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Wavefront Compensation Applied to AVLIS Laser Systems

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ABSTRACT

The efficiency of an AVLIS system depends upon the power density and uniformity of the laser system. Because of wavefront aberrations the realized beam quality is not ideal. Wavefront compensation provides a means to improve beam quality and system efficiency.

INTRODUCTION

Atomic Vapor Laser Isotope Separation (AVLIS) systems which employ a copper vapor laser (CVL) as the pump source for a dye laser (DL) amplifier are under development. In these systems there exist many effects which reduce optical quality of the laser beam and thus degrade AVLIS performance. First, the output beam leaving the DL amplifier chain is aberrated. These aberrations are due to errors in the CVL beam which "print through" the amplification process, as well as to optics and atmospheric effects in the DL optics and also to turbulence in the dye flow field. Additional aberrations occur in the DL beam delivery optics, again due to distortions of the optical elements and turbulence within the beam path. Lastly, the path through the separation cell itself contributes to the aberration of the beam. Within the cell, in addition to the thermal and diffraction effects, the beam also is degraded by the atomic absorption and vapor density variations across the cell [1].

Real-time wavefront compensation offers the possibility for active maintenance of the laser beam phase both spatially and temporally. Real-time wavefront compensation systems have been in use for correction of atmospherically induced aberrations for two decades. Similar systems have been fabricated to compensate high energy laser systems for laser-internal beam and thermally induced errors. Thus, the technology presently exists that would allow correction of the beam quality in the AVLIS system. Such a system, capable of correcting only low order spatial and temporal aberrations, has been in operation at the Lawrence Livermore National Laboratory (LLNL) AVLIS system for some time [2].

In this paper, the current performance capabilities of wavefront compensation systems are compared to the requirements of the AVLIS application. From this comparison, a concept for a beam control system is developed. Special attention will be paid to the key parameters of the adaptive optical system, namely correction bandwidth and number of channels. Finally, a low-cost diagnostic wavefront sensor which can be upgraded to support a complete active wavefront compensation system will be described.

ADAPTIVE OPTICAL SYSTEMS

An adaptive optical system includes a means by which the optical propagation path may be modified both spatially and temporally in real time. The use of an adaptive optical system to correct, in real time, for atmospheric disturbances in astronomical observations was proposed in the 1950s [3, 4]. With the advent of laser devices another potential use of adaptive optics, to correct for aberrations of the laser source and the laser beam delivery system, was also proposed. In the last several decades extensive research and development of adaptive optical systems and the associated components technologies has occurred [5, 6, 7]. Most of this development has been for the purposes of astronomy or ground based surveillance/imaging of orbiting satellites. However, because the critical design parameters (i.e., number of channels, control bandwidth and aperture size) of those systems meet or exceed the needs of adaptive optics for a laser beam delivery system the developments are equally applicable.

There are three principal elements of an adaptive optical system: a) a wavefront sensor which measures the error of the optical wavefront; b) a control processor which converts the measurements of the wavefront sensor into correction signals; and c) a deformable mirror which converts the correction signals to optical surface deformations which are thus applied to the optical wavefront. These elements are usually operated as a closed loop control system whereby the corrections introduced by the deformable mirror are subsequently measured by the wavefront sensor. The control algorithm attempts to minimize the errors measured by the wavefront sensor and in so doing minimizes the residuals errors on the optical wavefront leaving the deformable mirror surface. A simple block diagram of the adaptive optics for a laser beam delivery system is shown in Figure 1.

The two parameters which most significantly define an adaptive optical system are the number of channels and the control bandwidth or update rate. The term channels refers most directly to the number of actuator elements in the deformable mirror. It also roughly represents the number of subapertures or sampling elements in the wavefront sensor. The correspondence is fuzzy because slight oversampling with the wavefront sensor is often used to improve system stability. An adaptive optical system designed for atmospheric compensation would have 200-1000 channels and operate at 100-150 Hz. However, for correcting the errors in a laser beam delivery system 60-100 channels should suffice and control bandwidths probably would not exceed 80 Hz. Typically the wavefront sensor and deformable mirror must support update rates of 10-15 times the control bandwidth to insure adequate stability of the control system.

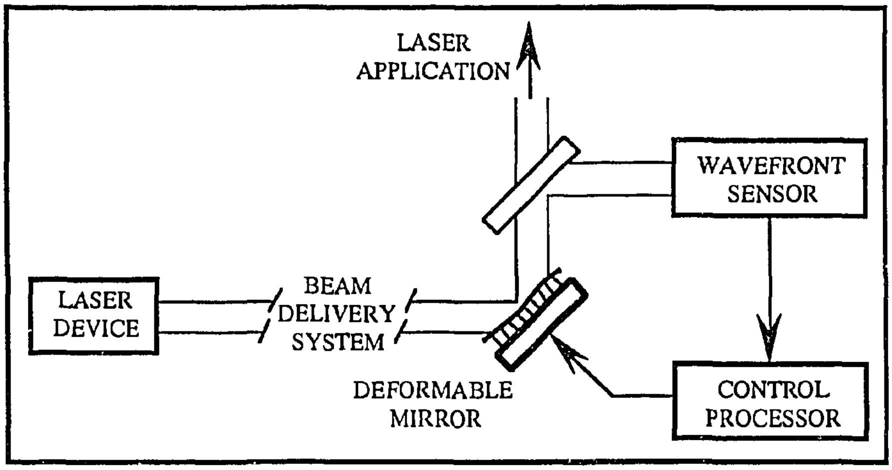

Figure 1. A Simple Schematic of an Adaptive Optical System.

The most common method for measuring the errors of a wavefront is by interferometry in which the wavefront to be tested is combined with a high quality plane wave. The resulting interference fringes encode the OPD of the test wavefront. Typically the wavefront sensor in an adaptive optical system does not have access to a high quality plane wave which is coherent with the test wavefront. In addition, the wavefront sensor rarely has sufficient signal to construct a plane wave internally (e.g., by spatially filtering a portion of its input). To overcome this constraint wavefront sensors interfere the input wavefront with a modified copy of itself (typically the copy is laterally offset or "sheared"), thereby encoding the phase information into an intensity fringe pattern [8, 9]. Such devices are referred to as shearing interferometers.

Another method for measuring the wavefront errors derives from the classical Hartmann test [10]. In this approach, the aperture of the wavefront sensor is subdivided in many small subapertures. In each subaperture a simple lens form a focused spot the position of which encodes the errors of the incident wavefront. A pictorial representation of the Hartmann method is shown in Figure 2. The Hartmann sensor requires precise and stable alignment of the subaperture lenses and the detector plane which only became practical with the development of microlens array technology [11].

Whether the wavefront errors are measured using a shearing interferometer or a Hartmann sensor, the characteristic size and number of the sampling subapertures will be set by the detector pixels. Similarly the sampling rate and ultimately the control bandwidth of the adaptive optics are set by the detector frame rate. Thus high frame rate, large area focal plane array (FPA) detectors represent a critical technology for the development of practical adaptive optical systems. Advances in silicon FPA technology based on charge-coupled devices have yielded detectors with the necessary characteristics. A typical adaptive optical system might use a 1024x1024 FPA framing at 50-100 Hz. For atmospheric compensation systems higher frame rates are necessary and subsequently the array size is reduced.

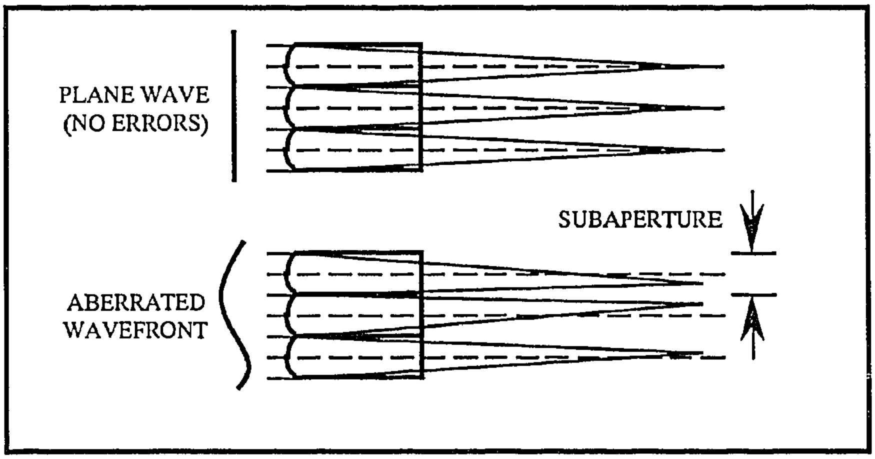

Figure 2. The Hartmann Wavefront Measurement Method.

The second element of the adaptive optical system which we will discuss is the deformable mirror (DM). The critical function of the DM is to covert electrical signals into motion of an optical surface. Most often piezoelectric type materials are used to construct small actuators whose length can be modified by the application of voltage. These actuators are then bonded to thin membrane which is fabricated with a reflective, high quality optical surface on the opposing face [12]. Other technologies for deformable mirrors have been investigated with less success. Unlike FPAs which benefit from the miniaturization associated with integrated circuit technology, DMs are fabricated with relatively large scale components. Thus a typical 100 channel adaptive optical system would use a Hartmann sensor with subapertures measuring a few hundred microns but with a DM which has 5-10 millimeter actuator separation.

Of particular importance to the application of adaptive optics to laser beam delivery systems is the power loading capacity of deformable mirrors. Deformable mirrors have been constructed with a series of water channels integrated into the mirror membrane to remove heat deposited into the mirror under high power applications [13]. Such a deformable mirror could accommodate the power levels encountered in a typical materials processing laser system.

Of the three primary elements of the adaptive optical system, the control processor is the most complex. This is because the control processor must perform a myriad of functions. In the real time data path the control processor performs a series of algorithms to convert the wavefront sensor measurements into control signals for the deformable mirror. These algorithms are depicted in Figure 3. First, the processor must convert the pixel intensities into a wavefront phase metric. For a shearing interferometer this conversion takes the form a multi-bin phase detection algorithm. In the case of a Hartmann sensor a centroid location algorithm is used. In all cases, the wavefront measurement data must be corrected for instrument errors. This may include correcting for response variations in the FPA as well as subtracting the phase errors introduced by the wavefront sensor optics.

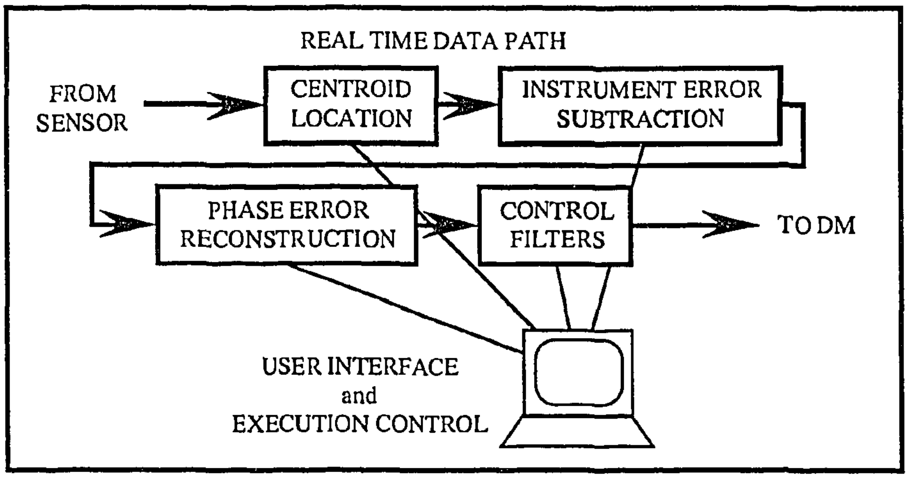

Figure 3. Schematic of Control Processor Elements.

Both a shearing interferometer and a Hartmann sensor result in a wavefront metric which is related to the derivative of the phase errors; therefore the second algorithm step involves reconstructing the phase errors from these derivatives. This is usually accomplished by an inverse matrix multiplication. The matrix includes not only the relation between sensor measurements and phase errors but also the relation between deformable mirror actuator motion and the optical phase introduced by the deformable mirror surface. The second relationship is included because moving a single actuator usually produces a non-localized mirror deformation. This deformable mirror characteristic is called the influence function.

The output of the reconstruction algorithm represents the instantaneous errors at each of the deformable mirror actuators. The final algorithm step is a control filter which converts the error signal to actuator commands. The filter algorithm is typically a simple integrator and low pass filter. However, the control algorithm may, in addition, remove or modify low order spatial modes such as tilt and focus either to apply these to separate special purpose active optical elements or to otherwise modify the system optical output.

In addition to the real time data processing, the control processor must also coordinate software execution and system configuration. In typical operation, wavefront sensor and deformable mirror calibration data must be collected, post processed and stored for use within the real time algorithms. Also one or more sets of reconstruction matrices and control filter coefficients must be loaded and potentially switched during operation. Finally, given the complexity of an adaptive optical system, the control processor usually includes built-in diagnostics for the processing software as well as for the wavefront sensor and the deformable mirror.

Because of the extremely high data throughput of the real time processing algorithms, a special purpose processing architecture is needed. Early adaptive optical systems relied on highly parallel analog electronic circuits to meet this demand. But the tremendous advances in digital integrated circuits has allowed more flexible digital signal processing architectures to meet the adaptive optics processing demands. Still these architectures rely on special purpose VLSI devices to handle the large amounts of data input/output associated with adaptive optics algorithms [14]. Only recently has commercial processing hardware become available which can meet the high data throughput demands of the adaptive optical system processing.

APPLICATION TO AVLIS SYSTEMS

Virtually all laser systems exhibit some degradation of their beam quality from the diffraction limited ideal. There are many potential causes for the corruption of the phase and intensity distribution of a laser beam. They may be broadly categorized as either static or temporally varying and further as to the relative strength of their impact on the phase and/or intensity of the laser beam. An example of a static defect might be a manufacturing error in one of the beam delivery optics. This leads to an error in the phase of the laser wavefront. Depending upon the effective optical propagation distance from the aberrating optic to the isotope separation cell such a phase error may appear as either a phase or intensity error in the beam.

A typical example of a temporally varying beam error is the aberration induced by the heating of the optical element by the impinging laser beam. This heating bends the optical elements thus distorting of the laser wavefront. The time scales for these effects are typically fairly slow (several seconds). Other thermally driven effects involve the generation of turbulence in fluid portions of the beam path. Depending on the type and amount of beam path conditioning these effects will exhibit shorter time scales on the order of 10-100 milliseconds.

Table 1 below summarizes the typical characteristics of a number of aberrations that may affect a materials processing laser system. Comparison of adaptive optical system performance capabilities and the data in Table 1 shows that the range of aberration strengths and time scales that might be encountered in an AVLIS laser system are within the region for which adaptive compensation is possible and has been demonstrated.

Table 1. Typical Aberration Characteristics.

Aberration Type	Strength (λ)	Time scale (sec)	Example
Optics Errors	0.25 - 2.0	Static	Fabrication Tolerance
Laser Quality	0.1 - 5.0	Static	Beam Divergence
Turbulence, Intracavity	0 - 1.0	0.01 - 1	Dye flow field
Turbulence, Beam Path	0.1 - 2.0	0.01 - 1	Atmospheric Turbulence
Thermal, Optics	0 - 30	0.01 - 10	Bending due to Heating
Thermal, Laser	0 - 2.0	0.01 - 10	Mechanical drift of cavity

The anticipated configuration of an AVLIS system which incorporates adaptive optical elements is shown in Figure 4. The primary adaptive compensation would correct the laser wavefront propagating in the isotope separation cell. This single compensation loop could correct both wavefront errors on laser beam leaving the DL and errors introduced by propagation through the separation cell. An optional, additional compensation loop might be used to correct for wavefront errors on the CVL beam before DL amplification. Such a loop could improve the beam quality and amplifier efficiency of the DL.

Returning our attention to the characteristic time scales described in Table 1 and noting that beam path turbulence would present the most rapidly varying disturbance, we would expect to require an adaptive compensation control bandwidth of 80-100 Hz. Similar review of the disturbance strengths would suggest that optic bending will dominate the wavefront profile and might result in as much as 10 waves of OPD error. However, this error will be a low order spatial mode and will therefore drive the dynamic range of the adaptive optical system. The number of channels in the adaptive optical system will be governed by the disturbances with the highest spatial frequencies which again will most likely be beam path turbulence. Without detailed knowledge of the AVLIS system beam path conditioning we can also speculate that a 60-100 channel adaptive optical system would be required.

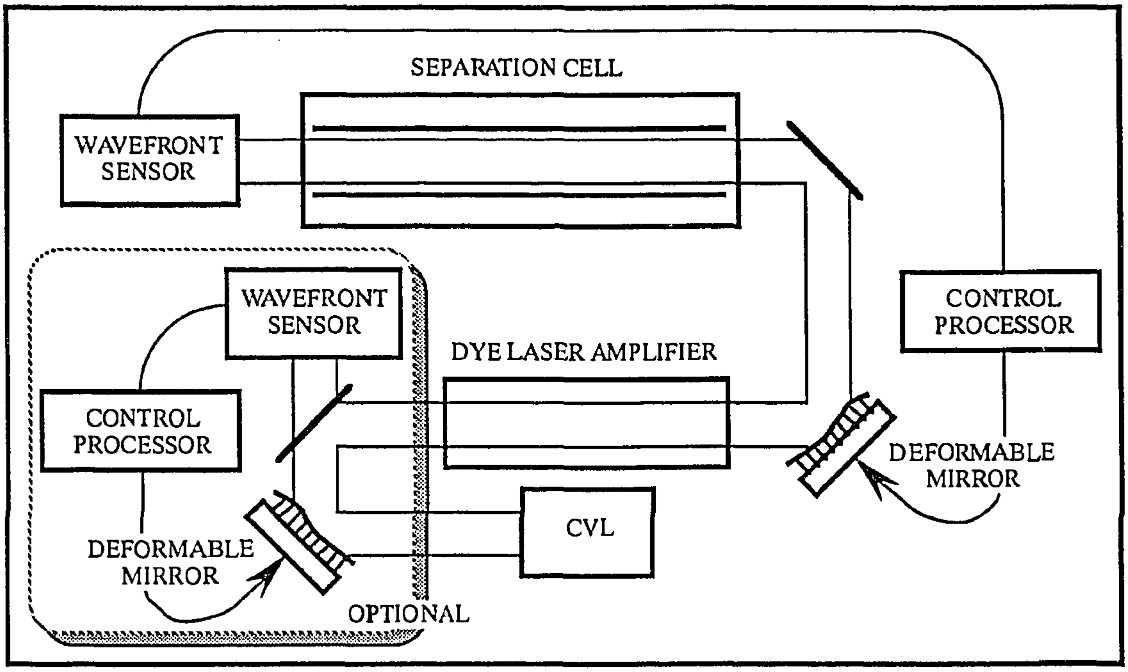

Figure 4. Proposed AVLIS Adaptive Optical System.

United Technologies/Adaptive Optics Associates has recently delivered a diagnostic wavefront sensor and data processor for installation into an AVLIS laser system. This system uses a Hartmann wavefront sensor to measures the incident wavefront on a 32x32 subaperture grid. The wavefront sensor utilizes a fast framing 256x256 silicon detector array which frames at up to 500 Hz. The subaperture data is stored and then processed to obtain high accuracy wavefront error measurements. Since the instrument will initially be used as a diagnostic tool the data processing is performed on a general purpose computer workstation. In the future this system can be expanded with additional processing equipment and a deformable mirror to provide a complete real time adaptive optical compensation system.

SUMMARY

We have described the construction and performance capabilities of typical adaptive optical systems developed for atmospheric compensation. Upon reviewing the anticipated sources of beam degradation in an AVLIS system, we find that adaptive optics can compensate the laser wavefront in these systems. The anticipated requirements for such an adaptive optical system fall well within the current capabilities of adaptive optics technology. We have recently constructed a diagnostic instrument which can be upgraded to provide a full real time adaptive optical system of this type. We anticipate that the diagnostic instrument will enable evaluation of the key system parameters, namely the temporal and spatial frequencies of the optical disturbances affecting AVLIS systems, which will ultimately govern the specification of the adaptive optical system requirements for this application.

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