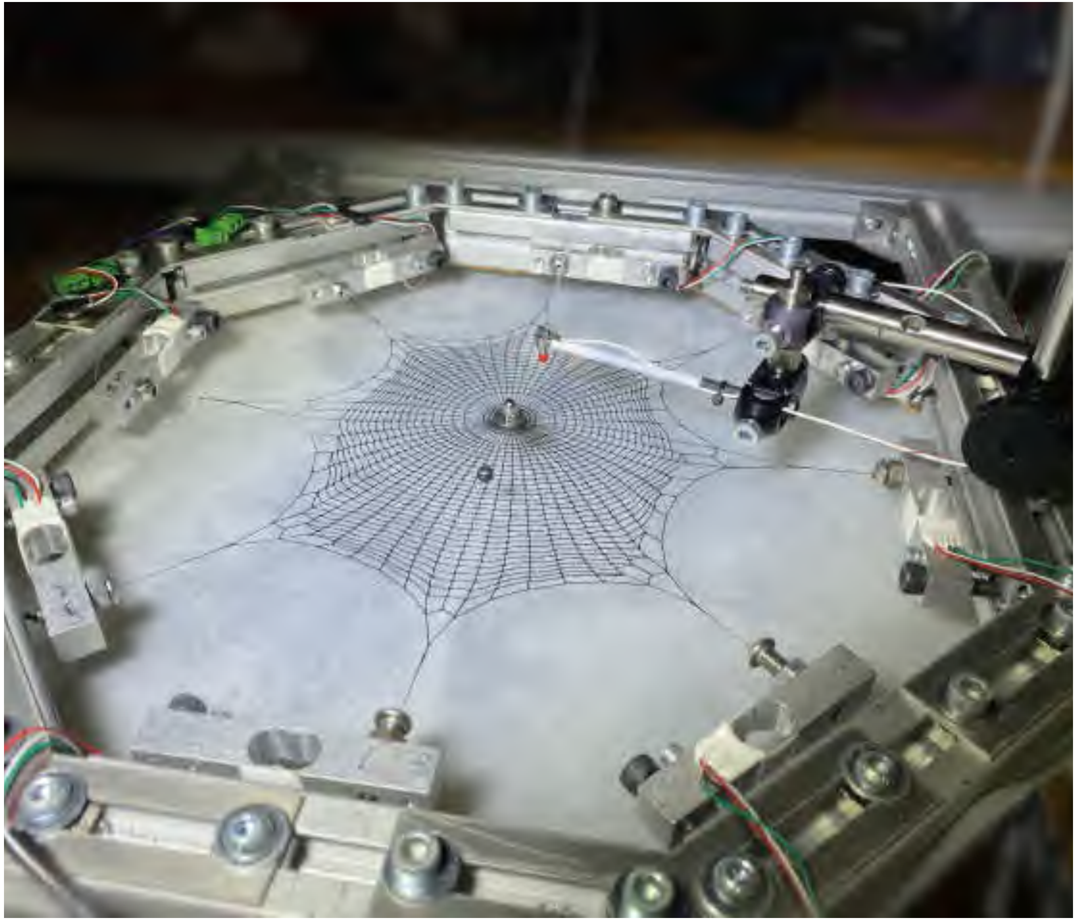
λ_d is less strict than λ_0

Applying orthogonal gradients is challenging when:

- Structures are lightweight and flexible
- Structure is very big
- Aerodynamic structures



Thank you



DIC | **Digital Image Correlation**

Image alignment technique as displacement estimator

DIC | **Digital Image Correlation**

Image alignment technique as displacement estimator

$T(x, y)$

DIC | **Digital Image Correlation**

Image alignment technique as displacement estimator

$$\min_{\delta x,\delta y} \sum_p [T(x - \Delta x - \delta x, y - \Delta y - \delta y) - I(x,y)]^2$$

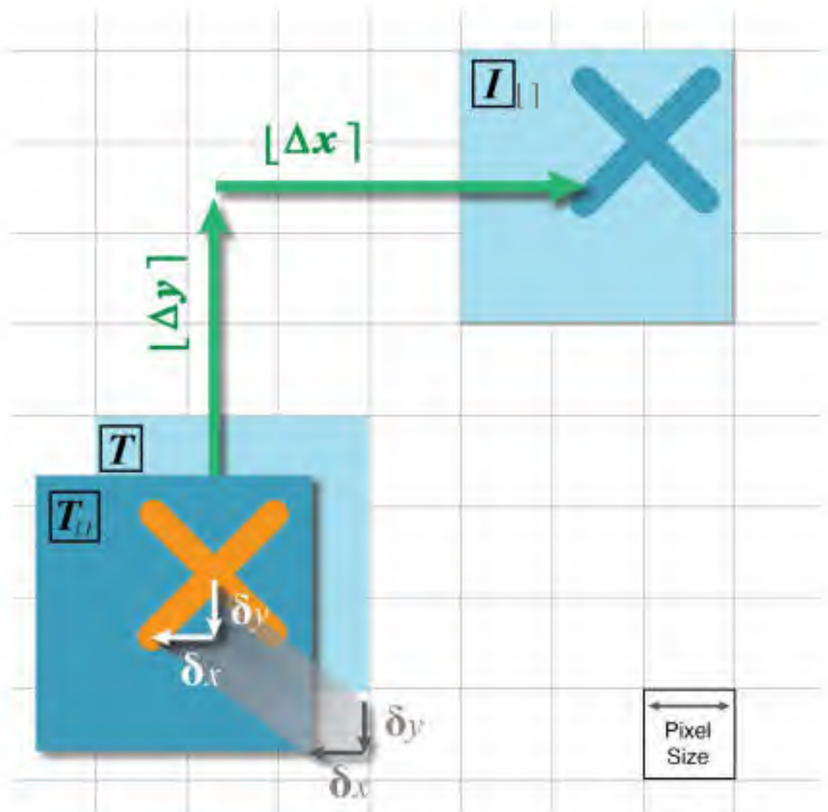
$$\Delta x \leftarrow \Delta x + \delta x$$

$$\Delta y \leftarrow \Delta y + \delta y$$

$T(x,y)$

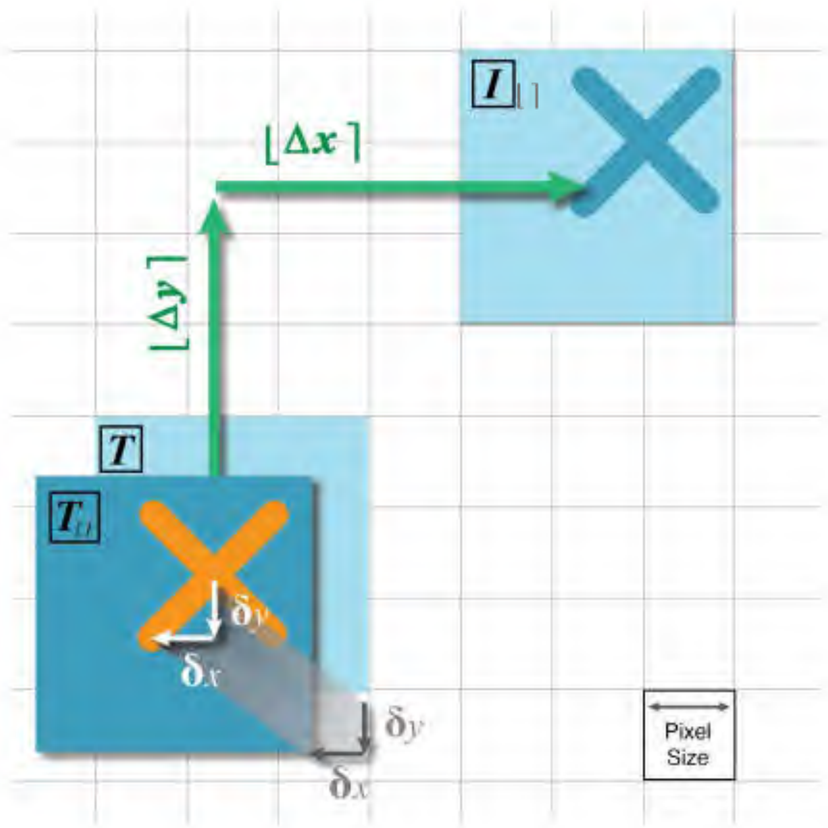
DIC | **Digital Image Correlation**

Image alignment technique as displacement estimator



DIC | **Digital Image Correlation**

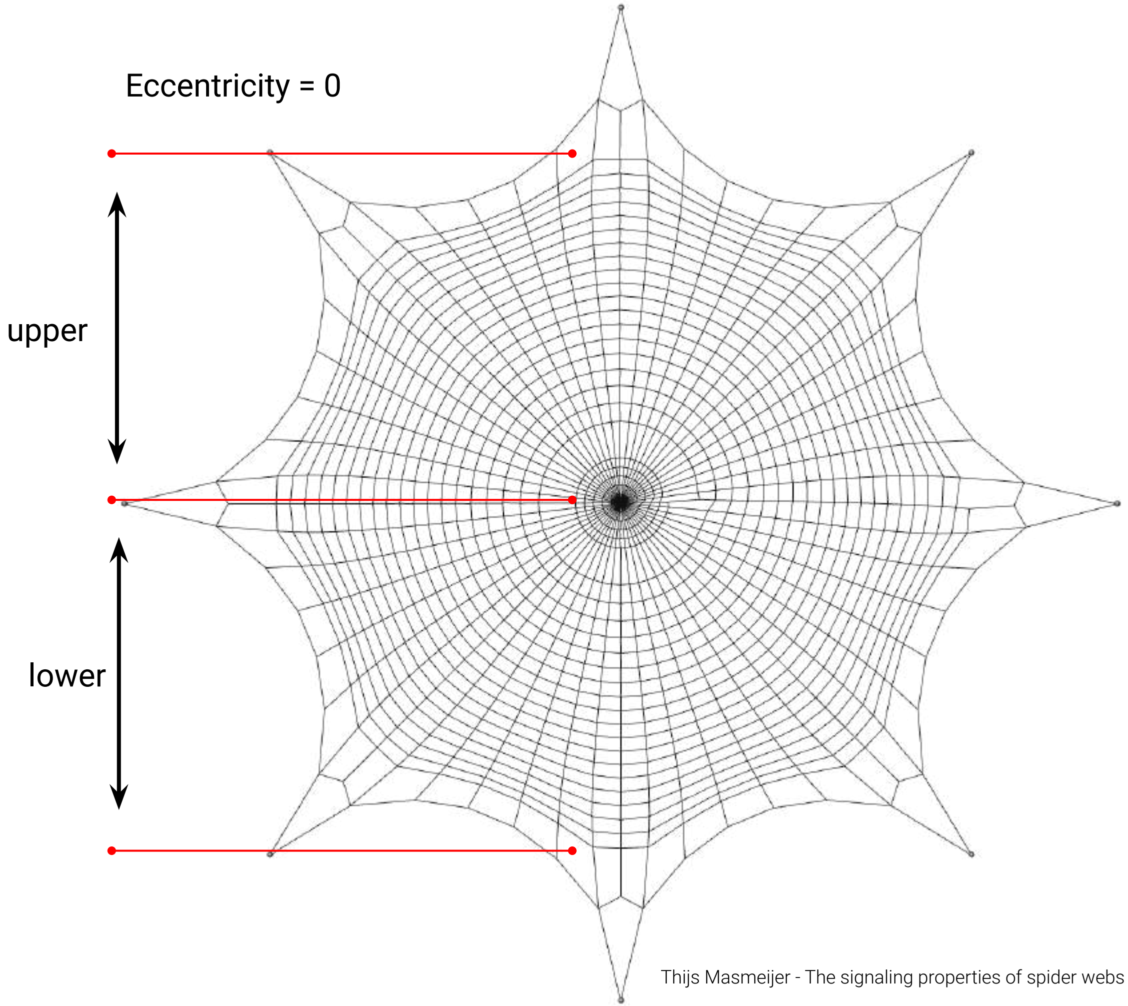
Image alignment technique as displacement estimator



Focus on design

Sequentially increase eccentricity

Eccentricity = (upper−lower)/(upper+lower)



Focus on design

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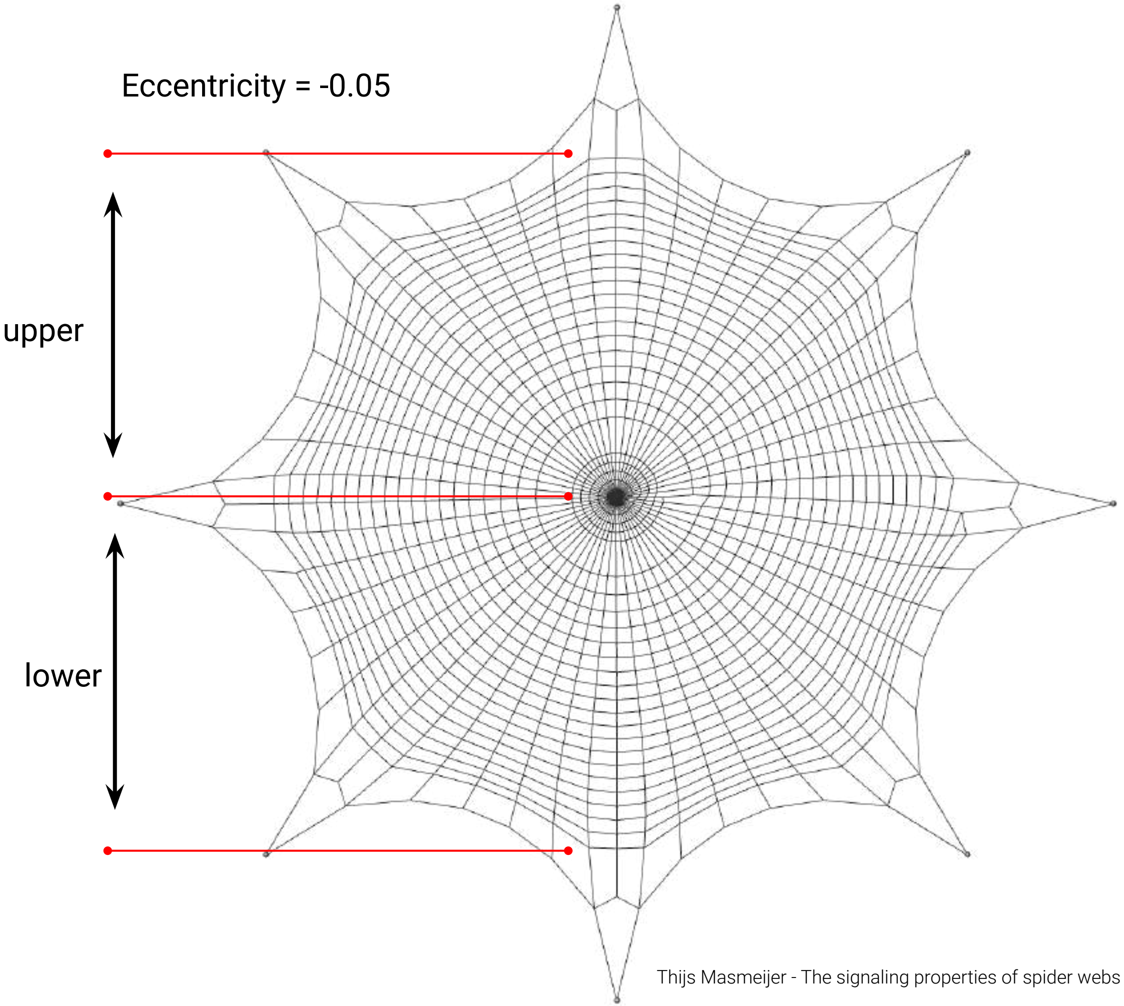
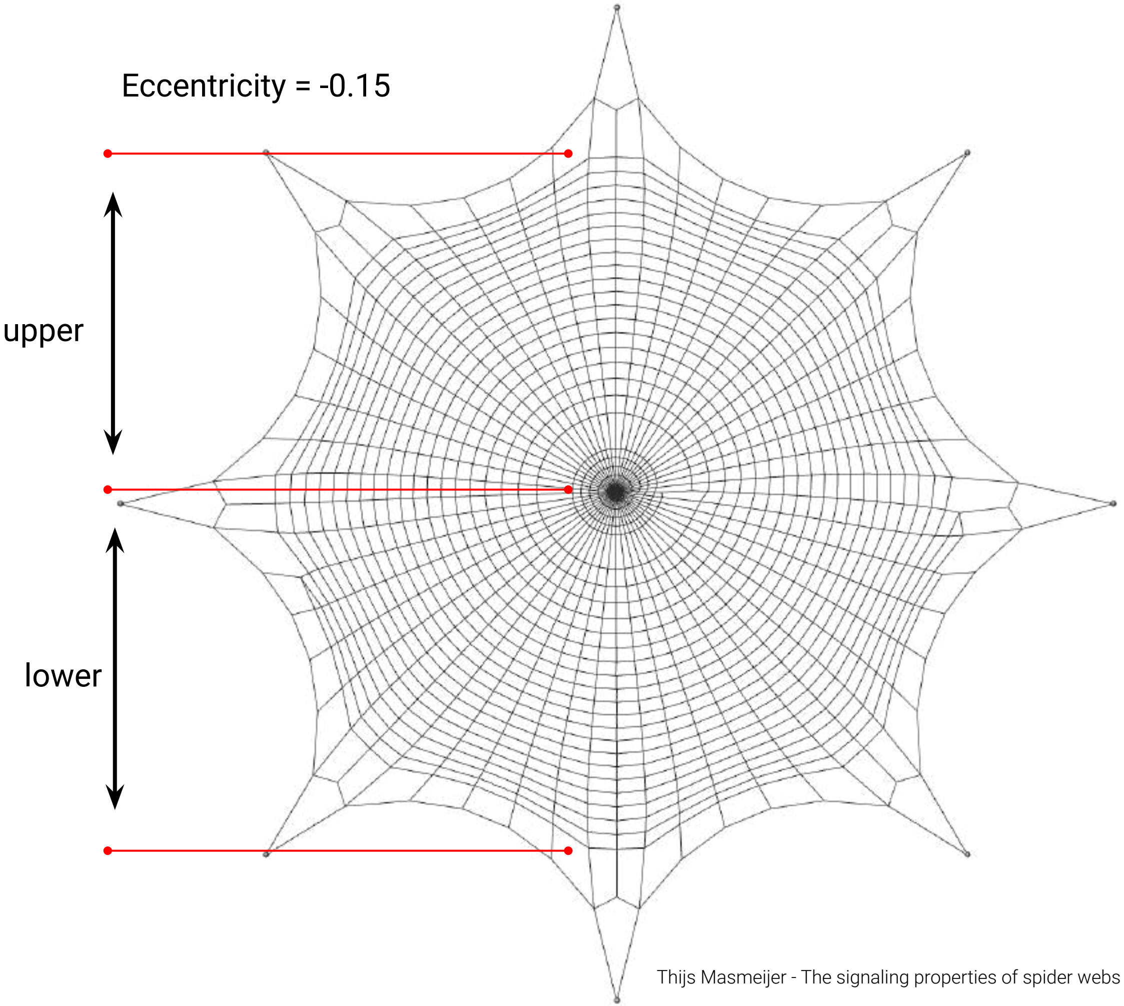


Thijs Masmeijer - The signaling properties of spider webs

Focus on design

Sequentially increase eccentricity

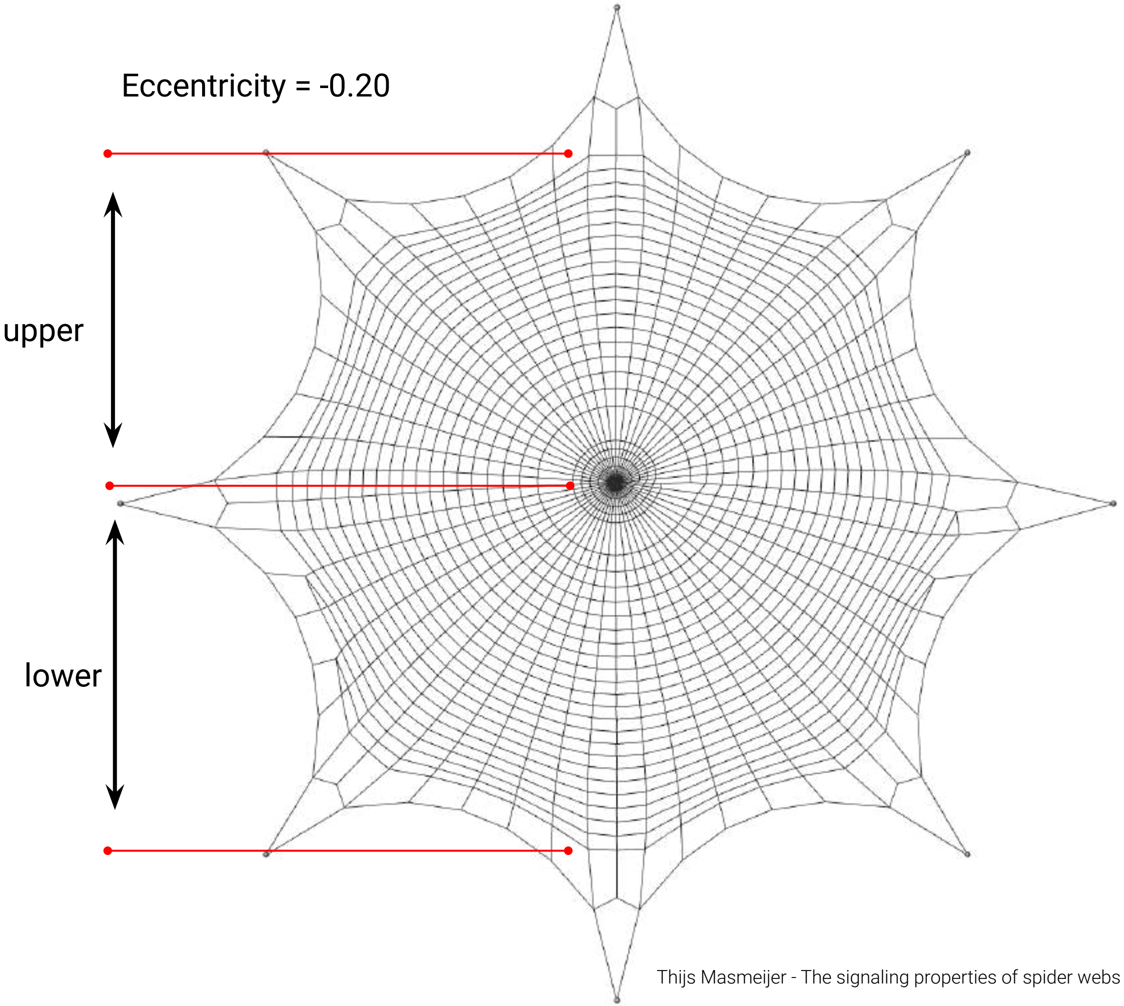
Eccentricity = (upper−lower)/(upper+lower)



Focus on design

Sequentially increase eccentricity

Eccentricity = (upper−lower)/(upper+lower)



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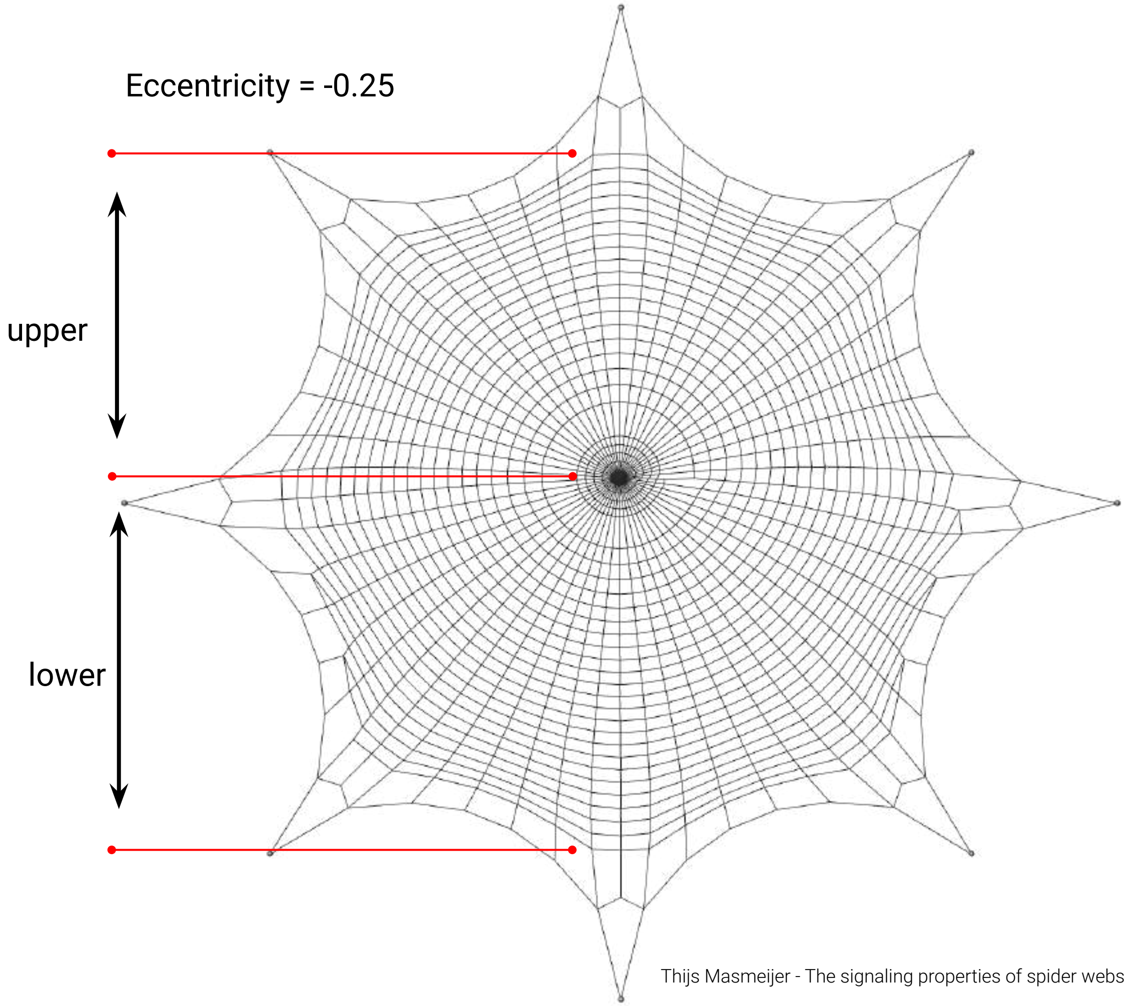

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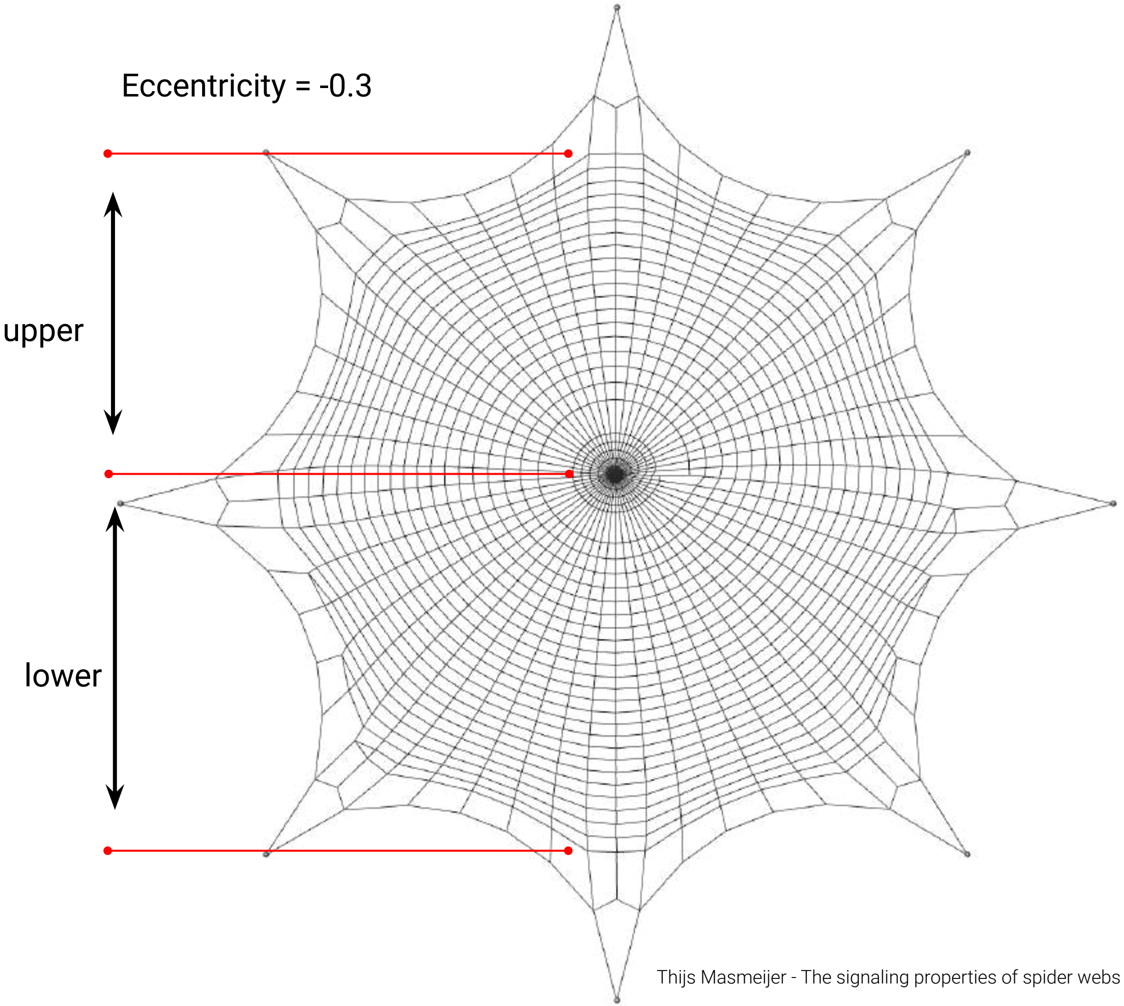
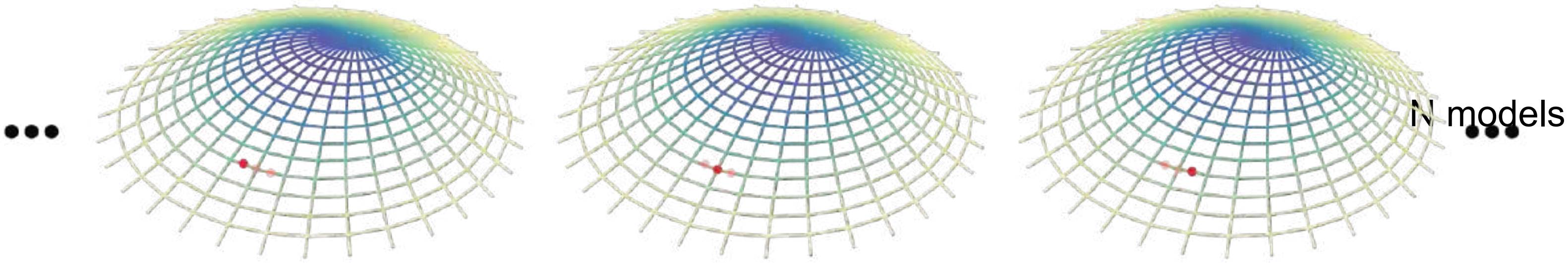


Map the dynamics of webs

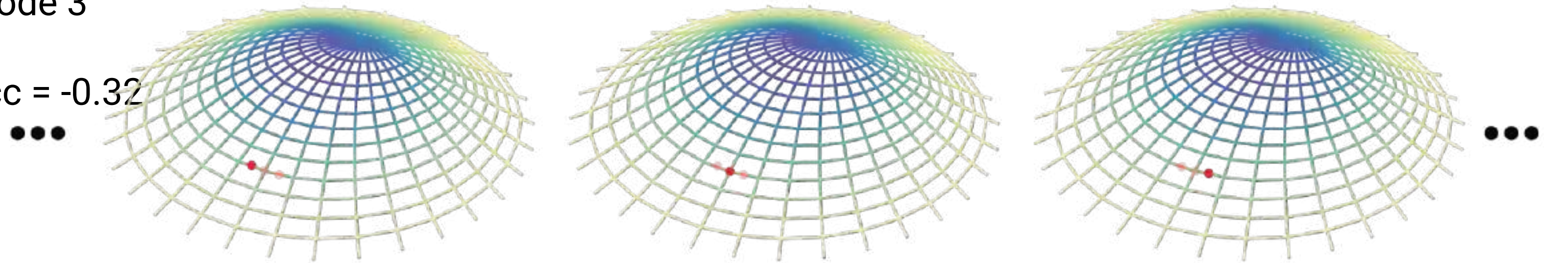
FE model

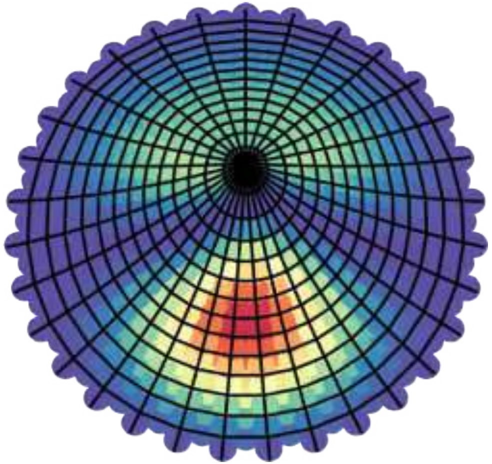


Map the dynamics of webs

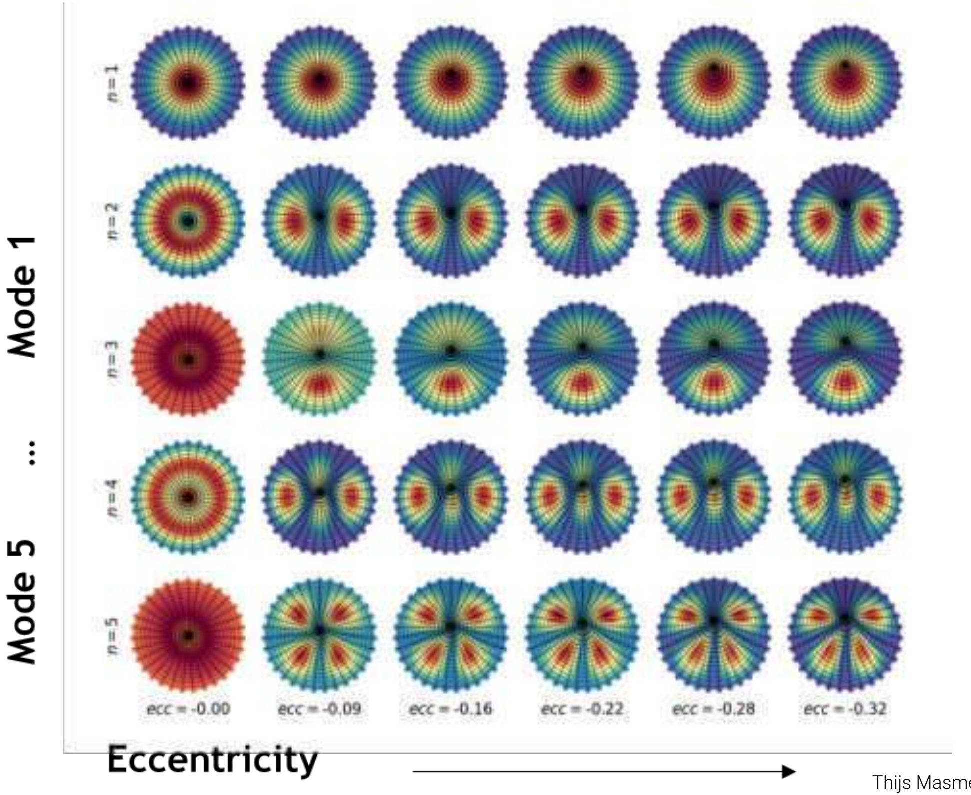
Mode 3

ecc = -0.32





Mapping the Dynamics | Effect of Eccentricity



Masmeijer, T. C. P., Méndez Echenagucia, T., Slavič, J., Loendersloot, R., & Habtour, E. (2023, July 2). Effect of eccentricity on sensing in spider web inspired cable nets. *EuroDyn 2023*.

Mapping the Dynamics | Effect of Eccentricity