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# Single-Shot Composite Fringe Projection Profilometry for Real-Time Dynamic 3D Measurement


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# Fringe Projection Profilometry

3 s +

Traditional fringe projection profilometry

vs.

0.2 s

Real-time fringe projection profilometry



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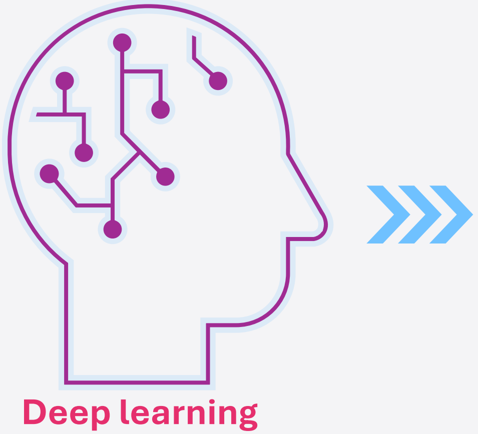
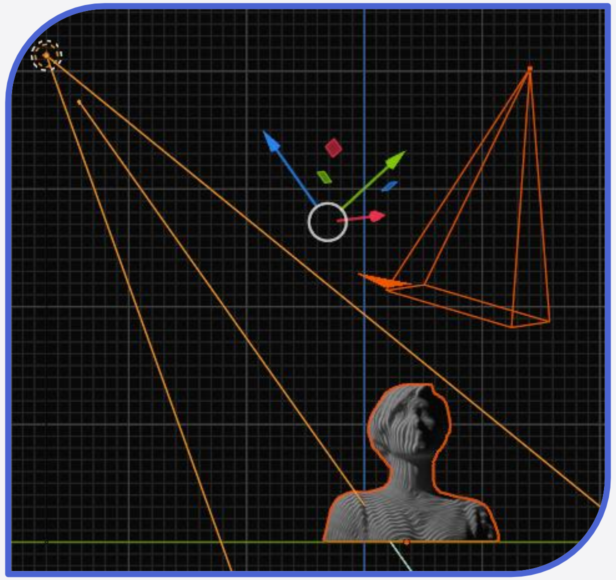
# Outline

- Introduction & Motivation
- Methodology
  - Composite Fringe Pattern
  - U-Net Network
  - Uncertainty Evaluation
- Experiments
  - Data Collection
  - Model Training
  - Validation & Analysis
- Conclusion



FPP system

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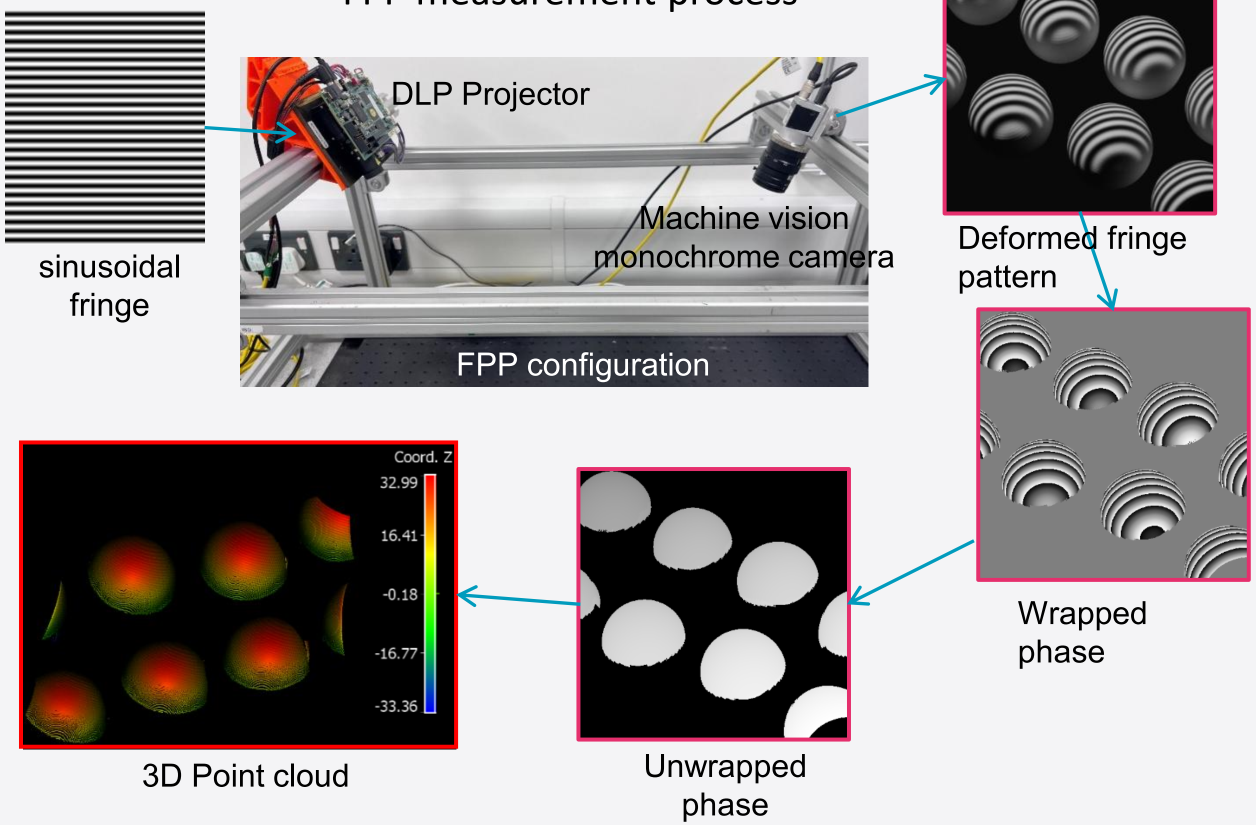
# Introduction & Motivation

Fringe projection profilometry (FPP), also known as structured light profilometry, is a non-contact measurement method that reconstructs an object's 3D shape by projecting sinusoidal fringes onto its surface, and then capturing the deformed fringe patterns with a camera. The phase of the fringe pattern can then be reconstructed into a 3D point cloud using calibration data.

| Applications | Advantages | Disadvantages |
| --- | --- | --- |
| Industrial Inspection | Non-Contact Measurement | Sensitivity to Surface Characteristics |
| Medical Imaging | High Resolution and Accuracy | High algorithmic complexity |
| Robotic Vision | Low Cost | **Low measurement speed** |
| Cultural Heritage Preservation | Full Field Measurement | |

FPP measurement process



# Introduction & Motivation



There are two main factors that determine the 3D measurement speed of FPP:

1. **The performance of hardware devices.**
2. **The number and coding strategy of projected patterns required by the software algorithms.**

The speed of hardware devices

| | refresh rate (frames · $s^{-1}$) | exposure time (μs) |
|---|---|---|
| **Projector** | 4,225 (1-bit binary) / 120 (8-bit grey) | 235 (+230) |
| **High-speed Camera** | ≥ 120 | $1\times10^4$ - $3\times10^4$ |

| | CPU | GPU | RAM |
|---|---|---|---|
| **Computer** | Intel i9-13900K | RTX 4080 / 4090 | 32GB |

The number of patterns required of the software algorithms

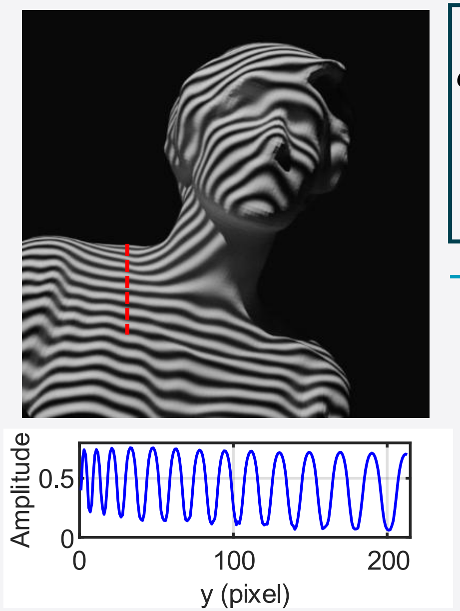
| | Number of patterns | Accuracy | Need machine learning? |
|---|---|---|---|
| PSP-binary (Defocus) + Gray code | $3 + \log_2 M$ | ✓✓✓✓ | No |
| PSP-binary (Defocus) | 3 | ✓ | No |
| Speckle image | 1 | ✓✓ | No |
| FTP | 1 | ✓ | No |
| FTP-composite fringe | 1 | ✓✓ | No |
| Color composite fringe | 1 | ✓✓ | Yes / No |
| Single sinusoidal fringe | 1 | ✓✓ | Yes |
| FPP-composite fringe | 1 | ✓✓✓ | Yes |

Phase-shifting profilometry (PSP)
Fourier transform profilometry (FTP)
M: the number of fringe periods

# Introduction & Motivation

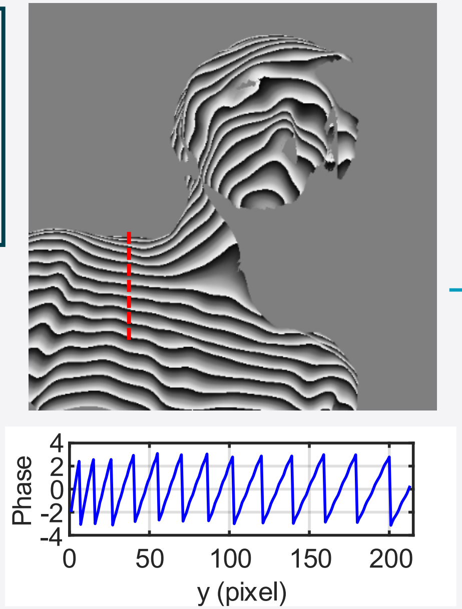
**From an algorithmic view: Why real-time measurement is challenging in FPP?**

Fringe pattern




$$\phi(x,y) = arctan\frac{\sum_{n=1}^{N} I_n(x,y)\sin(\delta_n)}{\sum_{n=1}^{N} I_n(x,y)\cos(\delta_n)} = arctan\frac{N(x,y)}{D(x,y)}$$

Wrapped phase

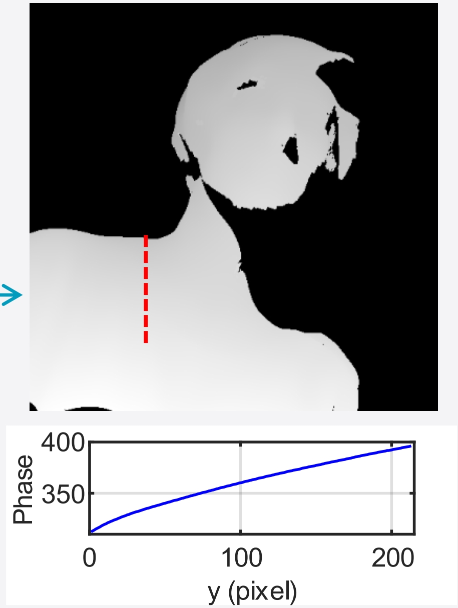



?

**Time domain**

(Multi-Frequency Phase Unwrapping)

Unwrapped phase



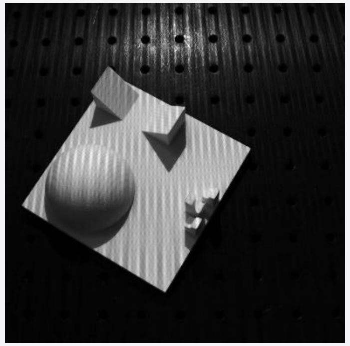

Phase-Unwrapping Approaches Used in FPP

| Approach | Number of patterns | Accuracy |
|---|---|---|
| Spatial domain | 3+ | ✓✓ |
| Frequency domain | 1 | ✓ |
| **Time domain** | 6+ | ✓✓✓✓ |
| Machine learning | 1 | ✓✓✓ |

# Introduction & Motivation

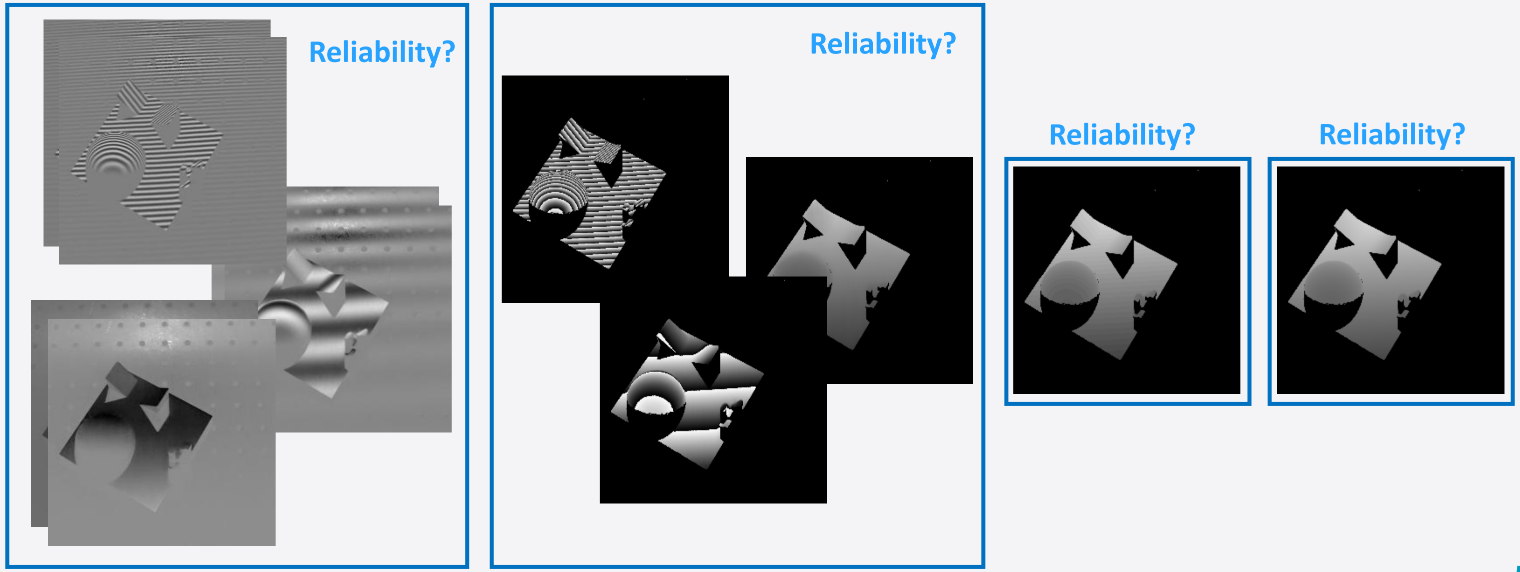
**How much confidence can we place in the predicted results?**

Are the predicted results reliable?

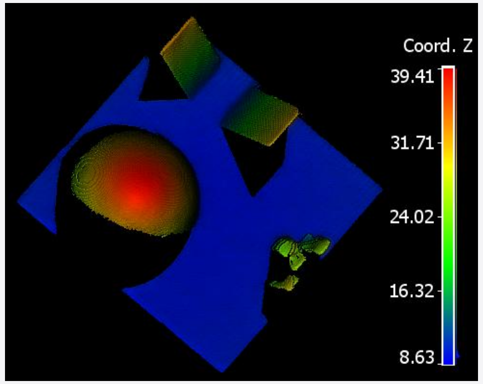


Fringe pattern

**Deep Learning**




**Predictions**

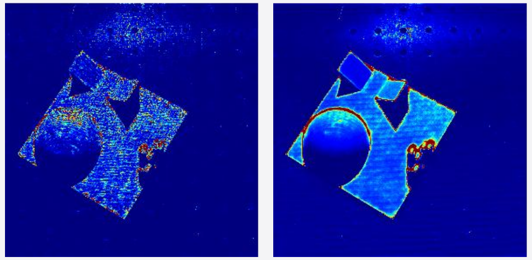



3D point cloud

?

*Evaluation is only possible with ground truth*

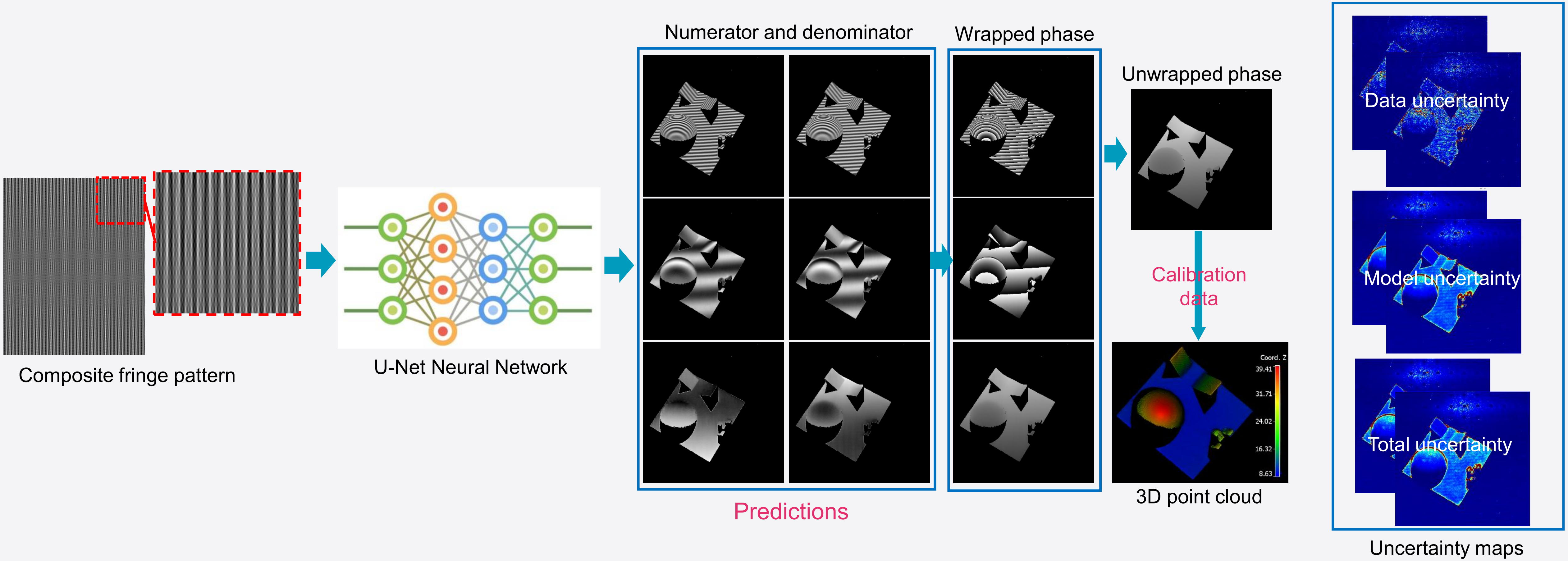
**Ground Truth** ?



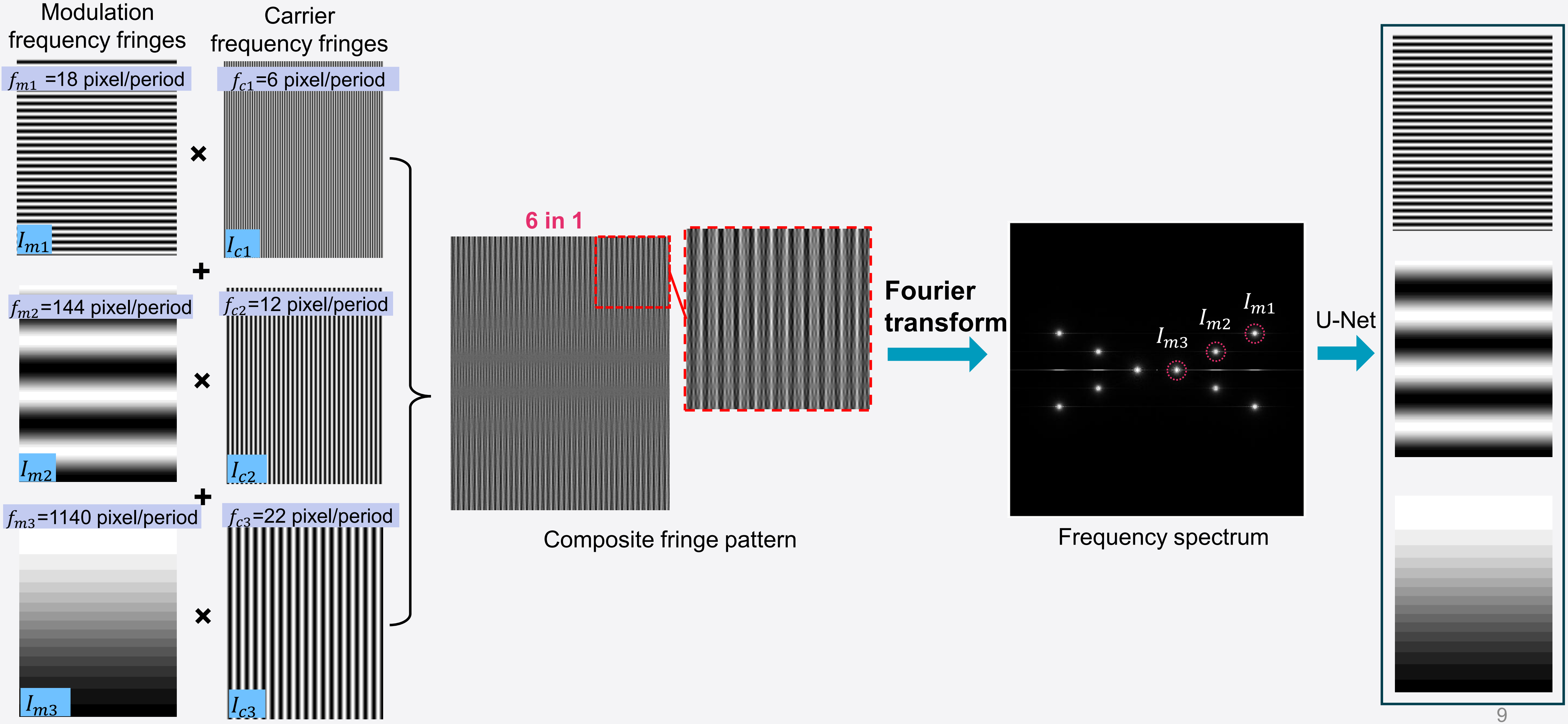
Uncertainty maps

# Method

In this work, we propose a deep learning-based multi-frequency phase unwrapping method using a novel single composite fringe pattern, which also outputs uncertainty maps to estimate the confidence of predictions.

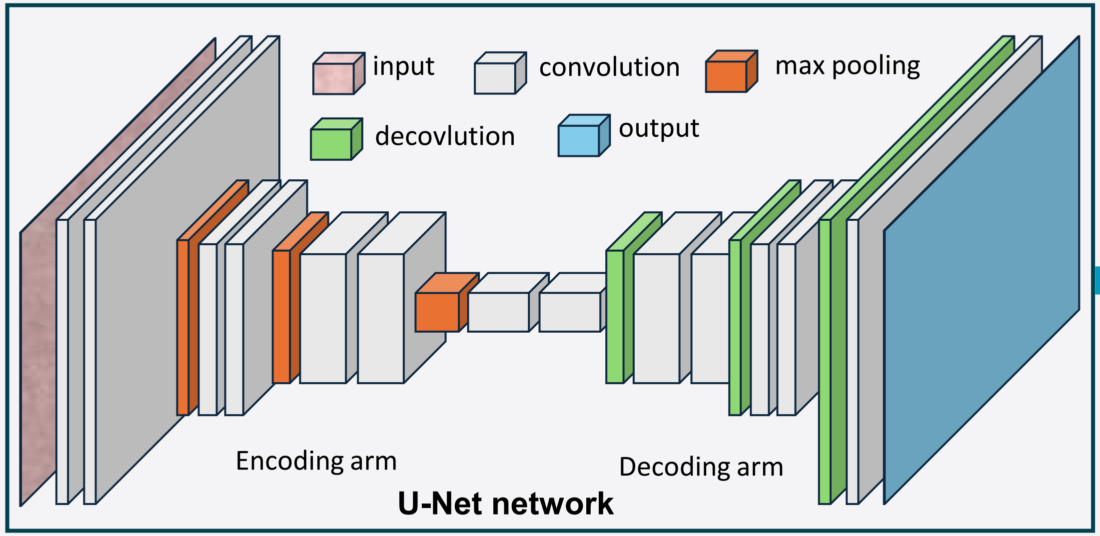


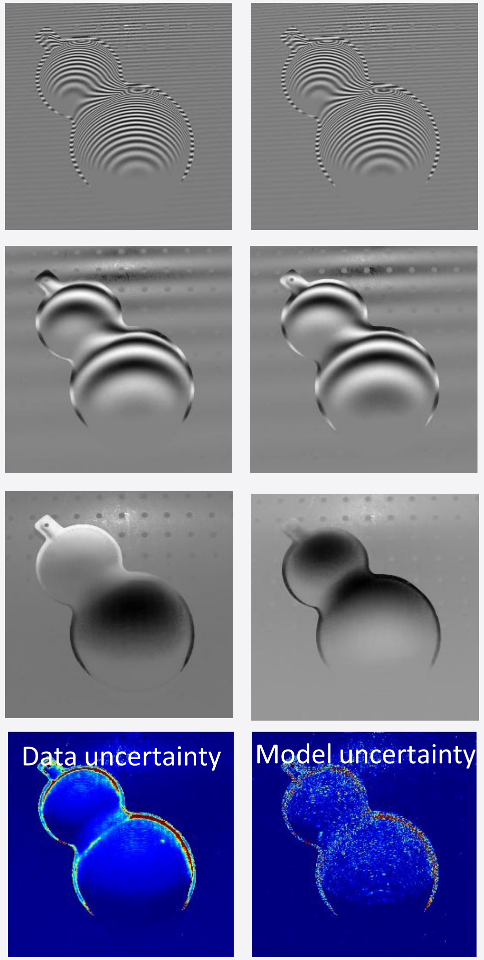
# Method: Composite Fringe Pattern



# Method: U-Net Network

**Standard U-Net loss:** Mean Squared Error (MSE)
**Limitation:** The network does not output or learn the uncertainty of each pixel



Uncertainty maps

**U-Net Architecture Overview**

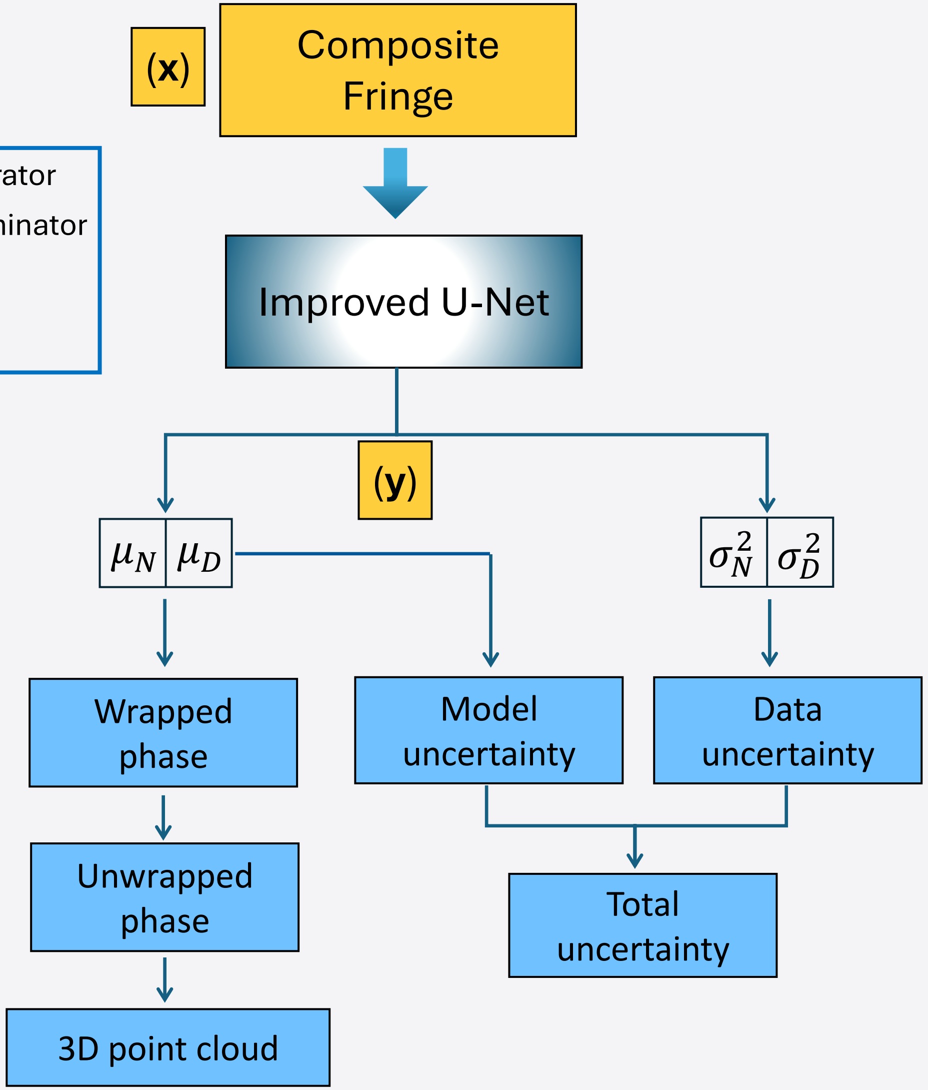
| Component | Configuration |
|---|---|
| Encoder Channels | 1 → 64 → 128 → 256 → 512 |
| Bottleneck Channel | 1024 |
| Decoder Channels | 512 → 256 → 128 → 64 → 1 |
| Output Channels | 4 (N & D & Uncertainty) |
| Activation Function | ReLU (hidden layers), Tanh (output layer) |
| Skip Connections | Yes (between encoder & decoder at each stage) |

**Alternative loss:** Gaussian Negative Log-Likelihood (NLL)
**Data uncertainty:** Arises from observation noise, inherent ambiguity, or measurement errors.

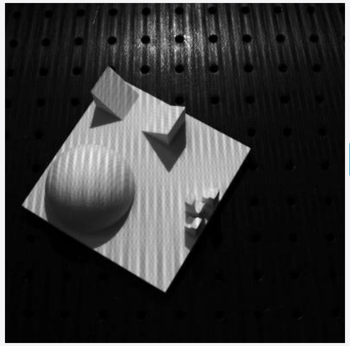
**Snapshot Ensemble**: Save model weights at multiple training stages
**Model uncertainty:** Stems from the model's limited knowledge of the data distribution, e.g., insufficient or incomplete training data, leading to multiple plausible parameter solutions

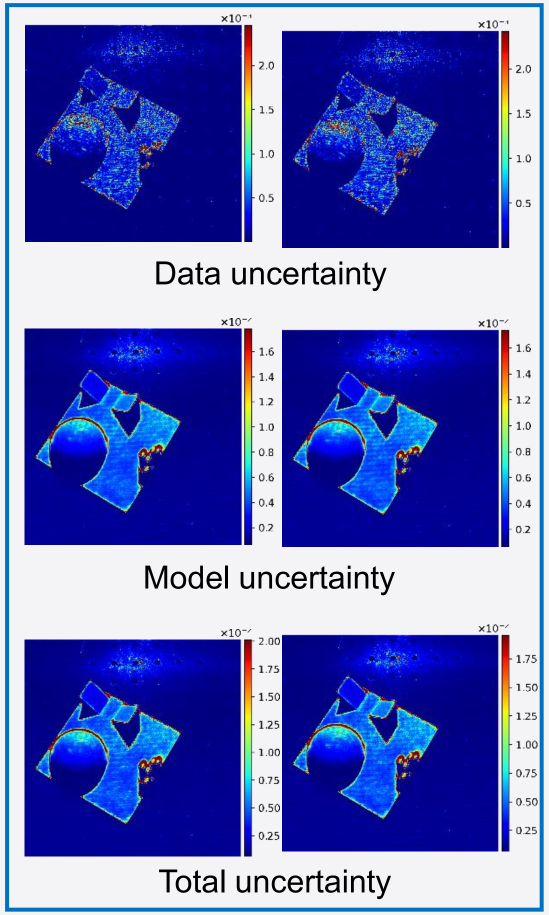
# Method: Uncertainty Evaluation

- $\mu_N$: predicted mean of the numerator
- $\mu_D$: predicted mean of the denominator
- $\sigma_N^2$: variance of the numerator
- $\sigma_D^2$: variance of the denominator



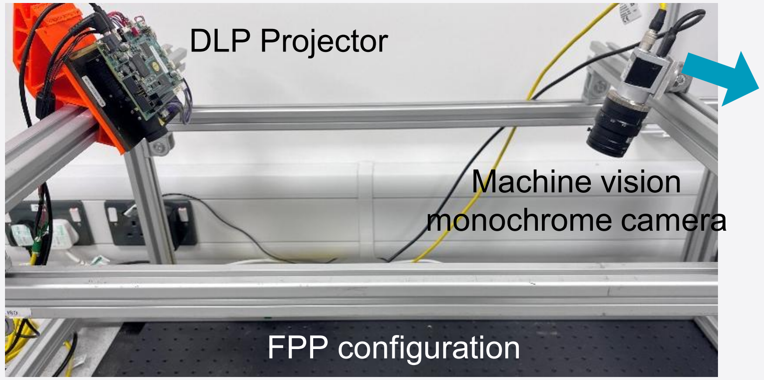

Workflow of the improved u-net combined with composite FPP






Uncertainty maps

# Experiments: Data collection

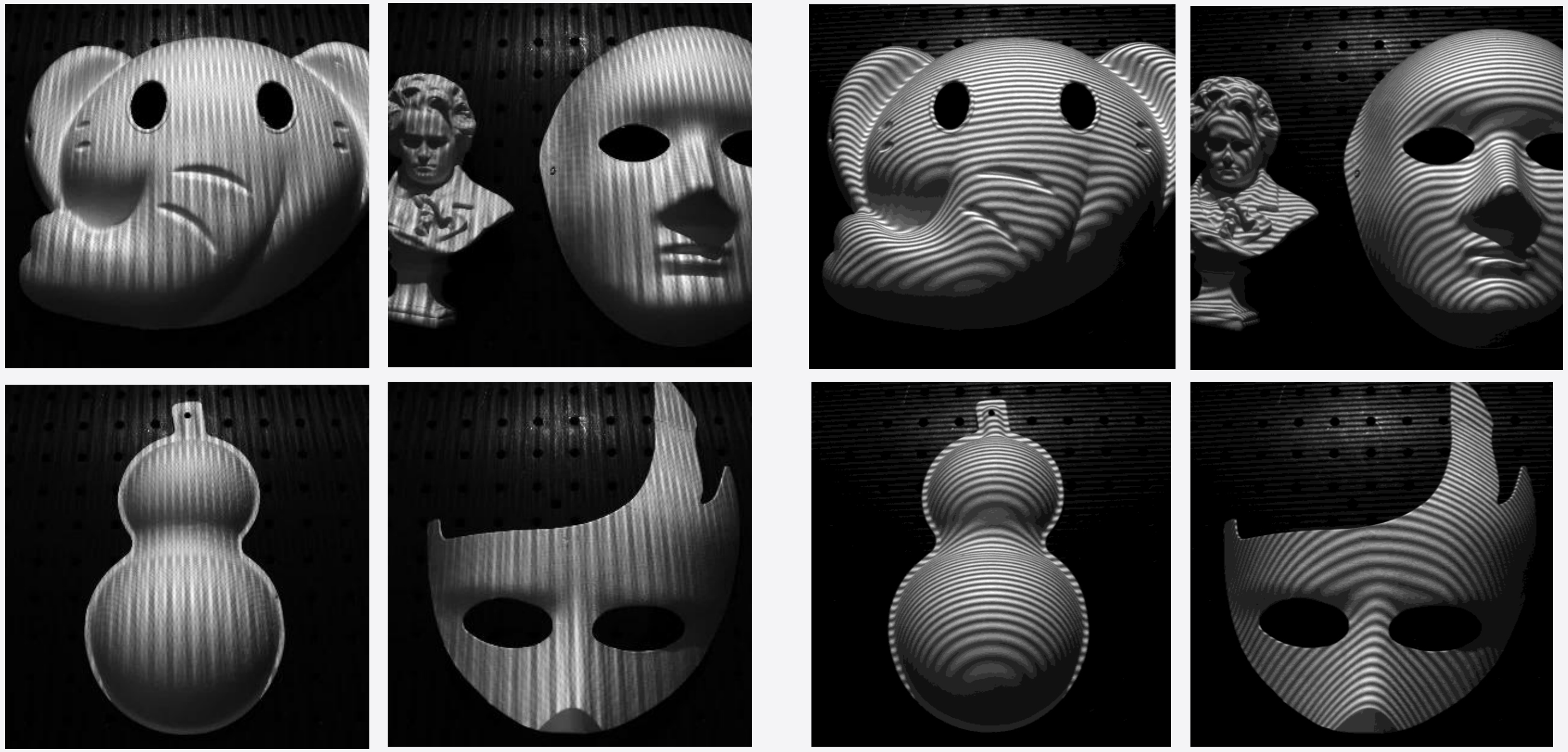



| Number of images | 985 × (21+1) = 21670 |
| --- | --- |
| Collection Time | 5 days |
| Exposure time $t_c$ and $t_p$ (projector and camera) | 50 ms |
| Period time | 110 ms |

$$\text{period time } = \max(t_c, t_p) + t_{\text{capture}}$$

$$t_{\text{capture}} = t_{\text{margin}} + t_{\text{buffer}} > \frac{1}{\text{FPS}_c} = 58.8\ ms$$

Training dataset



Input

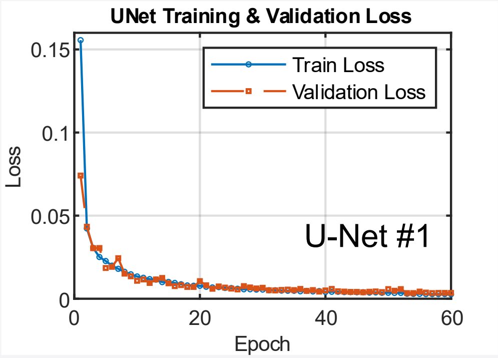
Ground truth (numerator only)

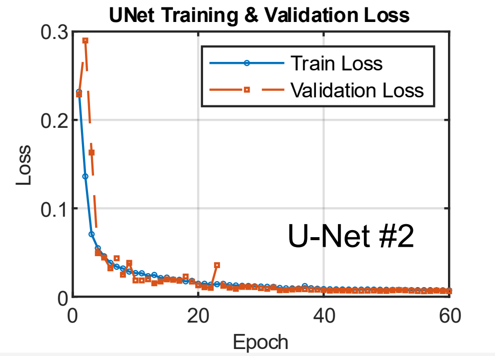
# Experiments: Model training

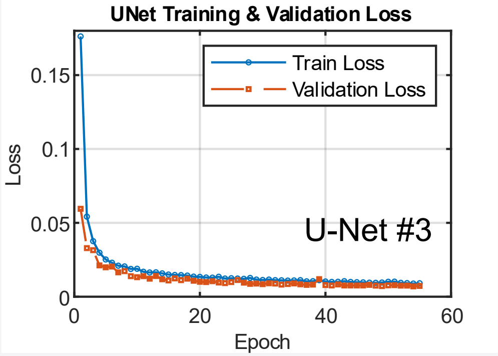
| | | |
|---|---|---|
| Dataset details | Image size | 912×912 |
| | Number of samples | 985 |
| | Training & validation ratio | 8:1 |

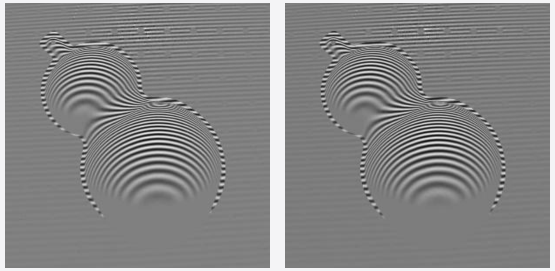
| | | |
|---|---|---|
| System configuration | Computer | Lenovo ThinkStation P3 Tower |
| | CPU | Intel® Core™ i9-13900K processor |
| | GPU | NVIDIA GeForce RTX 4070 (12 GB GDDR6X) |
| | OS | Windows 10 Enterprise 64-bit |

| Parameter | Value | Explanation |
|---|---|---|
| Batch size | 4 | Samples per iteration |
| Num epochs | 60 | Max training epochs |
| Learning rate | 5e-4 | Initial learning rate |
| loss function | MSE and NLL | Measures prediction error of the model |

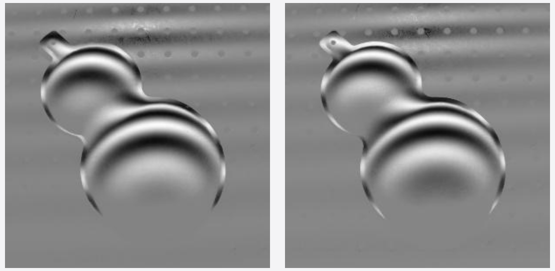


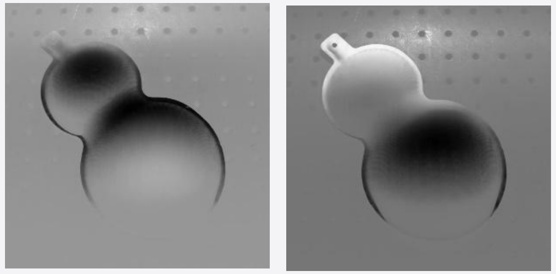



+ Uncertainty map

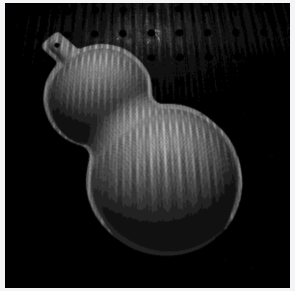


+ Uncertainty map



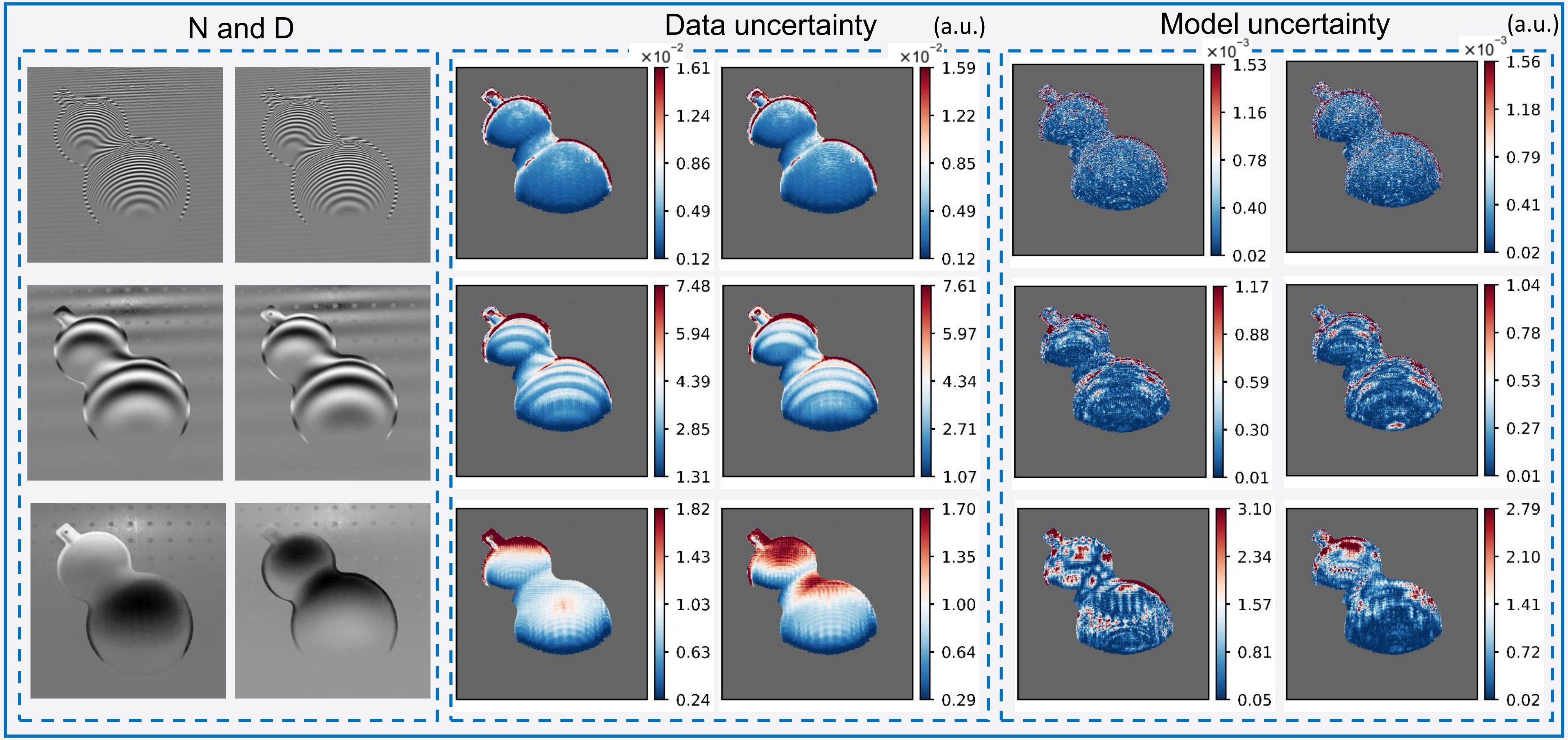
+ Uncertainty map

# Experiments: Validation & Analysis



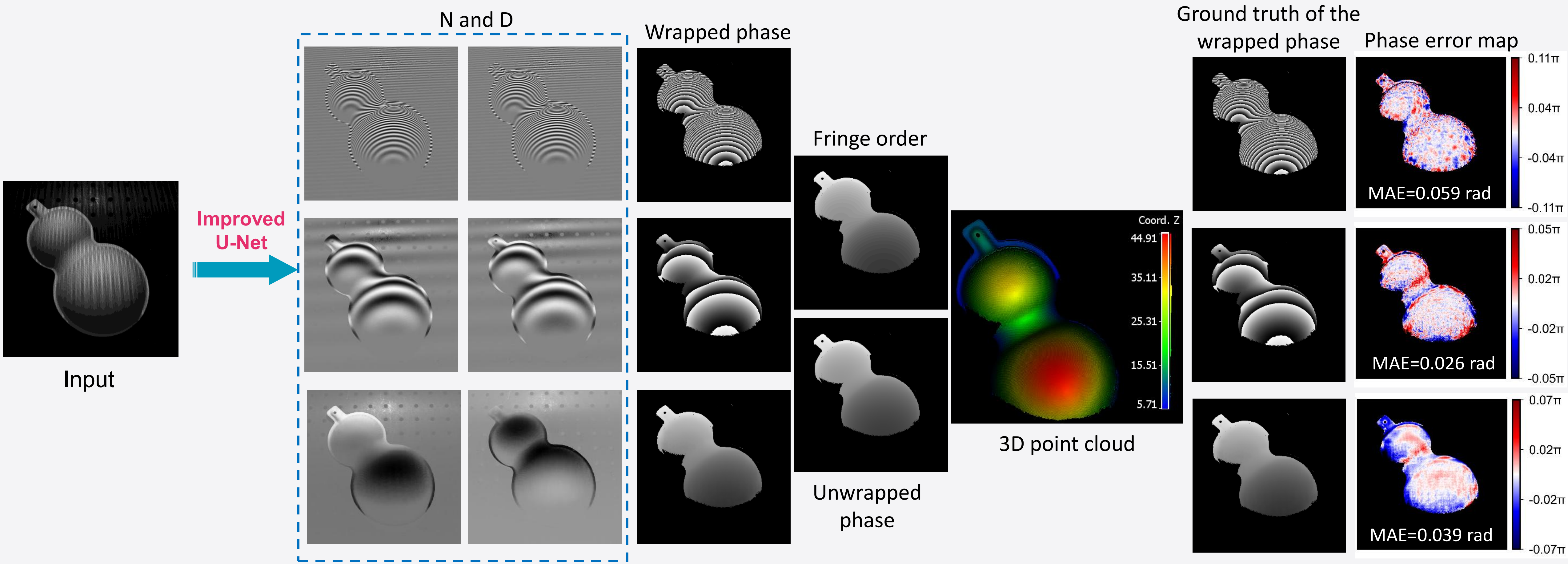
Input

Improved U-Net



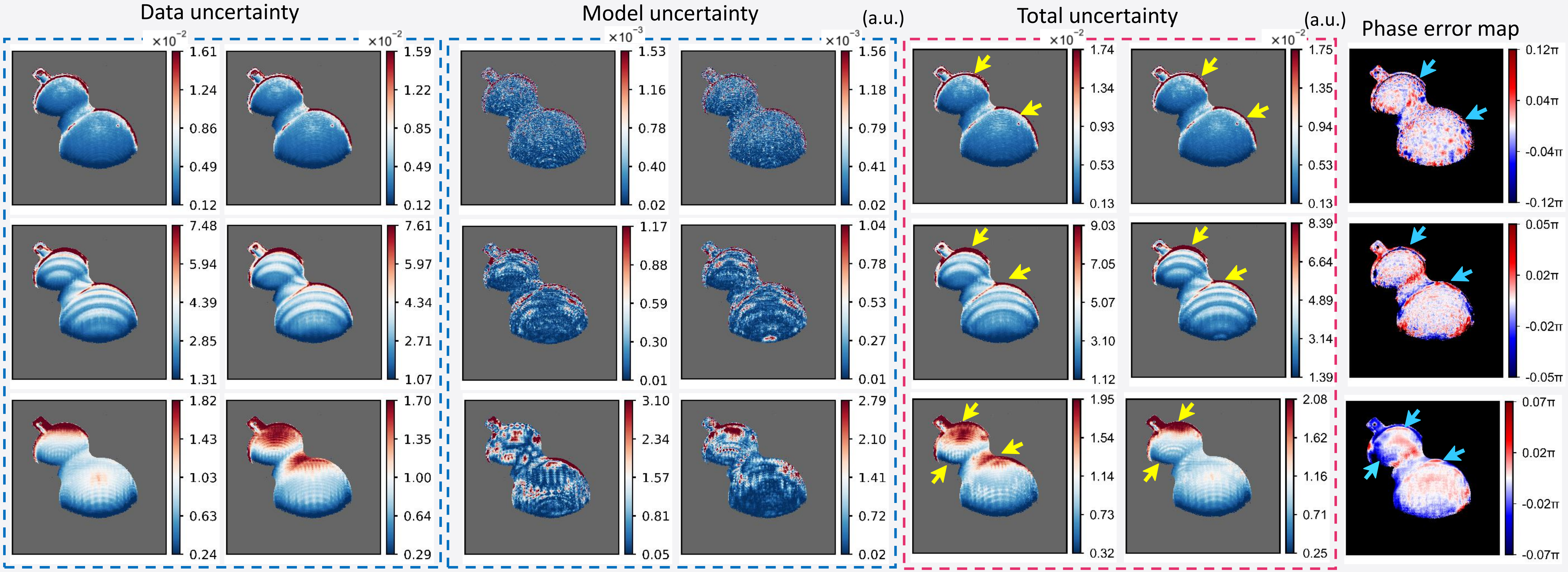

Outputs

# Experiments: Validation & Analysis

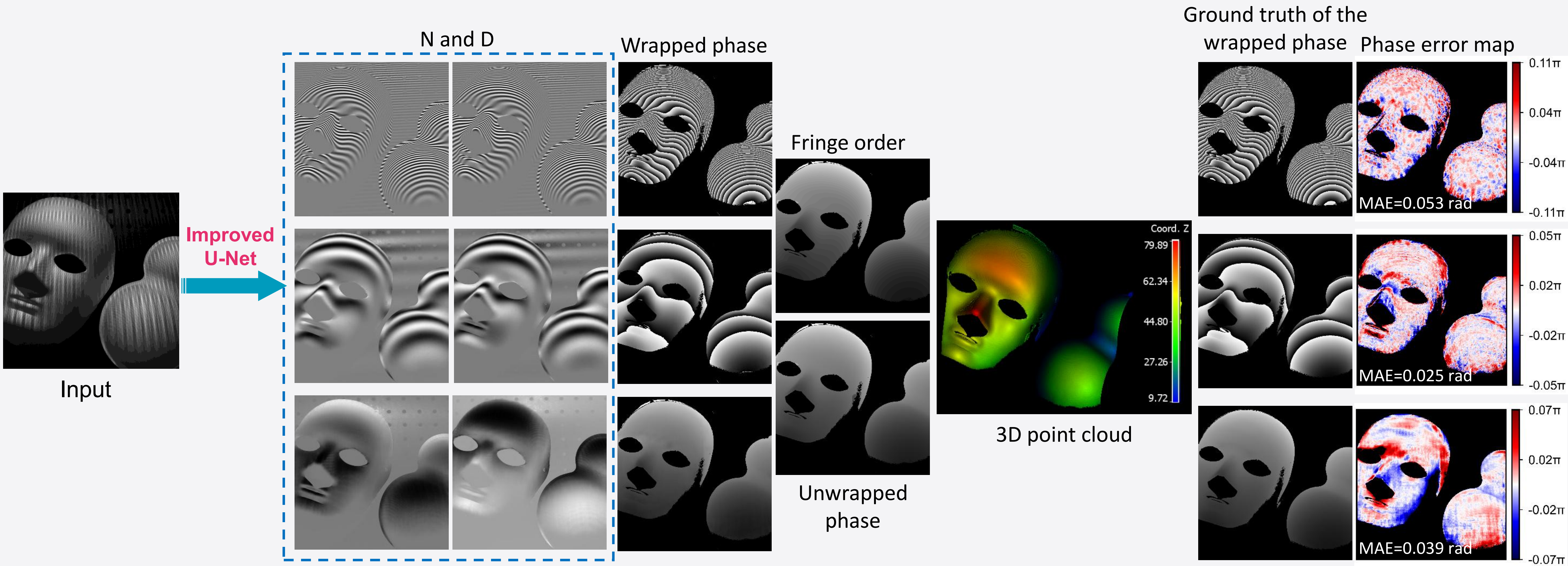



MAE: Mean absolute error

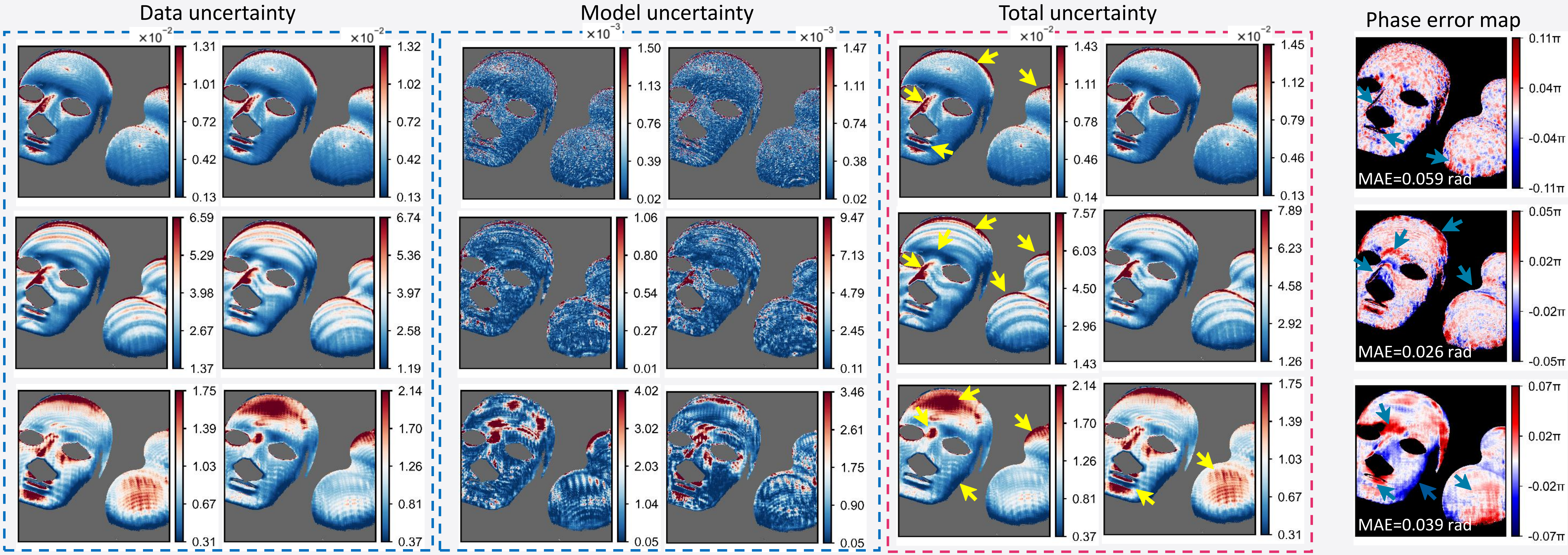
# Experiments: Validation & Analysis



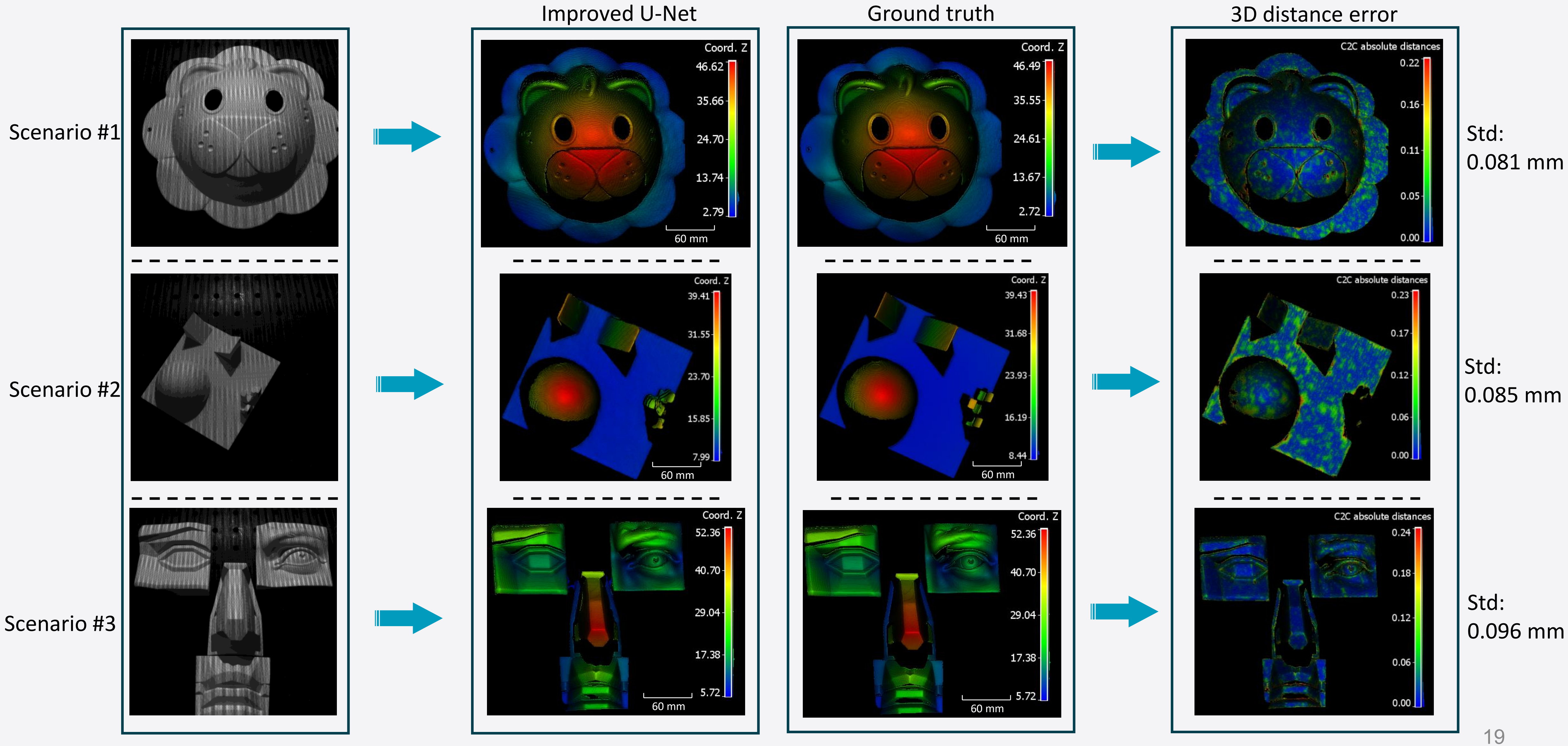
# Experiments: Validation & Analysis



# Experiments: Validation & Analysis



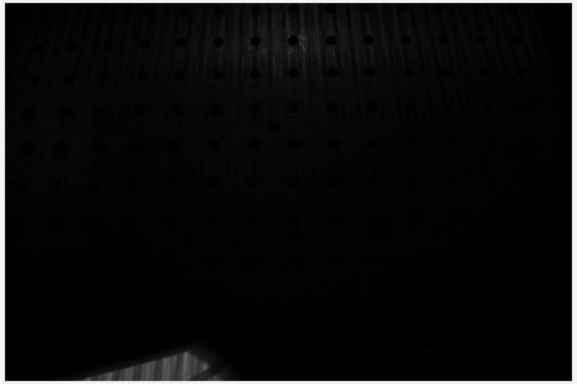
# Experiments: Validation & Analysis



# Experiments: Validation & Analysis

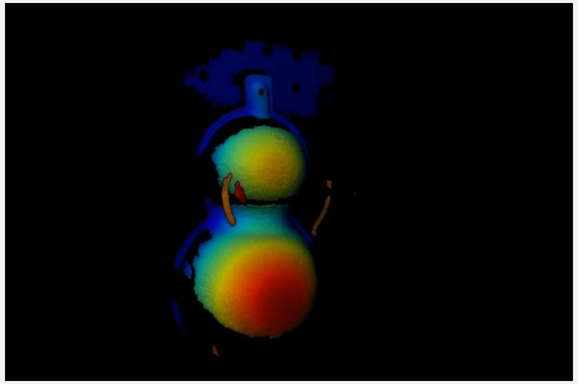
| | Exposure time |
|---|---|
| Projector ($t_p$) | 25 ms |
| Camera ($t_c$) | 25 ms |

| Period time | 300 ms |
|---|---|



| | Exposure time |
|---|---|
| Projector ($t_p$) | 25 ms |
| Camera ($t_c$) | 25 ms |

| Period time | 200 ms |
|---|---|



# Conclusion

**Current contributions:**

- **Composite multi-frequency fringe design**
  Generated a composite fringe pattern that simultaneously encodes six spatial frequencies, providing three independent wrapped-phase maps for robust phase unwrapping.
- **Single-shot U-Net pipeline**
  Trained a customised U-Net to regress the numerators and denominators of the three wrapped phases directly from the composite image, enabling real-time 3D reconstruction.
- **Uncertainty evaluation**
  Replaced the traditional loss function with Gaussian NLL and incorporated Snapshot Ensemble, which enabled the improved U-Net to generate an uncertainty map for estimating prediction confidence.

**Future work:**

- Enhance the resolution of the U-Net model.
- Reduce fringe order errors to improve the accuracy of the unwrapped phase by designing different frequencies or adopting alternative solutions.
- Develop an digital twin of the FPP setup for collecting the synthetic data for model training.

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