Robotic fastener hole inspection with 2D ultrasonic phased array

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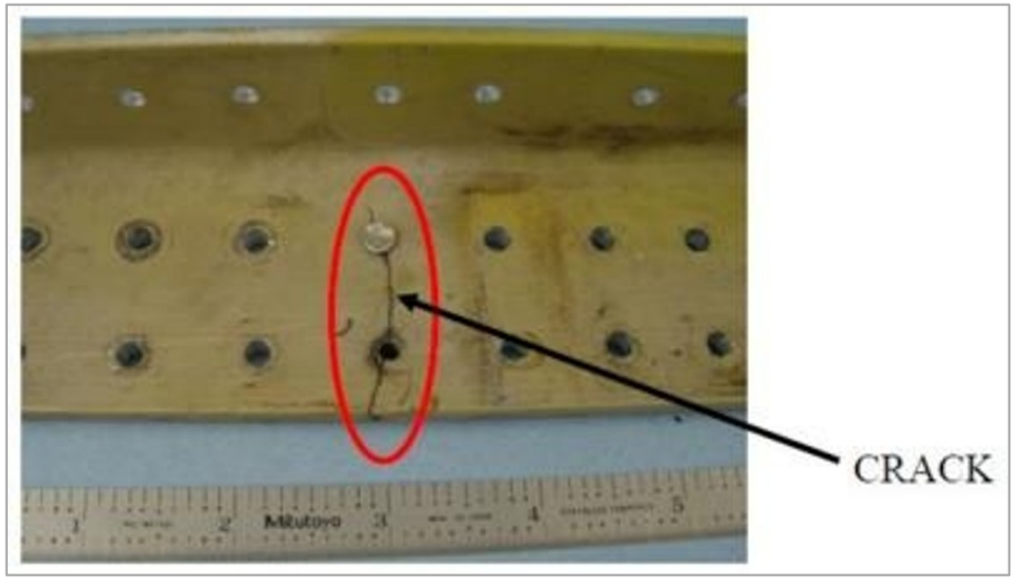
Overview

- ❑ Background & motivation
- ❑ 2D ultrasonic array inspection techniques
- ❑ Inspection optimization and new array design simulation
- ❑ Robotic fastener hole inspection
- ❑ Conclusion

❑Background & motivation

(a)



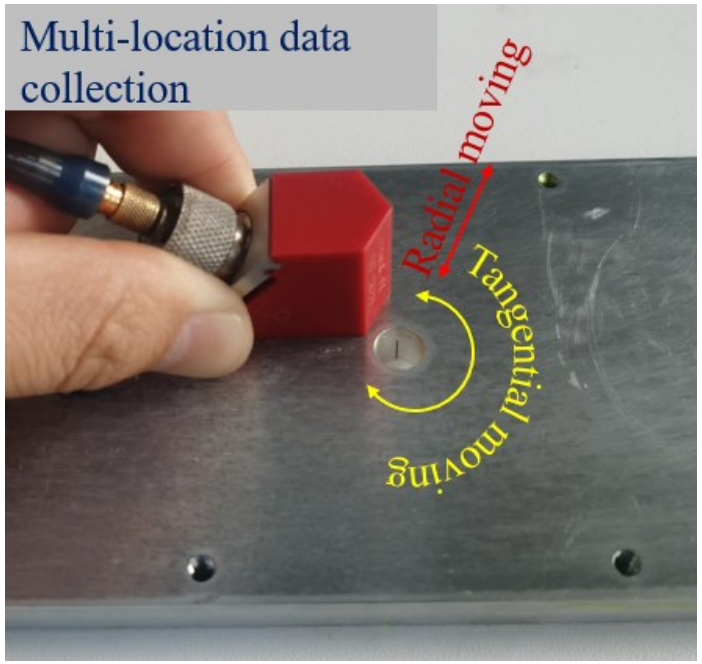
(b)

Eddy current inspection

- Need fastener removal
- Difficult to characterize

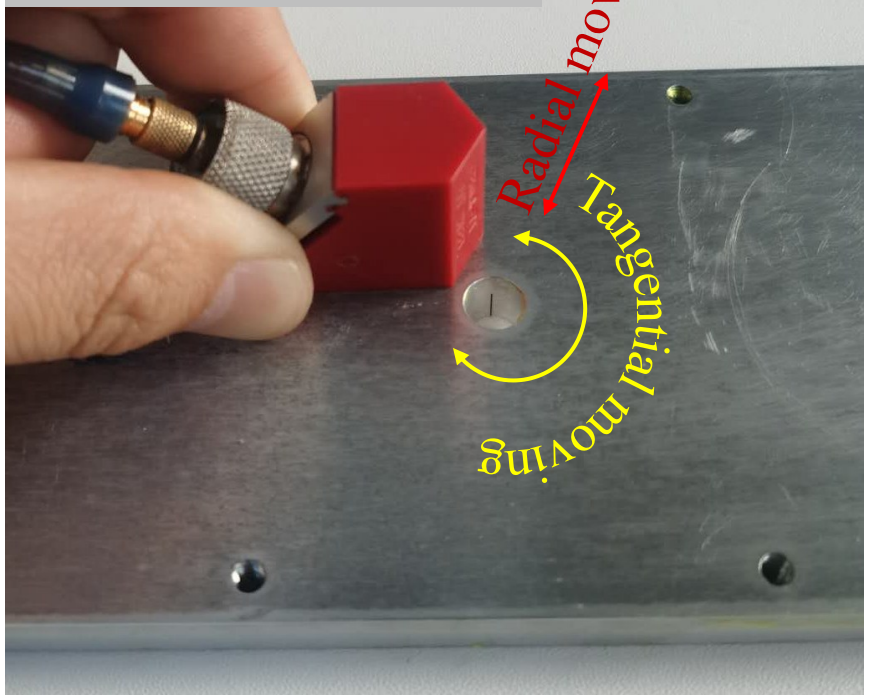
Ultrasonic inspection

- Need lots of probe movement
- Low inspection efficiency

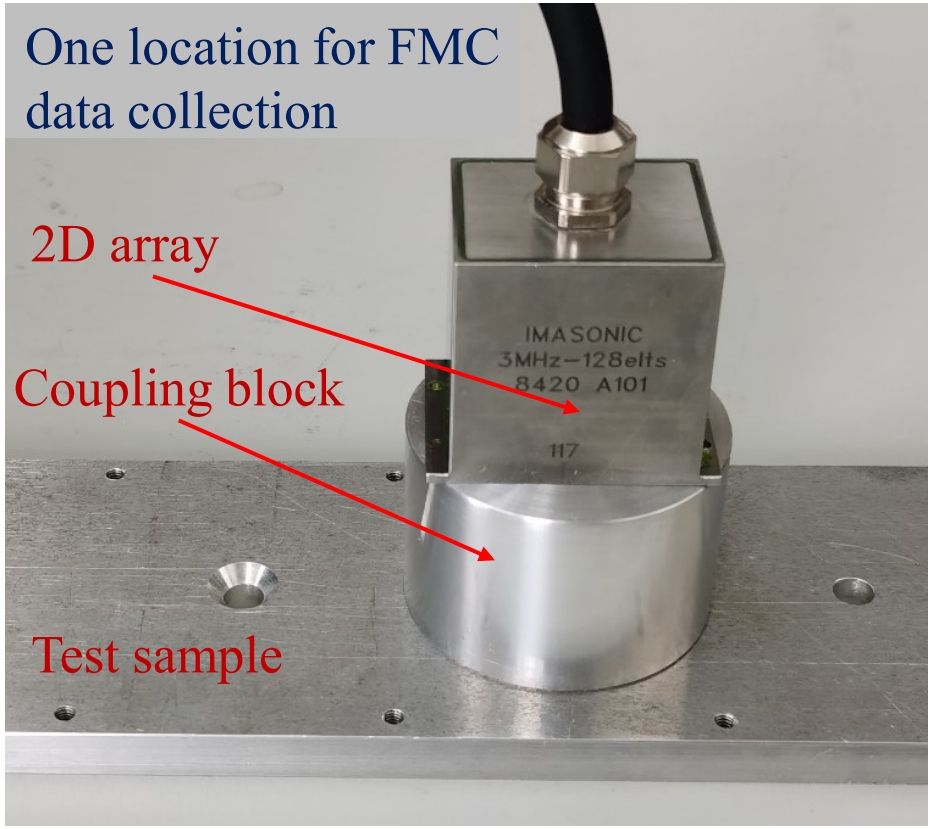


❑Background & motivation

Multi-location data collection

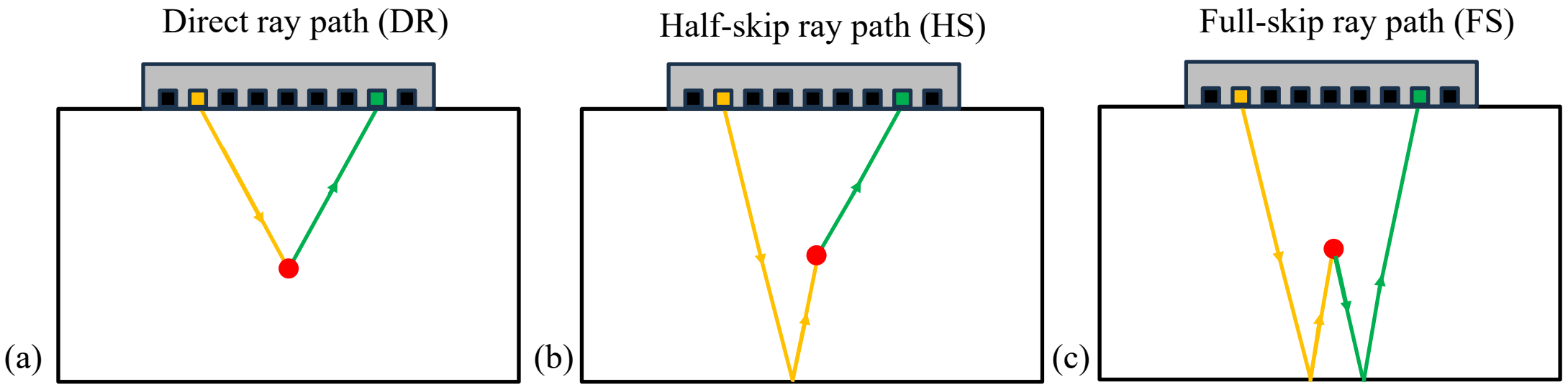


One location for FMC data collection

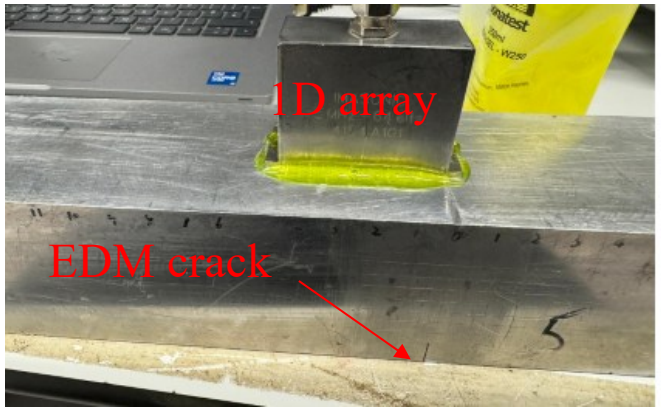


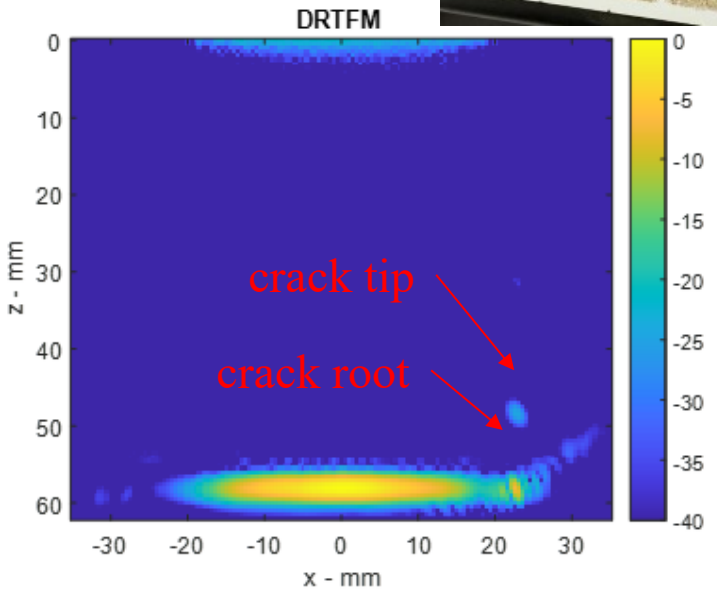
Simplify the inspection process / improve the efficiency / better result visualization

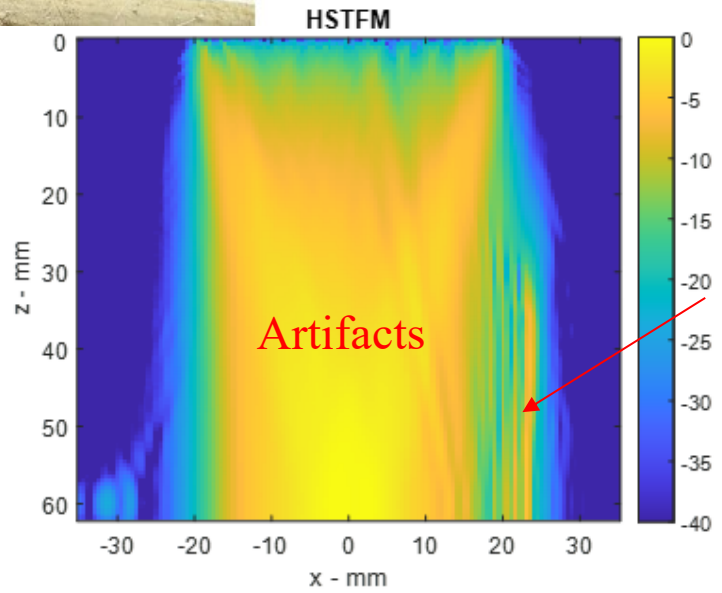
- **Imaging solution**



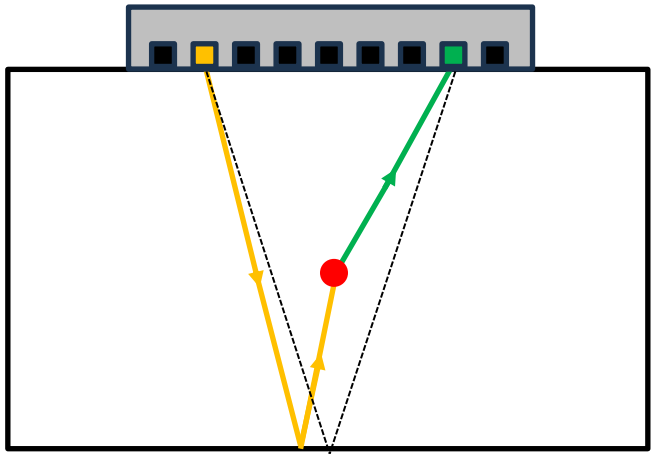
- **HS – coherent noise**

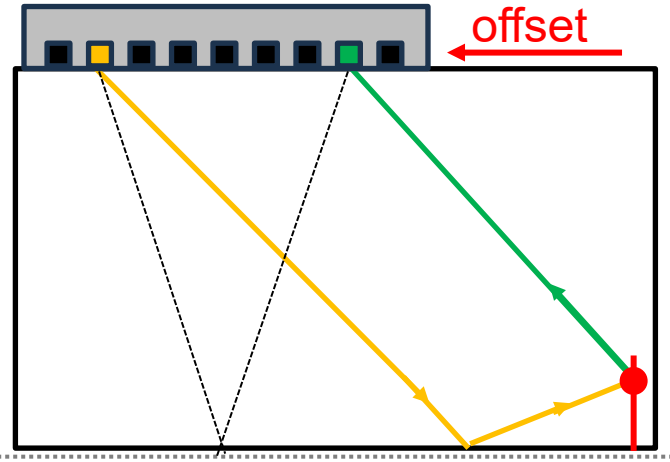




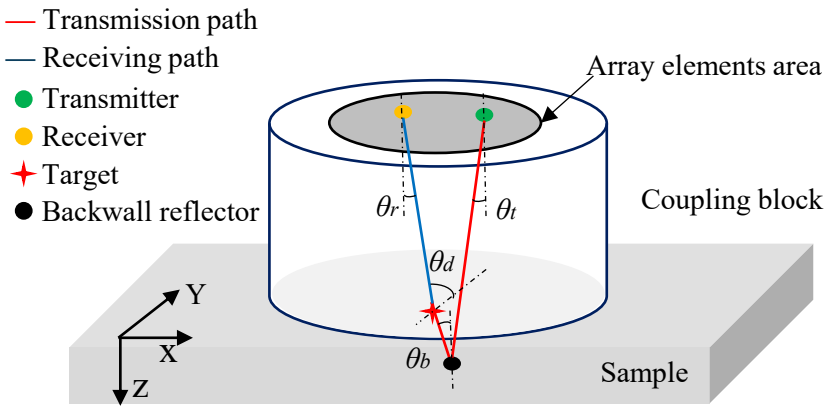


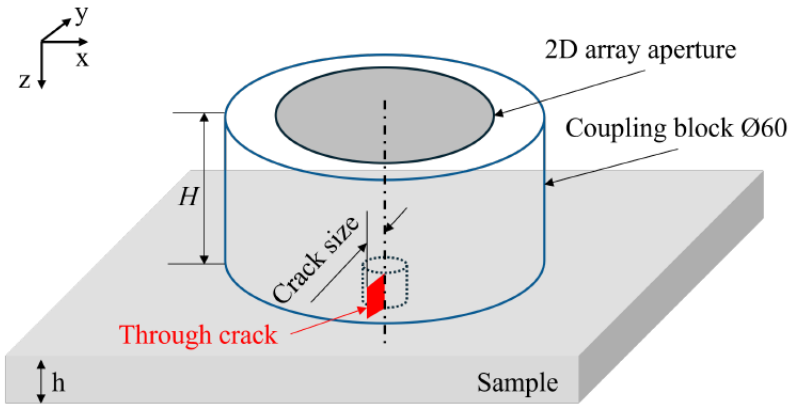
Half-skip ray path

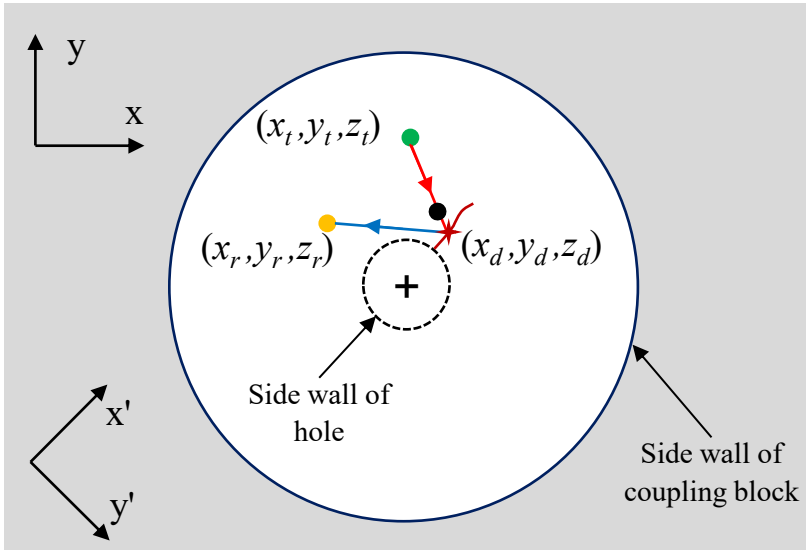


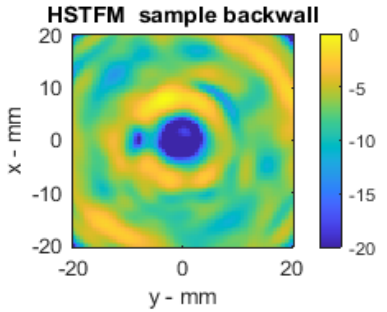


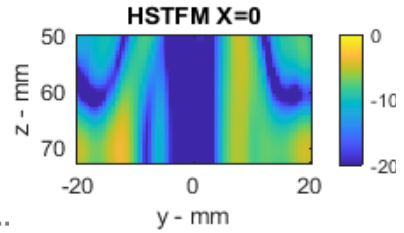
- **HS – coherent noise**

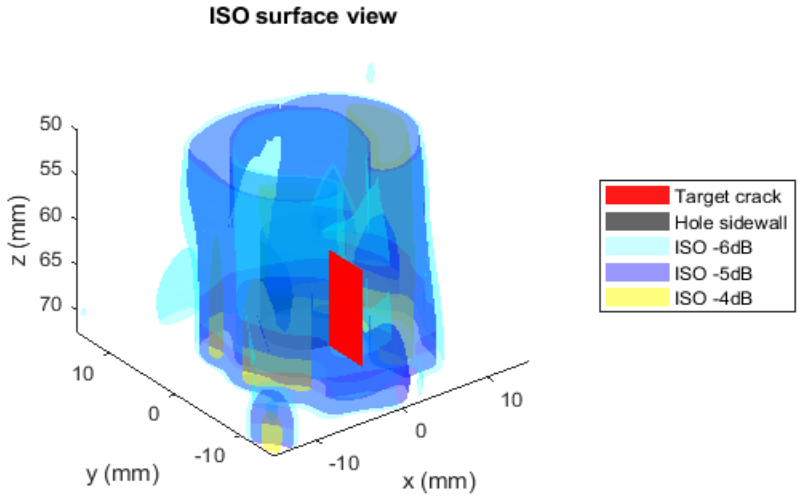




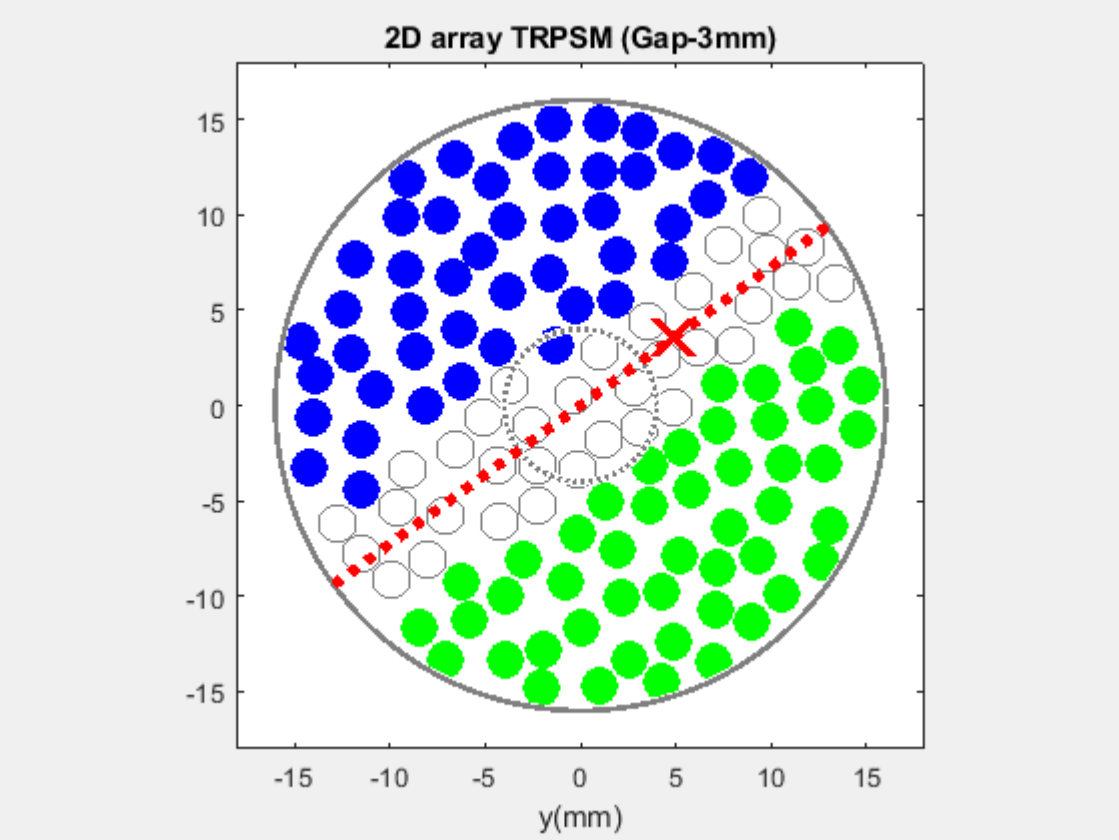




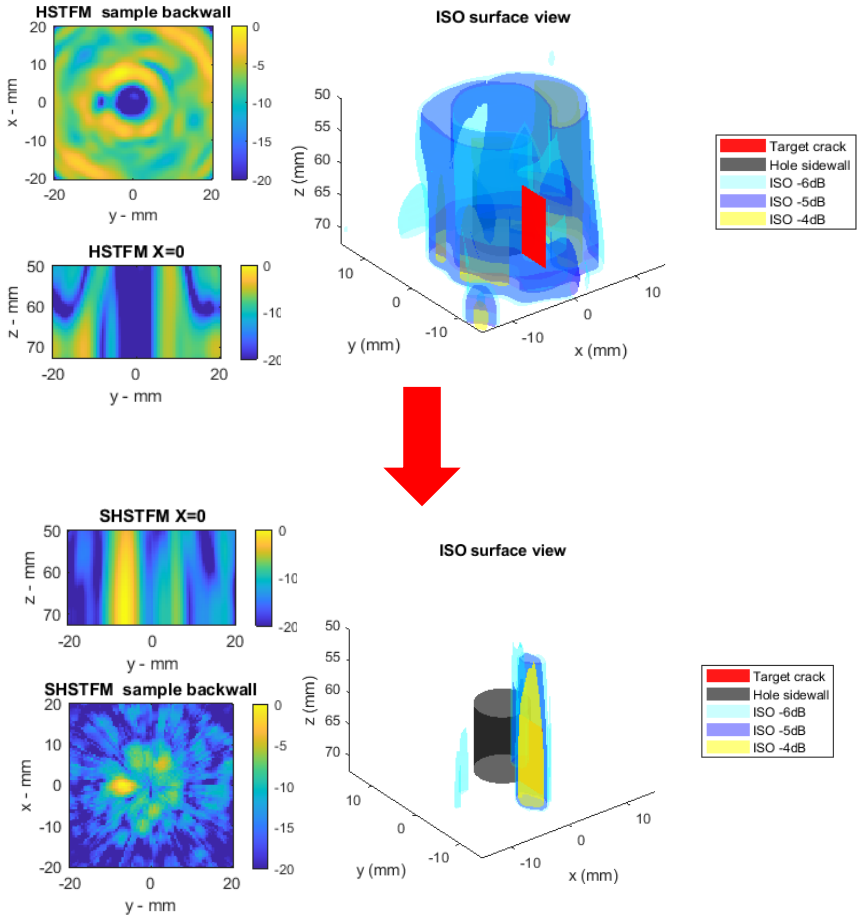




- **HS – TRP selection**

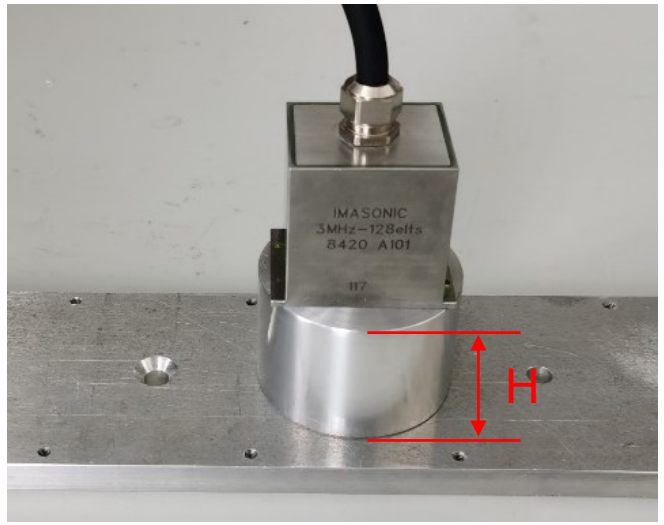


$$I_{\mathrm{r,HS}}(x,y,z) = \left| \sum_{ij \in \mathrm{S}^{(1)}_{\mathrm{r,HS}}} h_{ij}(\tau^{\mathrm{HS}}_{ij}(x,y,z)) \right| + \left| \sum_{ij \in \mathrm{S}^{(2)}_{\mathrm{r,HS}}} h_{ij}(\tau^{\mathrm{HS}}_{ij}(x,y,z)) \right|$$

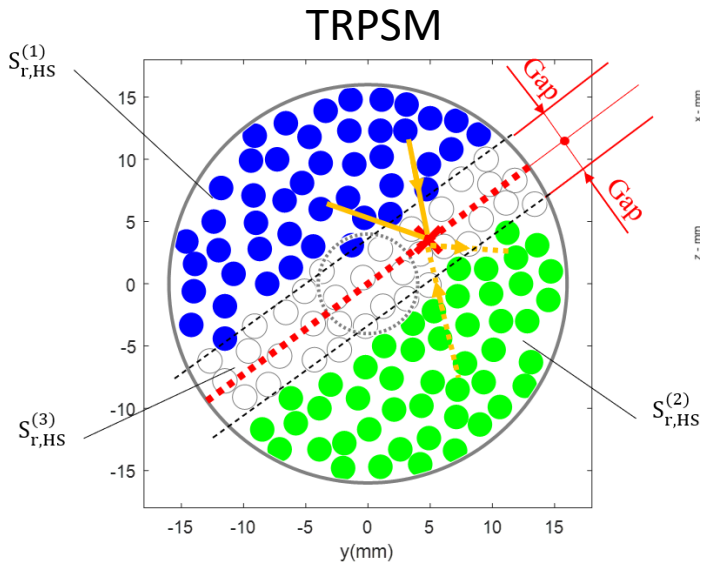


❑Inspection optimization and new array design simulation

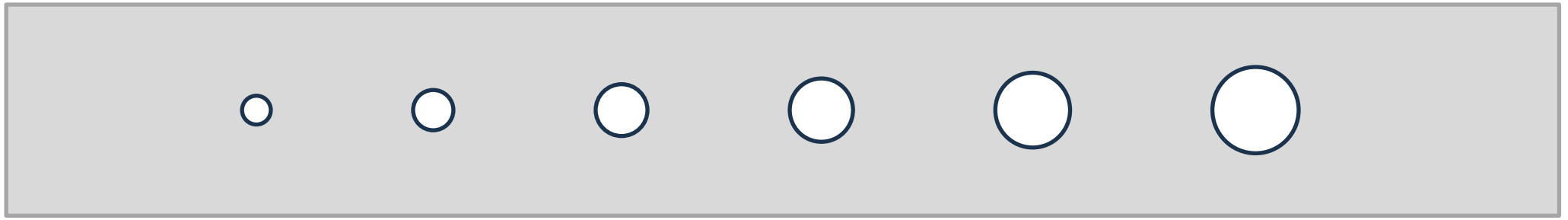
Q1: What's the best choice of coupling block **height** ?



Q2: What's the best choice of **Gap**?

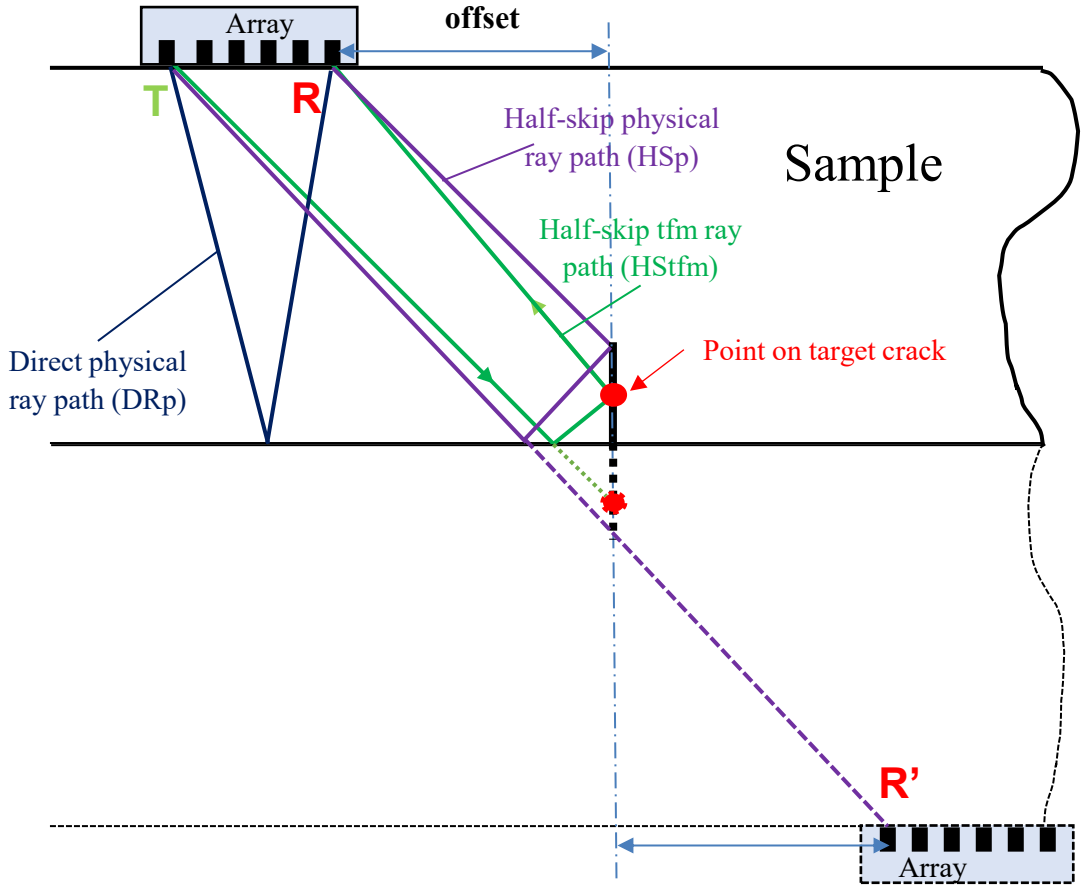


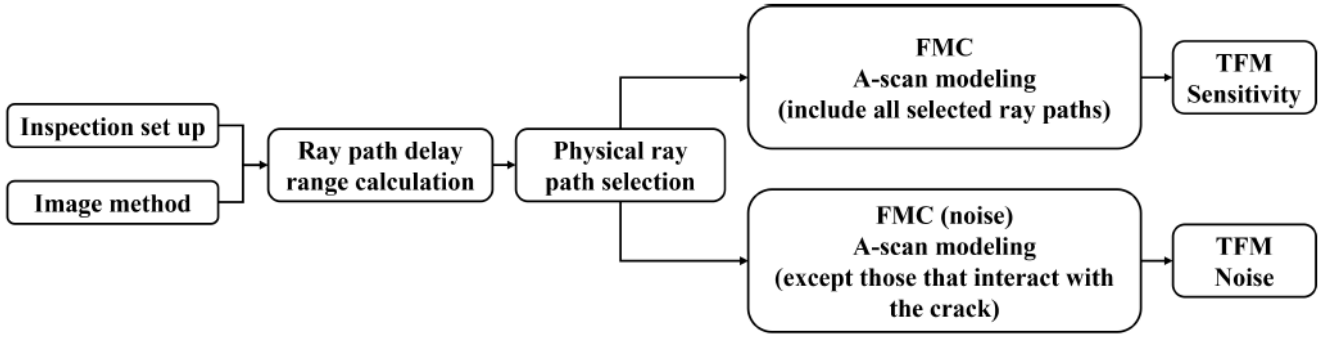
Q3: How to **distribute the array elements** for a **new array** which can make full use of each elements?



❑Inspection optimization and new array design simulation

- **Ray – based semi-analytical model**





- Ray path selection:

$$[\tau_{min}^{TFM}, \tau_{max}^{TFM}] \cap [\tau_{min}^{phy} - t^{pul}, \tau_{max}^{phy} + t^{pul}] \neq \varnothing$$

- Modelling the A-scan in FMC :

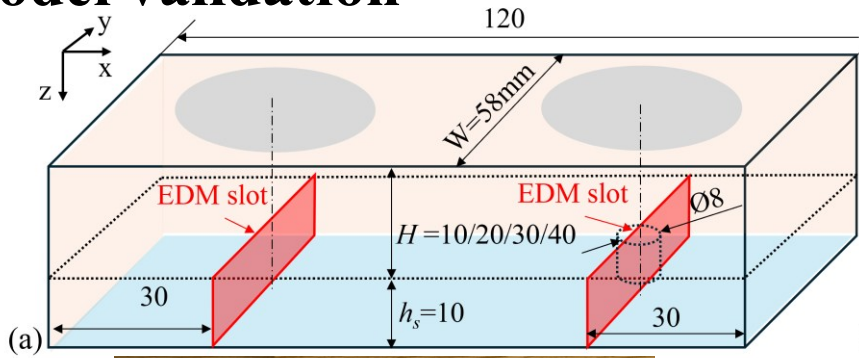
$$A_{tx,rx}^{s}[n] = \sum_{s} \eta_{tx,rx}(\mathbf{r}_s)\, h^{p}\left(n\Delta t - \tau_{tx,rx}(\mathbf{r}_s)\right)$$

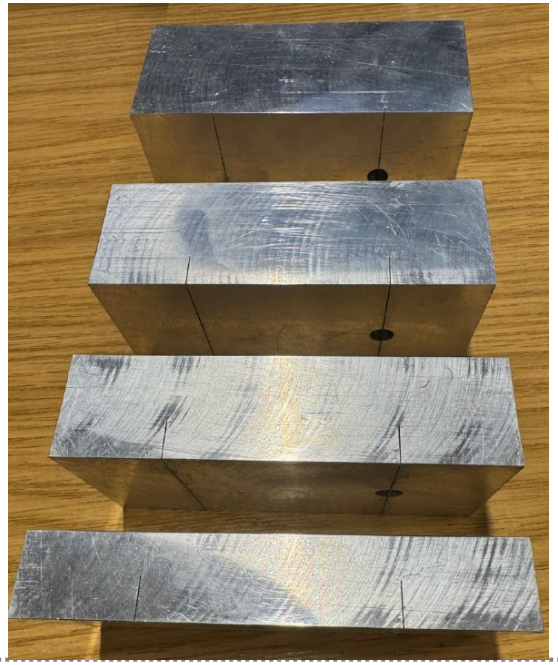
- Sensitivity calculation:

$$S^{\beta}(x,y,z) = \left| \sum_{tx,rx \in \mathrm{SFMC}} h_{tx,rx}^{\beta}(\tau_{tx,rx}^{\beta}(x,y,z)) \right|$$

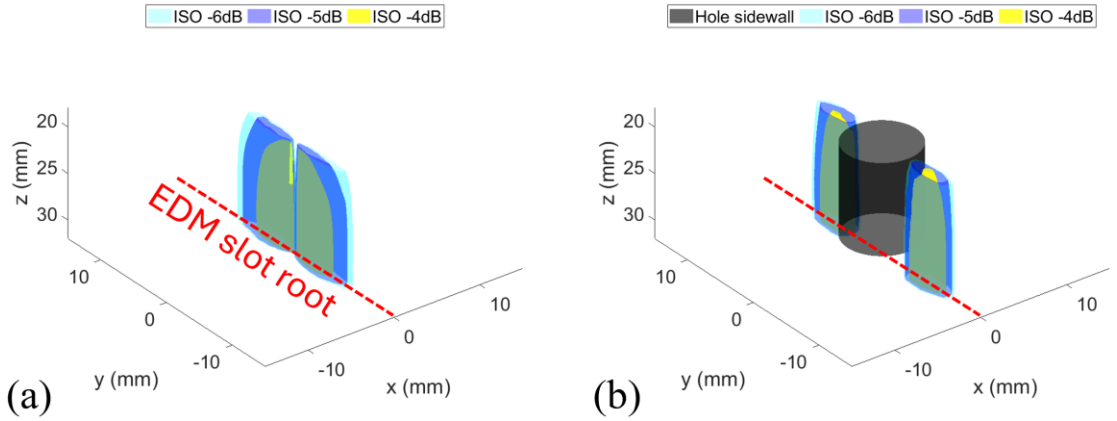
❑Inspection optimization and new array design simulation

- **Model validation**

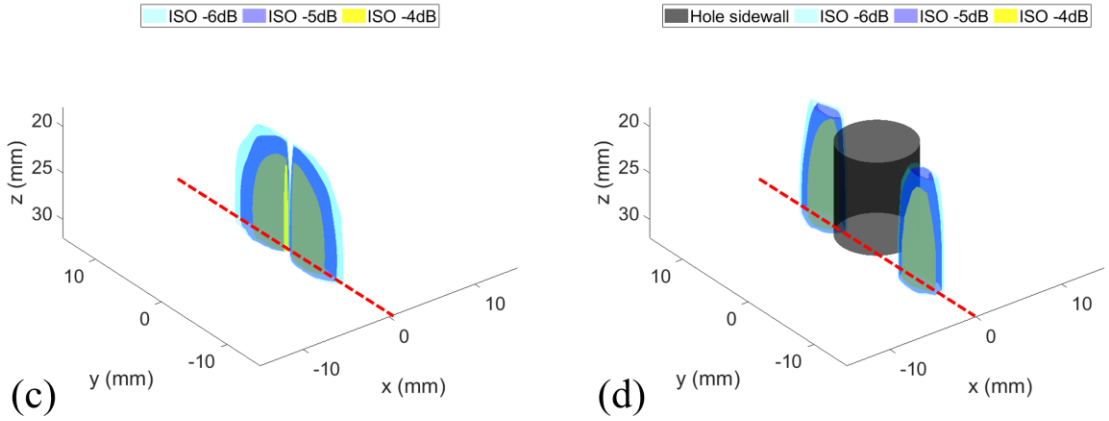




Simulation data HS-TFM

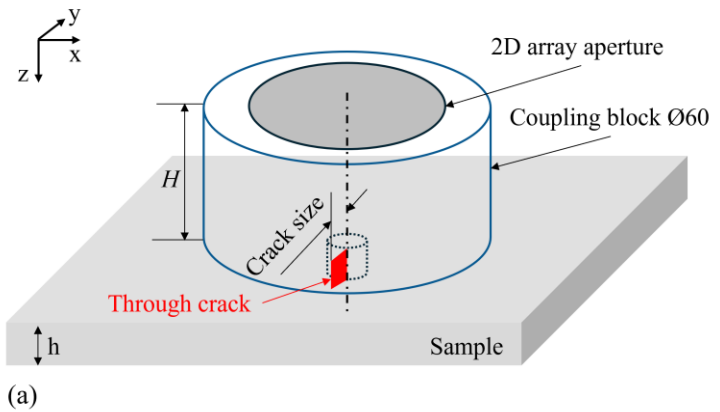


Experimental data HS-TFM

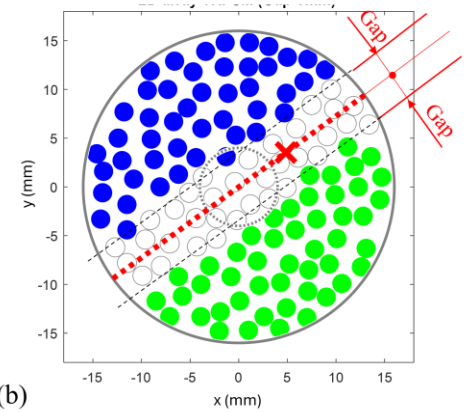


❑Inspection optimization and new array design simulation

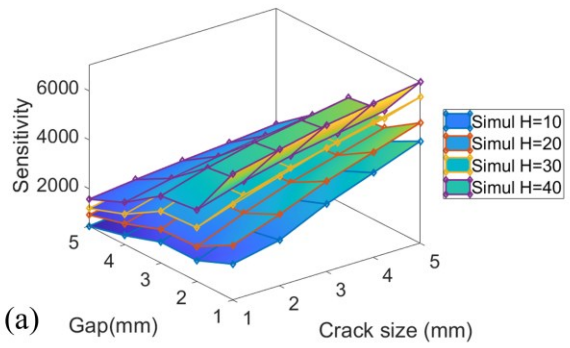
- **Model application I – inspection setup optimization**



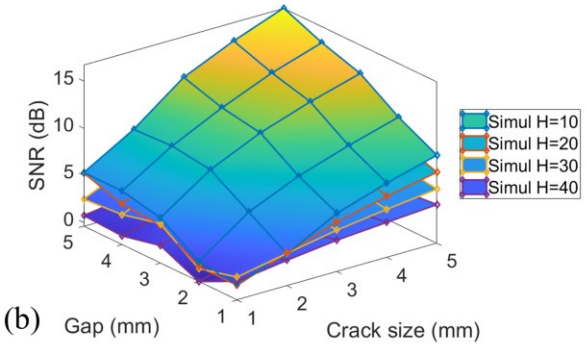
(a)



(b)

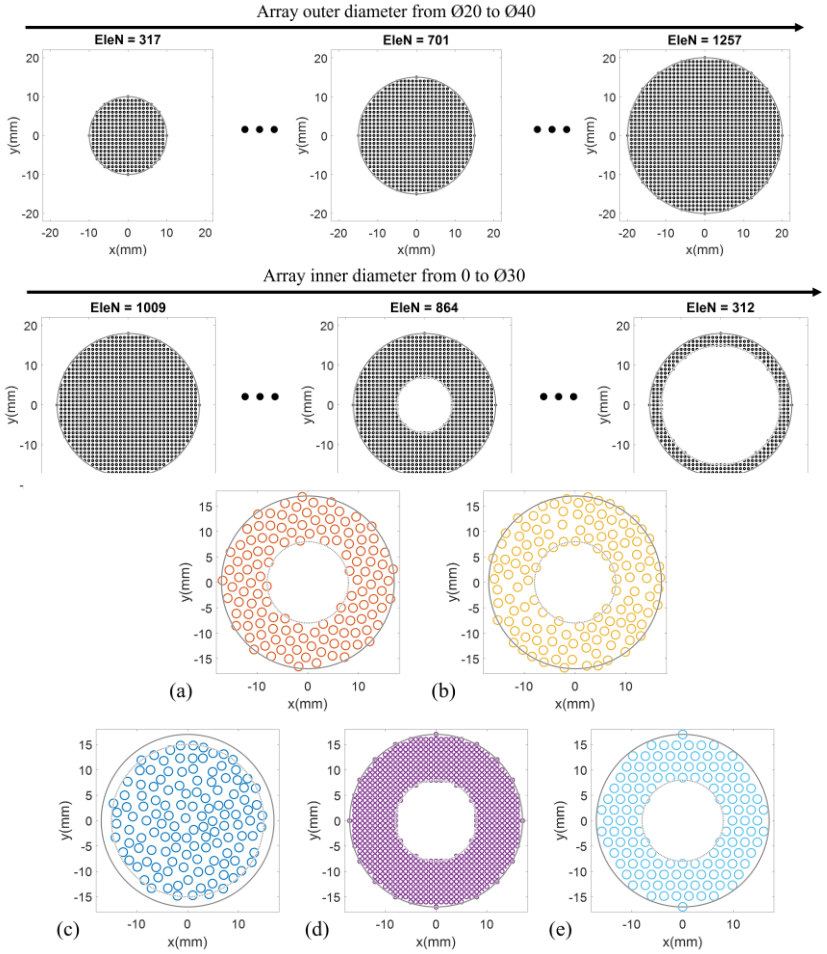


(a)



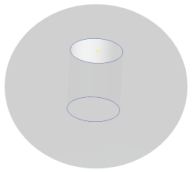
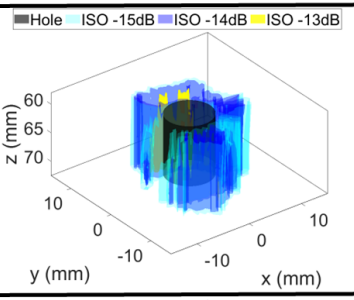
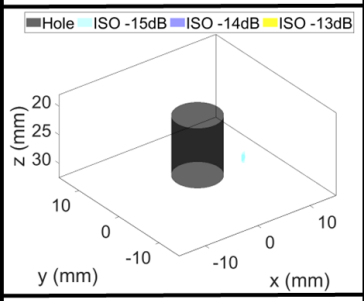
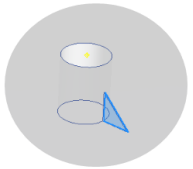
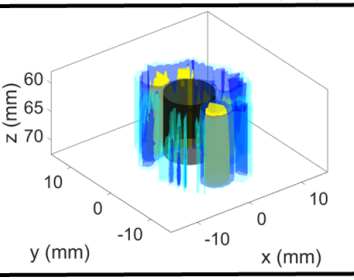
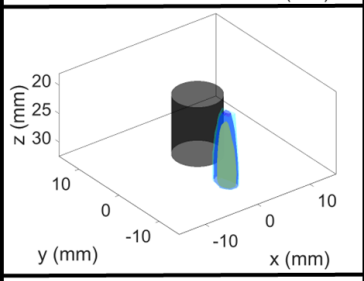
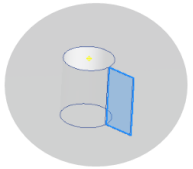
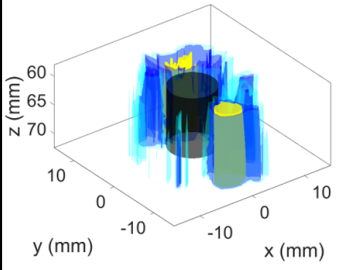
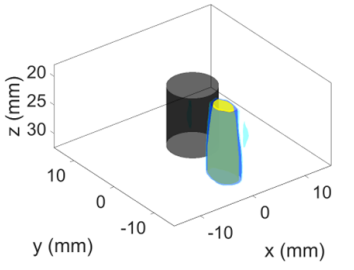
(b)

- **Model application II– 2D array design simulation**



❑Inspection optimization and new array design simulation

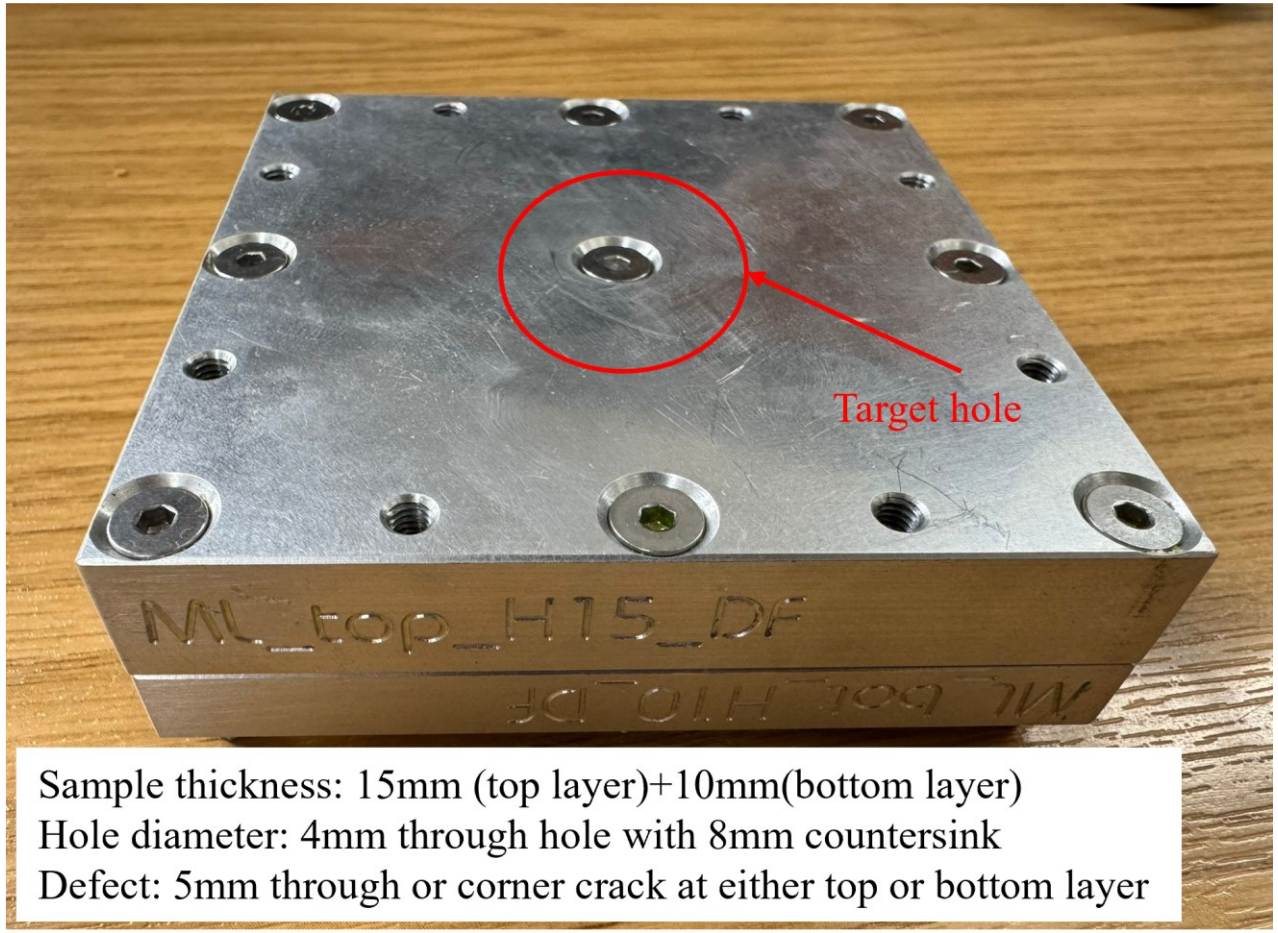
- **Model application I – test results comparison**

	Geometry	HS-TFM image (Original H=60)	HS-TFM image (Optimized H=20)	SNR change (dB)
Defect-free				Reference
Corner crack				+4.74
Through crack				+4.52

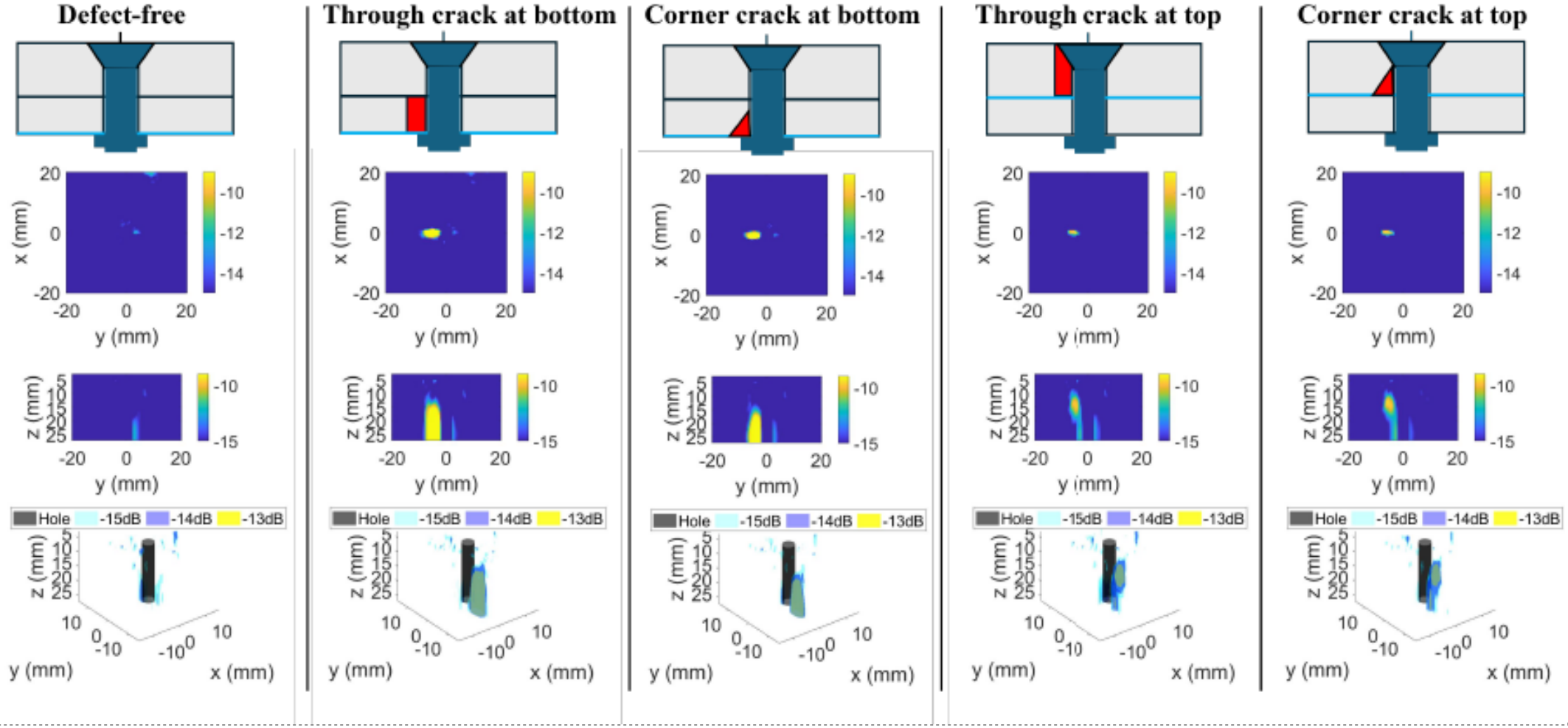
Corner crack

Through crack

- **Model application I – multilayer sample test**



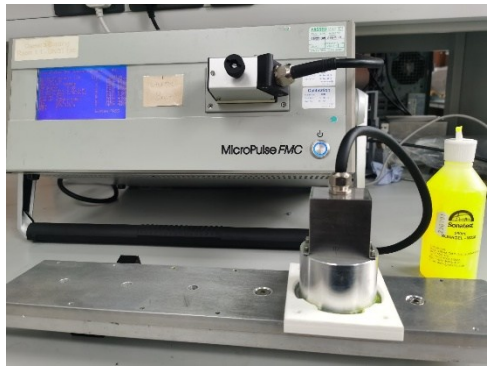
- **Model application I – multilayer sample test**



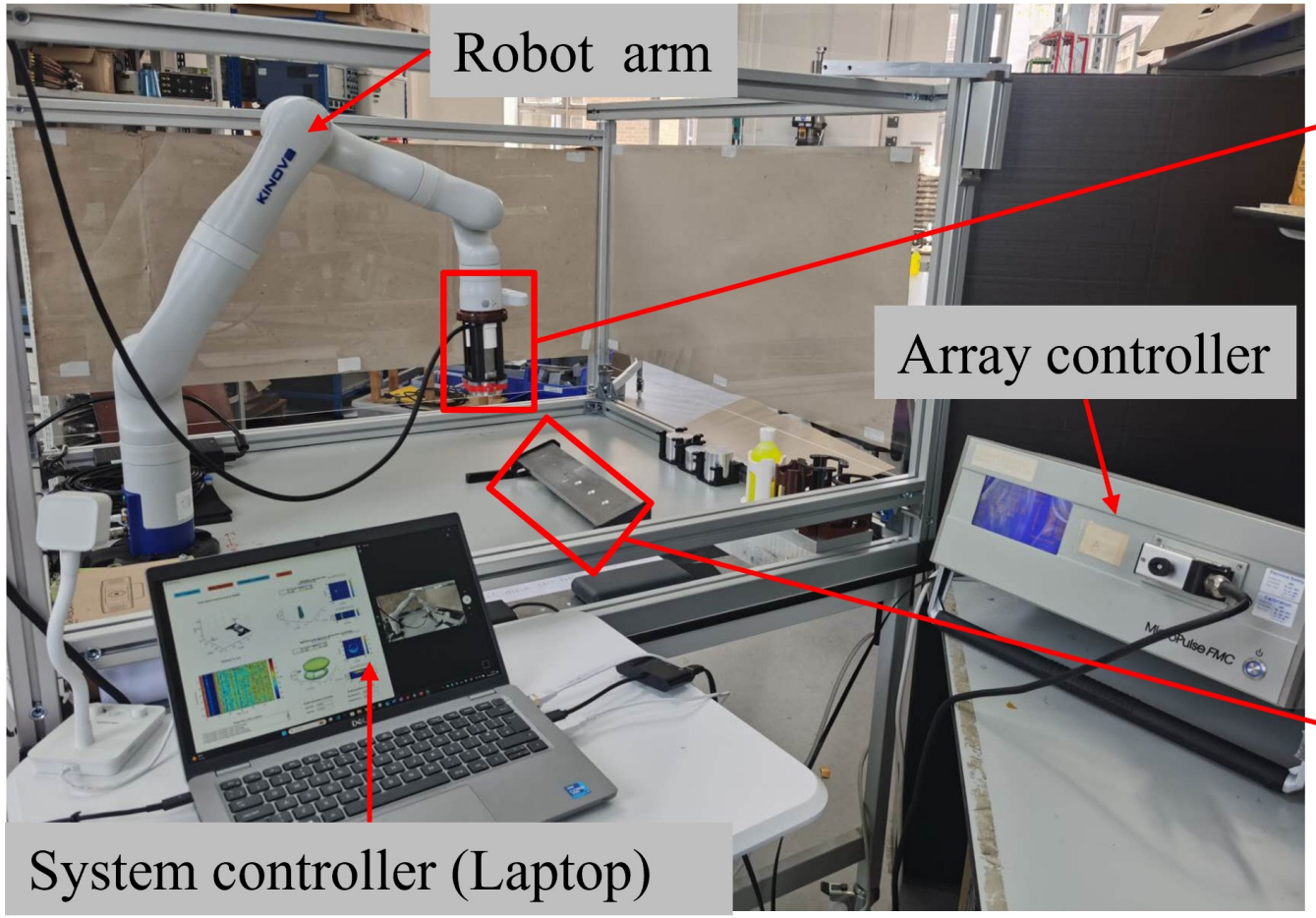
❑Robotic fastener hole inspection

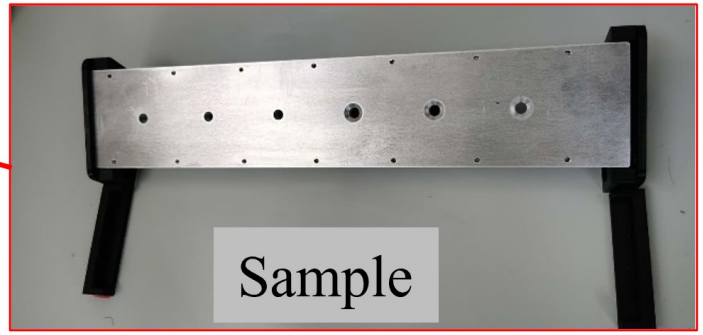
Why robotic?

- Inspection efficiency
- Accessibility
- Inspection reliability
  - Coupling force
  - Coupling condition
  - Probe positioning



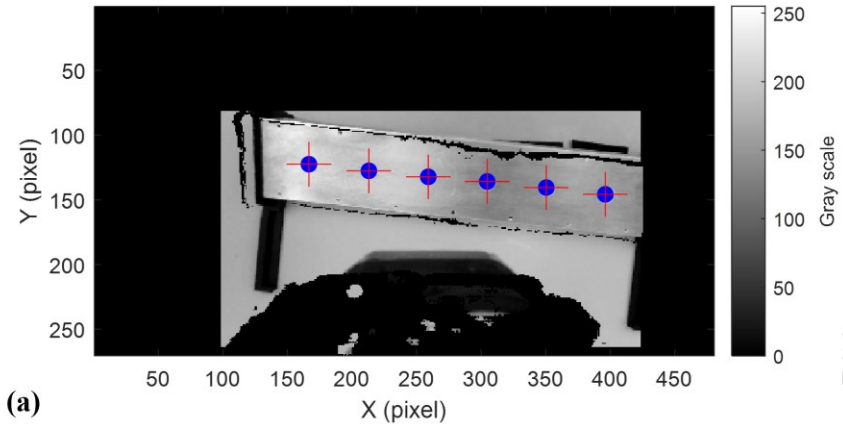
❑Robotic fastener hole inspection

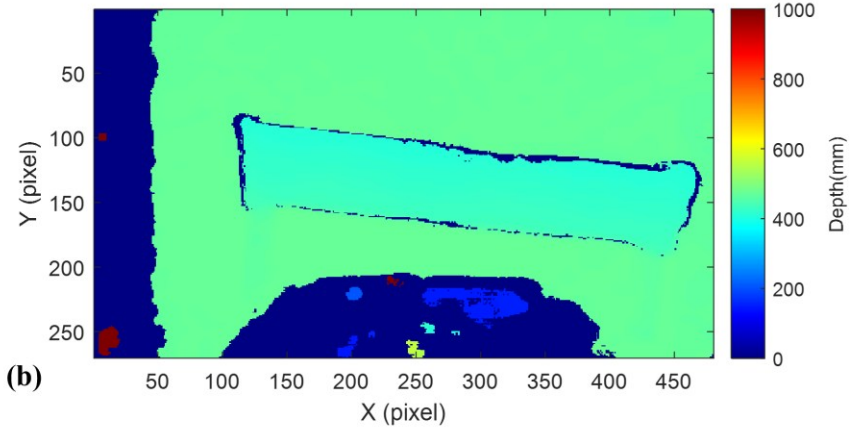


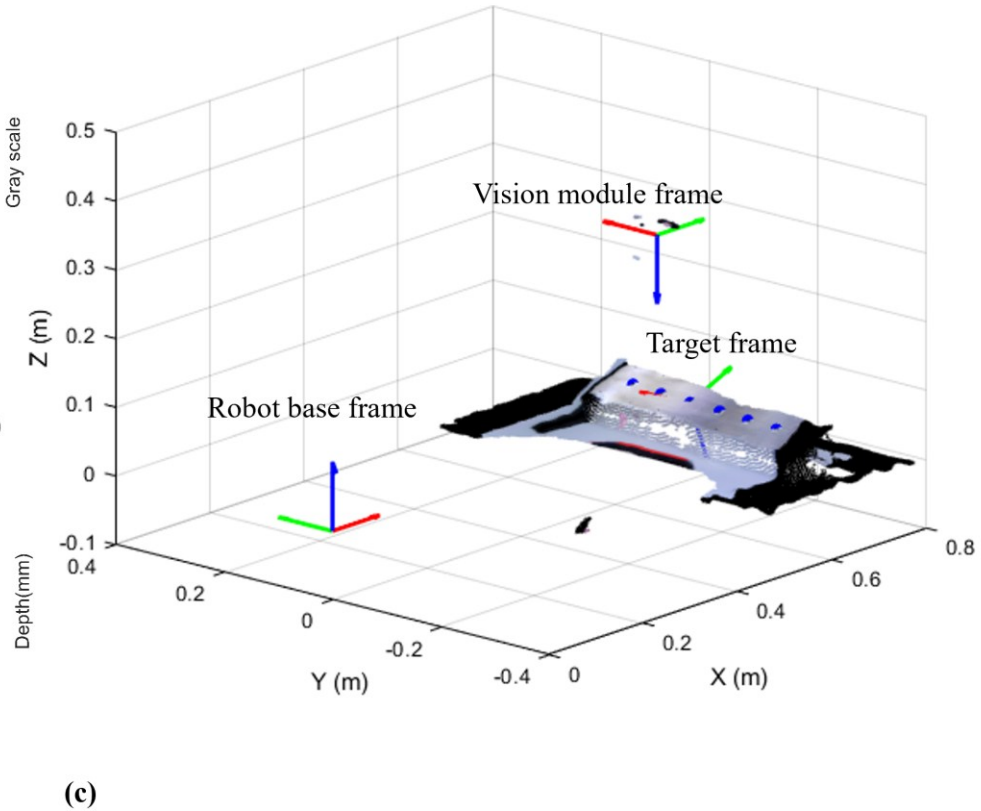


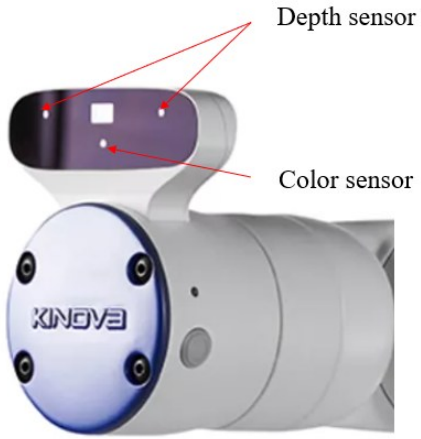
❑Robotic fastener hole inspection

- How to locate the target surface and target hole?



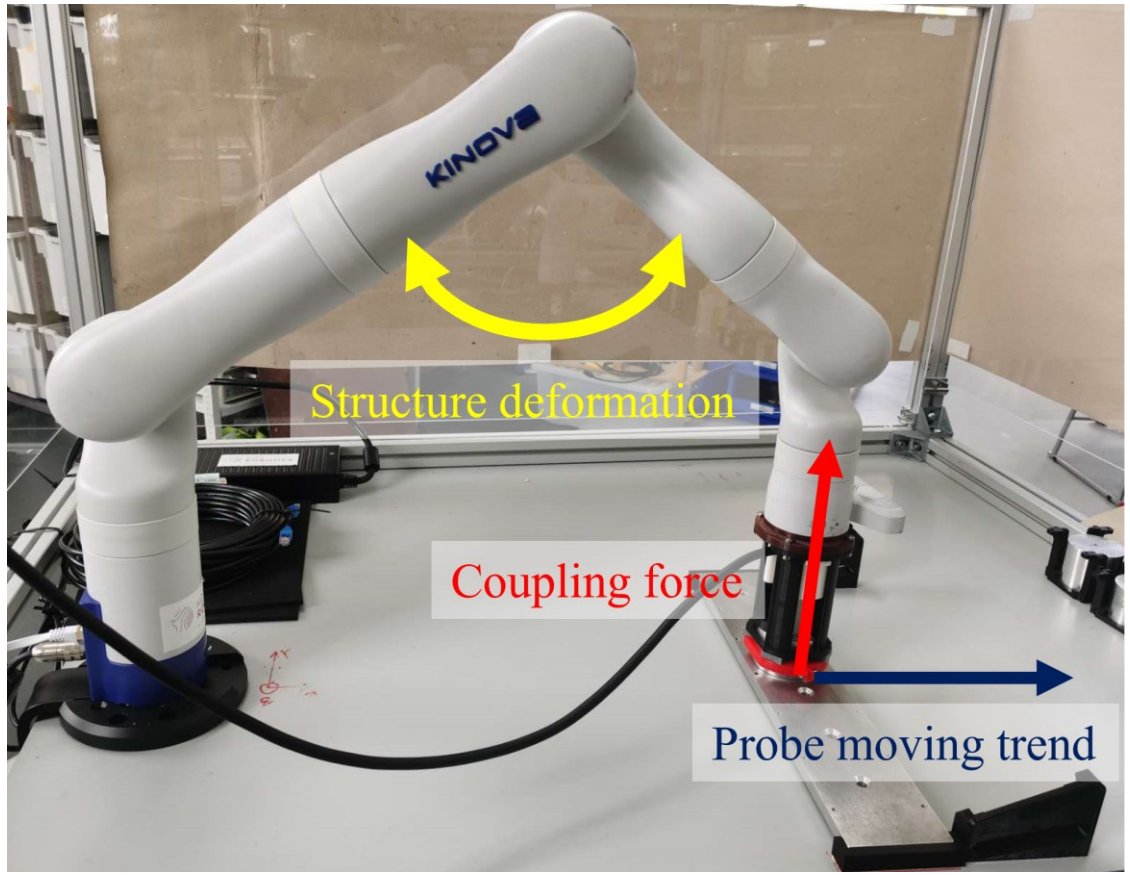






❑Robotic fastener hole inspection

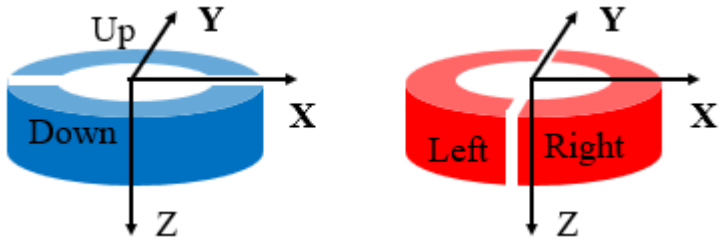
- How to compensate for robot arm movement when applying coupling force?
- How to confirm the coupling condition is good enough?



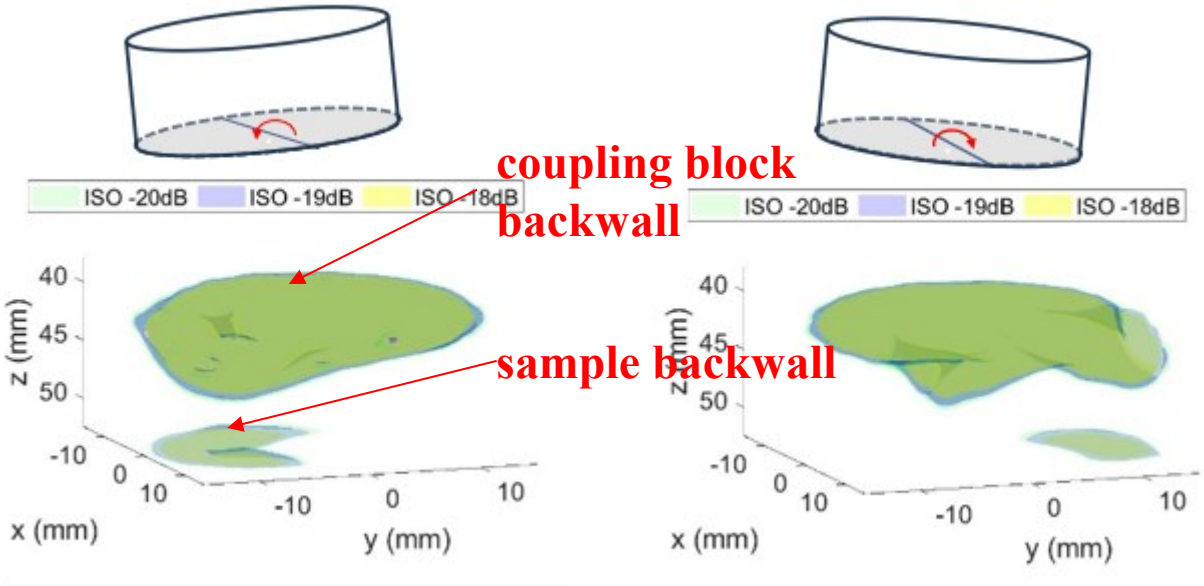
❑Robotic fastener hole inspection

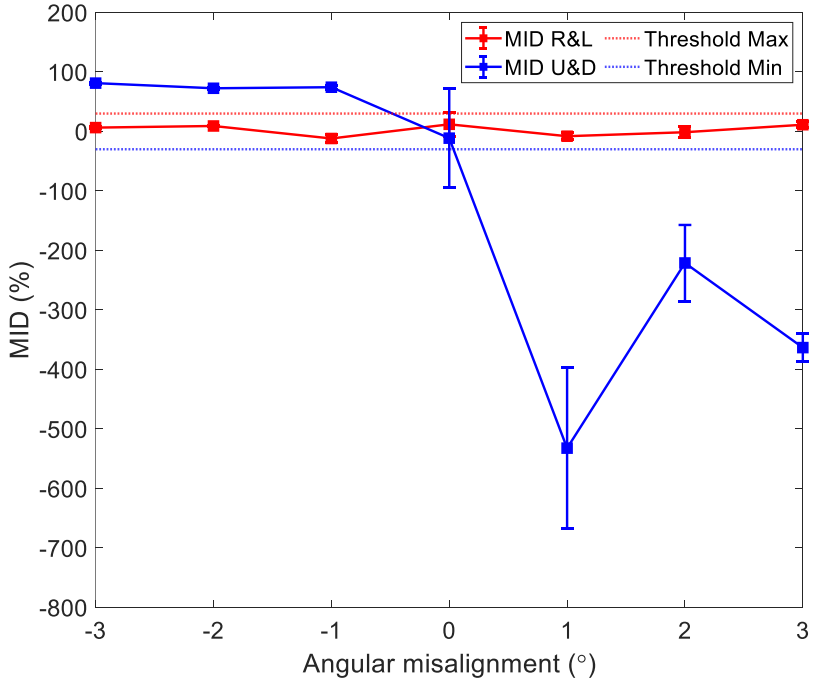
▪ Ultrasound probe orientation correction

- Computer vision - rough probe orientation (angular misalignment ≈3°)
- Ultrasound – fine probe orientation adjustment (angular misalignment <1° is required based on experiments)



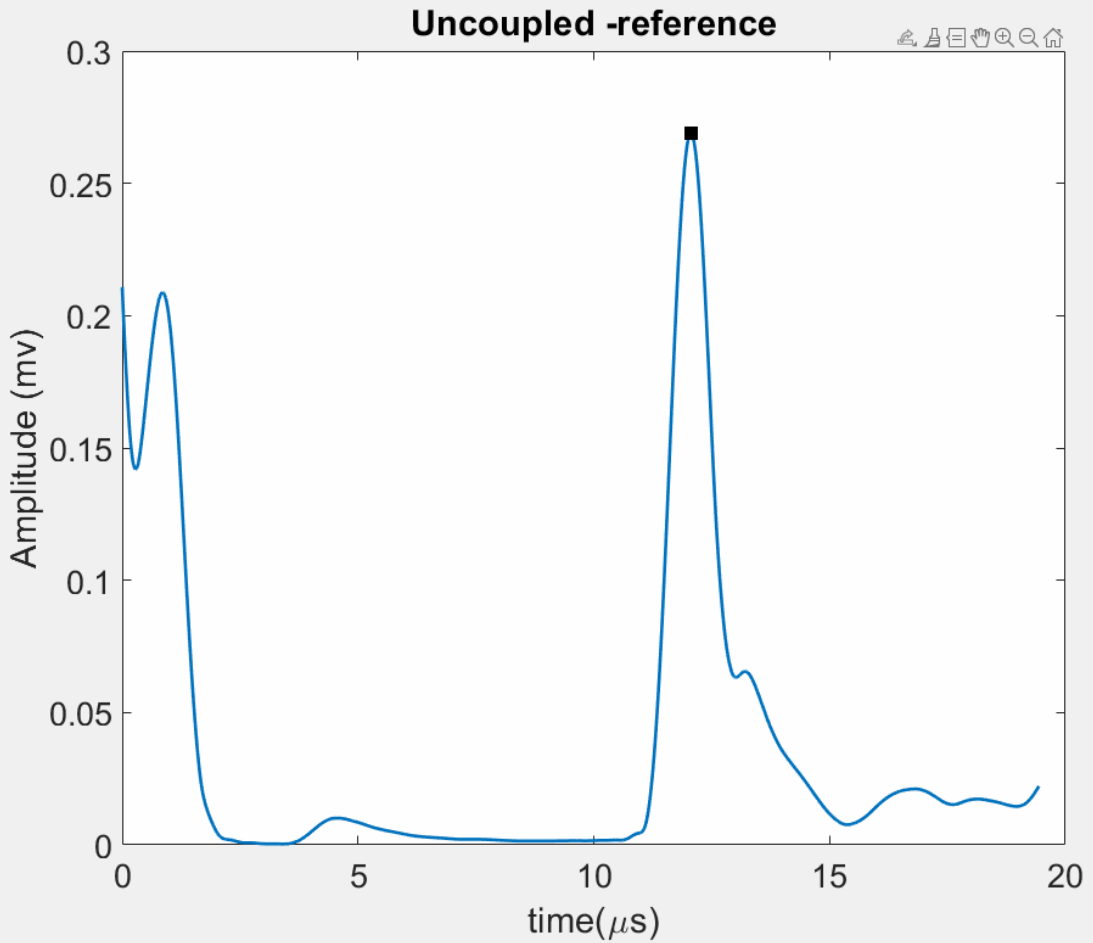
Angular error = -1° **Angular error = 1°**

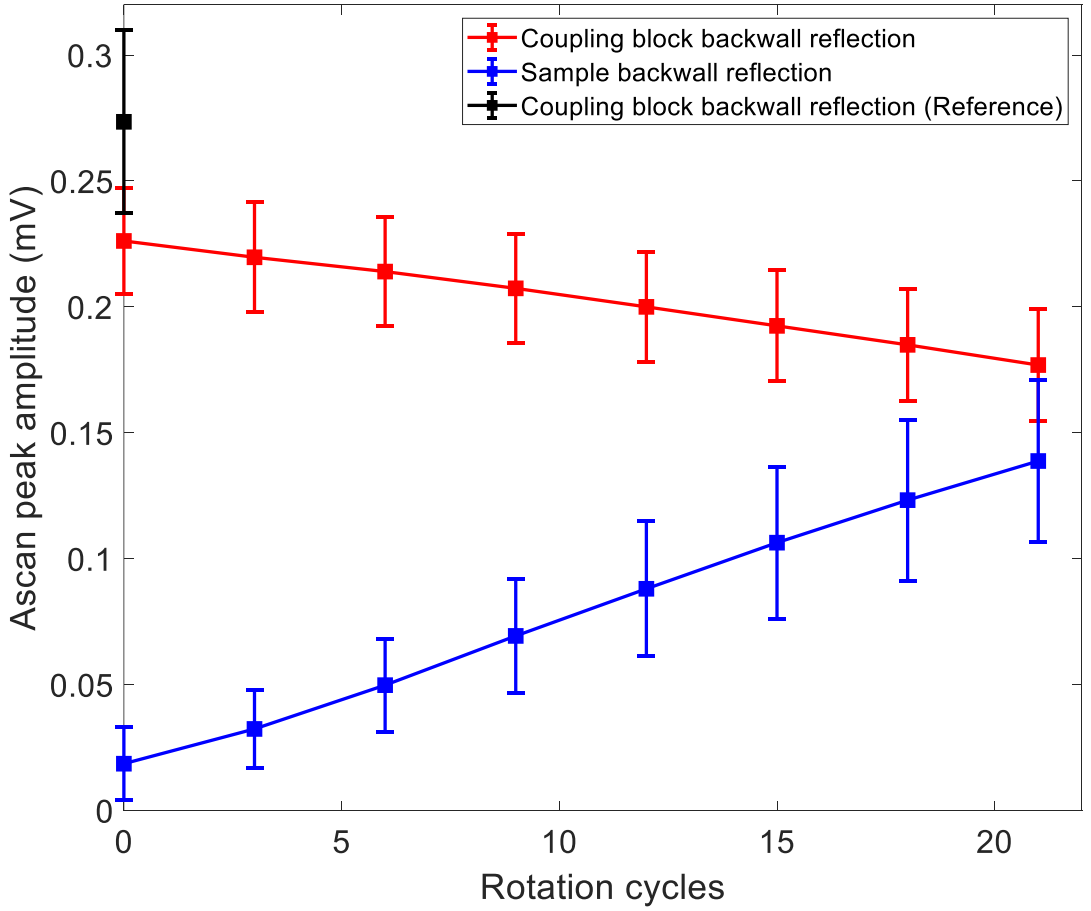




❑Robotic fastener hole inspection

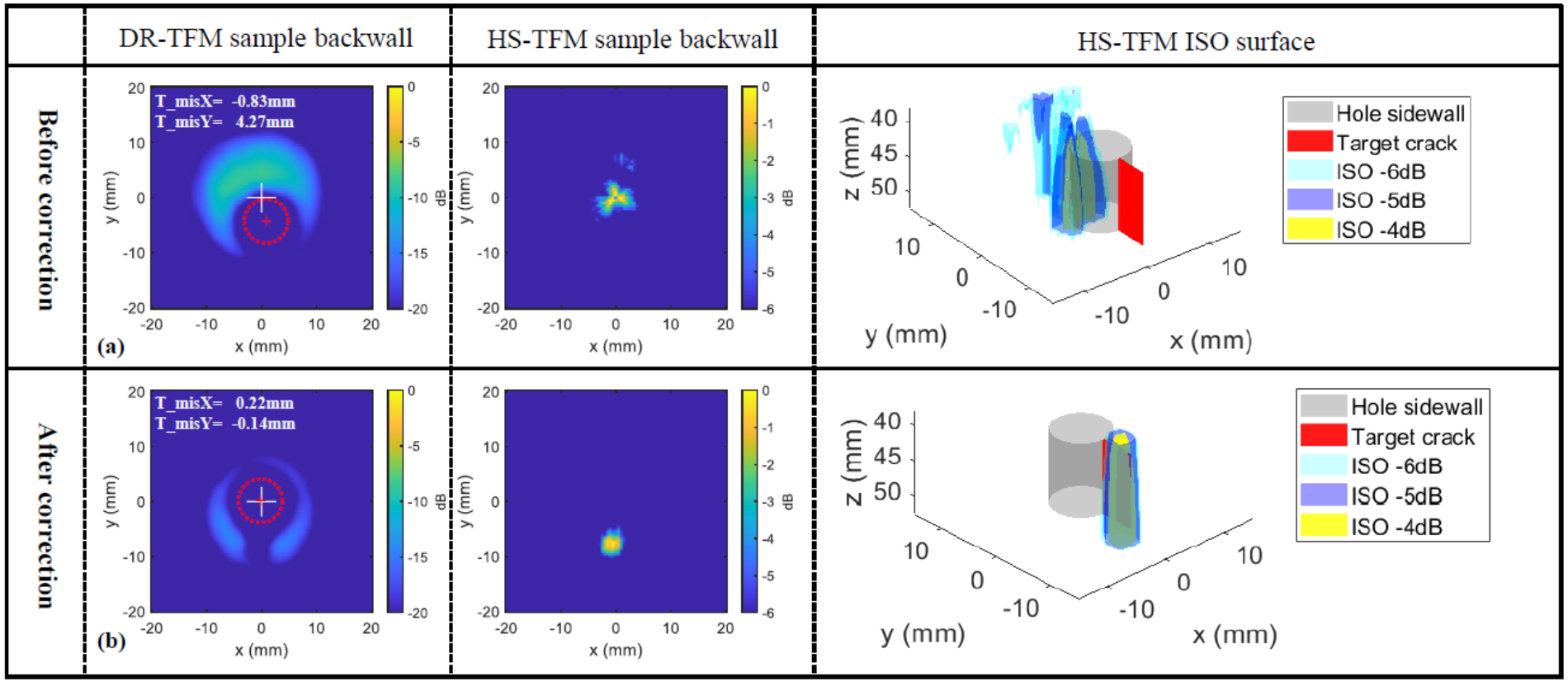
- Ultrasound probe coupling condition improvement – Rotationally oscillating the probe



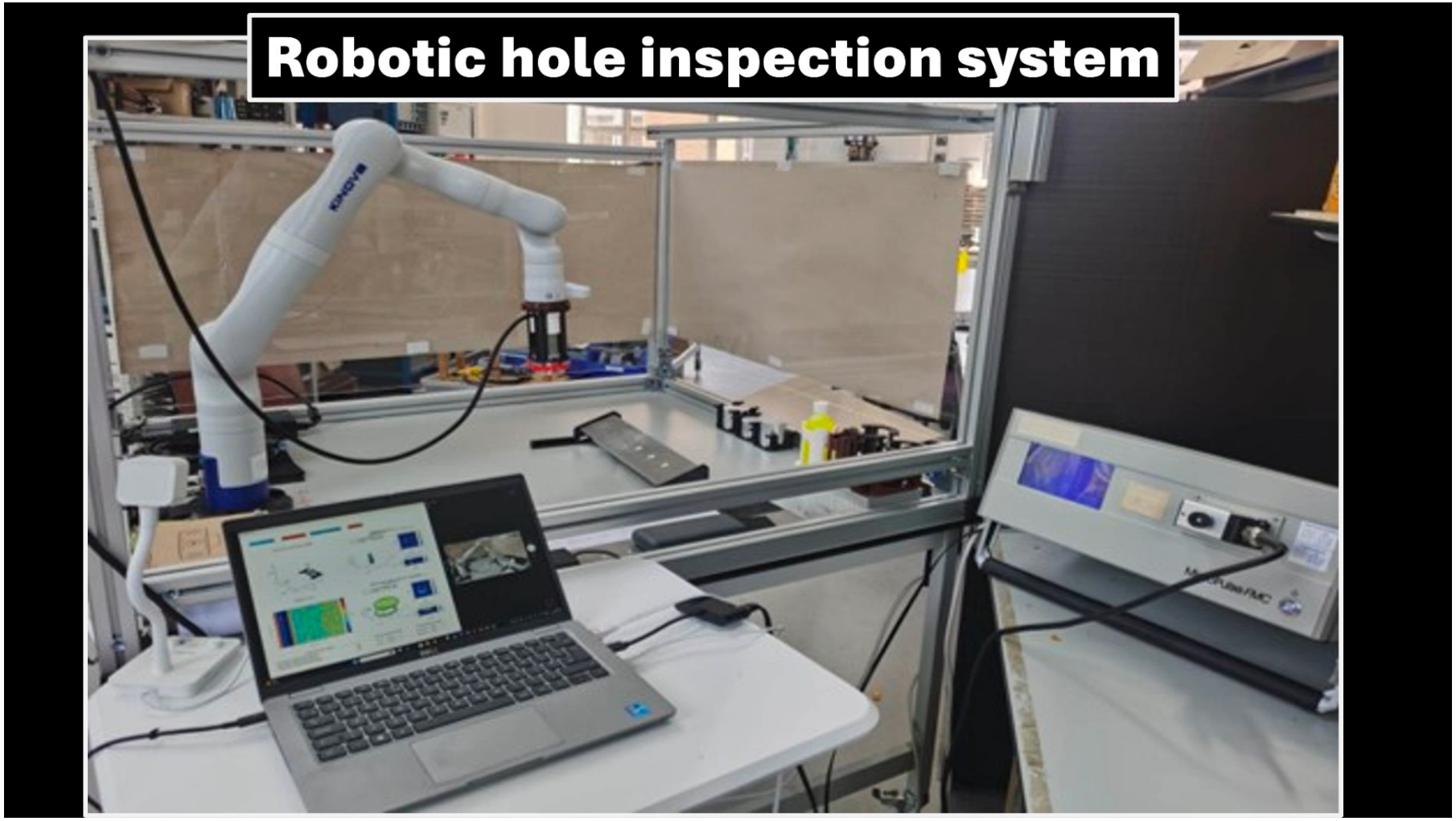


Ultrasound probe position correction

- Computer vision - rough probe position (translation misalignment ≈ 5~10mm, including the robot structure deformation influ
- Ultrasound – fine probe position adjustment (translation misalignment <1mm)



❑Robotic fastener hole inspection



Thank you for your attention.

Please feel free to contact me if you would like to discuss further

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[1] Wu, Yanghao, Paul D. Wilcox, and Anthony J. Croxford. "Fastener hole inspection using 2D phased array." *NDT & E International* 143 (2024): 103057.
[2] Wu, Yanghao, Paul D. Wilcox, and Anthony J. Croxford. "Robotic inspection of fastener holes with hybrid visual and ultrasonic motion control." *Journal of Manufacturing Systems* 83 (2025): 770-783.