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MANUFACTURING METROLOGY TEAM

3DMC 3D METROLOGY CONFERENCE

A flexible method for the geometric characterisation of a multi-view fringe projection system

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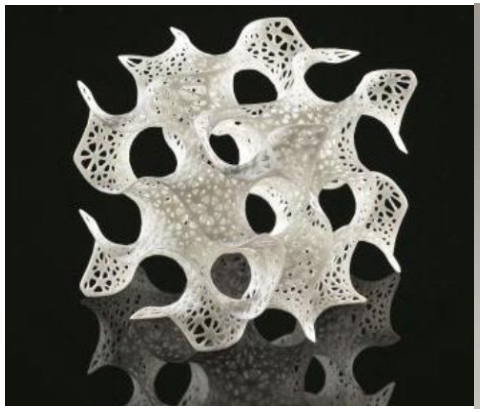
4th 3D Metrology Conference
November 5-7, 2019, London

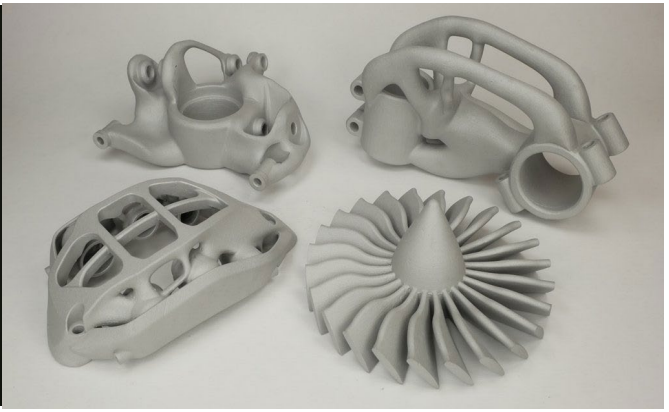
H2020 – Grant Agreement
No 721383

PAM²

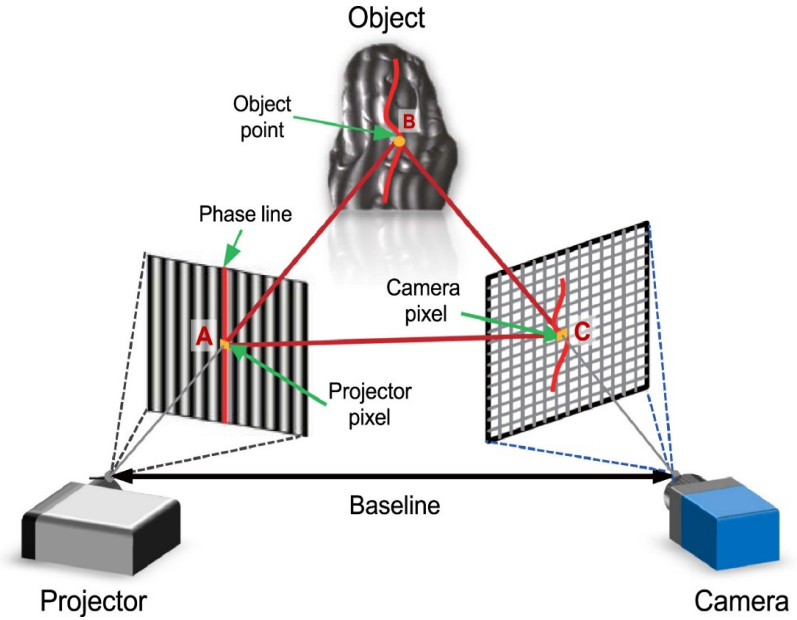
Form measurement in AM

- Form measurement is critical in AM
- Methodologies
  - Coordinate measuring machines (CMMs)
  - Optical measurements
  - X-ray computed tomography (CT)
- Exploit all a priori information (CAD, models, coarse measurement data)





CMM



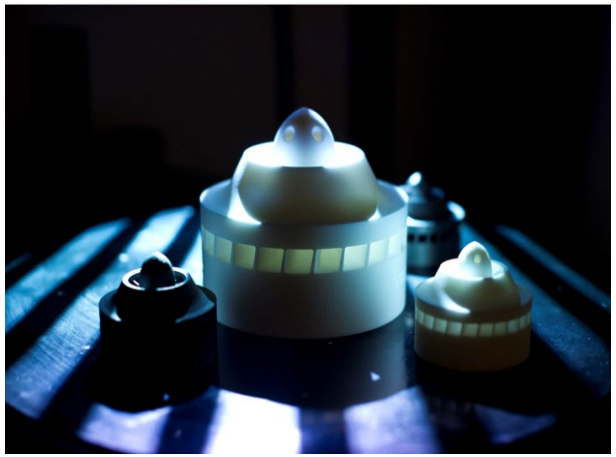
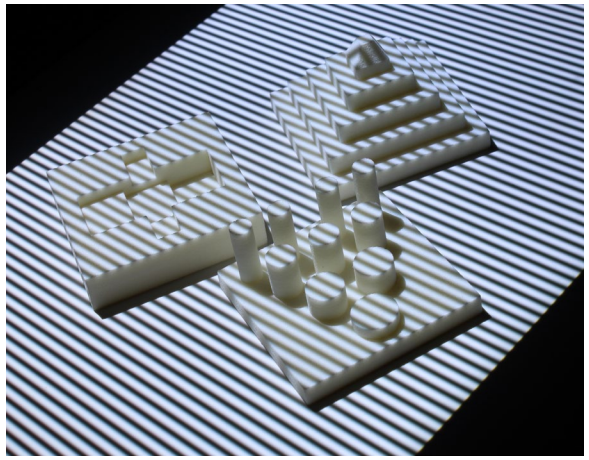
Structured light technique

Zuo et al. 2016 Opt. Laser Eng. 85

Fringe projection advantages

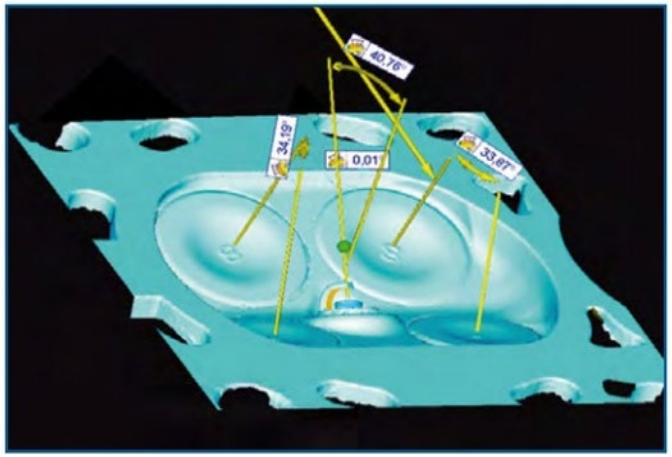
Advantages

- Non-contact
- Non destructive
- Fast acquisition rates
- More data points

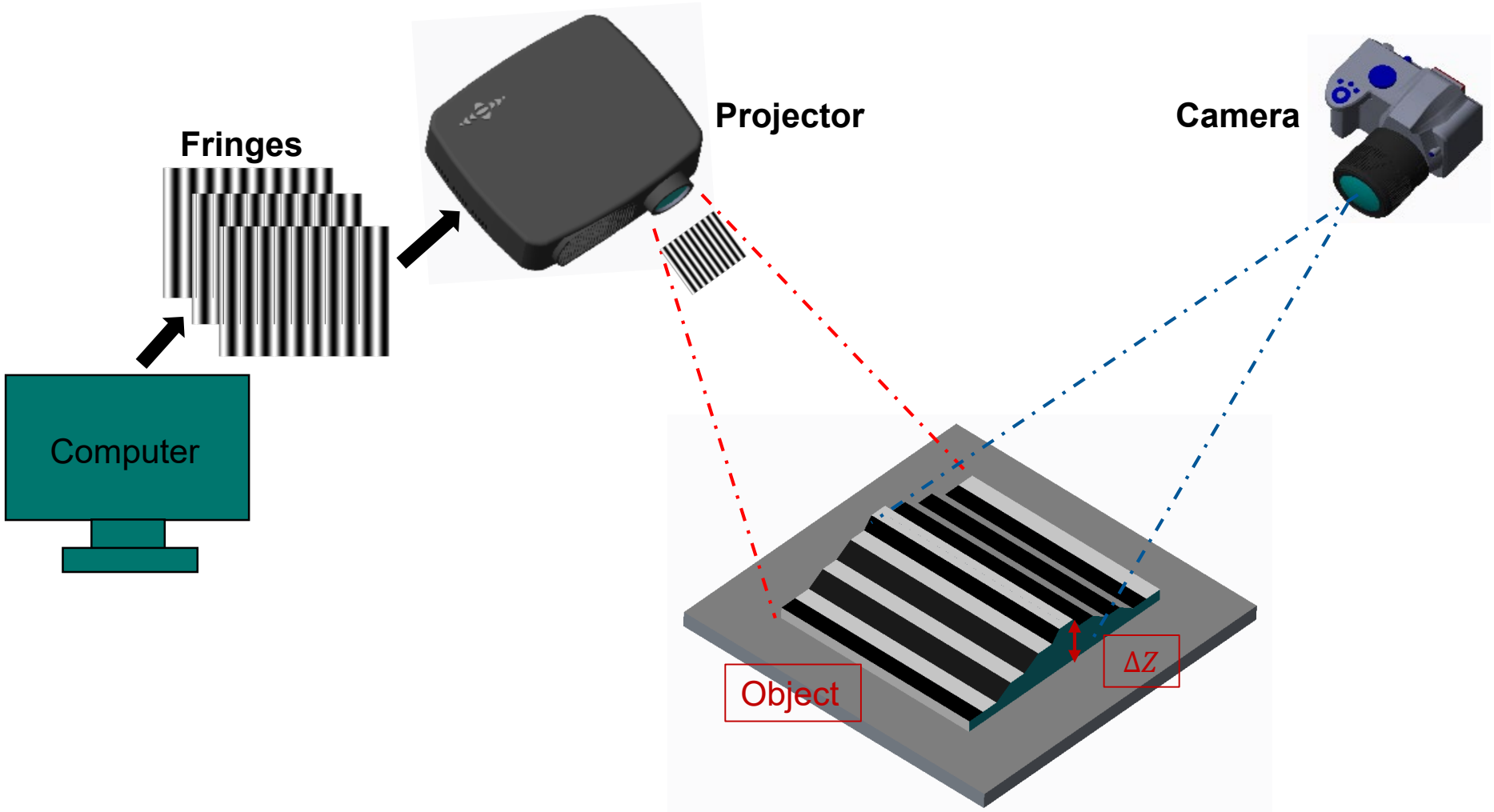



Applications

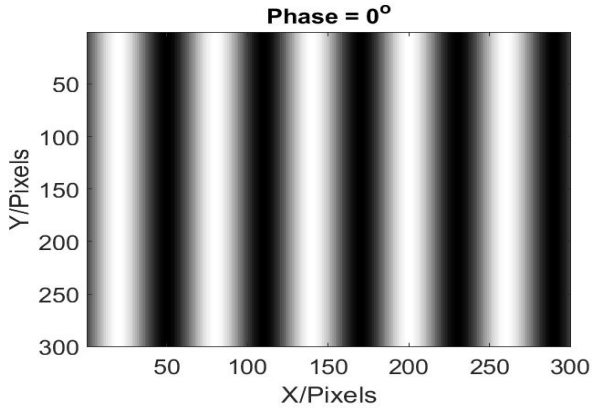
- AM quality control
- Reverse engineering
- Biomedicine
- Automotive
- Aerospace

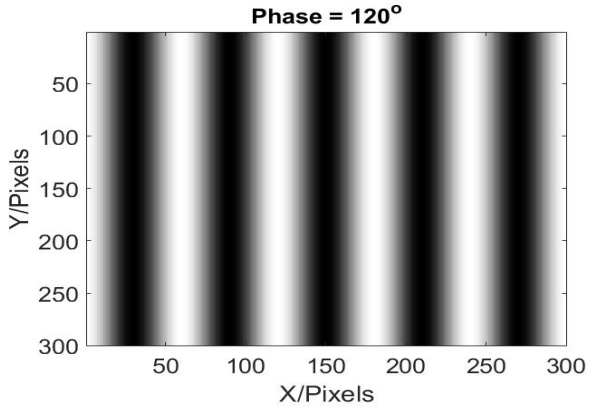


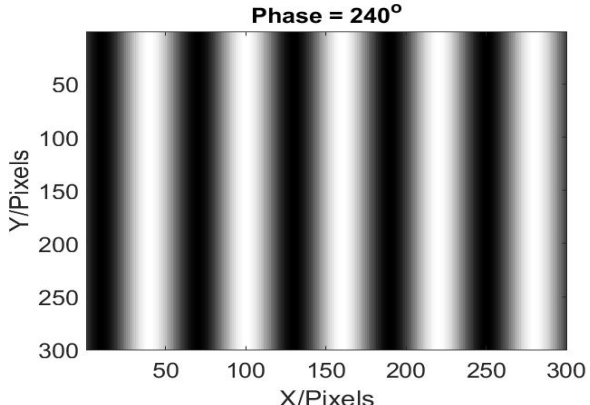
Fringe projection technique



The concept of phase in fringe projection



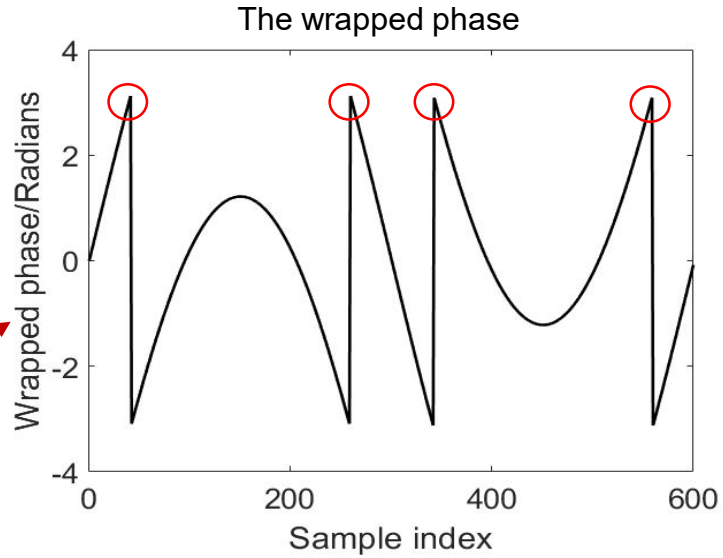


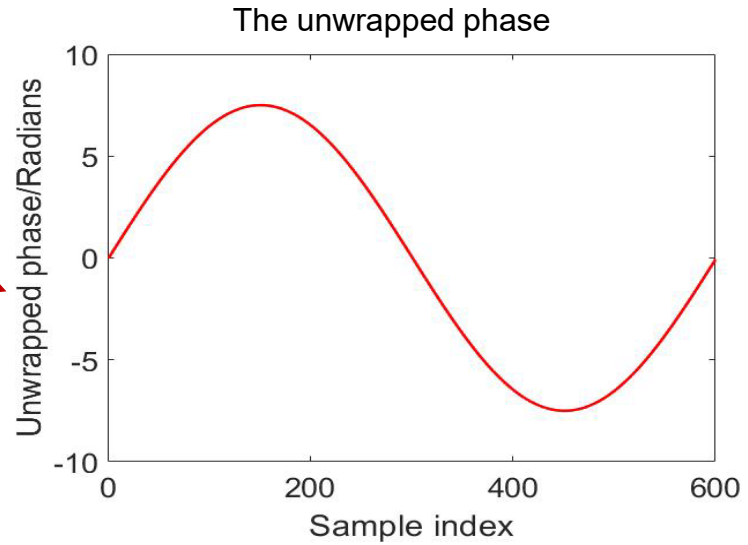


$$\varphi(x,y) = -\tan^{-1}\left(\frac{\sum_{i=1}^{N} I_i \sin\delta_i}{\sum_{i=1}^{N} I_i \cos\delta_i}\right)$$

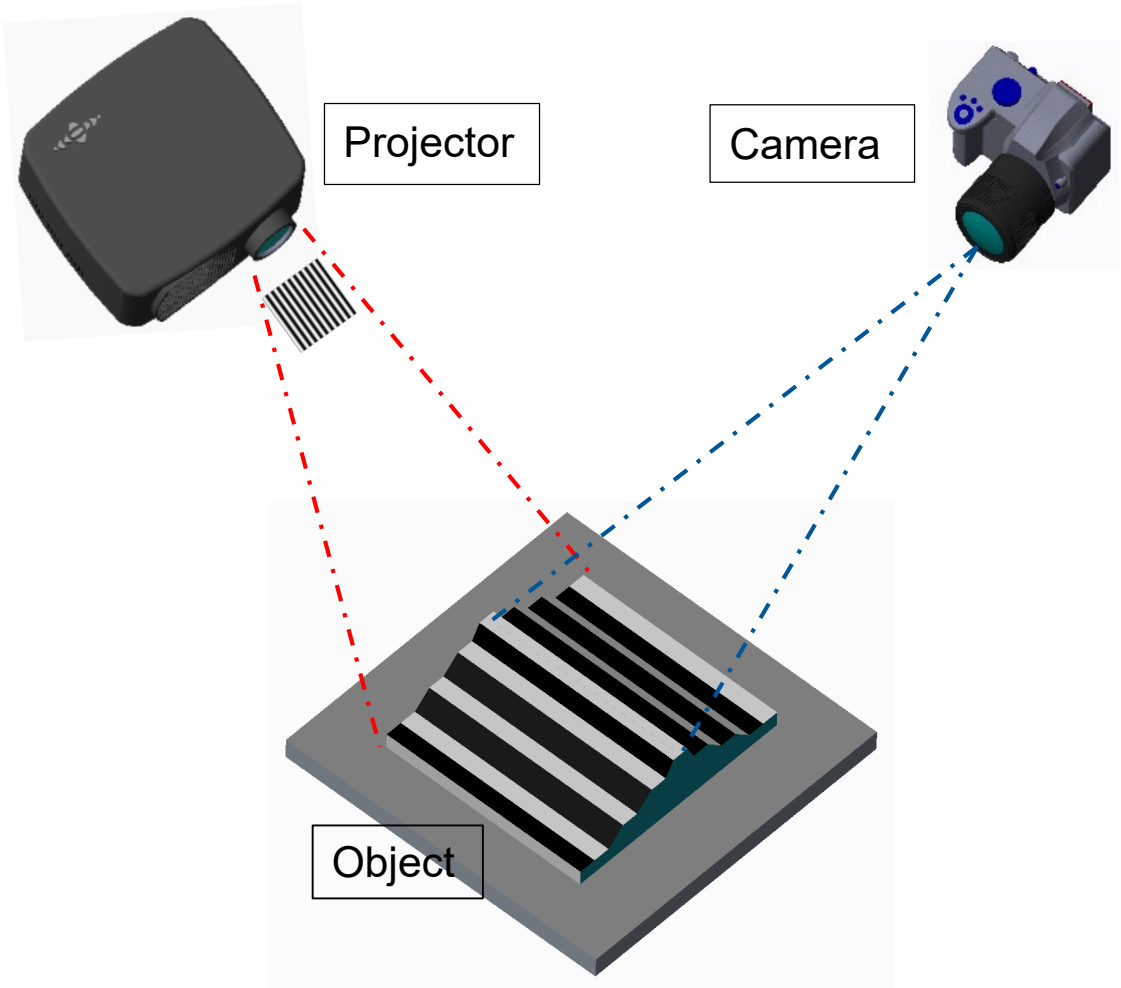
$$\varphi(x,y) \rightarrow [-\pi,\pi]$$

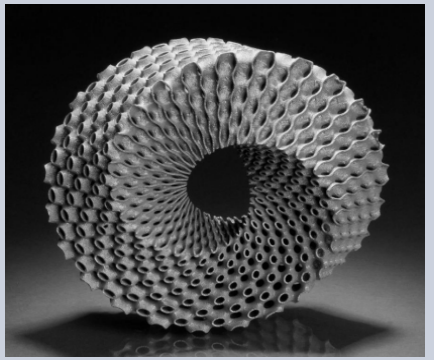
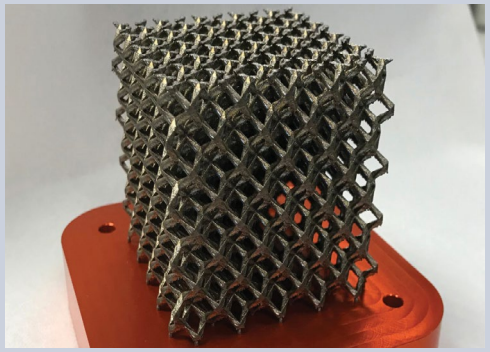
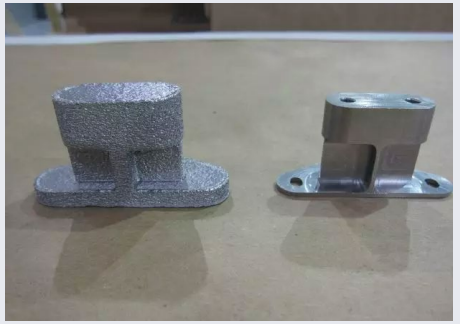
$$\boldsymbol{\phi}(x,y) = \varphi(x,y) + k(x,y) \times 2\pi$$





Current challenges of fringe projection system



Constraint	
Freeform, occlusions, shadows, line of sight issues	 
Surface properties (specular reflections)	
Material range (Nylon-12, TiAl6V4, Inconel, Maraging steel, etc.)	

Challenges of commercial fringe projection systems

- Slow speed for a full 3D scan
- Multiple orientations of the object
- Robotic arm
- Less economical
- Limited information is accessible (black box)

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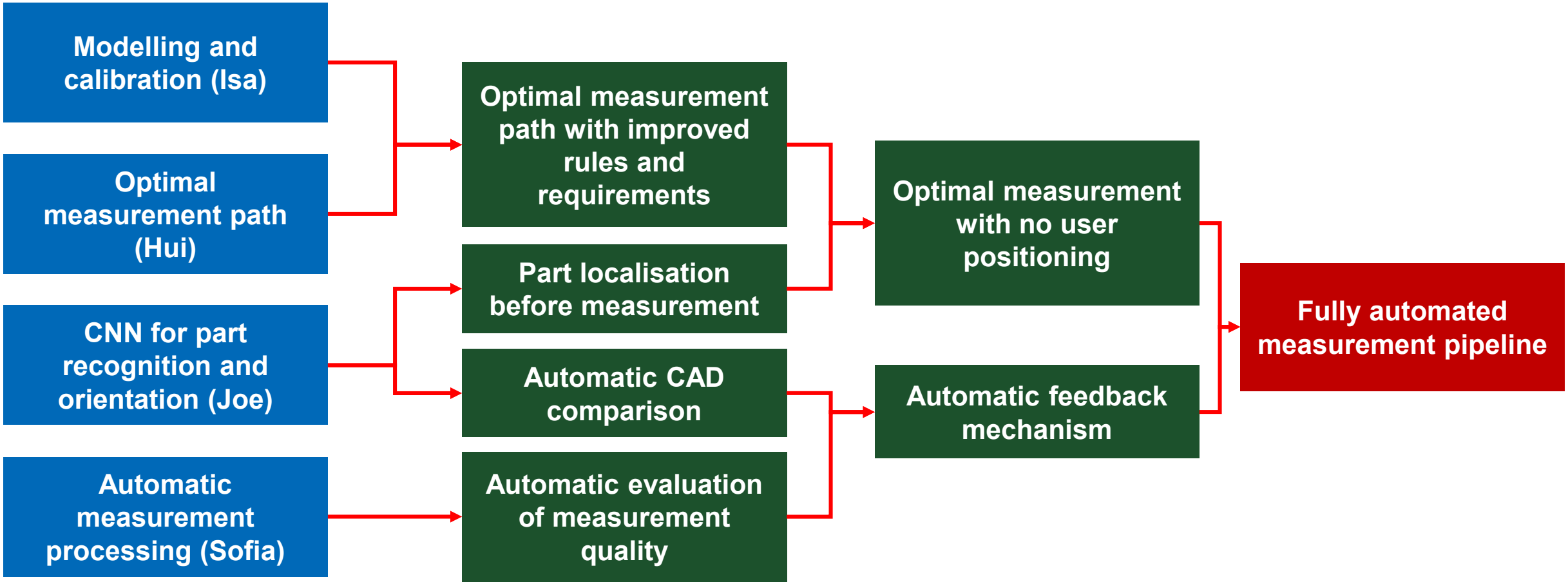
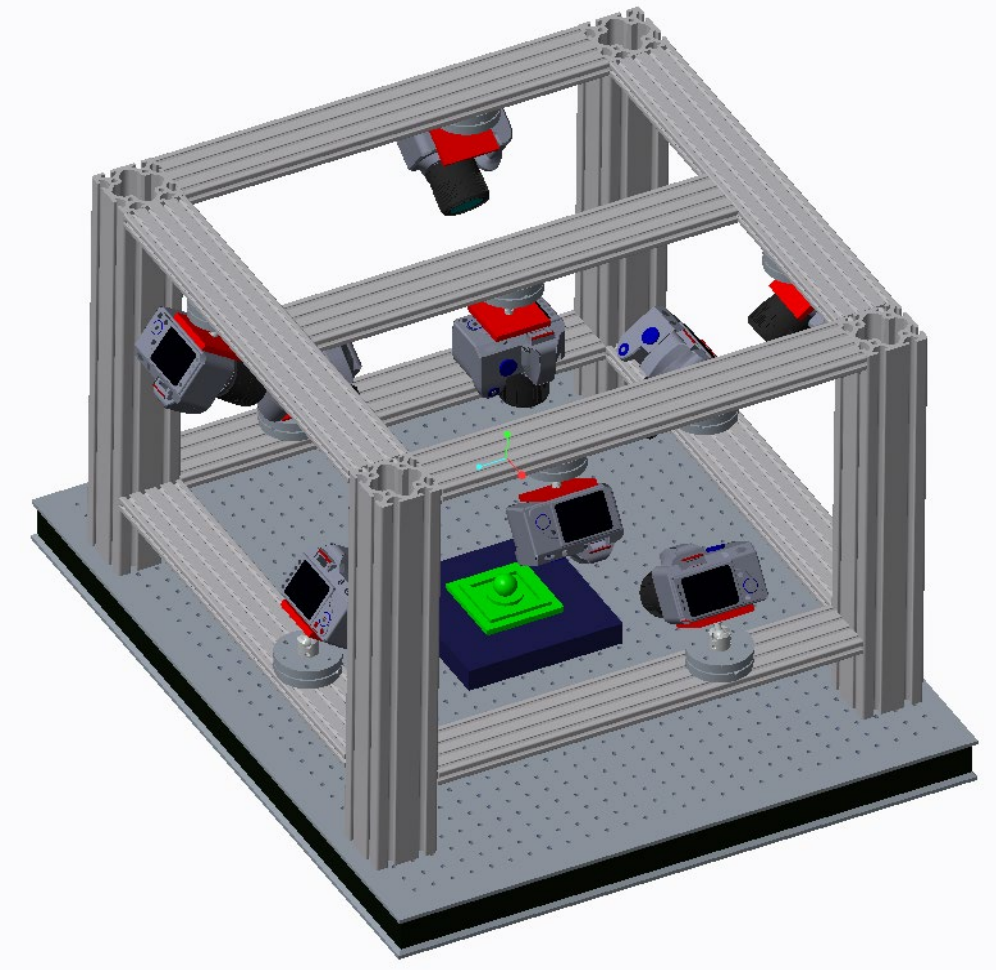
Multi-view fringe projection system

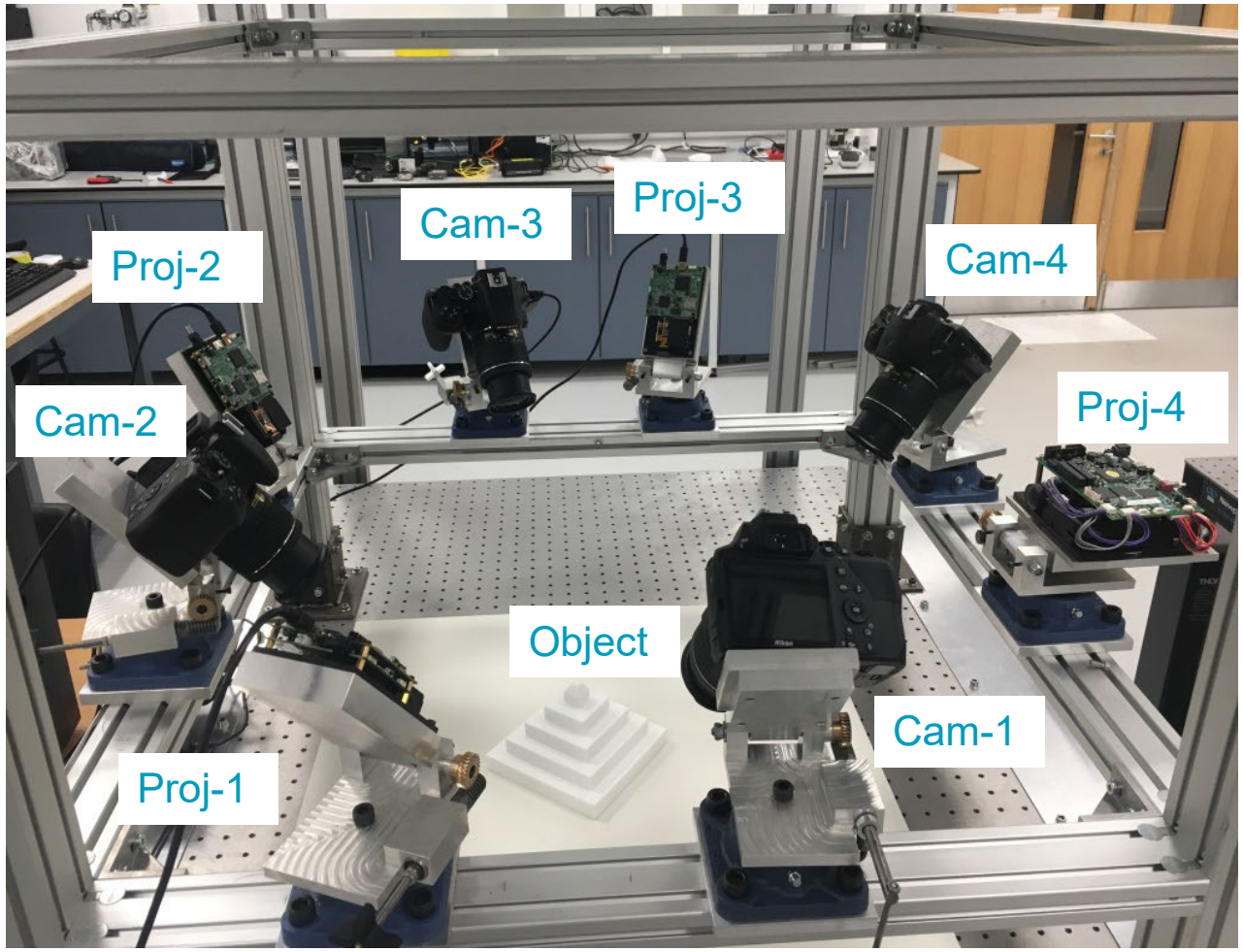
Combining smart solutions – MMT Nottingham



JABEH - Multi-view fringe projection system

The multi-view fringe projection system is capable of reconstructing the form of complex additively manufactured parts





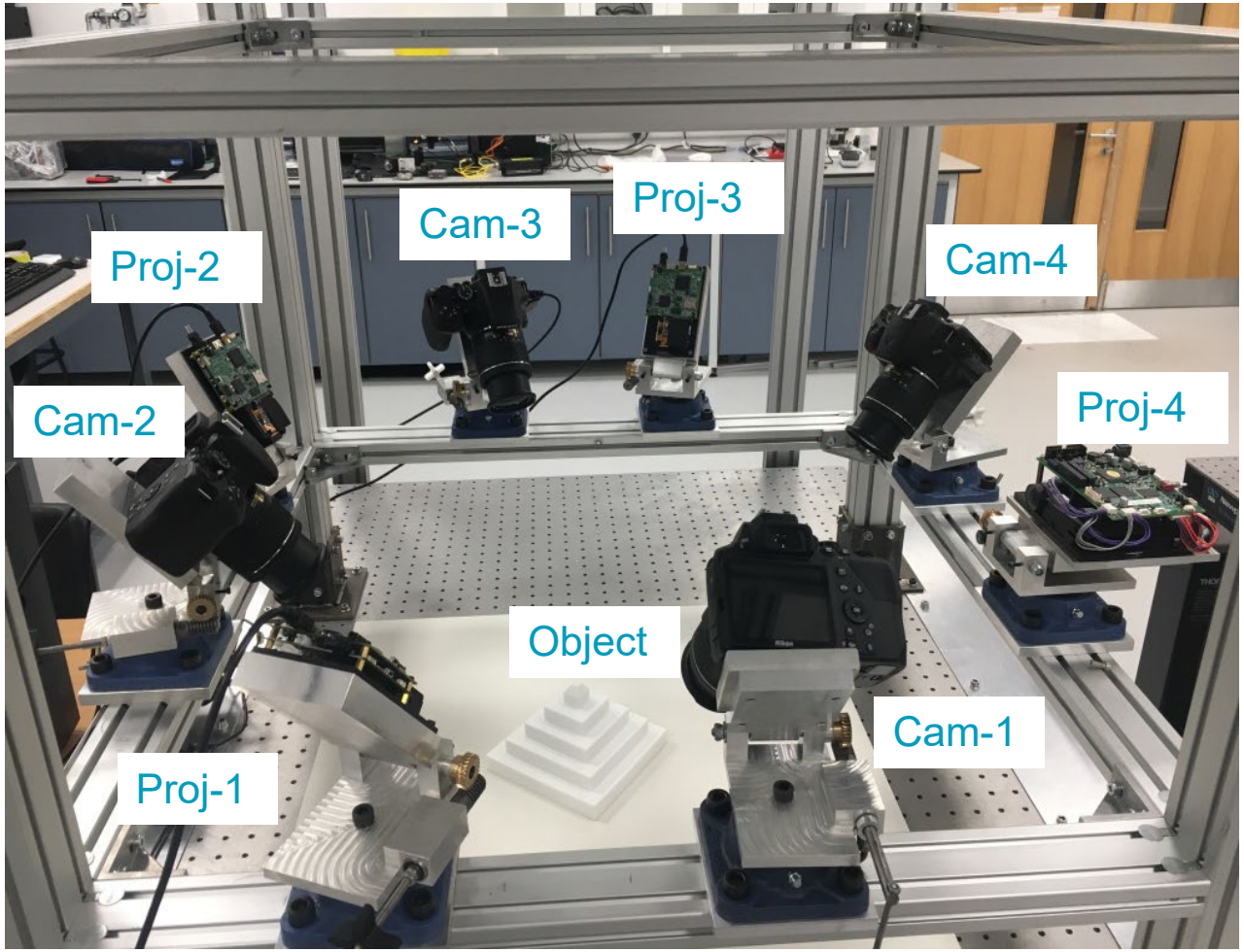
What do we want?

Current setup

- DSLR cameras – testing the system

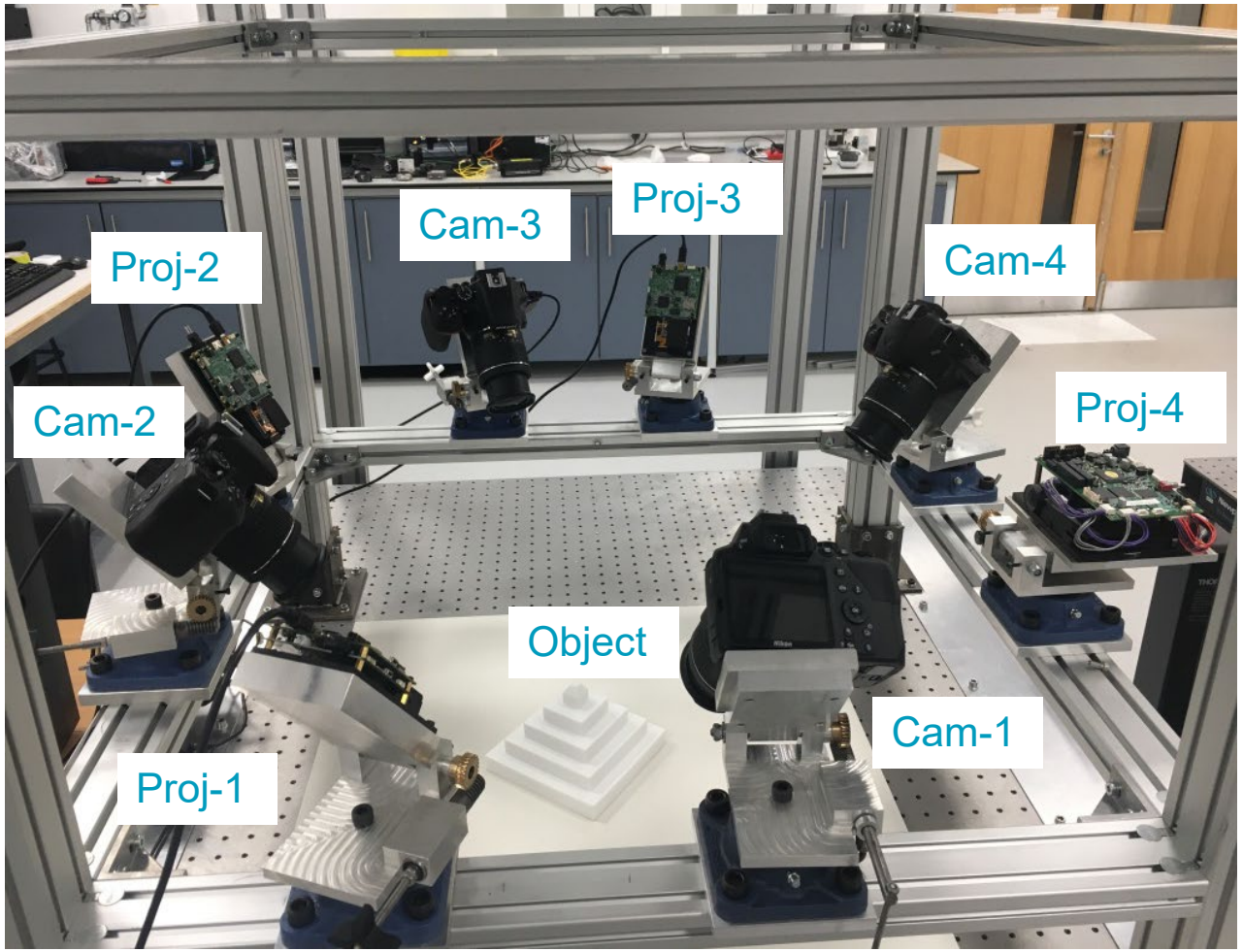
- Not one shot with DSLR
- cameras

- In the future – industrial cameras
  - High speed acquisition
  - Overcome camera noise

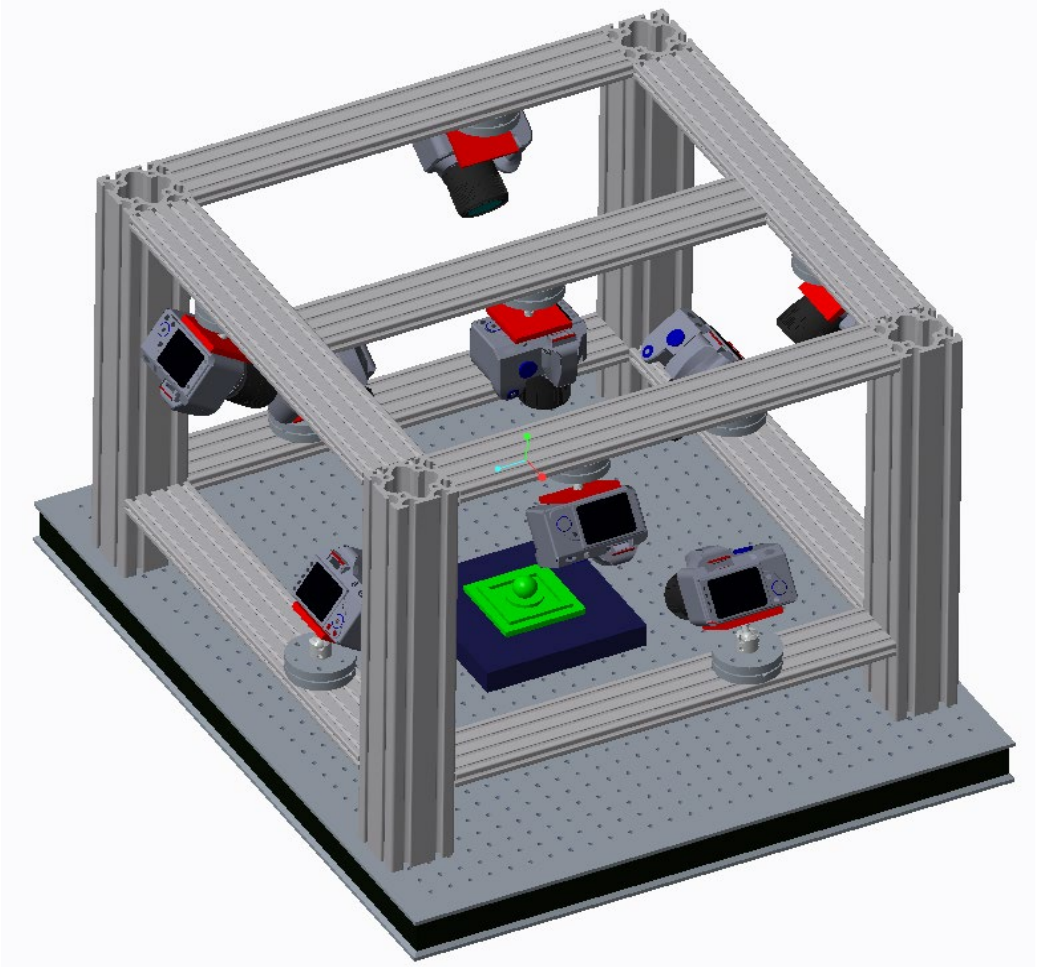


JABEH - Multi-view fringe projection system

- Measurement volume:
  (250 mm × 250 mm × 250 mm)
- Target MPE: 30 μm
- Fully automated
- Digital Micromirror Device (DMD) control
- Projector's overlapping
- Black box enclosure



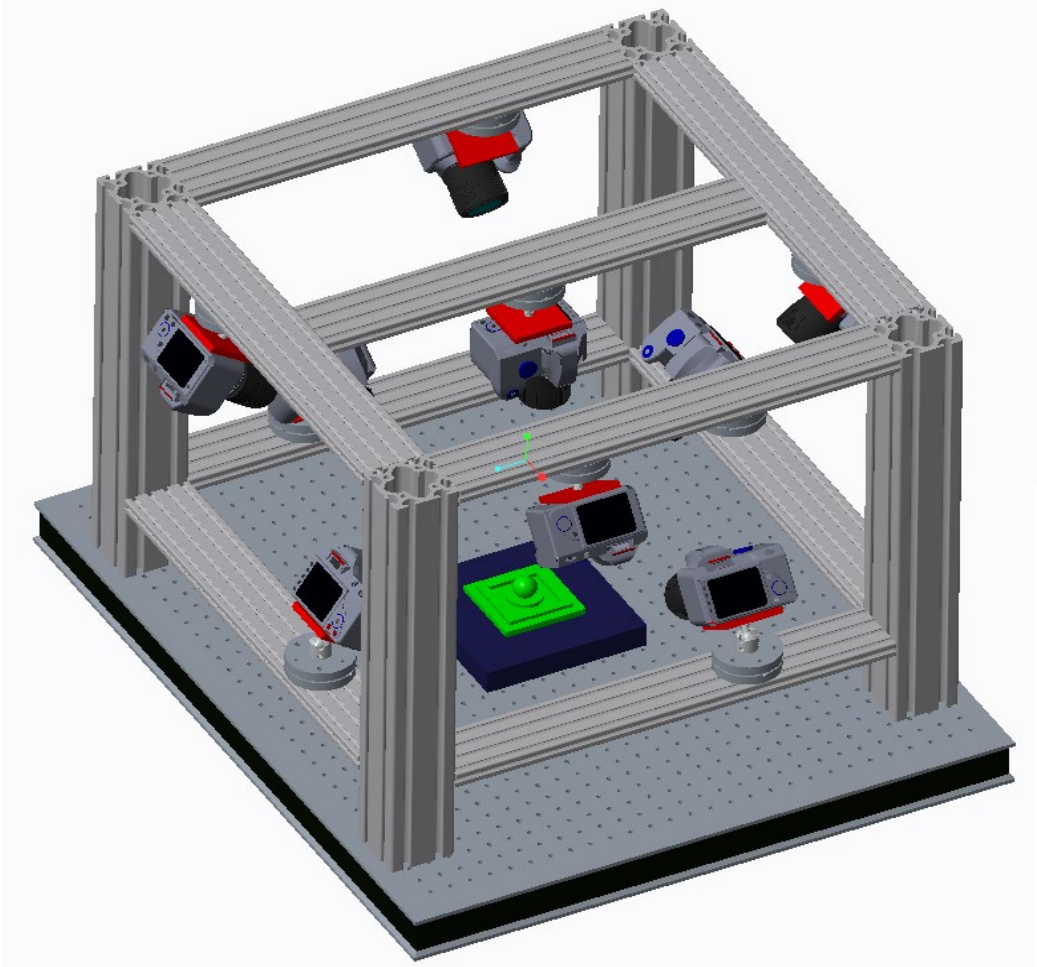
Novelty - Multi-view fringe projection system



Form/geometry

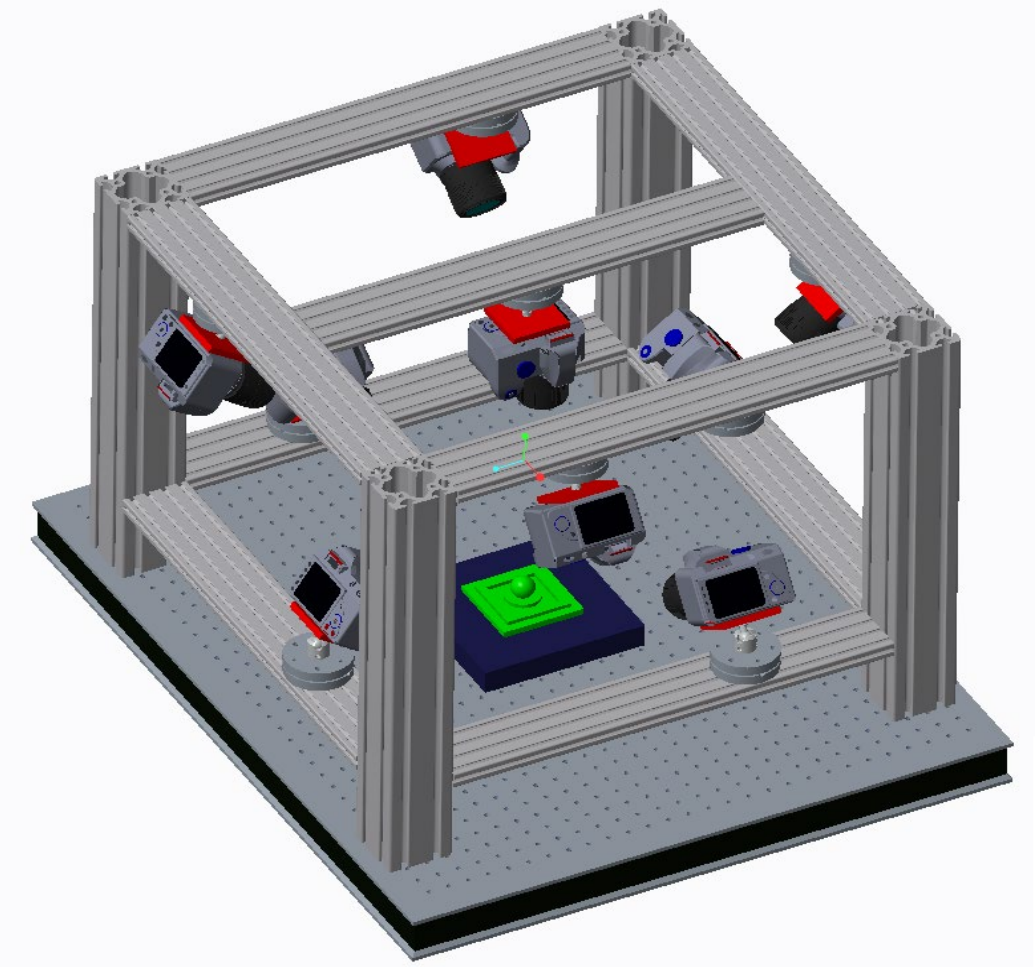
Multiple projectors/cameras + IRM
(Information rich metrology, CAD)

Novelty - Multi-view fringe projection system



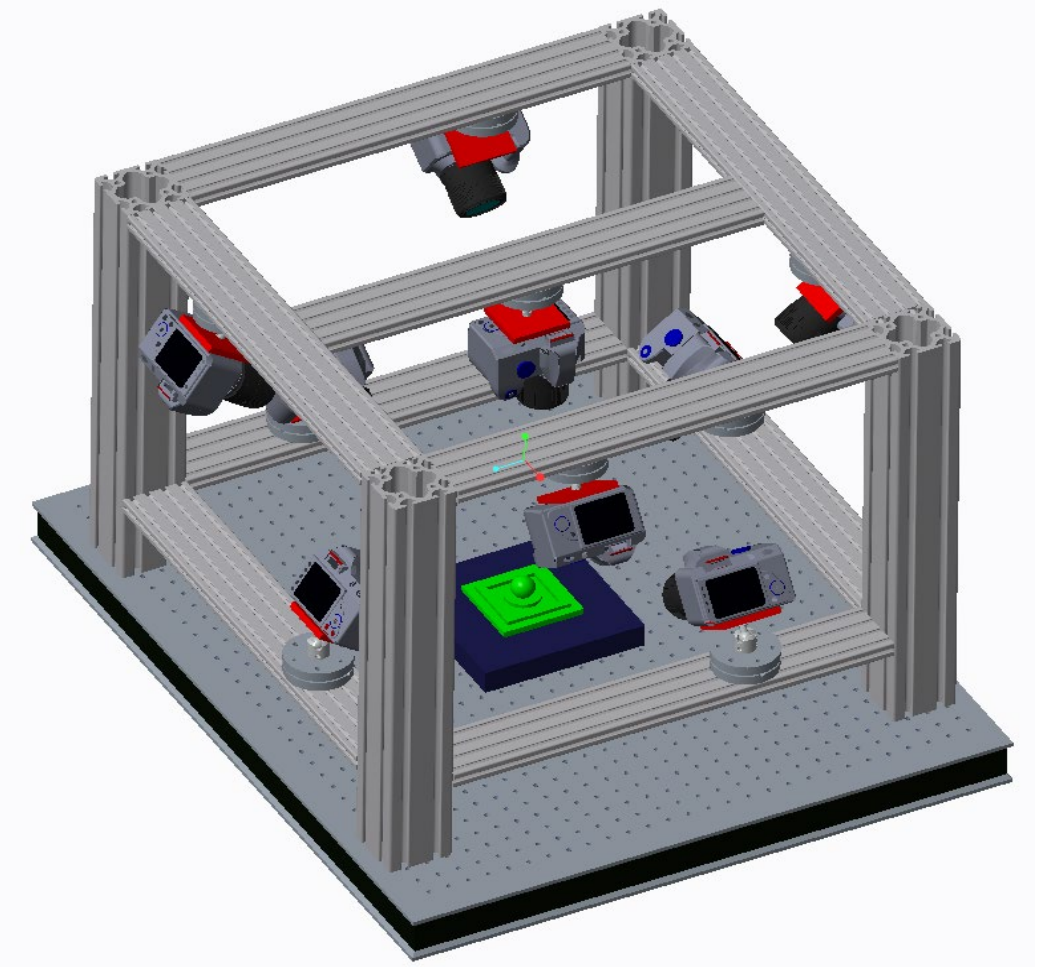
Form/geometry	Multiple projectors/cameras + IRM (Information rich metrology, CAD)
Overcoming the surface texture	Projector/camera pose optimisation

Novelty - Multi-view fringe projection system

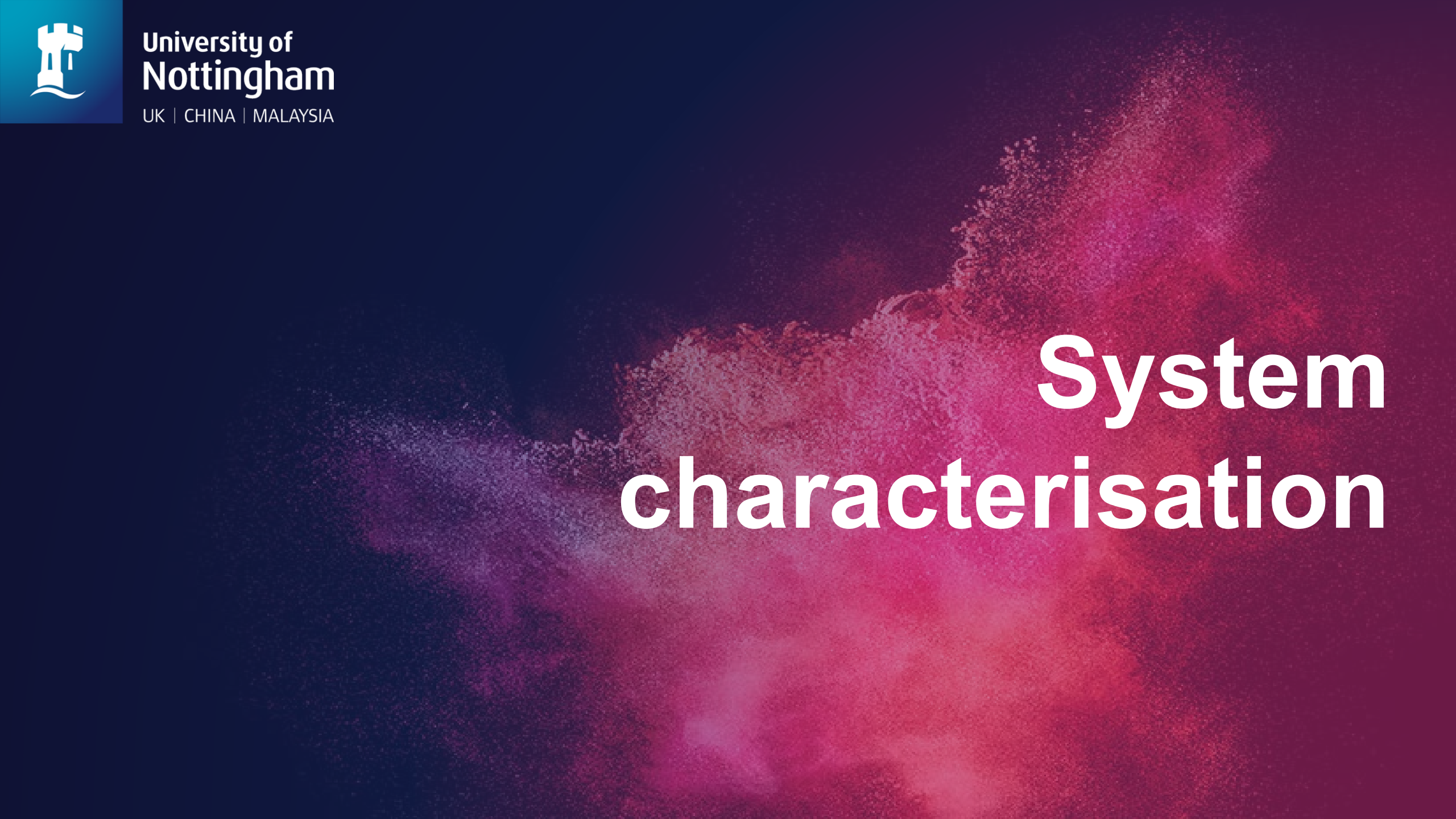


Form/geometry	Multiple projectors/cameras + IRM (Information rich metrology, CAD)
Overcoming the surface texture	Projector/camera pose optimisation
Speed	One shot – Robust, high-speed 3D reconstruction

Novelty - Multi-view fringe projection system



Form/geometry	Multiple projectors/cameras + IRM (Information rich metrology, CAD)
Overcoming the surface texture	Projector/camera pose optimisation
Speed	One shot – Robust, high-speed 3D reconstruction
Voids and gaps in pointcloud	Full 3D coverage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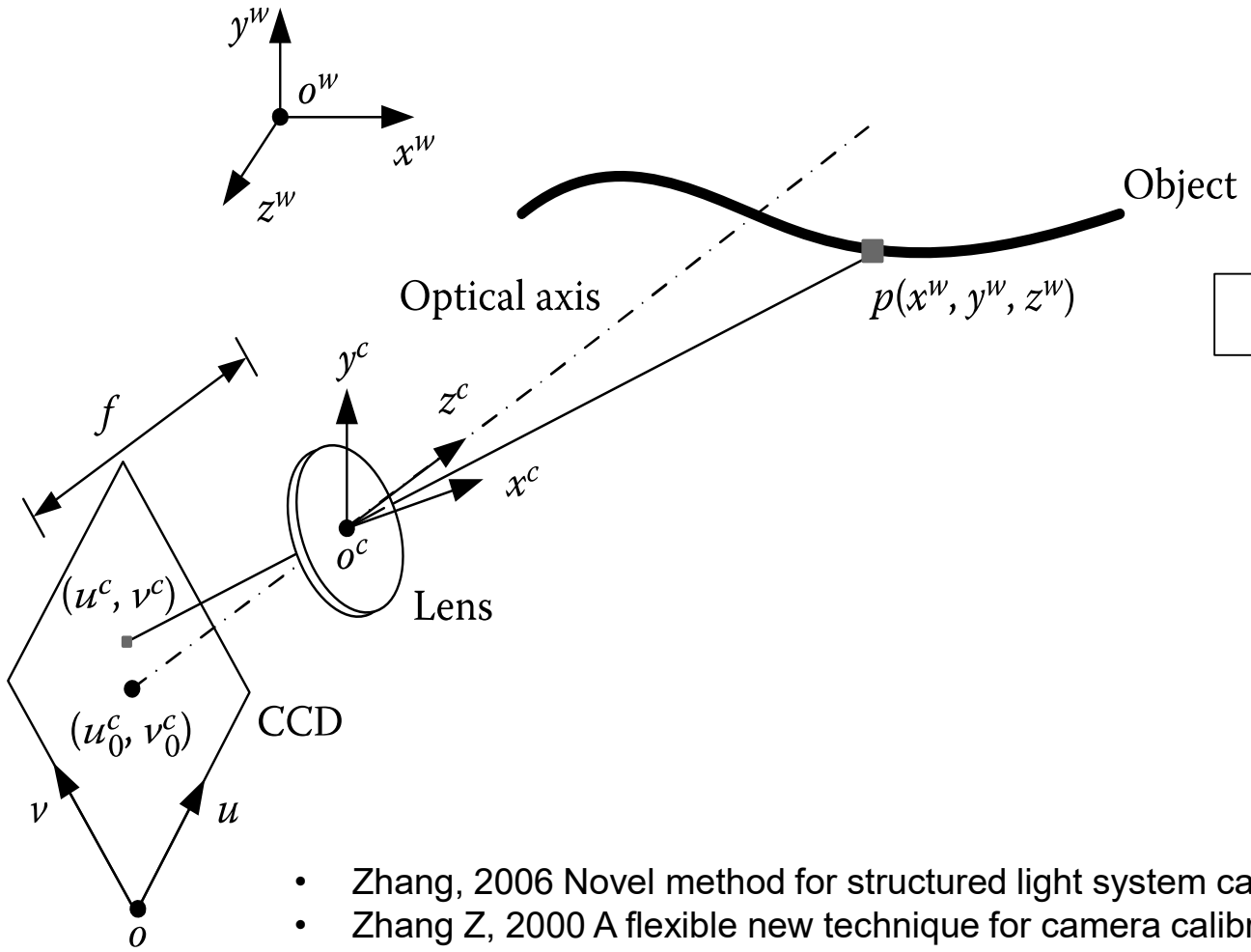
System
characterisation

Camera pinhole model



$$S^c I^c = A^c [R^c, T^c] X^w = A^c M^c X^w$$

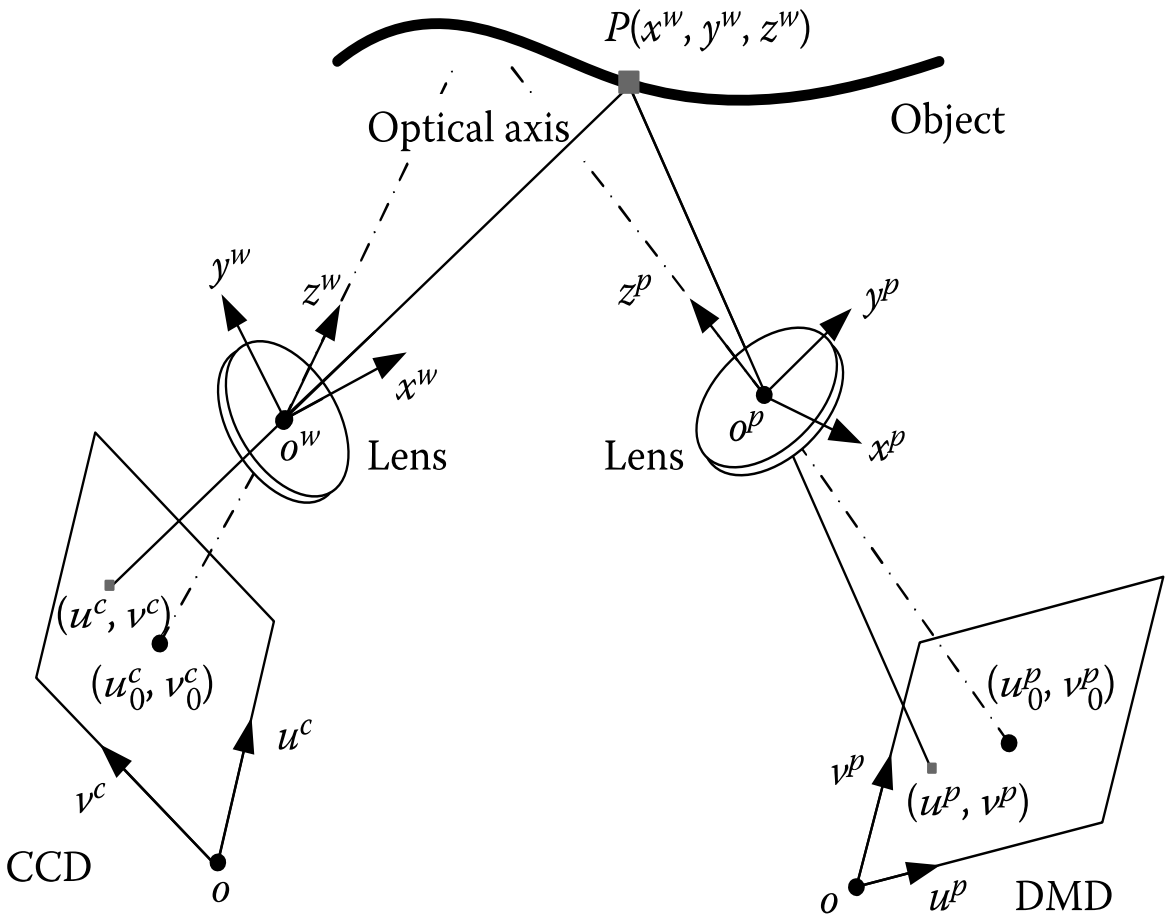
$$I^c = [u^c, v^c, 1]^T$$

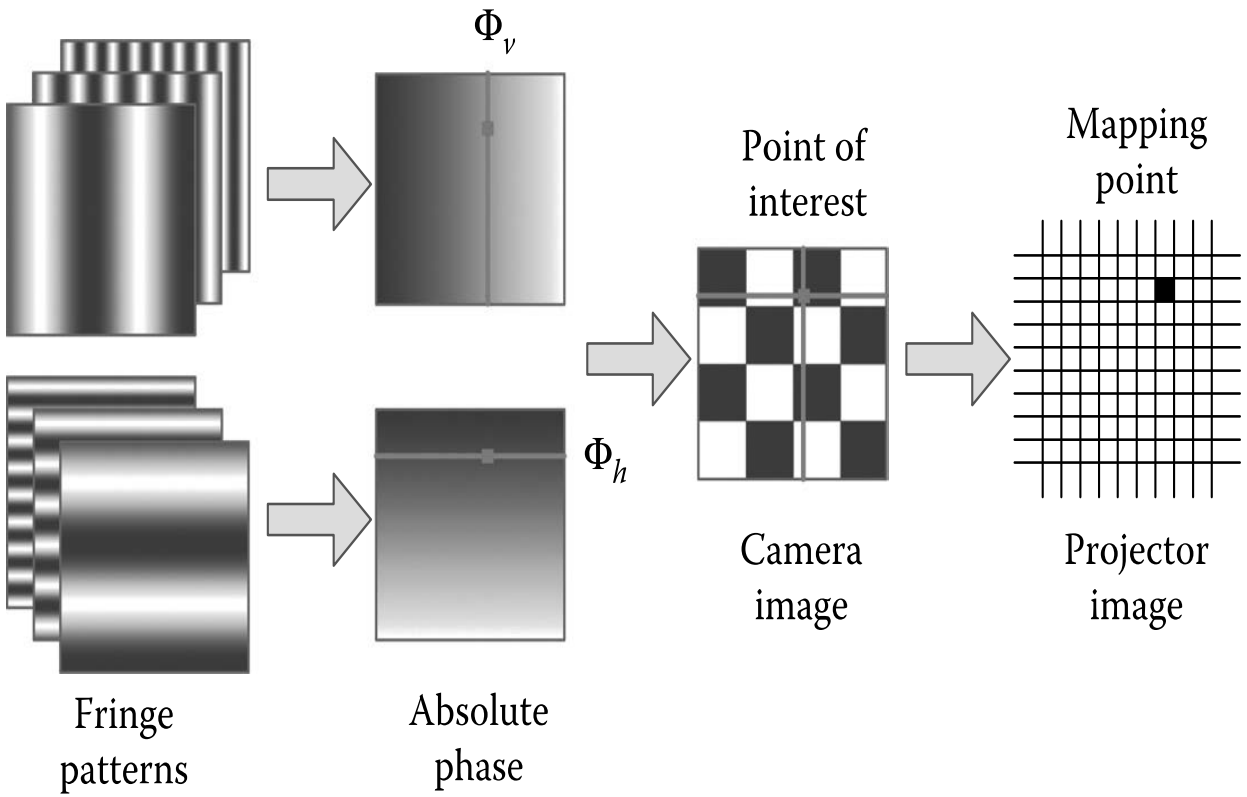
$$X^w = [x^w, y^w, z^w, 1]^T$$

$$A^c = \begin{pmatrix} \alpha^c & \gamma^c & u_0^c \\ 0 & \beta^c & v_0^c \\ 0 & 0 & 1 \end{pmatrix}$$

- Zhang, 2006 Novel method for structured light system calibration, Opt. Eng. **45**
- Zhang Z, 2000 A flexible new technique for camera calibration *IEEE Trans. Pattern Anal. Mach. Intell.* **22** 1330–1334
- Huang Z et al. 2015 Accurate projector calibration based on a new point-to-point mapping relationship between the camera and projector images *Appl. Opt.* **54** 347–356
- Zhang Z H Y 2004 Camera calibration with one- dimensional objects *IEEE Trans. Pattern Anal. Mach. Intell.* **26** 892-899

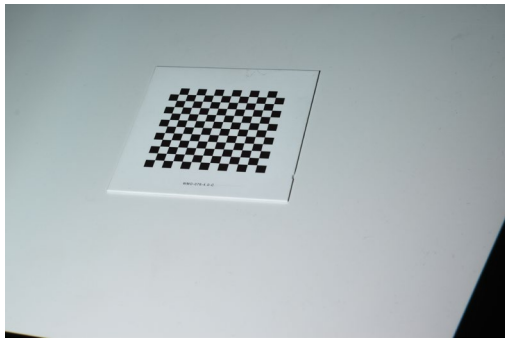
Camera to projector mapping

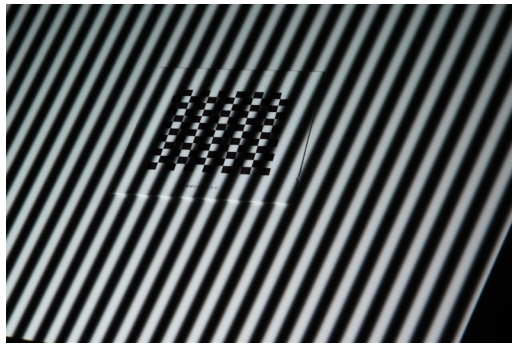


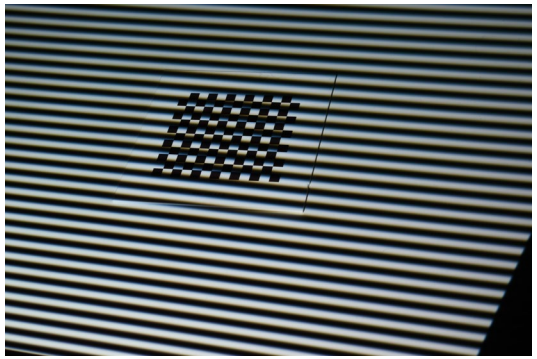


Zhang, 2006 Novel method for structured light system calibration, Opt. Eng. **45**

Characterisation - Pipeline







Images of checkerboard

Camera parameters

Project sinusoidal and binary fringes

Capture horizontal and vertical fringes

Absolute phase (temporal phase unwrapping)

Projector parameters

Global frame of reference

Measurement - triangulation principle

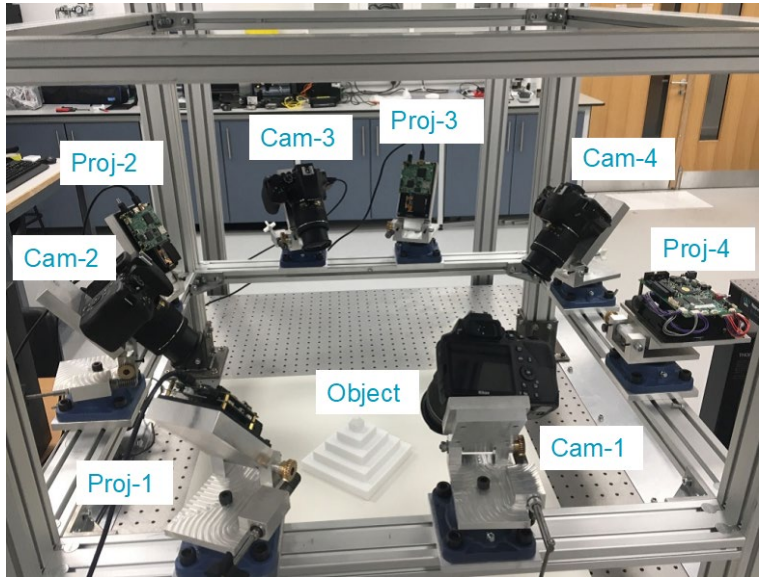
Each camera-projector is a stereo pair

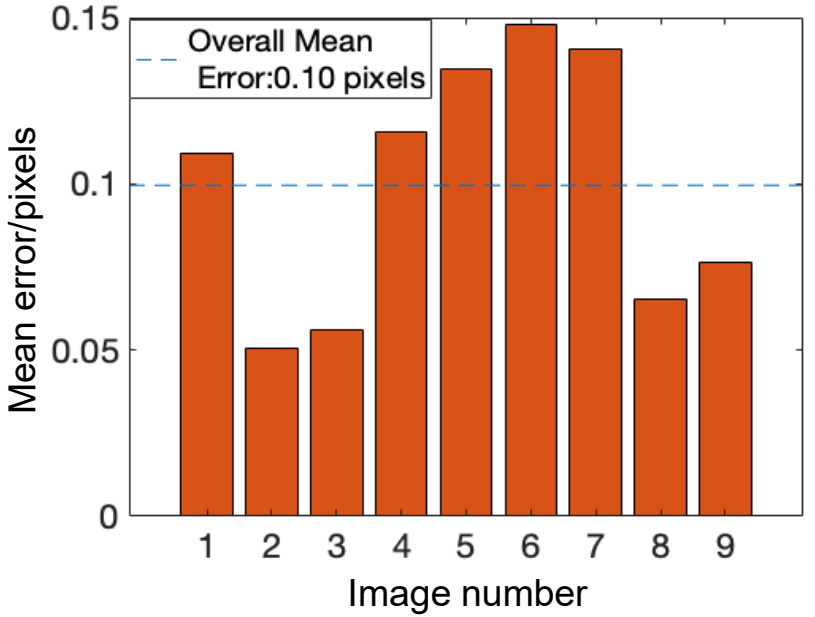
Three-dimensional reconstruction

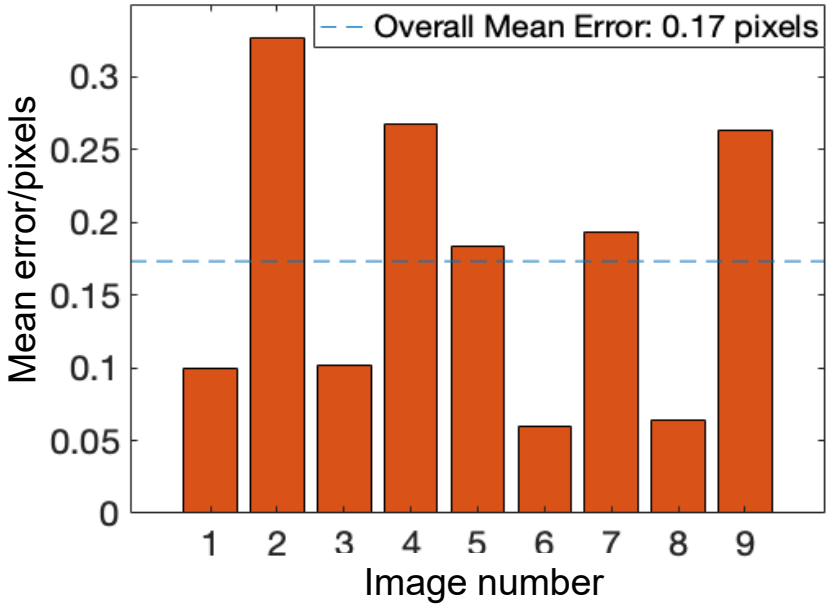
ICP and fine registration of point clouds

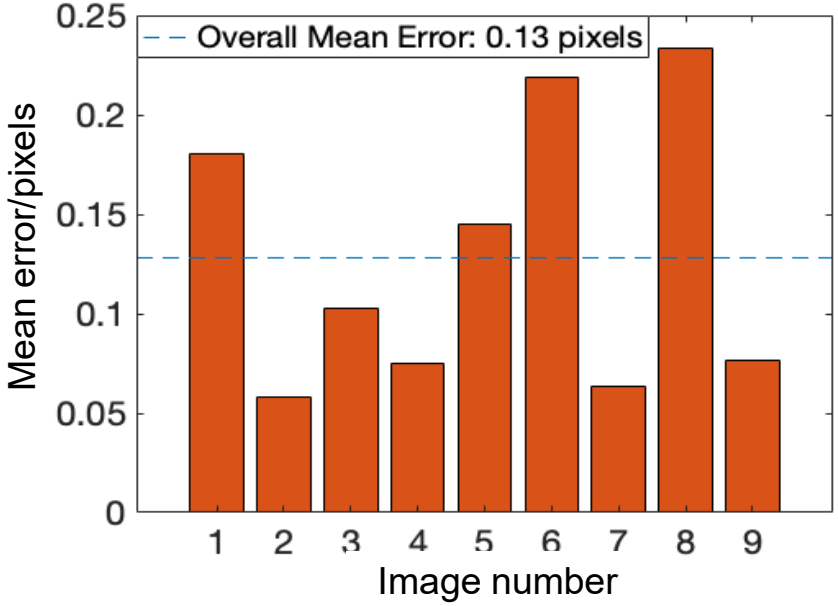
Catalucci, 209 Intelligent system for optical form measurement: automated assessment of pose and coverage, Proc. ASPE.

Projector characterisation

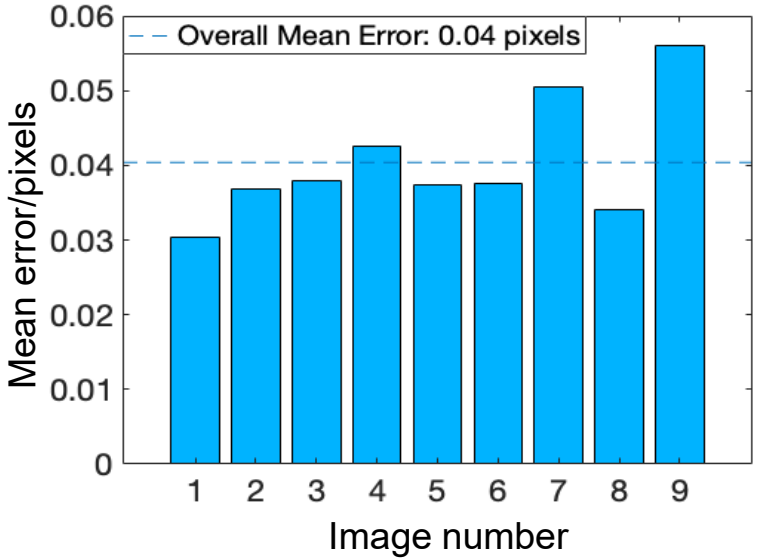


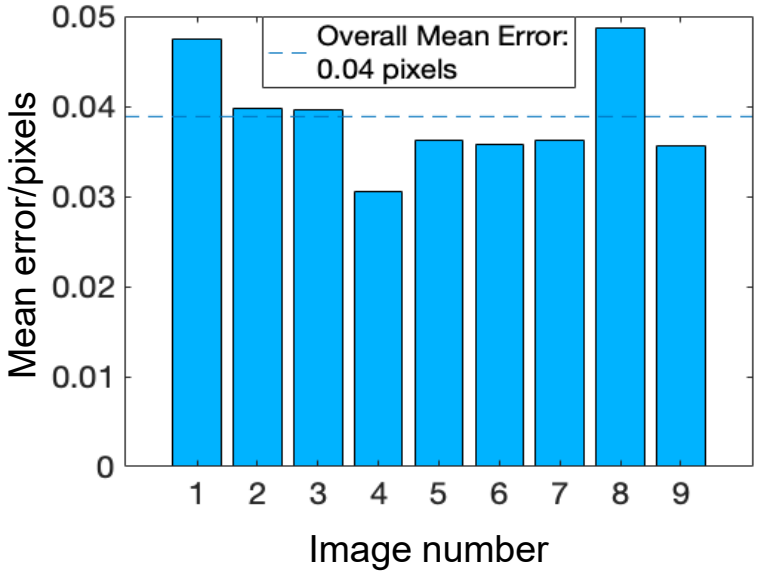


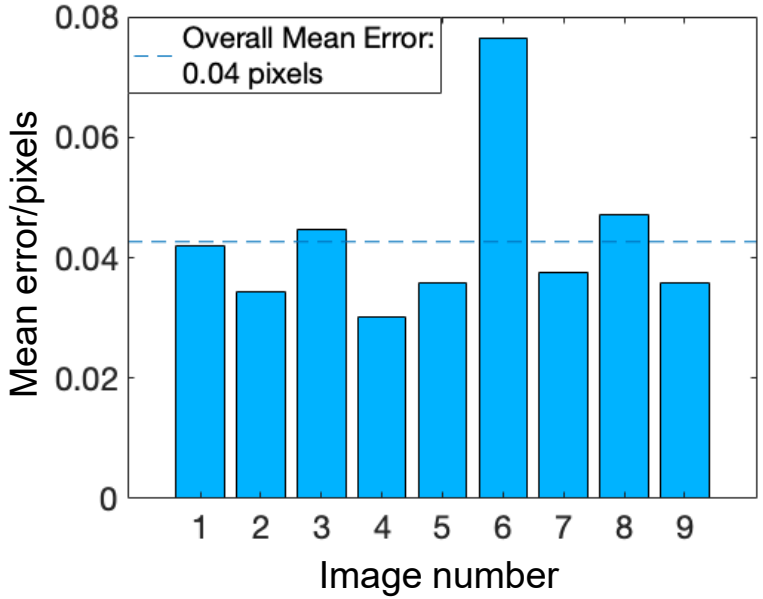


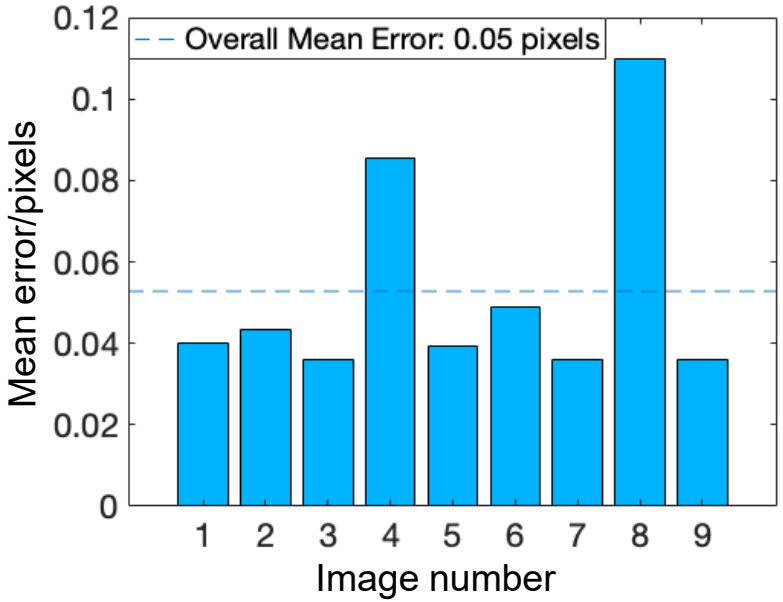


Camera characterisation









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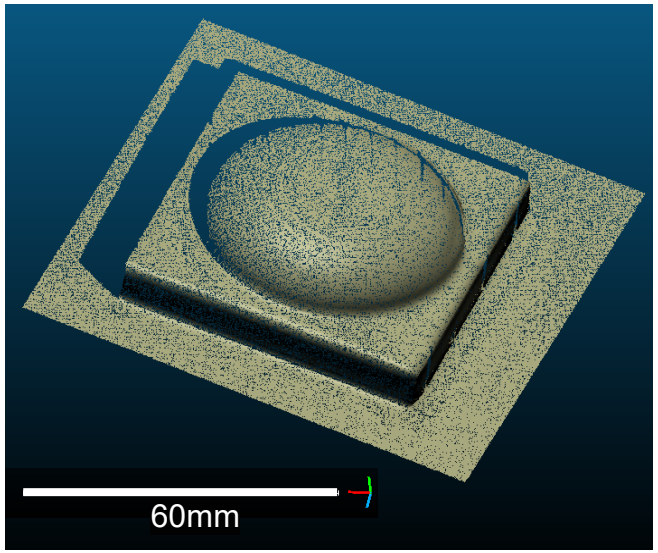
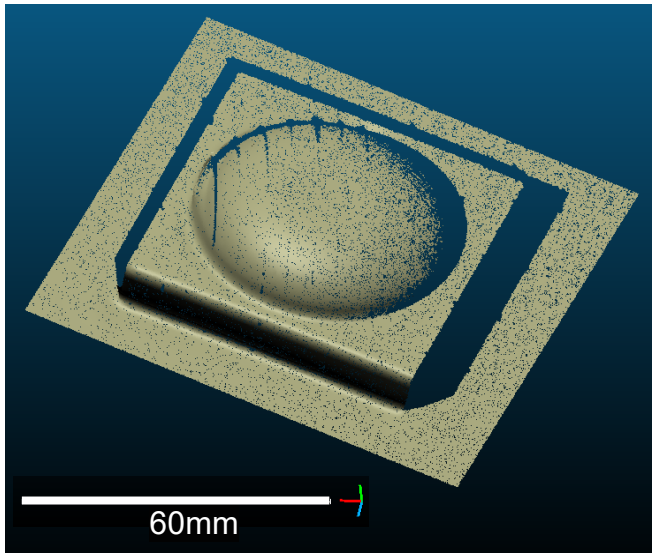
3D
reconstruction
results

Results with two different projections

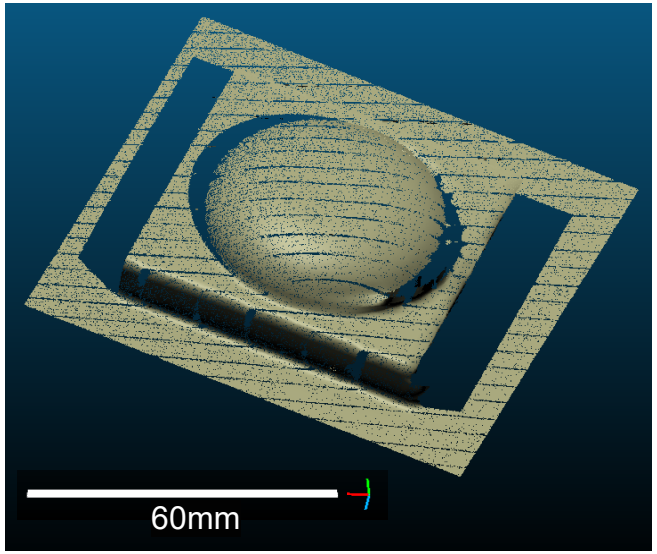
Camera 1 | Camera 2

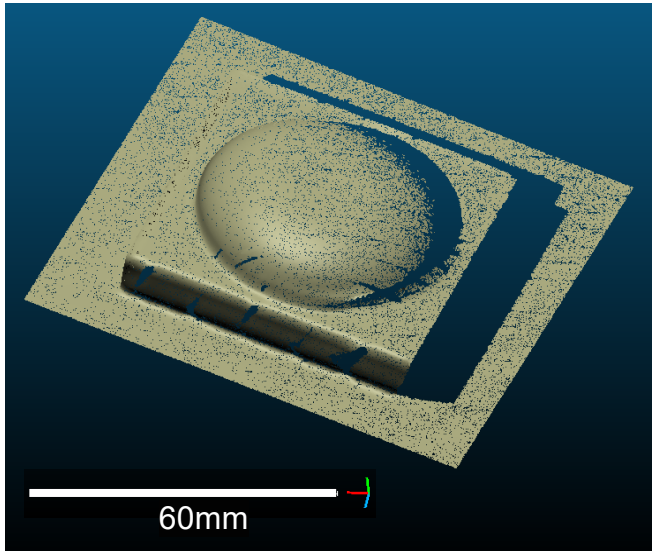
Projector 1

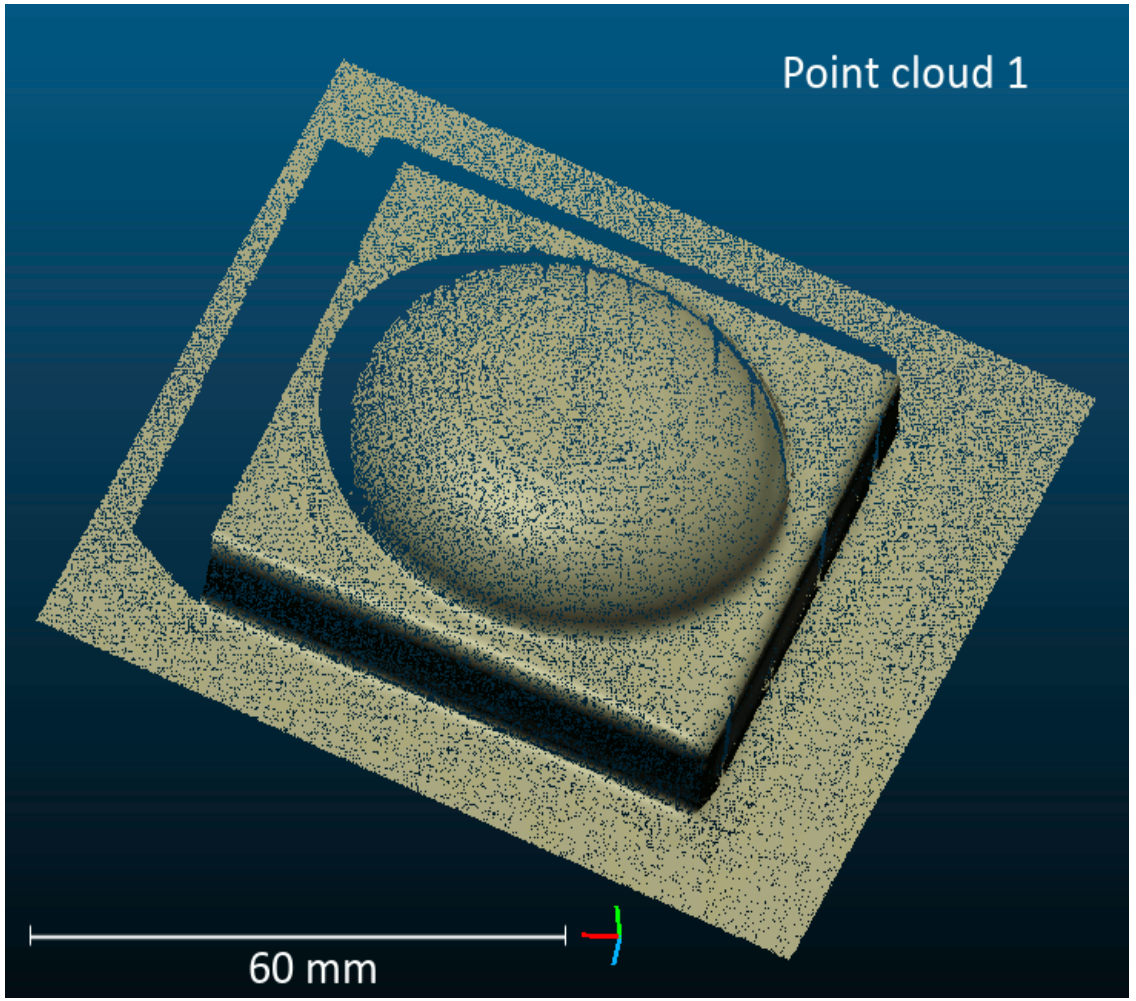




Projector 2







Nylon-12 (60 mm × 60 mm × 20 mm)

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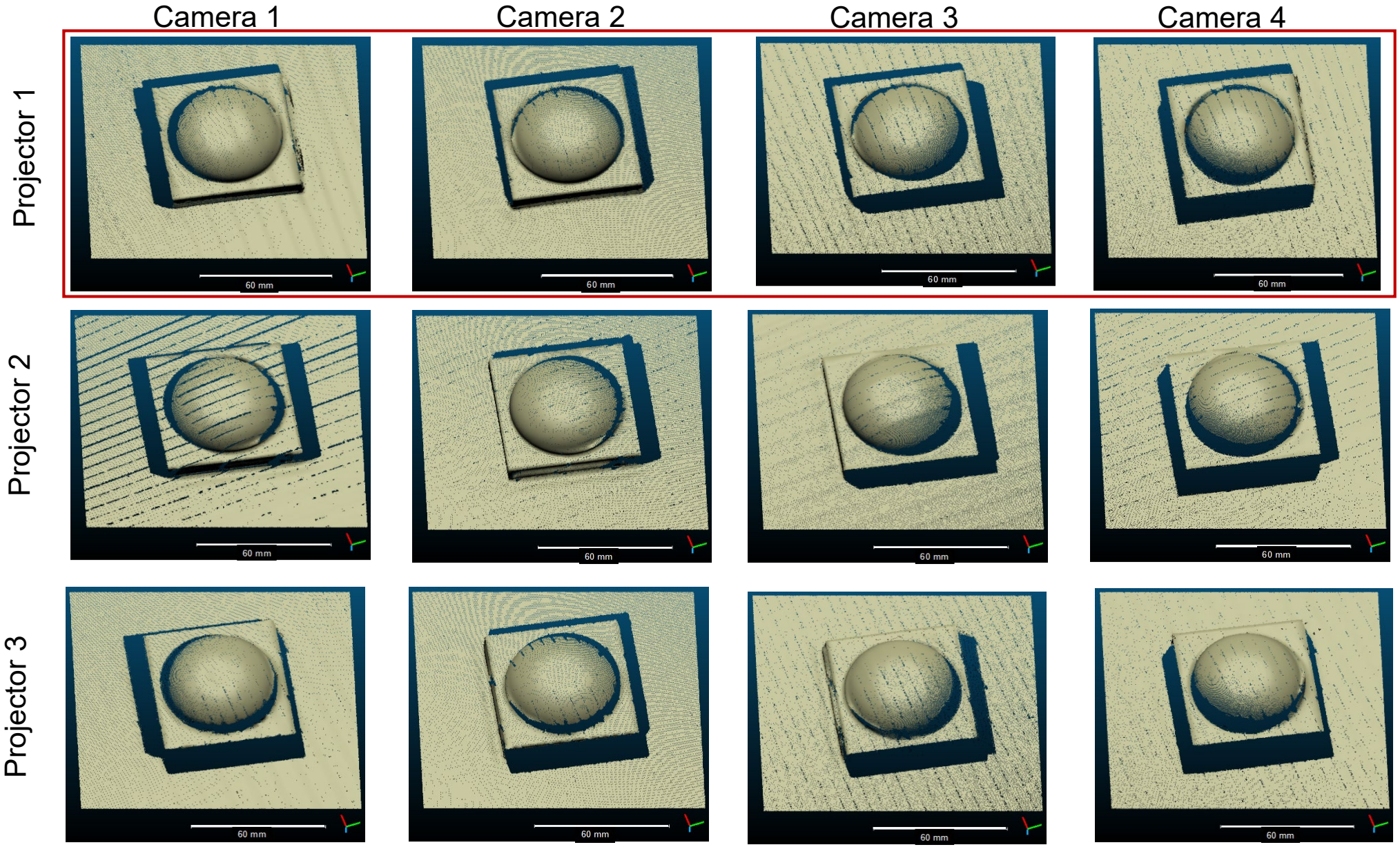
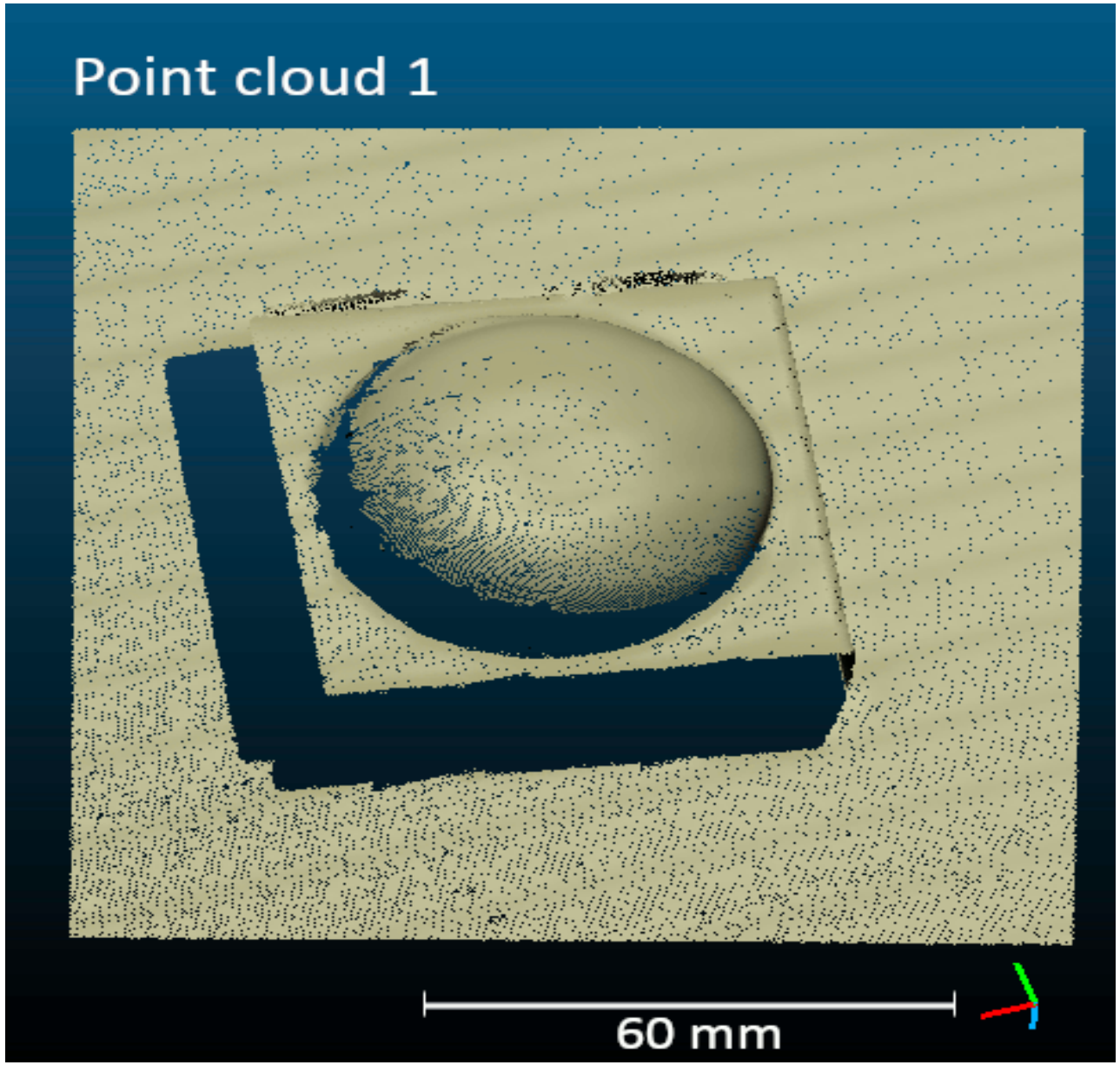
Results with three different projections

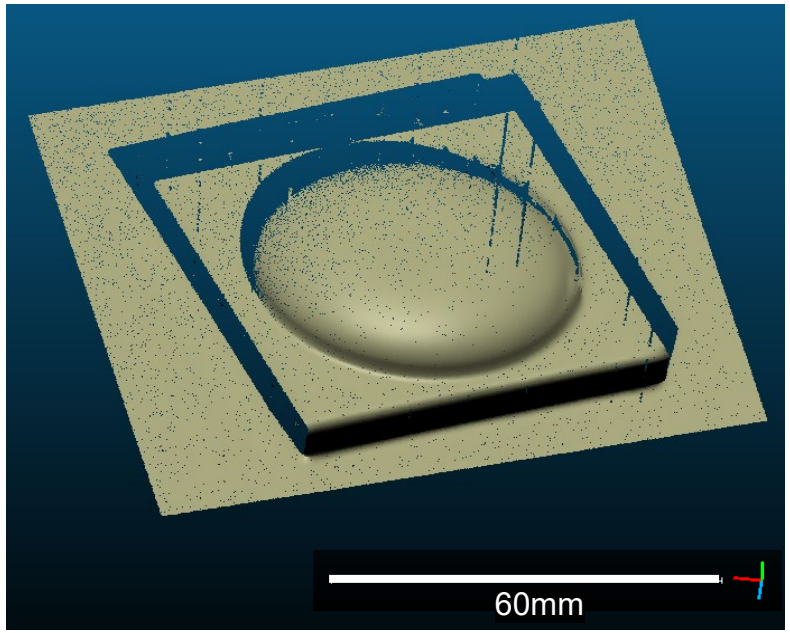


Results with three different projections

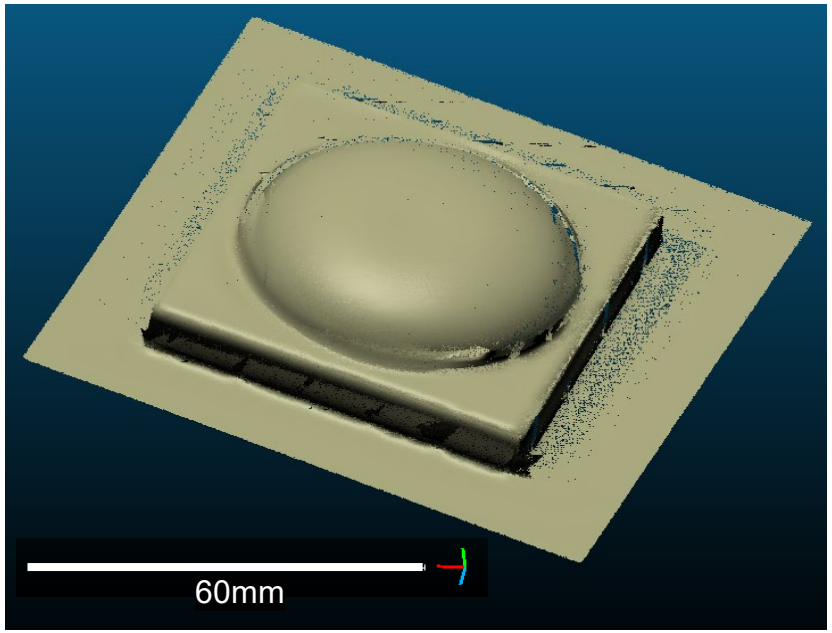


Material: Nylon-12
Sample dimensions:
(60 mm × 60 mm × 20 mm)

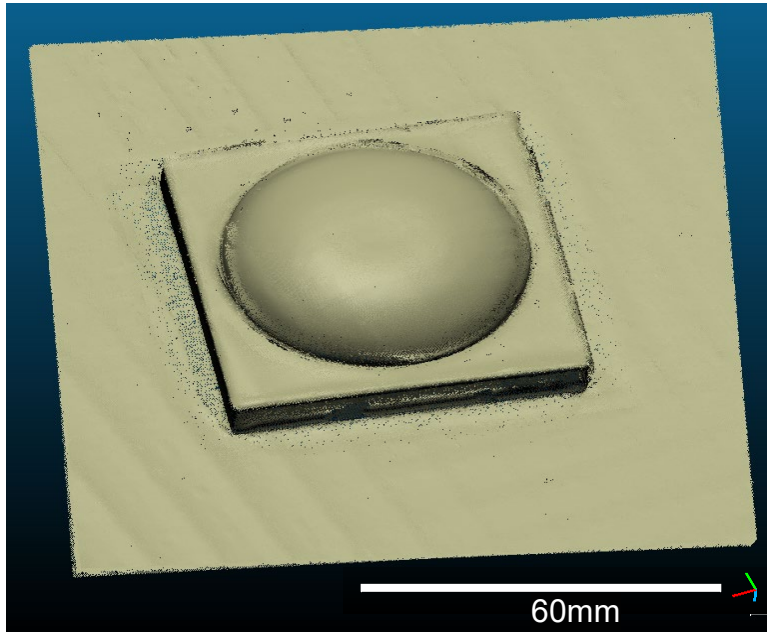
Results comparison - Multiview fringe projection system



One camera-projector



Two cameras-projectors



Four cameras-three projectors

Conclusions and future work

Conclusions

- Fringe projection technique - advantages
- Challenges of a single camera - projector based systems
- Multiview fringe projection system
- Geometric characterisation of multi-view fringe projection system
- 3D shape measurement of an AM part with the multi-view fringe projection system

Future work

- Optimisation of multi-view fringe projection system
- Phase error measurements
- Incorporating a priori information (CAD data)
- Pose estimation with machine learning (Joe Eastwood's work)
- Uncertainty evaluation (George Gayton's work)

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MANUFACTURING METROLOGY TEAM

Manufacturing Metrology Team at Nottingham

Horizon 2020

EPSRC Centre for Doctoral Training in Ultra Precision Engineering

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