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Fringe projection for shape measurement of manufactured parts

Y. R. Huddart and A. J. Moore

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Acknowledgements

- EngD project through Renishaw Plc and Heriot-Watt University

- Supported by JWI-IMRC project (researcher Jesus Valera)

- Other contributors: Nick Weston, Tim Featherstone, Ian McLean, David McKendrick (all Renishaw Plc)

- 4 patents pending, 1 paper submitted to Optics Express, 2nd paper in preparation

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Coordinate measuring machine (CMM)

- Contact shape measurement
- Highly accurate (~1μm)
- Fast for known shapes
  - e.g. plane, sphere
- Slow for general objects


Zeiss F25M


Letiz PMM-G

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Renishaw REVO™ head and scanning probe

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Project aims

- Investigate non-contact measurement techniques
- Measure of complex objects with free-form surfaces and discontinuous features
- Measurement should be fast, accurate (~50μm), automatic with minimal user input
- Device to attach to articulating head on a CMM
  - Light, compact, robust (no moving parts)

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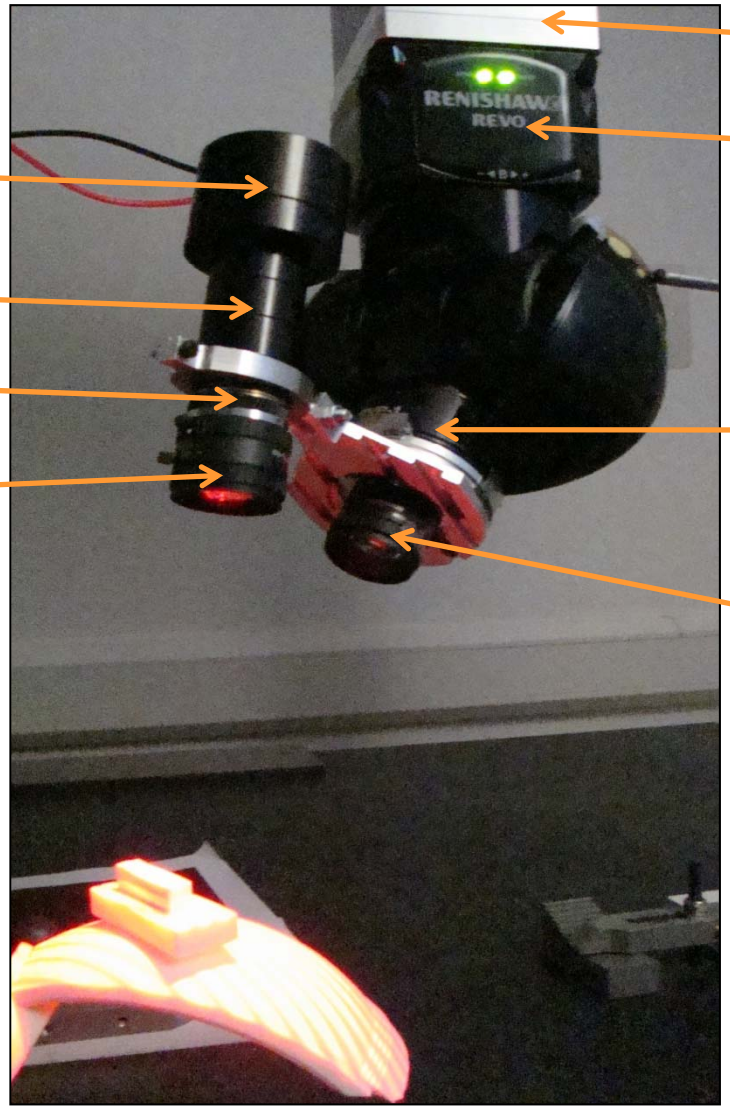
CMM-mounted fringe projection probe



Quill of three-axis CMM

Two-axis articulating head

LED

Condensing optics

Sinusoidal amplitude mask

Projection lens

Imaging sensor

Imaging lens

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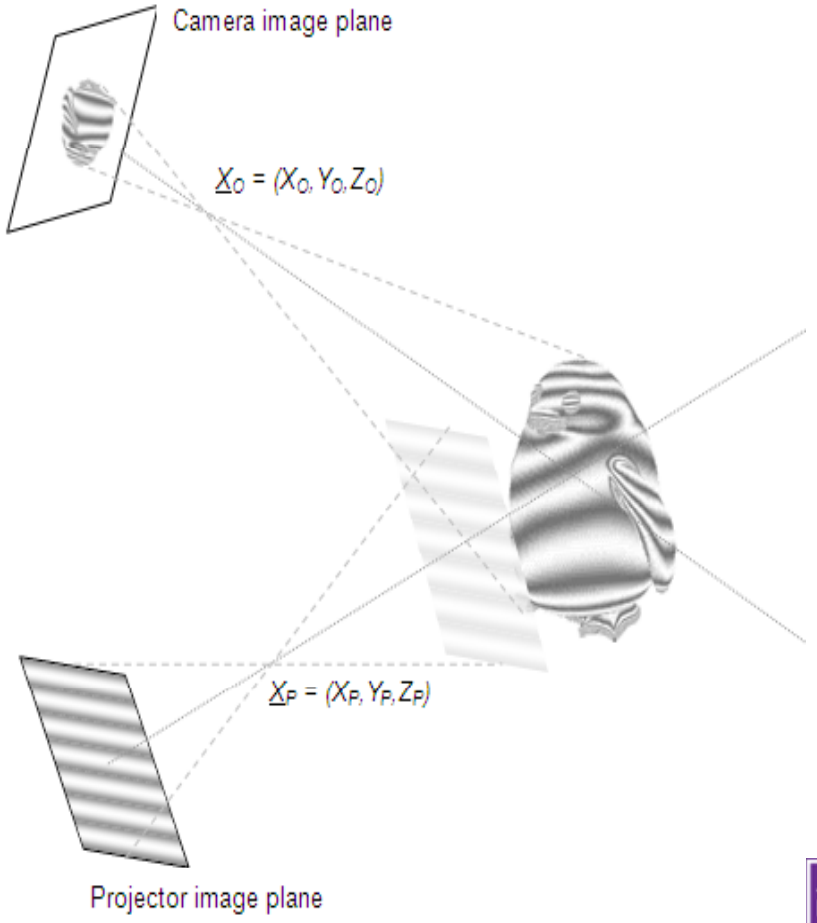
Fringe projection

- Sinusoidal fringe pattern projected onto object, imaged with a camera
- Height encoded in phase of imaged pattern
- Full-field technique (fast)
- Accurate enough
- Difficulties with light, compact, robust, and automatic



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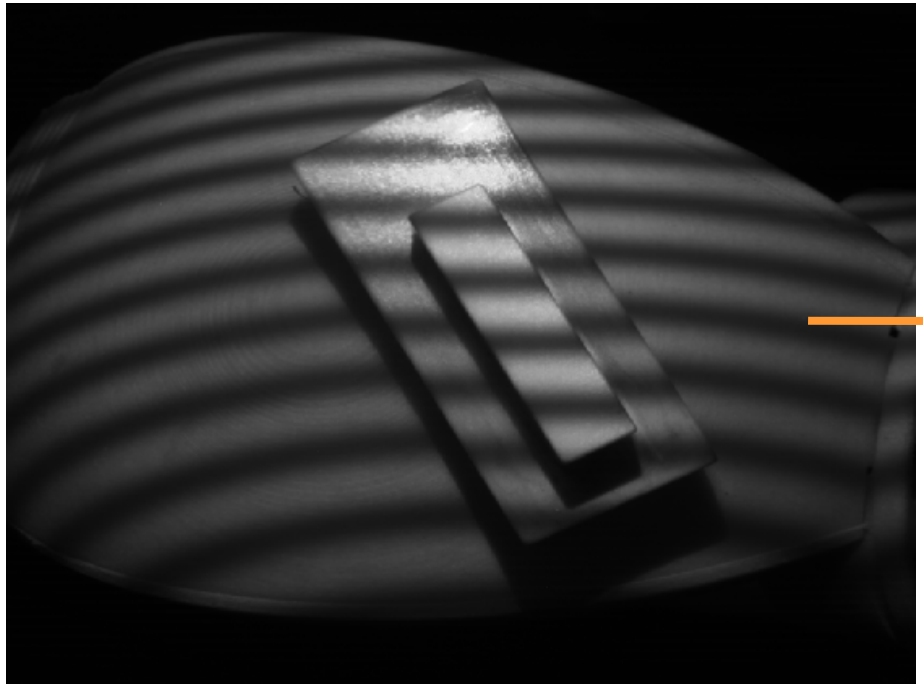
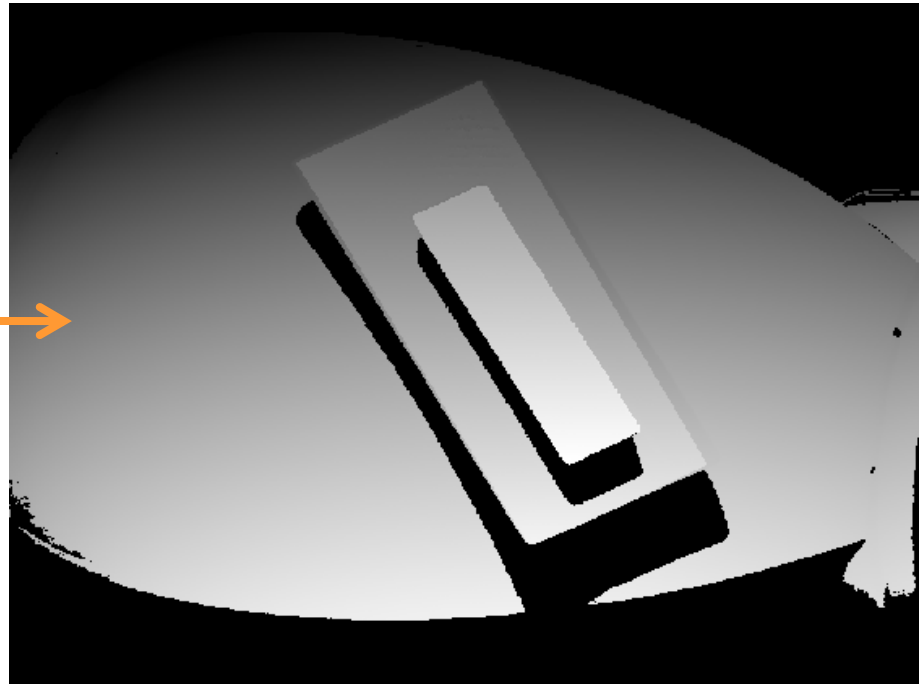
Fringe analysis

Recorded intensity

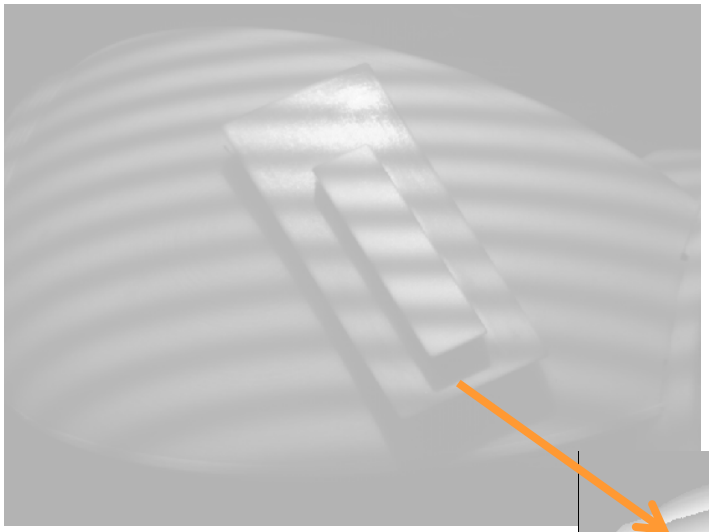
Height



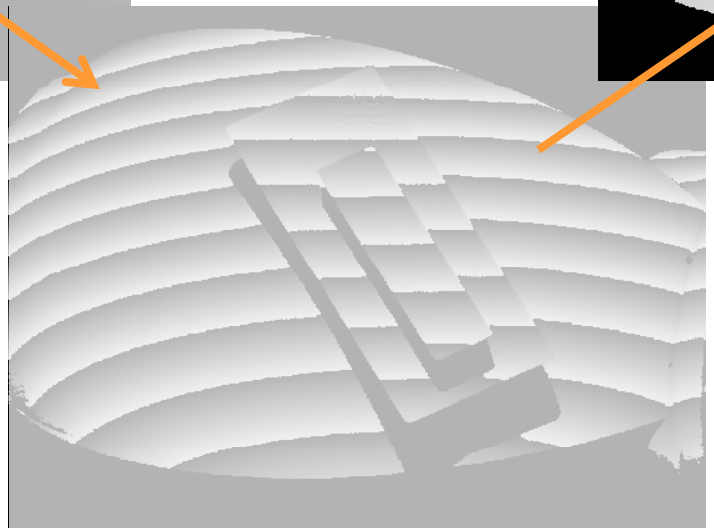


Fringe analysis

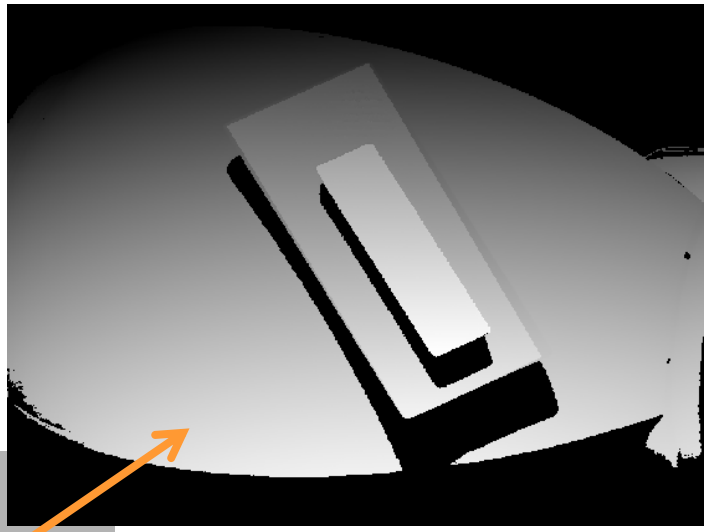
Multiple phase-stepped fringe images



Wrapped phase map



Unwrapped absolute phase/height map



Phase stepping

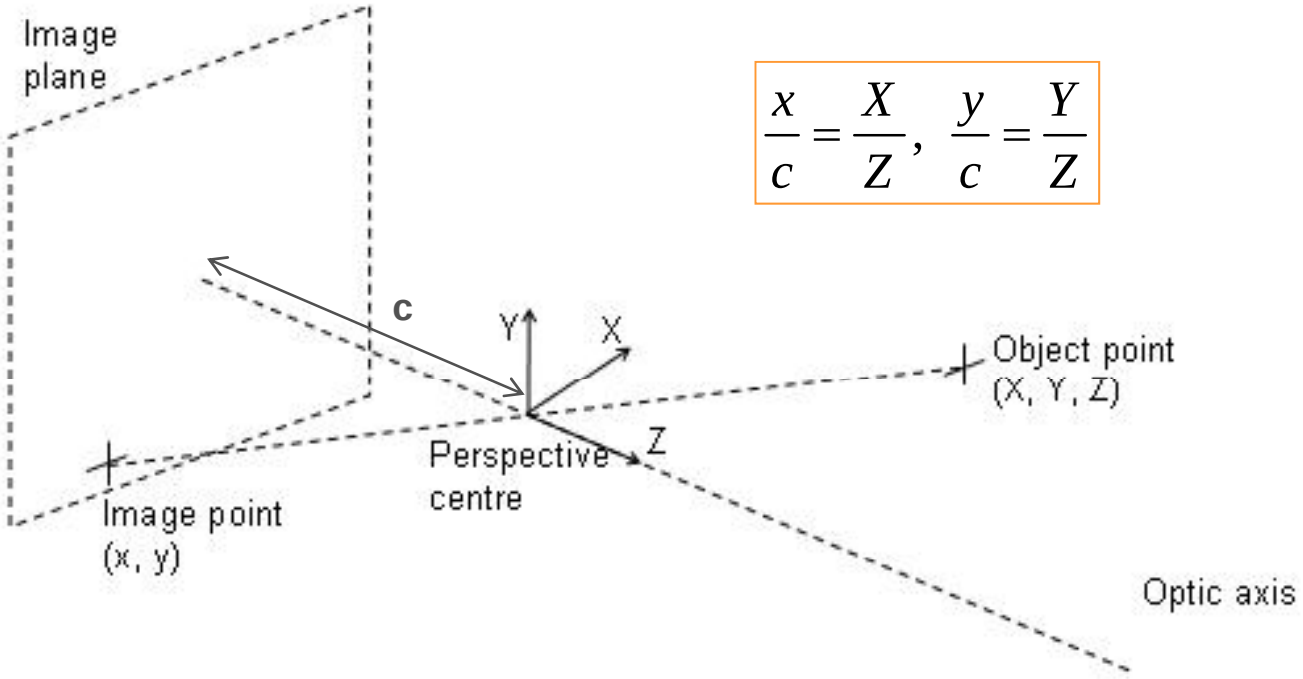
- Traditional technique

Implementation	Disadvantage(s)
Programmable projector	Low resolution and brightness Heavy Lack of thermal stability
Internal moving slide or light source	Lack of robustness

- Solution

Implementation	Disadvantage(s)
Move projector using the CMM (small moves, up to around 1 mm)	Camera moves as well so images require compensation

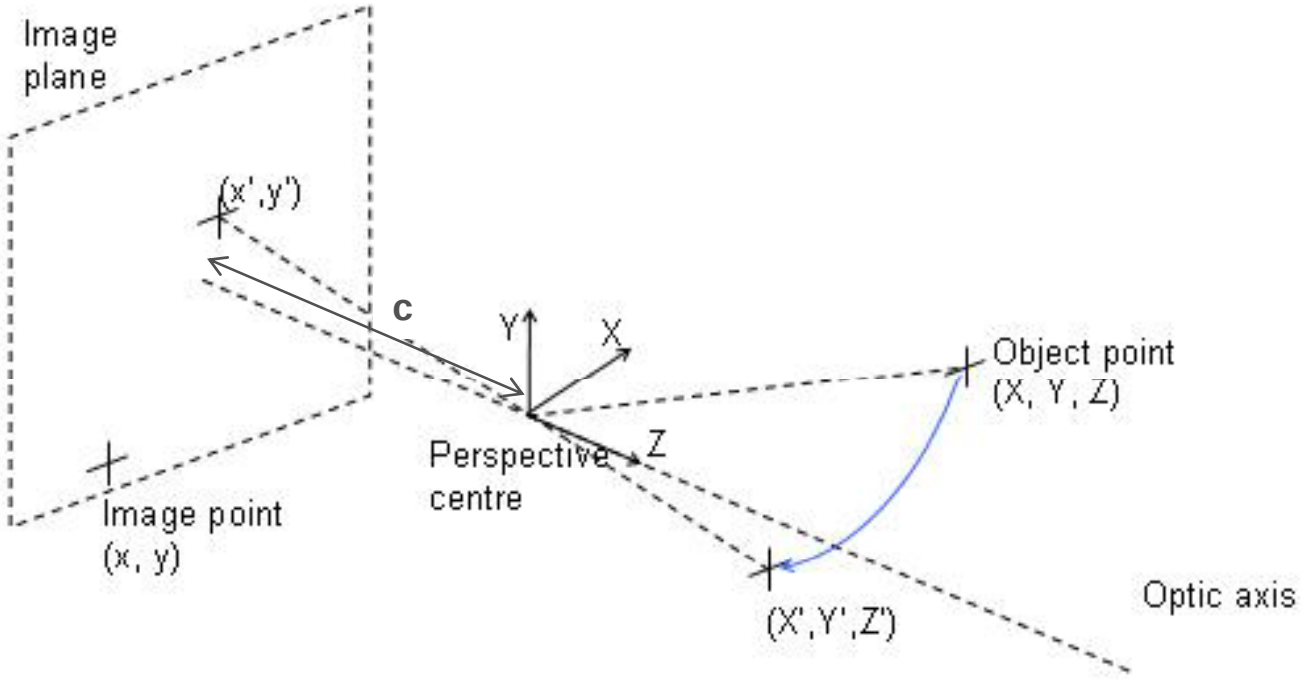
Phase stepping – the pinhole camera model



$$\frac{x}{c} = \frac{X}{Z}, \quad \frac{y}{c} = \frac{Y}{Z}$$

- If probe is translated, compensation depends on unknown distance to the object

Phase stepping by rotation about the camera pinhole



- If probe is rotated about the perspective centre, images can be compensated independently of the distance to the object
- Phase shift created by this motion varies throughout the measurement volume

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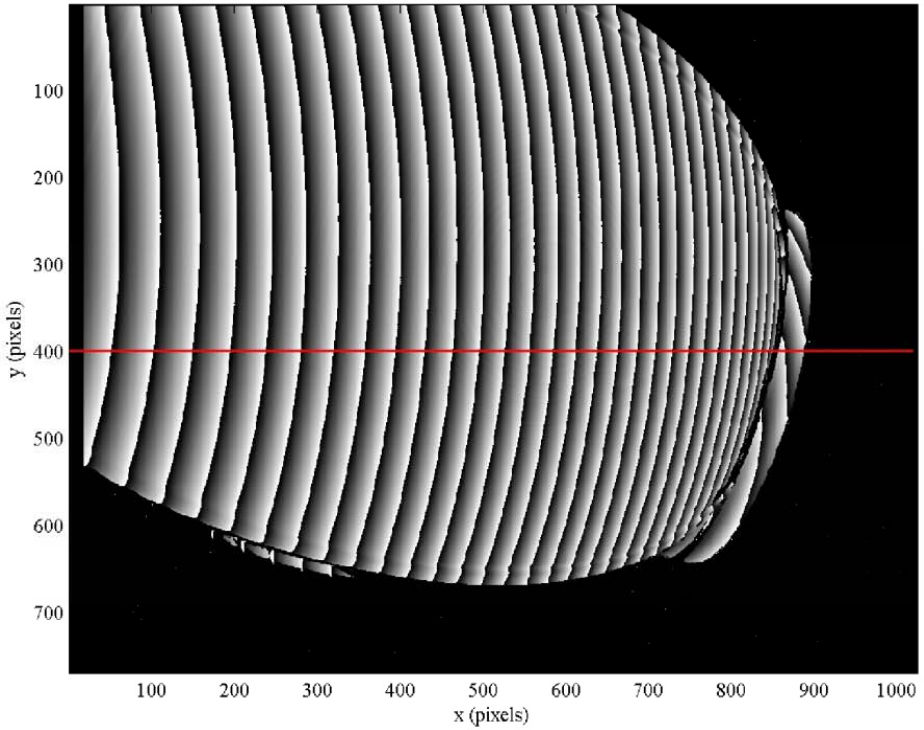
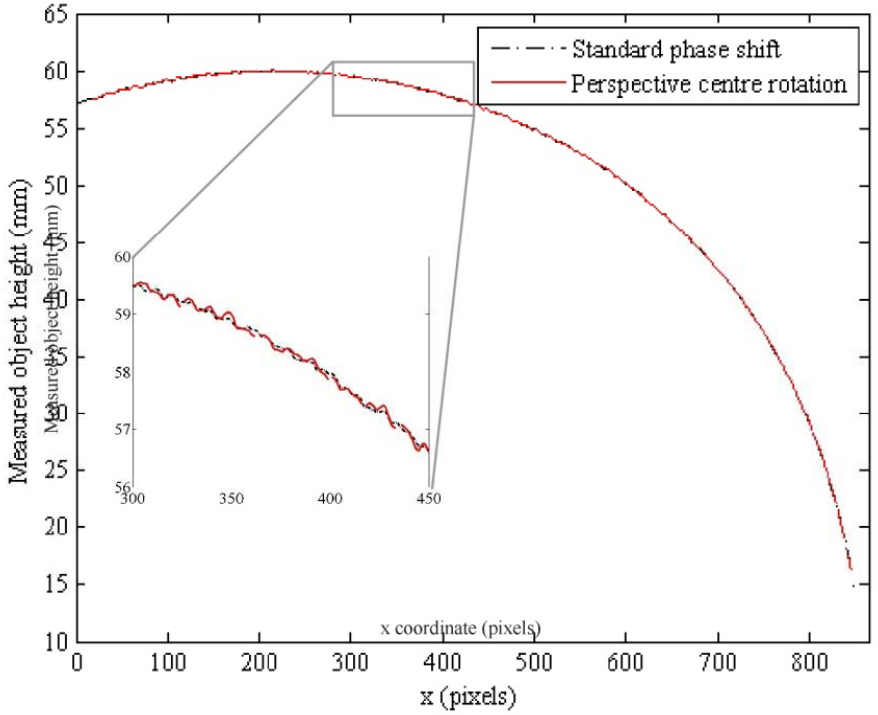
Phase stepping by rotation about the camera pinhole



Wrapped phase map created using new technique



Comparison to traditional phase stepping

- Comparison of traditional temporal phase step and new result show rms difference of 60μm, or 1.5% of a fringe period
- Difference in results mainly due to different phase calculation algorithms required for phase calculation

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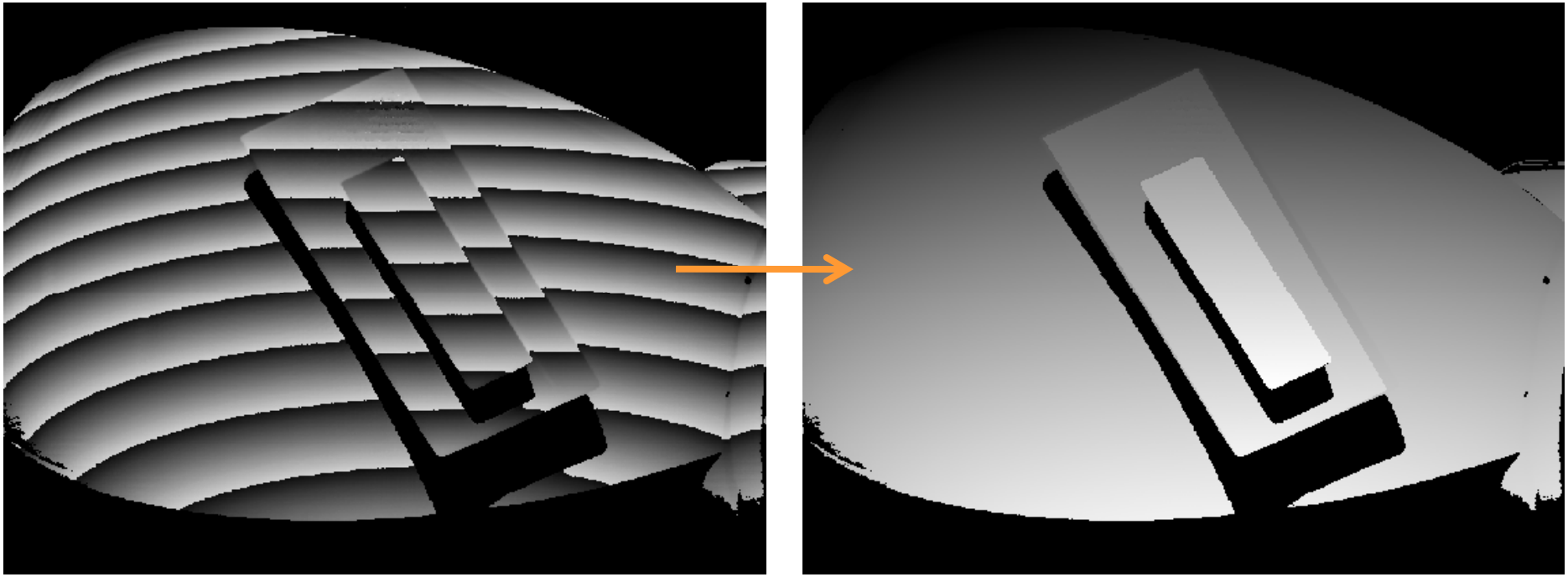
Phase unwrapping

Wrapped phase map

Unwrapped absolute phase map



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Phase unwrapping

- Traditional techniques

Implementation	Disadvantage(s)
Multiple pattern projection (e.g. different fringe frequencies) using programmable projector	Low resolution and brightness Heavy Lack of thermal stability
Multiple pattern projection using interchangeable slides	Moving internal parts – lack of robustness
Zero order fringe marking (spot or line projection)	Difficult to automate

- Solution

Implementation	Disadvantage(s)
Move fringe projection probe to different perspectives using the CMM (large moves, up to 100 mm)	Requires segmentation of images into isolated surfaces

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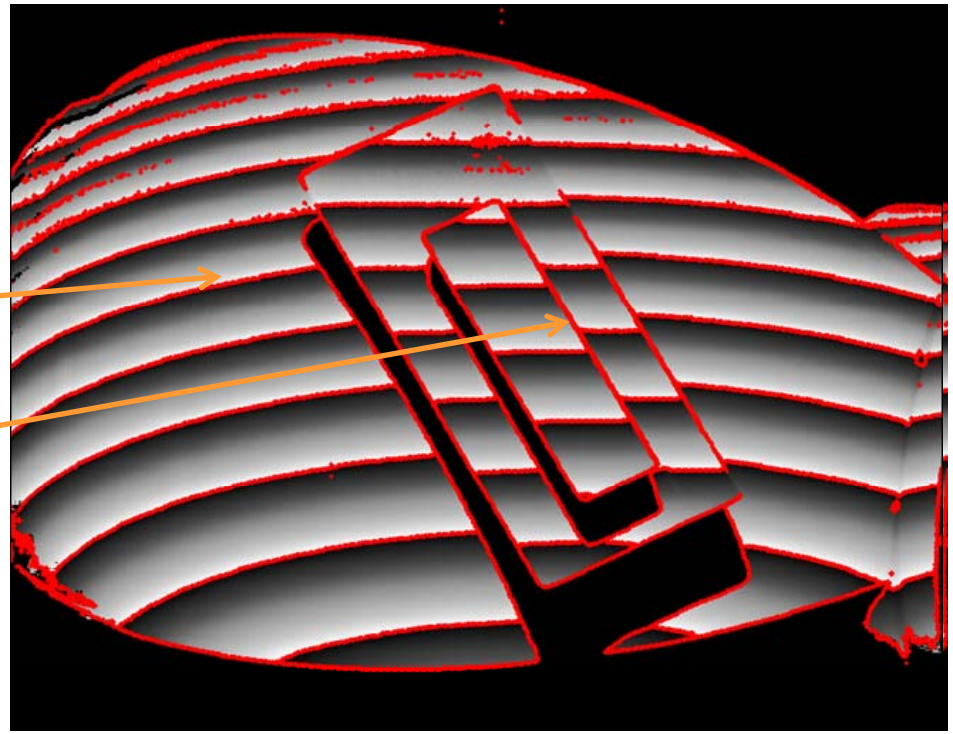
Phase unwrapping – image segmentation

Image segmentation

- Process fringe images in different orders
  - 2π wrapping discontinuities from phase calculation appear in different places
  - Real object edges stay in the same place



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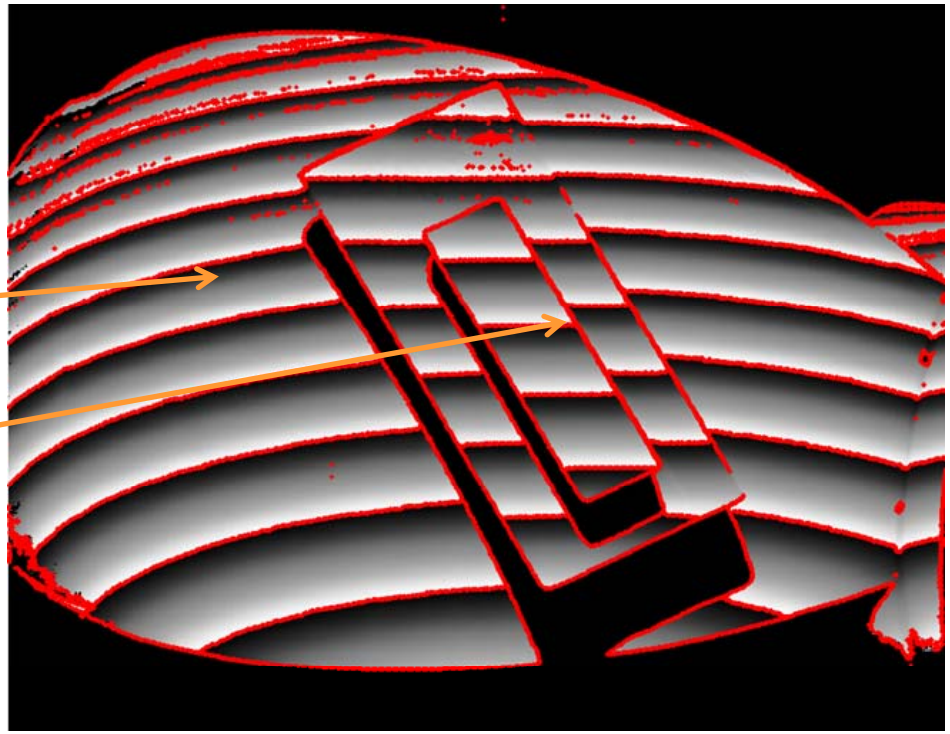

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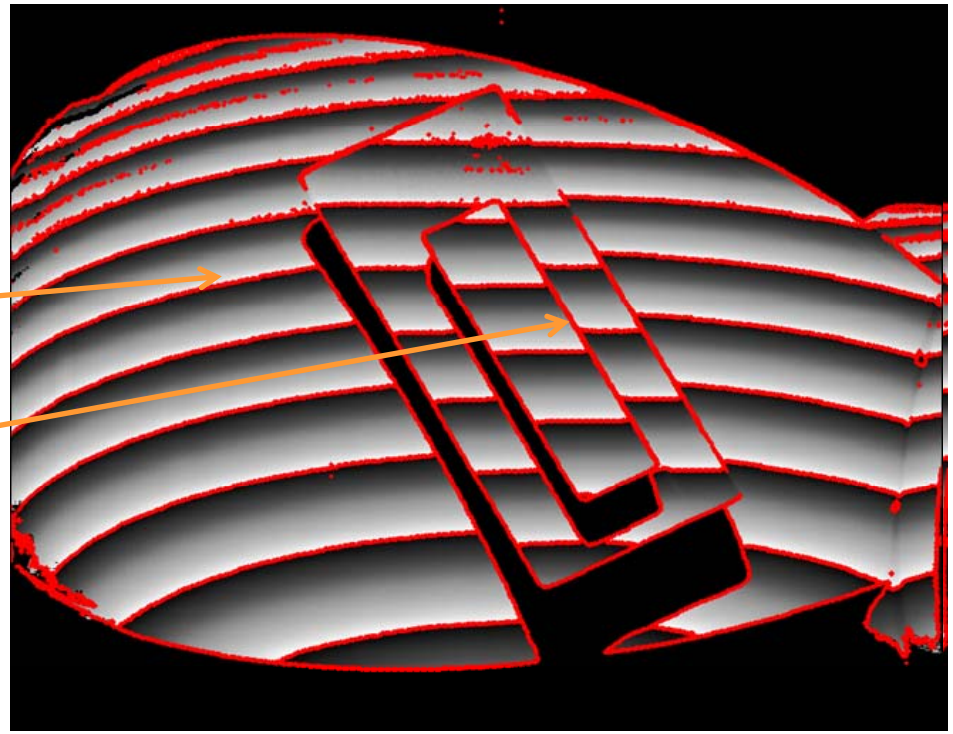

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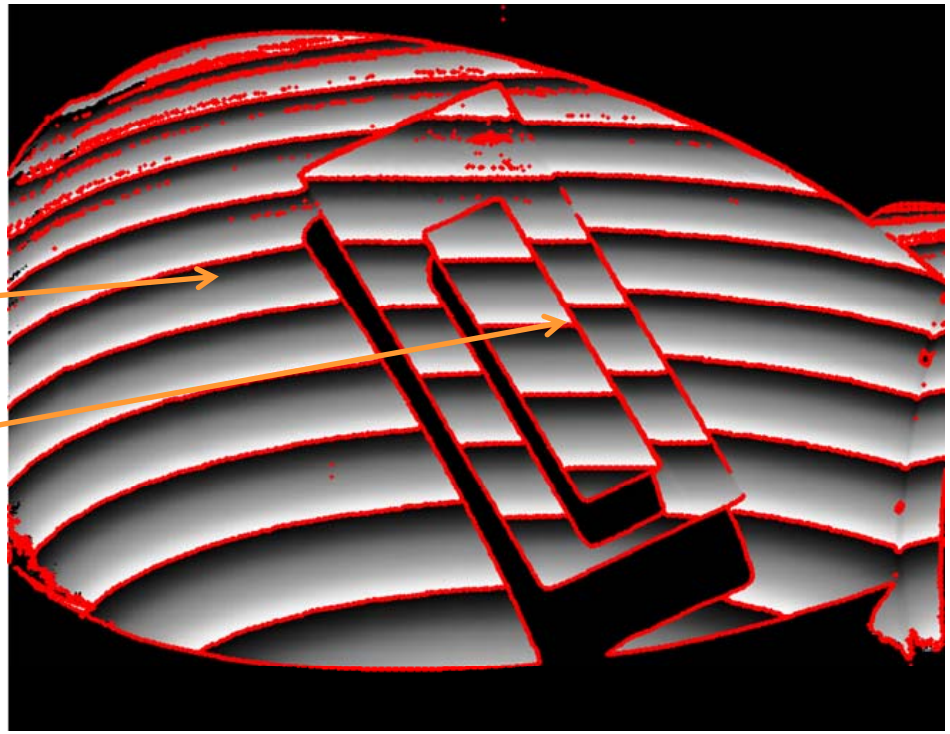

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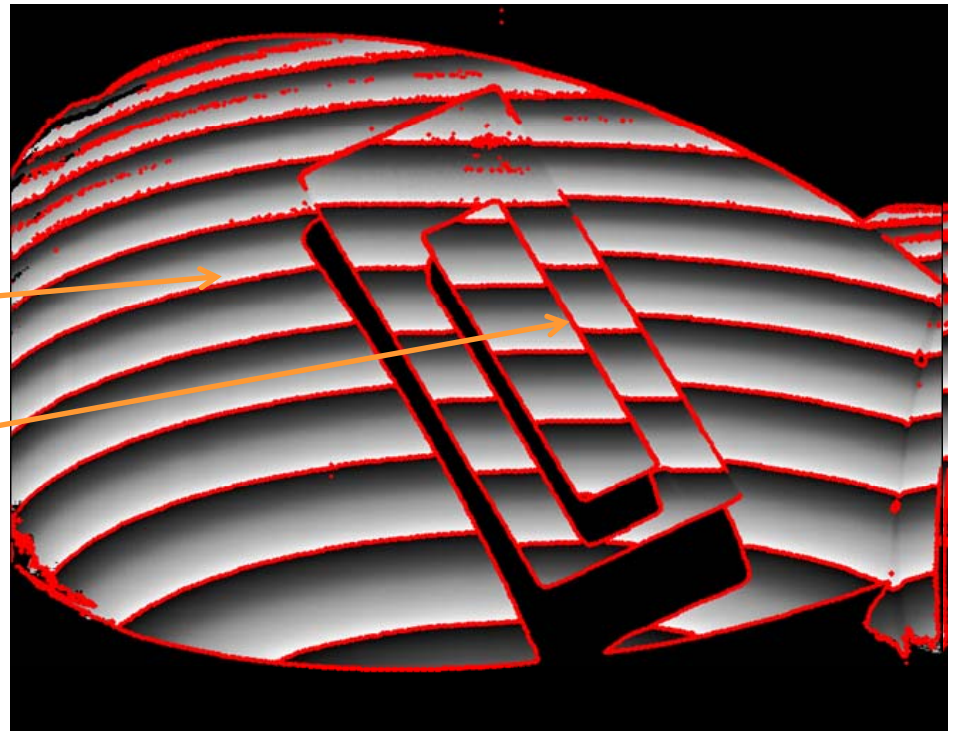

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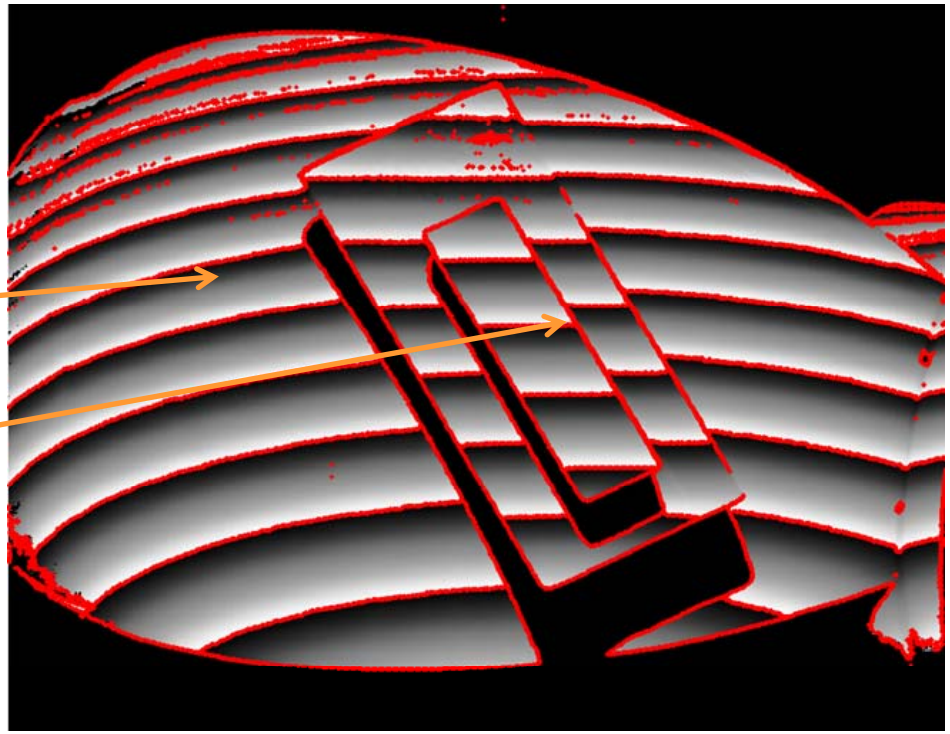

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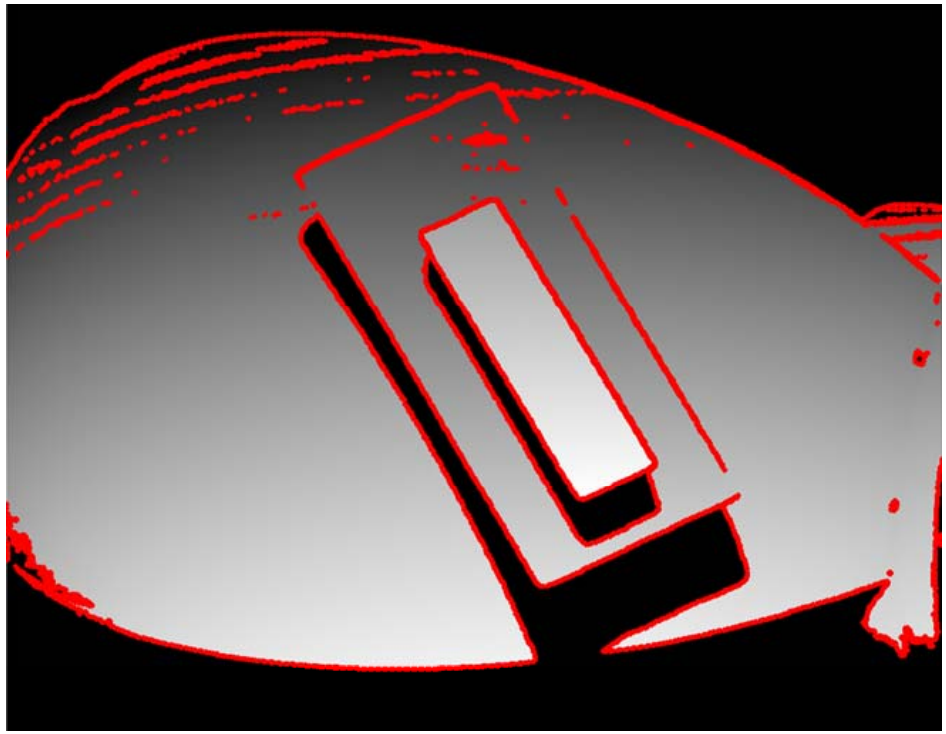
Phase unwrapping – image segmentation

Image segmentation

- Discard 2π wrapping discontinuities
- Unwrap phase on areas bounded by object edges
- Edge threshold is related to phase
  - Depends on the fringe period, not ambient lighting
  - Easier to automate than traditional image processing



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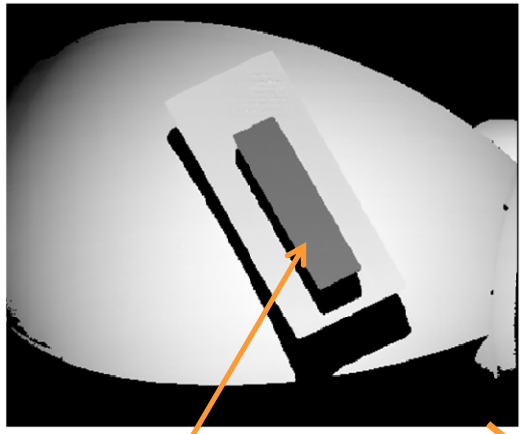
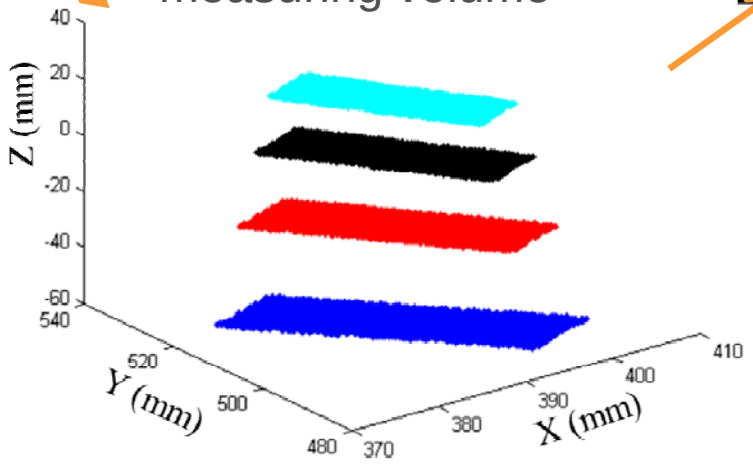
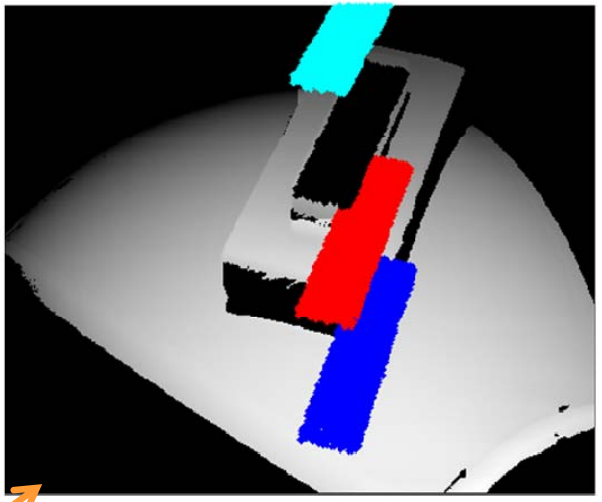
Phase unwrapping – absolute phase calculation



Area of interest in first perspective

Construct possible 3D surfaces corresponding to area of interest. Number of surfaces limited by probe measuring volume





Reproject possible surfaces onto second perspective and compare expected phase for each surface with recorded phase

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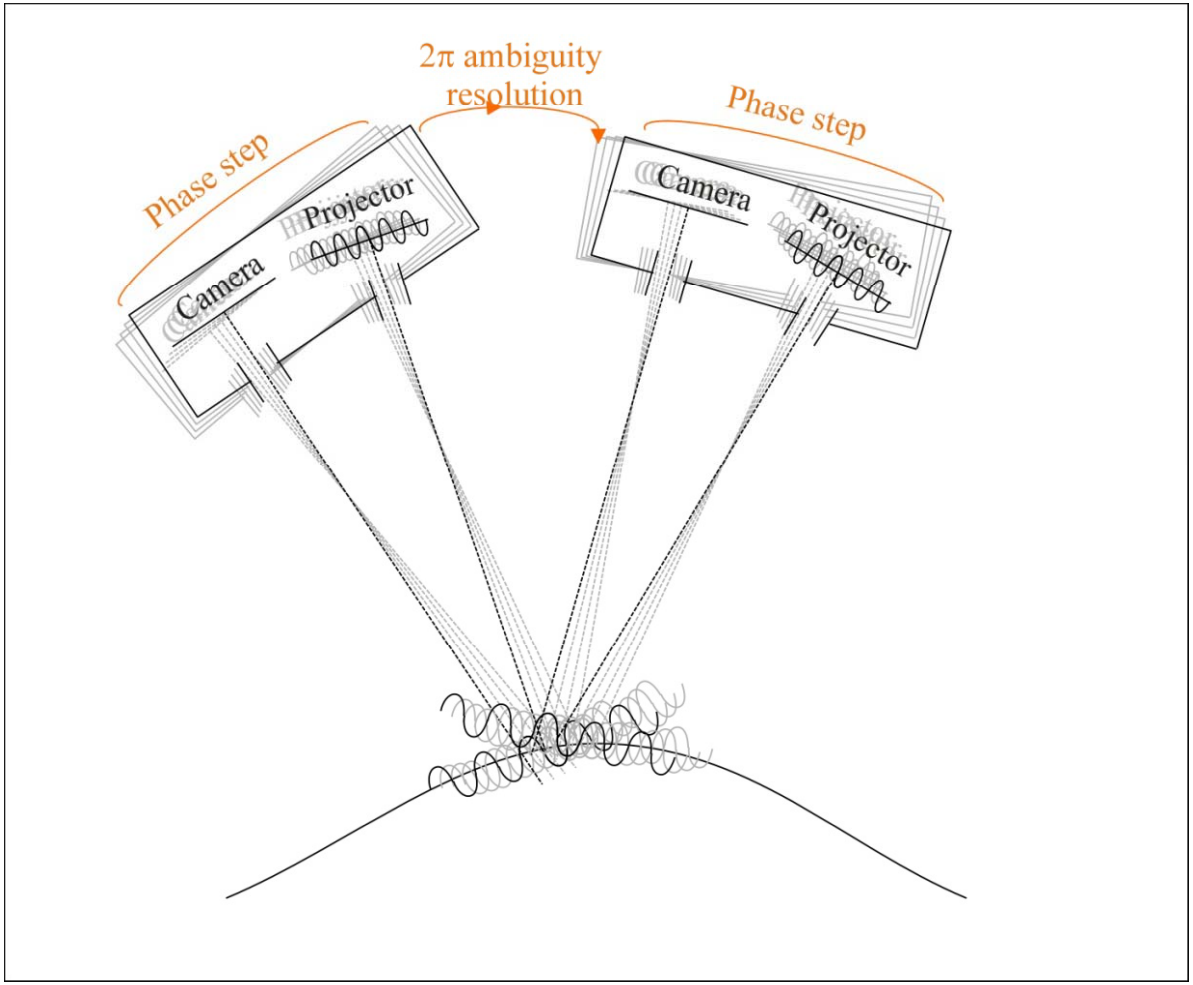
CMM-mounted fringe projection probe

- Small moves to create phase steps
- Large moves to find absolute phase



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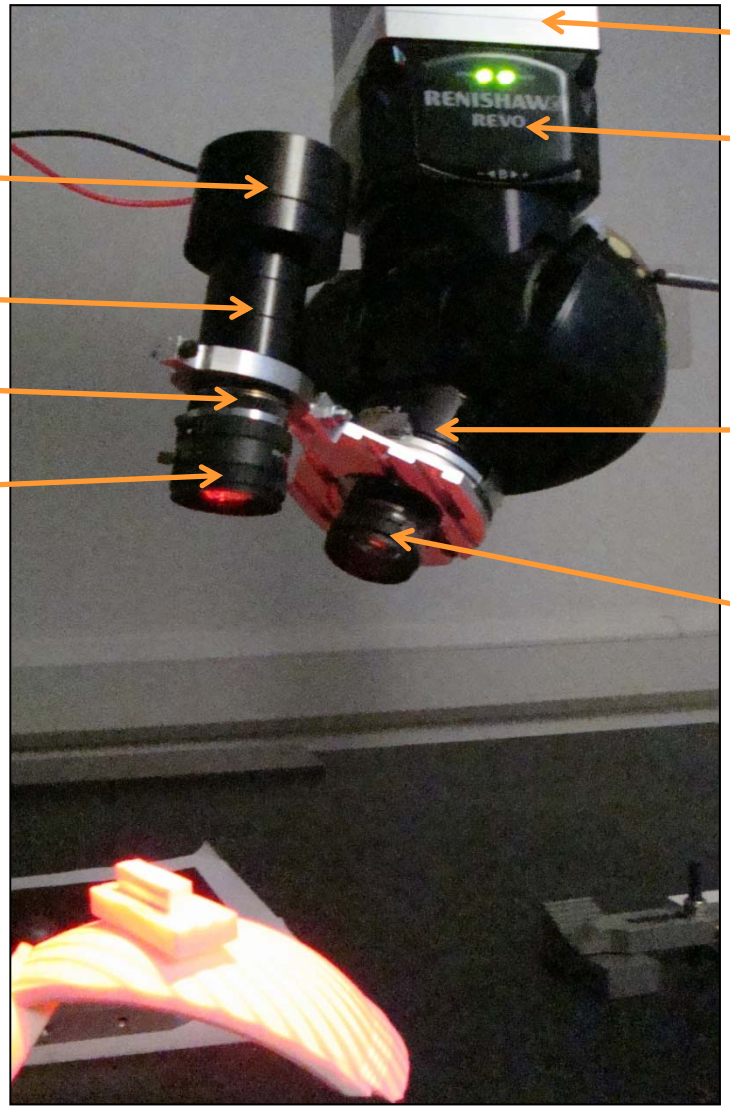

Quill of three-axis CMM

Two-axis articulating head

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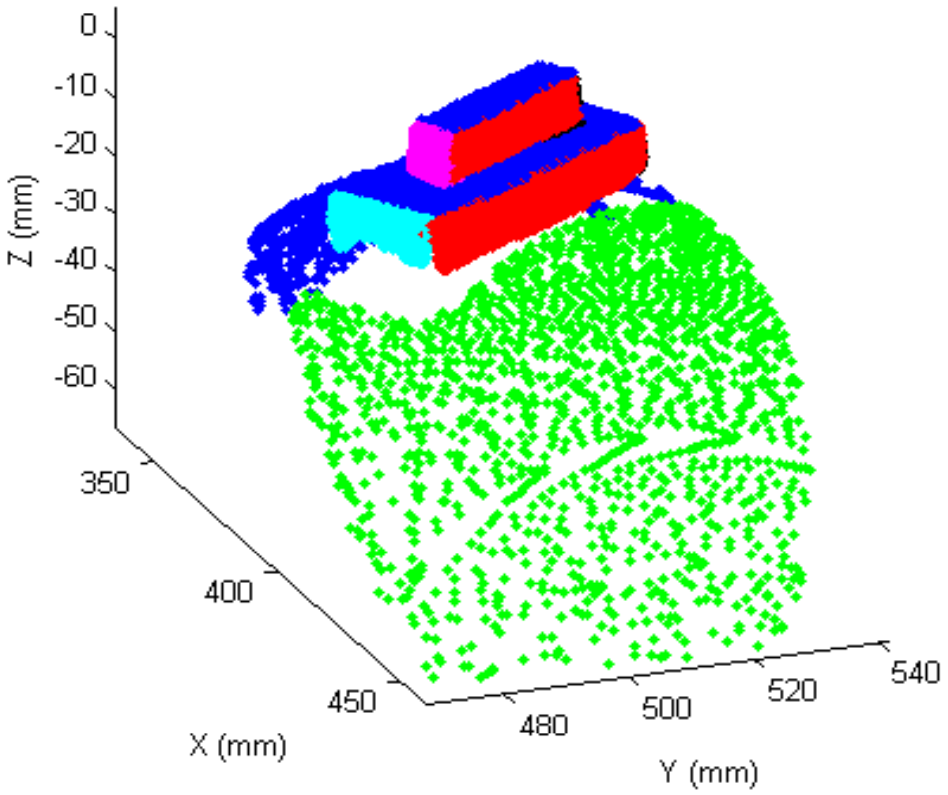
Results

- Dense 3D point cloud describing the surface
- ~1M points over 50mm square from 15 fringe images
  - 5 phase stepped images
  - 3 perspectives
- Data collection <10s per surface patch.
- Data processing <20s, with optimisation expected to be real time
- Whole object built up from different viewpoints



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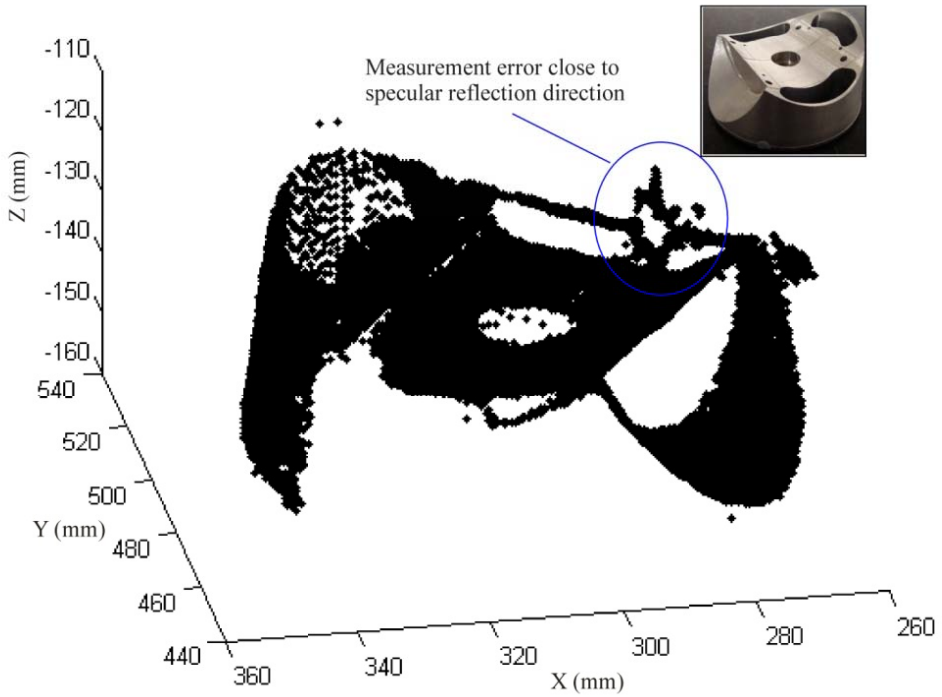
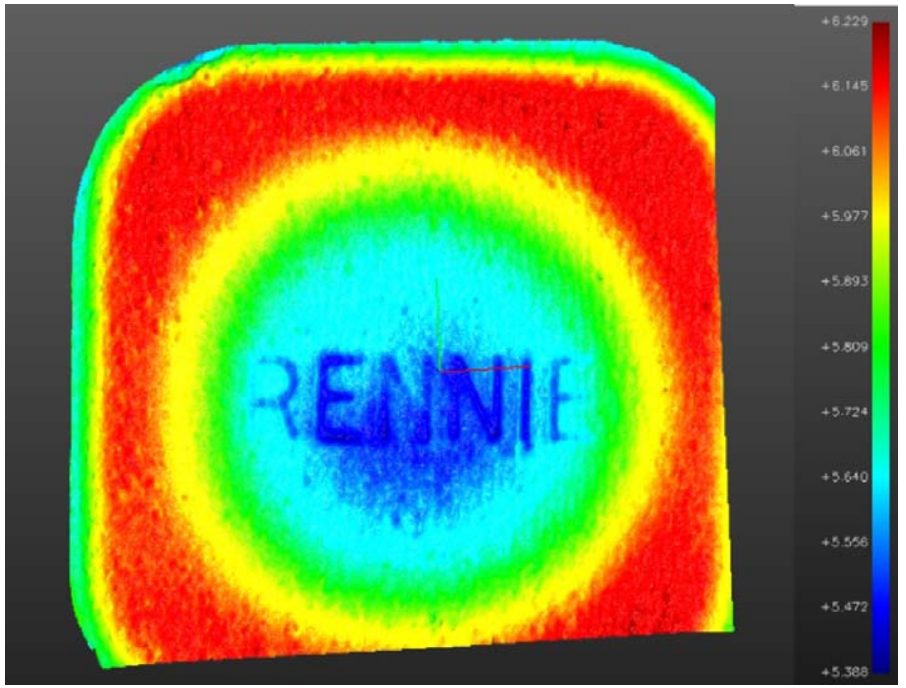
Results





- Accuracy to 1.5% of a fringe period (e.g. 15μm for 1mm fringes)
- Main error source is speckle noise
  - Accuracy dependent on surface properties
  - Averaging possible using multiple perspectives

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