Indigenous Development and Characterization of a closed loop Adaptive Optics system for Wavefront Control

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Introduction

• **Adaptive Optics (AO)** is an emerging branch of Optics wherein the optics modifies itself to changing environmental conditions to provide high resolution imagery.

• This concept started towards improving the astronomical images obtained with ground based telescopes.

• The Optical turbulence due to random refractive index fluctuations of the atmosphere (caused by factors such as pressure, temperature), induces several aberrations in the wavefront resulting in loss of resolution. AO was aimed at nullifying this effect.

• Today, the applications of Adaptive Optics range from Astronomical imaging to laser beam steering in free space satellite optical communication, high resolution imaging of the retina of the human eye, microscopy, etc.
A typical Adaptive Optics System

An Adaptive Optics system consists of a Wavefront Phase sensor, a Steering mirror and a Deformable mirror. The phase profile is continuously measured and corrected in real-time.
If $W(x,y)$ represents a wavefront, then partial derivative of it is given as

\[
\frac{\partial W(x,y)}{\partial x} = \frac{\Delta x}{f} \\
\frac{\partial W(x,y)}{\partial y} = \frac{\Delta y}{f},
\]

where
- $f$ is the focal length of the lenslet array
- $\Delta x$ & $\Delta y$ are the shift of spots along $x$ & $y$ directions.

Phase Profile measurement by Shack-Hartmann Principle
Wavefront Reconstruction

- There are two approaches for Wavefront Reconstruction – Modal and Zonal

- The **Modal reconstruction** scheme treats the wavefront (WF) as the sum of a series of basis functions. The method reconstructs the WF within a circular mask & whose output is a set of Zernike polynomial.

- It represents a WF as a series of whole aperture functions of increasing complexity.

- The **Zonal reconstruction** approach divides the aperture into an array of independent sub-apertures or zones.

- This allows us to generate actuator commands directly from the measured gradients without actually reconstructing the wavefront in the process.
Development of indigenous AO system

Work on AO started in the year 2000 with the development of an Indigenous Adaptive Optics system for DRDO, with a grant from IRDE under Phase-I of the National Program on Photonics.

Under this project, a Wavefront Sensor (WFS) was designed and developed at REC / NIT, Trichy.

Custom made software was developed for real time measurement of wavefront aberrations and several features were incorporated in this.

This WFS was then integrated with the tip-tilt mirror and deformable mirror at IRDE to form a closed loop system.
Optical Layout of WFS

S1, S2 micro controlled stepper motor shutters, M1 – Mirror, L1, L2, L3, - lenses, SPF-Spatial Filter, NDF-Neutral density filter, BS-Beam splitter, MLA-Microlens Array.
Photograph of the WFS Optical System developed
WFS (Total System)
Custom designed software was developed VC++ (MFC) environment with windows based, interactive, user-friendly features.

- Real-time display of Hartmann spots and wavefront profile
- Live Display of Zernike terms 0 to 14
- Live display of piston, X and Y tilts, Astigmatism, RMS, P-V etc.
- Provision to enable / freeze data capture and display of the above parameters.
- Display of processing speed as "Frames/sec" at the bottom)
- Provision to update reference centroid data
Features

Collimation testing

- Alignment and collimation checking by a pre-computed grid overlay on the imaging window, and possible automated adjustments until the spots coincide with grid crossings
Focus checking by display of intensity profile of any sub-aperture in the graphic window, and possible automated adjustments until the beam profile is narrow and has a sharpest peak.
Line Intensity Profile

Features

- Intensity checking by display of line profile, and possible automated adjustments to ensure that the intensities are in the linear range of the detector, to avoid saturation
X-Tilt
Y-Tilt
Specifications of the Wavefront Sensor

Wavelength of Operation : 400 -700nm
Sub-aperture for analysis : 16 x 16
Acquisition Frequency : 25 frames/sec
Tilt measurement Accuracy : 1.9 μ radians
Max. Tilt measurement range : ± 2m radian
Wavefront Measurement : λ/50
Pupil shape : Square
Applied tilt Vs Measured tilt using SHWFS
Closed loop tilt measurement / compensation setup
Wavefront Compensation for global tilt

Actuator commands for steering mirror are generated to compensate the tilt

240 micro radian 2-axis tilt

Corrected

Closed loop DM characterization
Wavefront Compensation for local tilt

- Actuator commands for the deformable mirror are generated to correct aberration
- The shape of the reflective membrane is controlled by control voltages to the membrane electrodes

## Wavefront Error correction - a typical result

<table>
<thead>
<tr>
<th>Wavefront error</th>
<th>Reference Wavefront</th>
<th>Aberrated Wavefront</th>
<th>DM corrected Wavefront</th>
</tr>
</thead>
<tbody>
<tr>
<td>X tilt (mic.Rad)</td>
<td>0.56411</td>
<td>32.903</td>
<td>-5.34336</td>
</tr>
<tr>
<td>Y tilt (mic.Rad)</td>
<td>0.73315</td>
<td>-31.2003</td>
<td>14.83812</td>
</tr>
<tr>
<td>S _focus ((\mu)m)</td>
<td>0.47368</td>
<td>23.45838</td>
<td>-5.31588</td>
</tr>
<tr>
<td>A\text{mag}</td>
<td>-0.94768</td>
<td>-46.92201</td>
<td>10.63284</td>
</tr>
<tr>
<td>C\text{mag}</td>
<td>0.03697</td>
<td>0.037</td>
<td>0.01449</td>
</tr>
<tr>
<td>S\text{pmag}</td>
<td>1.73026</td>
<td>4.96</td>
<td>-1.4102</td>
</tr>
<tr>
<td>rms (nm)</td>
<td>3.46462</td>
<td>8.1043</td>
<td>16.58731</td>
</tr>
<tr>
<td>PV (nm)</td>
<td>1.80323</td>
<td>47.42245</td>
<td>11.53924</td>
</tr>
</tbody>
</table>
Work on Adaptive Optics in Vision Science

- Eye has an imaging optics (lens + cornea combination)
- The image quality at the retina depends on the aberration of this optics

- Lower Order Aberrations:
  - Defocus, Astigmatism (~92%)
  - Can be corrected by Spectacles/ Contact lenses

- Higher Order Aberrations:
  - Spherical aberration, Coma, Trefoil.. (~8%)
  - Can be corrected by customized surgeries or one has to look for Adaptive Optics

- Ophthalmoscopy - Retinal imaging
  - Focusing lasers
As a first step, the WFS was used to measure the aberration content in human eye.
Analysis of Higher Order aberrations of Normal Eye

- HO Aberrations of Human eye were measured for a age group of 20 - 30 yrs.
- All of them had normal vision (6/6)
- Acuity test was done using a snellen chart
- Subjects were dilated using tropicamide eye drops for pupil elongation
- Tested for both 6mm pupil size
Wavefront Error

With defocus  |  Without defocus  |  Removing LOA

Intensity Profile and Interferogram for pupil size 6mm with and without defocus

Analysis of refractive errors in human eyes

- Study of correlation between lower and higher order aberrations

- Conventional correction methods like refractive surgeries leave the subject with significant presence of higher order aberrations, which deleteriously mar the vision – hence the need for this study, pre and post operative to arrive at spherical equivalent correction

Analysis of aberration caused by the Intervening medium in the line of Sight

- Intervening mediums affect the quality of images. For instance, seeing through a helmet visor, windscreen or windshield of a car or an aircraft **degrades** the image quality of a scenery when compared to seeing with the naked eye.

- A **simple** and a **novel** technique for the measurement of aberrations in transparent materials like glass sheets, perspex etc has been developed.

**Shack-Hartmann Technique**

Interferometry also can be used, but beam size is limited

**The new Spot-Pattern Test Chart Technique**

Large size optics testable easily


Proposed to apply for patent
Measurement of Moments or Centroiding using various methods

- Centroid estimation in Shack-Hartmann wavefront sensing plays vital role in phase estimation.
- AO correction being more accurate depends on how finely we are estimating the wavefront error in terms of pixel scale, processing time and accuracy.

<table>
<thead>
<tr>
<th>Applied shift</th>
<th>Statistical Averaging method</th>
<th>HFM Method</th>
<th>Least Square method</th>
<th>Wavelet Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated Centroid Position (Helm)</td>
<td>Calculated Centroid Position (Helm)</td>
<td>Calculated Centroid Position (Helm)</td>
<td>Calculated Centroid Position (Helm)</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Processing time (sec)</td>
<td>0.003</td>
<td>0.233</td>
<td>2.010</td>
<td>0.914</td>
</tr>
</tbody>
</table>

Current Works

Development of Wavelet Based Wavefront Sensing and Characterization under DRDO project

- Wavelet Based Wavefront Sensing has the advantages of variable resolution, and trade off between accuracy, resolution and speed.

- A full fledged system will be developed based on this, including a closed loop imaging system to work at 100 Hz, and tried with far field imaging.

- The WFS software has been modified incorporating Wavelet method for centroid estimation with multi resolution.

- We have applied Haar wavelet transformation on the image such that the image is decomposed into 4 different bands (frequency data) namely LL, HL, LH, and HH.

- More decomposition is possible with data in LL band which will increase the speed of centroid calculation but the resolution of the image may decrease.
Tilt Measurement with Statistical averaging

Given tilt 590 microrad

Measured tilt 561 microrad

64 frames / sec
Tilt Measurement with Wavelet method

Given tilt 590 microrad

Measured tilt 593 microrad

83 frames / sec
Characterization and correction of Foveal and Parafoveal Aberrations in Human Eye using Adaptive Optics under DST project

(In Collaboration with Sankara Nethralaya, Chennai)

- Foveal and Parafoveal aberrations in the Human Eye shall be measured on patients with and without foveal vision loss
- The visual functions, retinal stimulus and perceptual preference shall be assessed without / altered / with adaptive aberration compensation
- Expected outcome would be aberration combination for best subjective focus and improved vision for patients with foveal loss by using custom designed spectacles
Significant outcomes of the proposed project

• Establishment of combination of aberrations that results in subjective best focus for foveal images
  - Spectacle manufacturing companies are already working on customized aberration corrected lenses
  - Results of this study would help to improve these products for improvement in quality of vision

• Establishment of the possibility of correction of parafoveal aberrations in subjects with vision loss gives enormous HOPE for better vision for people with this defect
  - The results of this study could motivate manufacturers to produce customized parafoveal aberration corrected spectacles for people with foveal vision loss
THANK YOU