Design of an adaptive optical wavefront sensor for advanced missile seekers

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Abstract

Precision guided munitions(PGM) including cruise missiles are soon expected to fly with advanced seekers having 2D or 3D imaging capabilities for automatic target recognition(ATR) and terminal guidance against tactical targets. Advanced seekers usually are of dual or multi-mode in nature often with combination of Laser, IR, SAR and MMW imaging capabilities. LWIR and LADAR based electro-optical imaging seekers can provide the highest resolution for classification of tactical targets and thus robust terminal guidance. However the image quality of target scenes is severely affected by the wavefront errors introduced by the inevitable atmospheric turbulence through which light travels from target to seeker. Many other effects including of aerodynamic boundary layers of seeker head and line-of sight jitter are bound to cause wavefront errors particularly when the missile is fast maneuvering to track the target. Though there are tremendous advances in the image processing techniques, it is often complicated and time consuming to reconstruct the actual image by employing these techniques alone without providing real-time compensation for the wavefront errors of these images. Whereas an adaptive optical system in closed-loop operation with multi-actuator deformable mirror and a high resolution wavefront sensor compensates for turbulence and other opto-mechanical effects on the light reaching the receiver of seeker from targets by correcting different wavefront aberrations in real-time. This paper describes the design of integrated adaptive optical wavefront sensor(WFS) for laser and IIR seekers to obtain the high resolution images of target scenes using a MEMS deformable mirror based phase corrector. These wavefront sensors can also provide the much needed accurate line-of sight data for the laser spot seekers of PGMs and also for successful encountering of the active lasers and IRCMs against missiles and aircrafts. The paper also presents comparison among different wavefront sensing techniques for imaging seekers and line-of-sight tracking seekers of PGMs as in the case of semi-active homing guidance. Results of some of our recent experiments for correcting line-of-sight track errors and other higher order wavefront aberrations are also presented here.

1. Introduction

Advanced seekers for autonomous vehicles including PGMs and cruise missiles will play an important and crucial role for achieving the much desired high Probability-of-Kill against tactical targets. Probability-of-Kill of course further depends on navigation, flight control, guidance and targeting errors and type of weapon/target etc. LADAR seekers can provide cruise missiles in-flight retargeting capability by adding high-resolution search, acquisition and track modes. Ladar adds a third dimension(**angle-angle-range**) of high-resolution data for ATR and target track in clutter and camouflage. Dual mode seekers are being pressed in for mission critical target discrimination, tracking and aim point selection during stressing conditions. Laser and IIR seekers can play mission critical role of terminal guidance by robust detection and tactical discrimination of targets. The mission success and CEP of these image forming guided missiles are primarily dependent on the image quality and the tracking accuracy of the homing in on targets under conditions of severe clutter and camouflage. The stabilization of seekers will also contribute to the CEP significantly. The relative perpendicular motion between the target and missile seeker corresponding to the line-of sight drift and jitter will further distort the optical wavefront received from the target scene. Both LADAR based laser seeker and IIR imaging seeker will have an electro-optic sensor in the form of a matrix photo-detector onboard for imaging the targets. While laser spot seekers of semi-active homing in on munitions will track the laser designated targets by constant line-of-sight stabilization using quadrant or an array photo-detector. The performance of any electro-optical imaging system trivially depends on a number of factors including of target, background, the dynamics of intervening atmosphere, optics, stabilization platform, detector noise, electronics, image processing software, display and the operator interpretation of the displayed information. In case of missile seekers many of these factors become critical to the identification of real target in high hindering noise and clutter.

A closed-loop adaptive optical system having a phase corrector and a wavefront sensor with enough degrees of freedom corrects all the wavefront distortions in real-time for achieving both needful image quality and tracking accuracy if it is integrated with seeker control system. To correct the wavefront aberrations in real-time using a closed-loop adaptive optics system, one must first measure the wavefront aberrations quite accurately in real-time using an appropriate wavefront sensor. Wavefront sensors can measure the phase variations of optical beam by measuring the irradiance distribution generally in the pupil plane of receiving telescope aperture. There are several types of wavefront sensors, but Shack Harman and curvature wavefront sensors are most useful for practical field applications like these. Though Shack Hartman is more versatile than curvature wavefront sensor, wavefront reconstruction process takes more time for generating control signals to drive the phase corrector. Where as curvature wavefront sensor is much simpler in geometry and also straightforward in generating control signals.

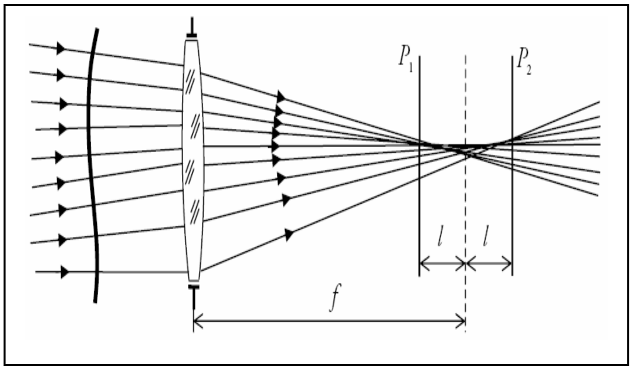
2. Design considerations of adaptive optical wavefront sensor

The performance characteristics of wavefront sensor depend on the application for which the sensor is used and the conditions under which it will function. The desirable features, limitations and trade-offs will have to be considered for designing a wavefront sensor for a particular application. Optical wavefront sensors based on interferometry are routinely used to evaluate the surface flatness of different optical elements. Shack Hartmann and curvature type of wavefront sensors are more suitable for integrating them in field usable systems as they are more robust and quite linear in response. In these wavefront sensors, the phase of the incoming wavefront at pupil plane of the optical system is converted into intensity distribution and the process is generally inverted mathematically to reconstruct the phase variations. In Shack Hartmann wavefront sensor, the incoming wavefront is sampled by a lenslet array to form an array of light spots at focal plane. The position of each spot is displaced in space as per the local wave front aberration or phase variation. A CCD matrix detector measures the displacement of these focal spots and a wavefront processor computes the phase map. Apart from phase and intensity distributions, various parameters such as peak-to-valley, root-mean square, Zernike coefficients, beam quality (M^2) , MTF could be calculated with the help of such a sensor. However, requirement of reference wavefront and long times for image processing of focal spots will limit its use in real-time wavefront measurement in applications like missile seeker. On the other hand, curvature wavefront sensor is simple to build and needs no reference wavefront to calculate the local phase variations with high S/N ratio and adequate spatial resolution.

In curvature wavefront sensor, the normalized difference of intensities of two defocused images at equally spaced points P_1 and P_2 from the focal plane of the optical system as shown in Fig 1(a) is measured simultaneously to deduce the local curvatures of the receiving wavefront which can be coneniently represented by a mathematical expression. The difference is proportional to the Laplacian which is nothing but curvature of the wavefront within the pupil and to the normal derivative of the wavefront along the pupil boundry. The curvature signal *S* is defined as the point-to-point contrast between the two recorded intensities as given by the equation:

$$S = \frac{I_1(r) - I_2(-r)}{I_1(r) + I_2(-r)} = \frac{\lambda f(f-l)}{2\pi l}\left\{\frac{\partial \phi}{\partial \rho}\left(\frac{f}{l}r\right)\delta_c - \nabla^2\phi\left(\frac{f}{l}r\right)\right\}$$

Where ∇^2 is the Laplacian operator, and δ_c is a linear impulse distribution around the edge. The wavefront curvature together with wavefront radial tilts at the aperture edge are measured in order to reconstruct the wavefront phase Φ by solving the Poisson differential equation with Neumann boundary conditions. For suitable phase correction, Membrane, MEMS and Bimorph mirrors can deform the wavefront locally into near spherical shapes. This allows their application for solving the Poisson equation directly avoiding any matrix multiplications in the feedback loop. This is a big advantage in applications like this where time is very critical. The working principle and optical schematic of curvature sensor are as below.



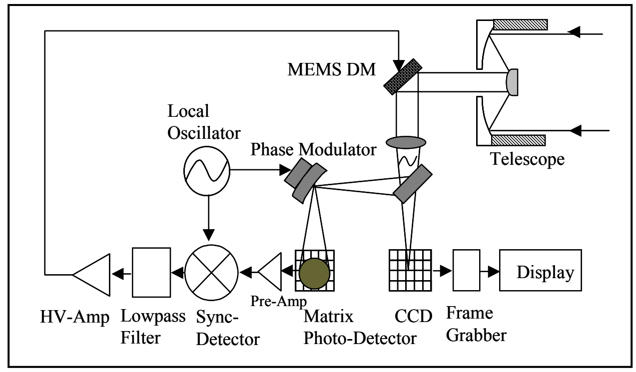
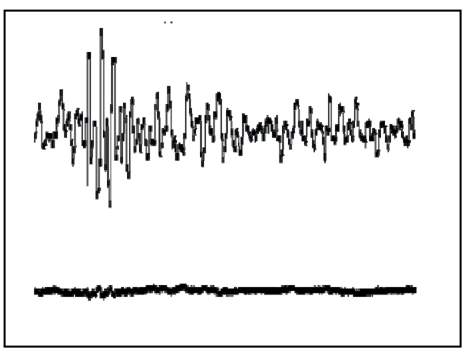


Fig.(1a): Optical-ray diagram for curvature depiction

Fig.(1b): Opto-electronic schematic for curvature WFS

The sensor consists of a vibrating curvature mirror as phase modulator located in the telescope image plane and a convex lens which re-images the telescope pupil on to a photo-detector detector array. The phase modulator oscillates between concave and convex shape, defocusing the pupil image approximately at 1-2kHz rate. The intensity distribution on the pixels of detector matrix varies in accordance with the local wavefront curvatures. Each of the modulated photo current signals from matrix photo-sensor is processed using phase-sensitive detection to generate control signal to drive the corresponding actuator of the MEMS deformable mirror. Amplitude and frequency of the phase modulator can be conveniently varied to optimize the sensitivity and resolution of local curvature sensing. The recordings of an adaptive optics experiment for line-of-sight error/ jitter correction is shown as below.



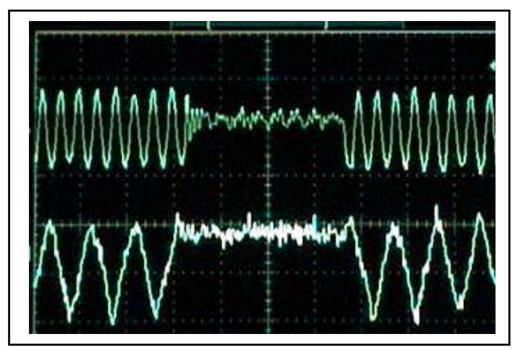


Fig.2(a). Correction of line-of sight errors

Fig.2(b). Closed-loop correction of simulated laser beam x-y tilts

3. Curvature Wavefront Sensor for Missile Seekers

As weight, volume, power and signal or image processing time are the serious concerns of missile seekers, an all integrated adptive optics system consisting of a MEMS deformable mirror and a compact curvature wavefront sensor is considered to be one of the most appropriate design approaches for ATP and terminal guidance. The design of an all integrated wavefront sensor based LADAR seeker is shown as below.

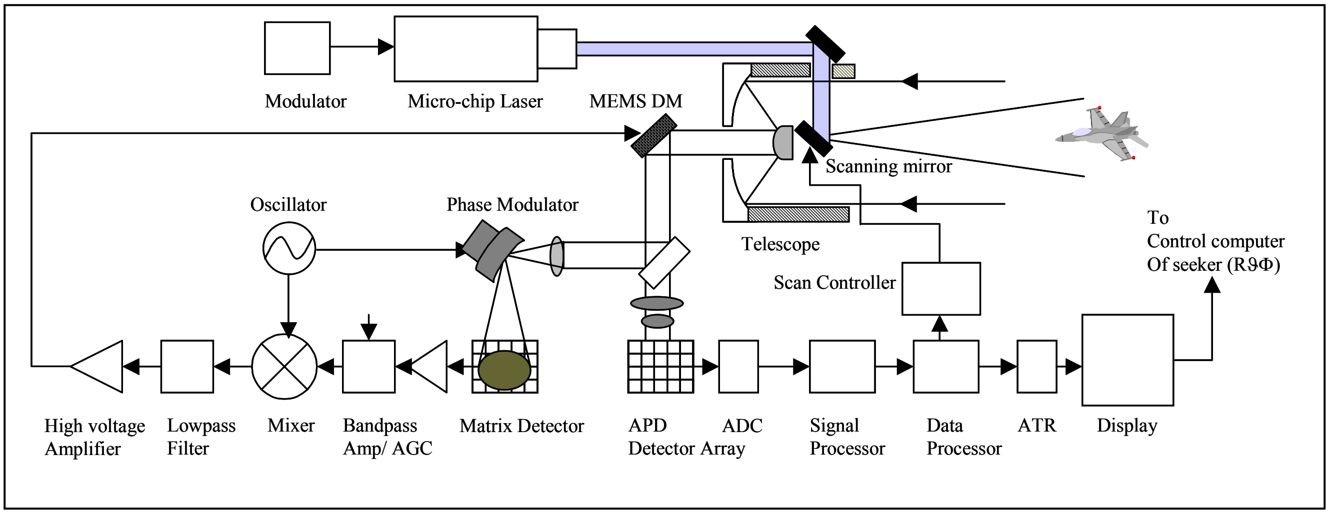


Fig.(3): Opto-electronic schematic of integrated wavefront sensor with Ladar missile seeker

Maturity of surface micro-machined MEMS deformable mirrors with large number of control electrodes and large enough strokes adds to the benefit of integration of closed-loop adaptive optics within the seeker control electronics. For intelligent wavefront reconstruction, prior knowledge of targets as in the case of tactical environment, wavefront processor algorithms can deduce the phase map directly from the relevant point spread function (PSF) instead of convoluting it from the phase error matrix. A small number of samples will be adequate to reconstruct the image that matches with the known target scene, voiding many iterations using multiple samples. This will save the precious time for required ATR and terminal guidance. Analog control for curvature wavefront sensor based adaptive optics loop is good enough to correct the time varying curvature signals with accuracies greater than 95% at > 30Hz closed-loop bandwidth.

4. Conclusions

The performance of LADAR and IIR seekers can be significantly increased to achieve the mission success by incorporating a closed-loop adaptive optics loop with missile seeker control system. The spatial resolution of 2D imagery of the target scenes can be considerably improved by the adaptive optical loop by compensating the wavefront errors caused due to intervening turbulent atmosphere and aero-dynamic boundary layers around the missile seeker heads during the engagement cycle. A MEMS based deformable mirror having sufficient number of control actuators and a compact curvature wavefront sensor can be conveniently integrated with seeker control system without much weight, volume and power penalty. Curvature wavefront sensor enables measurement of wavefront phase errors with enough spatial and temporal resolution to represent wavefront aberration coefficients up to several orders. Adaptive optics phase control loop with combination of a curvature wavefront sensor and MEMS deformable mirror having $D/r_0 \approx 5$ is capable of improving the image quality better than 25% corresponding to 0.75 Strehl ratio obtainable with seeker electro-optical imaging system.

5. References

1. Robert K.Tyson, Principles of Adaptive Optics, Academic Press, CA, 1998.
2. Allan Gibson, “Laser pointing and tracking” Proc. SPIE Vol. 4034 (2000)
3. Claude Roddier and Francois Rodier, J. Opt. Am.A,10(11), 2277-2287(1993)
4. Mark A. Ealey and John A. Wellman , SPIE Vol.1543 (1991)
5. V.V.Voitsekhovich and L.J.Sanchez, A&A, 339, 1177-1181(2003)
6. Jun Ho LEE, J. of K Phy soc., 49(1), 139-144(2006)