Design and implementation of pipelined parallel architecture for fast Wavefront Correction of interferometric data

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ABSTRACT - In adaptive optics (AO) technology, the wave propagation occurs in the atmosphere which constitutes a media with random optical inhomogeneities caused by atmospheric turbulence. These can be corrected which enables the telescope to reach the diffraction limited image quality. The atmospheric turbulence induces temporal and spatial variations in the beam propagation. Therefore the analysis and mitigation of atmospheric turbulence effects on the quality of wavefront become significant. This paper addresses the development and adaptation of faster simulation algorithm of wavefront correction for interferometric data using pipelined parallel architecture. The complete simulation package of shearing interferometer based wavefront sensor for adaptive optics applications has been reported.

Keywords: Shearing Interferometer, Parallel Processing, Deformable Mirror and Phase Screen

I) INTRODUCTION

When observed with a ground based telescope, the image of a star is not sharp due to atmospheric turbulence. To overcome atmospheric turbulence for ground based telescope, astronomers have developed the technique of adaptive optics (AO) [1] to actively sense and correct wavefront distortions at the telescope during observations. A telescope with AO measures the wavefront distortions with a wavefront sensor and then applies phase corrections with a deformable mirror [2, 3] on a time scale comparable to the temporal variations of the atmosphere’s index of refraction. Adaptive optics improves image resolution and increases the image’s coherence. The main part of the AO system is to detect the incoming distorted wavefront. For this wavefront sensor based on polarization shearing interferometry technique has been studied [4, 5 and 6]. The necessary theory for shearing interferometry has been developed. Theoretical Simulations of the interferometric records were carried out for the study of various aberrations in an optical system and the effect of noise and atmospheric turbulence in the interferogram was studied.

In this paper, the physical background of imaging through turbulence, using Kolmogorov statistics, and the Polarization Shearing Interferometry techniques to sense and to estimate the correction of the wavefront aberrations with pipelined parallel architecture has been discussed. We reported five developed module of simulated packages such as interferogram simulation, phase screen generation, phase extraction using Central Fringe Width Localization Algorithm (CFWLA) approach, Wavefront Reconstruction and Correction by deformable mirror (DM).

II) POLARIZED SHEARING INTERFEROMETER WAVEFRONT SENSOR SIMULATION SOFTWARE

In recent past several tools have been developed to simulate adaptive optics. They can be categorized into two types: numerical simulators and analytic codes. The basic idea for the simulation of adaptive optics system is to explore the limitation of AO Parameters and possible compensation for the turbulence affected image in a numerical method. The most important AO simulation tools (CIBOLA, Arroyo, CAOS and OCTOPUS) are developed in GUIs (IDL, C++ and Matlab). Due to differences in the design, these tools are suited for complementary purposes. For instance, the scripting languages like Matlab or IDL are easy to write, but their computational capacity can be worse compared to the codes using the native platform of the computers. There is no such simulation software for polarization shearing interferometer based wavefront sensor using single interferogram record. We attempted such software for Polarized Shearing Interferometer Wavefront Sensor by including turbulent phase screen and compensation of efficient algorithm.

The software required for the analysis of the interferometric images was developed in the LabVIEW platform. The advantage of the LabVIEW programming is that it has extensive libraries of functions for any programming task and also has the support for accessing instrumentation hardware. The developed Polarized Shearing Interferometer wavefront sensor simulation software has four

First we simulated the noiseless interferogram image and later we incorporated phase screen with Gaussian noise, due to which we got the distorted image. The phase is extracted from noisy fringe using CFWLA. The phase is unwrapped using unwrapping algorithm. The standard data reduction procedure expressing the slope as a function of Zernike polynomial has been adopted [7, 8]. To reduce the computation time we used pipelined parallel programming in the simulation. We fitted the Wavefront derivation to Zernike Polynomials. In this case, 11 Zernike co-efficient have been taken for wavefront determination and the Zernike coefficients are determined using least square method. Using these coefficients the wavefront is reconstructed and plotted. Once the slopes are found then through parallel program one process is used to develop wavefront reconstruction and another process for wavefront correction. In order to demonstrate the simulated closed loop adaptive optics system through shearing interferometer based wavefront sensor we adopted the following procedure.

III) THEORETICAL ANALYSIS OF INTERFERENCE FRINGE PATTERN

A simple wavefront equation having third order aberrations is derived from [9].

\[
W(x, y) = A(x^2 + y^2)^2 + Bx(x^2 + y^2) + Cy^2 + 3y^2) + Dy + Ey + Fx
\]

(3.1)

Where A - Primary Spherical aberration, B - Primary Coma, C -Primary Astigmatism, D – Defocus, E - Tilt in X direction and F - Tilt in Y direction. When the shear value in X and Y directions are small, the shearing wavefront can be approximated as the first order derivative function as

\[
W(x, y) = \frac{\partial W}{\partial x} s + \frac{\partial W}{\partial y} t
\]

(3.2)

where s and t are the shears in the x and y directions respectively. The intensity at the detector plane can be written as

\[
l = K_0 + K_1 \cos \left( \frac{2\pi}{\lambda} \Delta W(x, y) \right)
\]

(3.3)

In the case of Polarization Shearing Interferogram, the ideal conditions are described as the system having no aberrations but only defocus term. Considering the equation 3.1 for the general wavefront, the sheared wavefront for various aberrations can be derived by Keeping only the defocus and taking the other coefficients A, B, C, E & F equal to zero, s and t are the shears in the x and y directions respectively. The Figure 2 shows that the fringe profile in ideal condition (no aberration), and it was generated only by the defocus term which is given in equation 3.5. These expressions are very similar to the one described by Malacara [10].

\[
\frac{\partial W(x, y)}{\partial x} s = 2D_1 xs
\]

\[
\frac{\partial W(x, y)}{\partial y} t = 2D_2 yt
\]

(3.4)

\[
D_1 = \frac{d_1}{2R_0^2} \quad \text{and} \quad D_2 = \frac{d_2}{2R_0^2}
\]

(3.5)
3.1 Effect of Gaussian Noise on Interferogram

The signal to noise ratio of an interferogram is a quality estimation factor. It is a measure of how strong the signal is with respect to the external noise present at the time of observation. The presence of random noise alters the visibility and the contrast of the fringes drastically. For visualization and for illustration purposes, a Gaussian noise was additionally introduced in the same simulation. The effect of Gaussian noise on interference fringe pattern image is shown in Figure 3. These errors can be evaluated and subtracted from the interferogram. The effect of noise is introduced in the interferometric equation as an added Gaussian term in the phase. Since these noises are high frequency compared to the modulation frequency, it is convenient to remove this using Fourier technique.

![Figure 2: Interference Fringe Pattern](image)

![Figure 3: Interference Fringe pattern after addition of Gaussian noise](image)

3.2 Sub-harmonics method based phase screen

Sub harmonics method [11, 12] is a simple technique for modeling the effects of lower frequencies and to generate additional random frequencies and add their effects to the sampled frequencies using equation 3.6. This method consists of generating realizations of turbulence on two different size grids and uses a trigonometric interpolation to introduce low-frequency effects on the smaller (propagation) grid. It is proved that the phase screens generated by this method give a better representation of Kolmogorov turbulence since they include effects from the low-spatial-frequency part of the spectrum. This method can be considerably more efficient than a straightforward implementation of the FFT method on a very large grid. It provides a low frequency screen \( p(x, y) \) generated by sum of different number (Np) of phase screens, The low frequency screen as a Fourier series given by

\[
p(x, y) = \sum_{g=1}^{N_g} \sum_{n=-1}^{1} \sum_{m=-1}^{1} c_{n,m} \exp \left[ i 2\pi \left( f_{xn} x + f_{ym} y \right) \right]
\]

(3.6)

Where the sums over \( n \) and \( m \) are over discrete frequencies and each value of the index \( g \) corresponds to a different grid. The sample phase screens simulated are shown in Figure 4. It presents the typical atmospheric phase screen simulated by sub harmonics method with \( D/r_0 = 0.2 \) and \( L_0 = 50 \) m, \( l_0 = 0.01 \) m.

![Figure 4: Sample phase screens obtained by sub harmonics method](image)
The effects of turbulence in Shearing Interferogram due to phase screen have been shown in figure 5. The shearing interferogram incorporated the phase screen term to find out how the fringes are changing. This will lead to the expression for the distorted wavefront.

![Figure 5: A noisy interference fringe pattern affected due to Sub-Harmonics based turbulence phase screen](image)

The one-dimensional plot of the distorted fringe pattern was taken into account for identifying number of fringes but failed due to multiple peaks and valleys. Later the noisy 2D data are averaged by adding columns and plotted for unique peak and valley identification [14]. The values between valley to valley in the interferogram is taken for fitting fourier transform and in the frequency domain it is filtered with band pass filter. Finally, a smooth image is produced after an IFFT. The figure 6 shows that the averaged intensity with both its peak, valley identified by red and green dots respectively. The figure 7.A and B shows the filtered image using CFWLA of figure 3 and figure 5 respectively.

![Figure 6: Unique identification of peak and valley in the 1D distorted fringe patterns](image)

![Figure 7: The filtered images using CFWL Algorithm](image)

**IV) Phase Extraction using Central Fringe Width Localization**

Noise is an unwanted signal which is corrupting the original signal. To retrieve phase from the noisy interference fringe pattern we need to extract phase by removing noise. Noise degrades the quality of the information of the original signal. Extracting phase from the noisy interferogram involves the manipulation of the image data to produce a visually high quality image. The interferogram needs to be processed before it can be used for computing phase aberration. The desired information is obtained through analysis of the fringes. The analysis consists of manipulation of the fringes to obtain a function called the phase, which is related to the information to be obtained from the physical phenomena under study, i.e., a body deformation. The fringe manipulation involves the correction of non-plane illumination, contrast variations, and noise removal. The correction of contrast variations and that of noise removal are called normalization and smoothing. Phase estimation errors may cause phase retrieval algorithms to fail and one cannot do any wavefront correction. It is necessary to detect the phase and extract phase present in the interferometric images without losing signal by reserving the details of an image [13].
4.2. Reconstruction of Wavefront

Adaptive optics is the adaptation of the telescope optical system and works in such a way that it measures the incoming light from natural stars and gives information on the nature of the atmosphere at a certain point in time. The information most often used is the phase of the incoming light over a certain area, which gives a measure of the distortion.

A distorted wavefront comes into the system through the telescope aperture. It is reflected from a deformable mirror to a beam splitter that divides the beam to a wavefront sensor and a scientific camera. The measurements from WFS are fed into computers to compute the required instructions for the DM. The mirror is deformed using actuators, each of them having its own control voltage. The instruments used for this purpose are called wavefront sensors. The simulated noisy interference fringe profile (due to turbulence phase screen) and its sensed wavefront is shown in the figure 8.

![Figure 8: Reconstructed wavefront](image)

5. Control System

5.1 Control System

An adaptive optics system can be defined as a closed loop servo system. Wavefront sensors measure the shape of the wavefront and produce signals that represent the wavefront. It may be modal or zonal representation. It is the function of the controller to translate these signals and relay them to the correcting device. In most cases, parallel paths are employed whereby one channel controls lower order aberration modes, such as focus and tilt while another channel simultaneously controls the higher order wavefront errors with deformable mirror. The correction has been done in closed loop for AO. The wavefront sensor measures any remaining deviations of the wavefront from ideal and sends the correcting commands to the DM. This is why small imperfections of DM (like hysteresis or static aberrations) are not very important: they will be corrected automatically, together with atmospheric aberrations.

![Figure 9: Closed loop control system](image)

Here, the temporal form of negative feedback controls system for the closed loop is shown in figure 9. Where, \( x(f) \) - the input signal, \( y(f) \) – the signal applied to the DM, \( G(f) \) is the gain, and \( e(f) = x(f) - y(f) \) is the error signal as measured by the wavefront sensor. From conventional control theory, if the transfer function gain \( G(f) \) and feedback \( y(f) \) is known, the performance of the entire system can be found.

5.2. Control algorithm:

In this closed loop system, the residual wavefront error (i.e. the wavefront error which remains after correction) is continually measured by wavefront sensor and it is used to reshape the deformable mirror. This control algorithm manages analysing signals from PSI_WS wavefront sensor. These signals are used to determine the appropriate drive signals to send to the deformable mirror actuators so the mirror can compensate for wavefront aberrations. To characterize wavefront fitting performance for DM, an overview of the control theory [15] is needed. The slope measurements are used to build the phase to gradient interaction matrix. The interaction matrix D, relates the DM actuator commands \( C \) (voltages applied to deformable mirror)
to measure the wavefront. By applying voltages to individual actuators of the deformable mirror, one can measure the wavefront profile using the Polarized shearing wavefront sensor. By doing this, there develops a matrix called interaction matrix. Interaction matrix is the voltages applied to the deformable mirror and we get deformable surface profile with that in the end.

\[ W = DC \]  

(5.1)

The matrix D has a size of \( n_{\text{act}} \times n_{\text{pix}} \), where \( n_{\text{act}} \) is the number of actuators and \( n_{\text{pix}} \) is the number of pixels used to record the wavefront. To find the control vector that gives a certain wavefront phase W, the inverse of D is required and it is known as the control matrix M.

\[ C = MW \]  

(5.2)

By using the least square approach the control vector that minimizes a wavefront W is given by

\[ C = (D^T D)^{-1} D^T W \]  

(5.3)

The matrix \( (D^T D) \) is generally non-invertible due to \( n_{\text{pix}} > n_{\text{act}} \). Singular Value Decomposition (SVD) is used to find the generalized inverse of D and obtain a set of orthogonal mirror modes.

\[ D = U Q V^T \]  

(5.4)

Where, U contains the phase maps of the orthogonal mirror modes with each phase map stored as a vector.

Q is diagonal matrix containing the Singular values. Small singular values lead to large mirror mode gains when inverted and this creates noise amplification.

V contains the appropriate actuator command signals to recreate a particular orthogonal mirror mode. The actuator commands are then obtained

\[ C = V (Q^*)^T U^T W \]  

(5.5)

For our case of Polarization Shearing Interferometer, the noisy interference fringe pattern is directly proportional to the slope of the wavefront. So we have 256 intensity values which are considered as slopes but due to circular shape of telescope aperture we get less than 256 slopes. If we consider for 256 slope values then the size of interaction matrix is 256 X 128 and voltage matrix is 128 X 1. By using this matrix calculation we simulated a close loop adaptive optics system based on shearing interferometer wavefront sensor. By simulating the deformable mirror, the wavefront is corrected and achieved automatically in closed loop AO systems as shown in the figure 9.

![Figure 10: Wavefront Control Simulation](http://www.ijcttjournal.org)

**VI) TIME REDUCTION THROUGH PIPELINED PARALLEL PROCESSING**

In our simulation, some module is depending on another, we couldn’t afford parallel execution by assigning each module to run concurrently. One widely accepted technique for improving the performance of serial software task is pipelining. Pipelining is the process of dividing a serial task into concrete stages that can be executed in assembly-line fashion. We developed the simulation based on the parallel processing through pipelining to improve the computation speed. Pipelining for our application dramatically increase the throughput by increasing the speed.

In our application, we have five modules 1. Interferogram Simulation, 2. Turbulent phase screen 3. Phase Extraction, 4. Wavefront Reconstruction and 5. Wavefront Correction. This is an inherently serial task, to get the noisy interference fringe pattern, the turbulent phase screen module has to run and the values would be convolved to the noiseless interferogram. Also phase extraction module has to run before wavefront reconstruction module. We cannot run both concurrently at the same time. Instead we have used pipelining to take advantage of multicore system architecture.

Among the five modules in our application, each module takes 10 to 15 milliseconds to complete. This means that each module of the application takes 10-15 milliseconds to execute without pipelining and the application throughput is one computation every 75 milliseconds for the image size of 256 X 256. We have pipelined parallel programmed in our...
application by placing a feedback node (shift register) between each stage in Lab VIEW. After inserting the feedback nodes, each pipeline stage operates on the data provided by the previous stage (during a previous iteration). By using this pipelined parallel architecture we have reduced the computation time in each module and increase in throughput.

We have reduced the computation time drastically by using pipelining for our simulation; each module has been taken care by not allowing much longer time to complete than other module. This is done by the help of data parallelism with parallel loop execution for each module. Also special care has taken for data transfer between pipeline stages for core processor. From the five modules in our simulation we run interferogram simulation and turbulence phase screen concurrently. Once we have convolved both interferogram and turbulent phase screen, the data is passed to next module for phase extraction and wavefront correction. After extracting the phase, the data has been passed to wavefront reconstruction. The figure 11 shows the block diagram of the parallel execution of our developed application through pipelining.

![Figure 11. Block Diagram for shearing interferometer base wavefront sensor using pipelining](image)

**VII) CONCLUSION**

This paper has presented a complete simulation package of wavefront error estimation and correction based on shearing interferometer. Further, a novel method for implementation of high-speed closed loop adaptive optics design with pipelined parallel architecture algorithm has been demonstrated. The computation time for the proposed algorithm after parallel programming is drastically reduced to 50 milliseconds. Our design reduced the critical path, time and increased the throughput. Finally the wavefront error is estimated with CFWL algorithm and corrected using simulated deformable mirror. The combined parallel and pipelining techniques are implemented to eliminate the distortion introduced in the interference fringe pattern.

**REFERENCE**


