Enhanced Interferometry with a Programmable Spatial Light Modulator

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This presentation is approved for General Public release
Presentation Summary

- Summarize the problem & innovation
- Describe the hardware and software
  - Digital Interferometry with preconditioned wavefronts
  - Hybrid Hartmann/Digital Interferometry
- Typical measurements
- Potential Applications
- Future Work
The Problem Being Addressed

Modern optical components such as aspheres are difficult to inspect. Interferometry, the usual solution, lacks the required dynamic range. Too many fringes are produced. Adapting interferometry for null measurements currently necessitates special optical components for each inspected component.
Innovation/Solution

- Incorporate a programmable SLM into an optical inspection instrument enabling:
  - Combined interferometry and Hartmann Sensing
  - Virtually unlimited dynamic range
  - Extended dynamic range of interferometry by preconditioning waves
  - Null testing on almost any component using off the shelf optics.

- Incorporate Instantaneous Digital Interferometry Technology
Challenges Faced and Solved

- Incorporating the SLM into a PhaseCam
- Integrating Hartmann and Digital Interferometry
- Calibrating the SLM
  - Phase-only mode by controlling polarization
  - Corrected gamma curve, i.e. linear phase shift versus grayscale value
- Impressing the required phase function on the SLM
- Identifying and minimizing errors and noise
Lenslet diameters, \( d \), define spatial resolution over the wavefront being measured.

\[ \delta \propto f, \text{ which should be less than } d \text{ to prevent confusion} \]

\[ \delta = f \tan \theta \]

\'Measuring aberration of the eye with wavefront technology\'
Giuseppe Colicchi, et al
Zur Veröffentlichung eingereicht bei "Physics Education", 2006
Key Components: SLM, Pixelcam*

SLM for a compensator

- Programmable holographic optical element
- Produce wavefronts of any shape and can simulate freeform optical surfaces
- Holoeye SLM
  - SLM can produce a phase up to $2\pi$ at 632.8nm
  - Assign 0 to 255 grayscale values to 0 to $2\pi$ (or $1\lambda$)
  - Can generate higher phases by wrapping phase
  - Can provide more than 150 wave tilt
  - Pixel size ~ 19 microns.
    - 19.5 x 14.6mm size (1024 x 768 pixels)

Pixelated Phasecam for a detector

- Spatial phase shifting interferometer
- Single shot, insensitive to vibration

\[ I(x,y) = \frac{1}{2} \left[ I_r + I_z + 2\sqrt{I_r I_z} \cos(\Delta\Phi(x,y) + 2\alpha_p) \right] \]

*Produced and Trademark by 4D Technologies, Inc, Tucson, AZ [http://www.4dtechnology.com](http://www.4dtechnology.com)

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Hybrid Hartmann & Digital Interferometer

Optics Under Inspection

SLM preconditions the test wavefront

BS

polarizer $\lambda/2$

PBS

$\lambda/4$

$\lambda/2$

RCP

LCP

Pixelated Cam

Laser

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Using a SLM as a Scanning Shack-Hartmann Component

- SLM preconditions the test wavefront
- SLM selects a pencil of light from the wavefront and directs it to the test object and focuses it on the CCD
- Any deviations on CCD will characterize the quality of the test object.
Scanning Shack-Hartmann System

Control Screen

- Control screen is a map of a scanned aperture (or pencils light) of the SLM.

Data Screen

- No Overlap of Focused Spot
- Programmable Aperture Size

Diagram:

- Expanded Laser Beam
- Polarizer
- SLM
- Analyzer
- Test Object
- Lens
- CCD Sensor
Scanning Shack-Hartmann System

‘Pencils’ of light are deflected by the test object’s slope of wavefront as they scan the object.

SLM corrects Aberrations

Expanded Laser Beam

Polarizer

Analyzer

Test Object

SLM

Lens

CCD Sensor
Data screen maps, in time, the sequence of angular deviations caused by the object.

Dynamic range is limited only by the CCD size.
Constraints in conventional Hartmann Testing that can be obviated with this concept

- Sensitivity requires a longer focal length which can cause focused image overlap of adjacent light pencils.
  > SLM enables scanning in time, NO OVERLAP

- If the wave is aberrated, the focused spot will not be round, so its centroid is more difficult to locate, further reducing accuracy.
  > SLM enables preconditioning/aberration correction

- Spatial resolution is limited to the diameter of the lenses in the array.
  > Limited to fractional pixel size of SLM
Mandrel Used for Demonstration

Photo of the Mandrel

Geometry of the Mandrel

- Top diameter: 8.4”
- Bottom diameter: 8.2”
- Mandrel provided by NASA GSFC, 6-inches tall, top and bottom diameters are different, cone shape.

Mandrel Used for Demonstration

Mandrel provided by NASA GSFC, 6-inches tall, top and bottom diameters are different, cone shape.
System Design (Top view)

- **SLM**: Spatial light modulator
- **BS**: Beam splitter
- **polarizer**: Optical element polarizing light
- **PBS**: Polarization beam splitter
- **λ/4**: Quarter-wave plate
- **λ/2**: Half-wave plate
- **Cylinder lens**:Lens that produces cylindrical focusing
- **Object beam**: Beam generated by the system
- **Reference beam**: Beam for phase reference
- **Spatial filter, λ/4**: Element that filters light with a specific wavelength
- **Mandrel**: Object being imaged
- **Top/Bottom radius: 4.2/4.1 inch**: Dimensions of the mandrel
- **HeNe Laser, 10mW**: Laser source with a power of 10 milliwatts
- **Electronic s for SLM**: Equipment for controlling the SLM

Additional notes:
- **Pixelated Phasemcam**: Component for phase imaging
- **Jtrolinger@metrolaserinc.com**: Contact email
- **6-7-2010-Monday**: Date of the document
- **Irving, California**: Location of MetroLaser
The Hardware
Simulation Results

Beam size at cylinder lens: \( \approx 1.8 \text{inch} \)

150mm fl cylinder lens

Top view

Side View

Interferogram

Top portion

Middle portion

Bottom portion
Reducing the number of Fringes from a mandrel

Beam size at cylinder lens: \( \sim 1.5 \) inch.
250mm fl cylinder lens used

(Various waveplates and telescopes not shown)
Compensation of one of Mandrel’s wavefronts for a one inch beam

Before Compensation

After Compensation

4.6 waves

0.2 waves
Resolution & Signal to Noise

- Tilt by the flat mirror, ~7 waves

Interferogram

~ 14 fringes

3D view

PV. ± 3.4 λ

Tilt introduced by flat mirror

(Various waveplates and telescopes not shown)
Resolution and Signal to Noise (Cont.)

- Residual wavefronts, less than 0.05 \( \lambda \)

SLM can compensate tilted wavefronts with an accuracy of 1/20th wave, or better.
Determining System Aberrations with a Cat’s Eye

Due to SLM, cylinder lens, optical alignments, etc

Cat’s eye position

Coaxial position

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Cat’s eye wavefronts by ZEMAX based on Experimental results

Experimental measurement  Simulated Fringes  Leftover < 0.1\(\lambda\)

Fitted Zernike Polynomials upto 36 terms, found and put into Zemax

Simulated Cats’ eye wavefronts by ZEMAX
Simulated, No System Aberrations

Wavefronts at cat’s eye position at each height

Wavefronts at coaxial position at each height

Measured Wavefronts at coaxial position at each height

Beam: ~27mm
Net fringe due to a Mandrel

Coaxial position  Cat’s eye position  Simulated Net Fringes  Experimental Net Fringes

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Wavefronts from the Mandrel, II

Simulated Wavefronts of the Mandrel

Experimental Wavefronts
Unique Features & Applications

- Very wide dynamic range
- Applicable to aspheres and non axi-symmetric optics, i.e. freeform optics
- Enables null point testing
- Enables removing system aberrations
Summary and Conclusions

- Demonstrated wide dynamic range digital interferometry/Hartmann for advanced optical components using an SLM to:
  - provide wavefront preconditioning.
  - Hartmann & Interferometry in the same instrument
  - Scanning Hartmann
  - extended dynamic range.
  - Null point testing.
- Hartmann provides information needed to program SLM for wavefront preconditioning
- SLM Calibration procedure to produce Gamma curve.
- Procedure to subtract system aberrations.
- Accuracy of λ/20 with SLM in system.
- Concept extends dynamic range by more than 150λ
Future Work

- **Software Development**
  - Transforming Hartmann data into wavefront preconditioning data.
  - Automating Calibration
  - Interferogram stitching
  - System automation

- **Hardware improvements**
  - Calibration to push system accuracy
  - Incorporating improved SLM’s
  - System packaging
Back up Slides
Including System Aberrations

Side View

Top portion

Middle portion

Bottom portion

Beam: ~27mm

cat’s eye position

coaxial position

Simulated

Measured

coaxial position

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Key Components: SLM, Pixelcam*

**SLM for a compensator**

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- Holoeye SLM
  - SLM can produce a phase up to \(2\pi\) at 632.8nm
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    - Can generate higher phases by wrapping phase
    - Can provide more than 150 wave tilt
  - Pixel size ~ 19 microns.
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**Pixelated Phasecam for a detector**

- Spatial phase shifting interferometer
- Single shot, insensitive to vibration

Phase information of the object, \(\Delta \phi(x,y)\) can be obtained from the 4 intensities on each unit cell.

\[
I(x,y) = \frac{1}{2} \left( I_r + I_s + 2\sqrt{I_rI_s} \cos(\Delta \phi(x,y) + 2\alpha_p) \right)
\]

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INNOVATION
A unique optical inspection system incorporates a dynamic holographic optical element that combines and extends both Hartmann and digital interferometry with preconditioned wavefronts. The resulting system exhibits a wide dynamic range and will be especially useful for inspecting aspherical and free form optics.

ACCOMPLISHMENTS
- Demonstrated wide dynamic range optical inspection system
  - Wavefront preconditioning via spatial light modulator.
  - Hartmann & Interferometry in the same instrument
  - Scanning Hartmann
  - Extended dynamic range >150\(\lambda\).
  - Null point testing.
- Hartmann provides information for programming SLM/HOE
- Procedure to subtract system aberrations.
- Accuracy of \(\lambda/20\) with SLM in system.

COMMERCIALIZATION
- Basic concept patent application has been submitted
- Marketing to manufacturers of free form and aspherical optics
- Currently beta testing systems in service tests
- A wide range of customers have indicated interest
- Alliances made with two specific manufacturers
- This technology can provide significant savings of time and money over competitors
- This technology can enable inspections not provided by any competitors

APPLICATIONS/FUTURE WORK
- Government and Commercial Applications
  - X-ray telescope mirrors and mandrels
  - Free form Optics
  - Aspherical Optics
  - SiC telescope Mirrors
  - Ogive windows
- Future Work
  - Additional Software for System Operation and Automation
  - System Packaging
  - Noise floor and resolution improvement
**SLM Calibration**

- Gray scale value is varied on upper half of SLM
- Gray scale value is held constant at 0 on lower half of SLM

*Phase shift vs. gray scale value is measured interferometrically*

- Relative phase shift recorded to achieve an accuracy of data
- Gray value was varied from 0 to 255 on the top half, while it was held constant (0) on the bottom half
- Phase shifted vs applied gray value on the SLM produces gamma curve

**Interferogram Result**

- Applied gray values on the SLM:
  - Gray value: 63
  - Gray value: 0
- Applied gray values on the SLM:
  - Gray value: 127
  - Gray value: 0

*Gray value: 63*  
*Gray value: 0*  
*Gray value: 127*  
*Gray value: 0*

- S: Phase shifted amount
- P: Period of fringes
Corrected Gamma Curve

The calibrated gamma curve (blue color), is used to linearize the phase vs. gray scale response (red curve).

Errors when producing $1\lambda$ of tilt and corrected one after calibration.

S = 0.25$\lambda$ shift when 63 value applied.
Corrected Gamma Curve

The calibrated gamma curve (blue color), is used to linearize the phase vs. gray scale response (red curve).

Errors when producing $1\lambda$ of tilt and corrected one after calibration.

Grayscale Value applied on the SLM
Phase shifted value (wavelength)

Linear (Company Default)
Experimental Data
Calibrated gamma curve

$S = 0.25\lambda$ shift when 63 value applied
Producing cylindrical wavefronts

Applied Phase on the SLM

\[ \Phi \sim \alpha y^2 \]

*Matlab formula used to generate the phase.*

- Cylindrical wrapped phase written by Matlab code and applied on the SLM, which is good candidate compensating phase for a Mandrel.

- Phase produced and shown by the interferogram on the pixelcam
Producing arbitrary wavefronts

Applied Phase on the SLM

\[ \Phi = 20 \cdot (y - 0.25)^3 - x^2 + x \cdot y + x \cdot y^3 \]

Matlab formula used to generate the phase

- Arbitrary wrapped phase written by Matlab code and applied on the SLM
- Phase produced and shown by the interferogram on the pixelcam

Interferogram on the pixelcam

3D view
Compensation of Tilt

- Applied compensating tilt by the SLM

Wrapped phase applied on the SLM

Compensating wrapped phase applied on the SLM

(Various waveplates and telescopes not shown)
Compensation of Cylindrical wavefronts

Simulation

Measured Interferogram on the pixelcam

Applied Phase on the SLM

Residual fringes on the pixelcam
The phase on SLM is used to bring the dense fringes down into the measurement range of the pixelcam. i.e: extended dynamic range.
Wavefront Differences at Different Heights of Mandrel
A unique optical inspection system incorporates a dynamic holographic optical element that combines and extends both Hartmann and digital interferometry with preconditioned wavefronts. The resulting system exhibits a wide dynamic range and will be especially useful for inspecting aspherical and free form optics.