Programmable holographic optical elements as adaptive optics in optical diagnostics devices

James D. Trolinger, Amit Lal, Joshua Jo, and Stephen Kupiec

MetroLaser Inc.
Ph.: 949 553 0688 Fax: 949 553 0495 E-mail: jtrolinger@metrolaserinc.com

Abstract

This paper reports a combined, Hartmann/Digital Holographic interferometry inspection system for inspecting optical components that do not easily lend themselves to conventional interferometric or Hartmann inspection. A programmable holographic optical element (HOE) preconditions wavefronts to extend the dynamic range of interferometry measurements and also transforms the same system into a scanning Hartmann operation, which has lower resolution but higher dynamic range. Inspecting aspherical surfaces with existing interferometers requires special, computer generated holographic optical elements to transform the wavefront to within the dynamic range of the interferometer. The Hartmann measurement provides the information required to precondition a reference wave that avails the measurement process to the more precise phase shifting interferometry. The SLM offers yet other benefits including a method for minimizing the effects of speckle on the measurement. The paper provides example measurements, discusses the limitations, and suggests other potential applications.

Keywords: Digital holography, adaptive optics, holographic optical elements

1. Introduction

Commercially available spatial light modulators (SLMs) have reached a size and resolution that makes them useful in a wide range of digital electronic holography applications. We are exploring their use as programmable holographic optical elements in myriad optical diagnostics applications where it is useful to have unusual wavefronts available for the measurement, for example, a reference wavefront that is not plane or spherical.

In one application we have integrated an SLM into an instantaneous phase shifting interferometer (PhaseCam®[1]) to extend the dynamic range of the interferometer and also to enable Hartmann sensing in the same instrument. The SLM is employed as a programmable holographic optical element (HOE) that preconditions a wavefront before applying it to inspect an optical component. Wavefront preconditioning enables null testing as well as dynamic range extension.

The same SLM can also be programmed to scan a pencil of light (or multiple pencils) across the test item effectively enabling Hartmann sensing in the same instrument. This allows the instrument to cover a virtually unlimited dynamic range with high spatial resolution and sensitivity. This scanning Hartmann mode also extends the dynamic range and precision by removing constraints that normally limit a conventional Hartmann system as well as providing the information needed to condition the reference or object waves for the subsequent interferometry measurement.

Incorporating these features with MetroLaser's instantaneous phase shifting interferometry technology enhances the power and benefits of digital holographic

[1] PhaseCam is a registered trademark of Four-D Technologies Inc.

interferometry leading to extremely versatile optical inspection tools. Example applications include inspecting ogive shaped windows, biconics, mandrels, and aspherics.

2. Discussion of the concept

Fig. 1 illustrates conceptually how the SLM can enable two methods to be integrated into a single hybrid instrument. The key to this integration is the use of a spatial light modulator (SLM) as an extremely versatile adaptive optical component Shown in the figure as a transmission element transmitting a wave through an object under test, the SLM preconditions the test wavefront either before or after it passes through or reflects from an object under test (SLMs are available either as transmitting or reflecting elements). Such SLMs produce a measurement process that is both dynamic and adaptive, taking interferometry beyond the current state of the art.

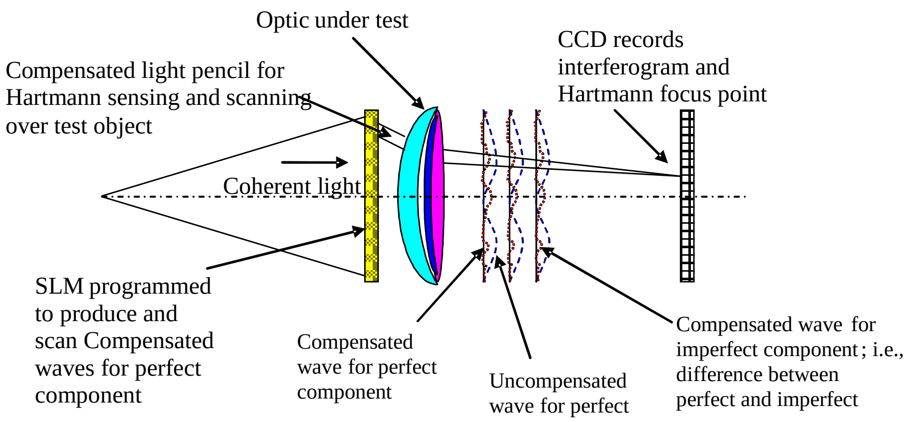


Fig. 1. Conceptual explanation of the concept for hybrid Hartmann and digital holographic interferometry inspection system employing programmable, dynamic adaptive optics.

SLM elements are typically one or two centimeters square in size so that demagnification is required for inspecting larger optical components.

The SLM can be programmed to subtract known, constant information from the test wavefront, leaving only the unknown error to be measured by the wavefront sensor, whether it is Hartmann or Interferometry. This provides a direct route to null point testing of the optical component. The SLM can also be programmed to remove some or all of the wavefront distortion that is anticipated by optics such as freeforms and aspheres, which can extend the dynamic range of the wavefront sensor that is employed to analyze the wavefront.

In the Shack-Hartmann mode the SLM acts as an amplitude element passing light only through a small aperture that is scanned over the test object. The pencil is designed to focus at a predetermined spot on the CCD, and any deviation of the test object from ideal will be reflected in the movement of this spot. If nothing is known about the test object, this measurement, which has essentially an unlimited upper range, can be used to estimate the wavefront needed for preconditioning in the interferometer mode.

In interferometry mode the conditioned wavefront is approximately collimated or spherical after passing through the test object.

Existing interferometers are often employed by inspecting small areas of such optics then stitching the measurements together to produce a phase map for the entire component. Another objective in our work is to produce the measurement with as little data stitching as possible.

3. Digital holographic interferometry

Recent developments in electro-optics and image processing, in general, have led to more advanced variations and applications of interferometry, improving speed, sensitivity, automation, and robustness [1-4]. The central interferometer used in these studies, known as a PhaseCam, is described in detail elsewhere [2, 3]. In summary, the PhaseCam is an instantaneous phase shifting interferometer, originally developed by MetroLaser and currently marketed by 4 D Technologies, Inc. It divides the wave into four segments, with each segment being phase shifted simultaneously relative to the reference wave by different amounts. This allows an instantaneous phasemap derivation from the four independent interferograms without the usual vulnerability to vibration. Various methods have been devised for producing the four phase shifts. Up to now these have been produced by placing a segmented mask directly on the CCD with each segment providing the appropriated phase shift to produce enough independent equations describing the interferogram, to be solvable.

This phase shifting function can, in fact, be performed by the SLM itself eliminating the need of a separate mask. The SLM can emulate the function of essentially any of the masks that are currently used to perform phaseshifting.

4. Hybrid system

Fig. 2 shows one implementation of a hybrid system. The ultimate hybrid system operation will work in the following way: A SLM Hartman software program automatically generates, scans and captures Hartman test patterns, generating the initial ray pencils used by the Hartman Test. The program initially generates a diffraction pattern consisting of “blazed” grating pattern with corrective terms added to the pattern. At present one pencil is generated for simple processing, but multiple pencils may be generated to accelerate processing.

In a conventional Shack-Hartmann sensor, a wavefront is divided into small pencils or rays of light by a microlens array that is usually placed near a CCD camera. Each pencil is then focused onto the CCD and the position of the focus determines the slope of the wavefront across the pencil. The sensitivity of the measurement is determined by the focal length of the lenses in the lens array and the ability to locate the centroid of the focused spots.

There are three constraints in a conventional Hartmann system: 1) Sensitivity requires a longer focal length and then confusion in adjacent light pencils can occur, 2) if the wave is aberrated, the focused spot will not be round, so its centroid is more difficult to locate, further reducing accuracy, and 3) spatial resolution is limited to the diameter of the lenses in the array. Since the SLM is electronically programmable, all three problems can, in principle, be solved by using the SLM to produce a single pencil of light that is preconditioned to pass through the object under test with little or no aberration and onto the CCD. Since the SLM is dynamic, the ray can be scanned over the test object, employing any desired focal length, eventually mapping out the entire test object. The selection of pencils with the SLM enables avoiding the usual problem in Hartmann sensing where pencils can overlap for highly distorting optics. In this way, all three problems can be solved.

The number of scan points is limited only by the pixel size, so there is virtually no spatial resolution limit for scanning an optical component. In principle, a Shack Hartmann measurement of this type could produce high resolution and sensitivity; however, the measurements take time, are sequential, and would not compete with the snapshot being produced by the interferometer for most applications.

We have tested the system with a variety of optical elements that are accurately known, so to assess the accuracy of the measurement. This work is still in progress and exact characteristics of the measurement accuracy will be published later.

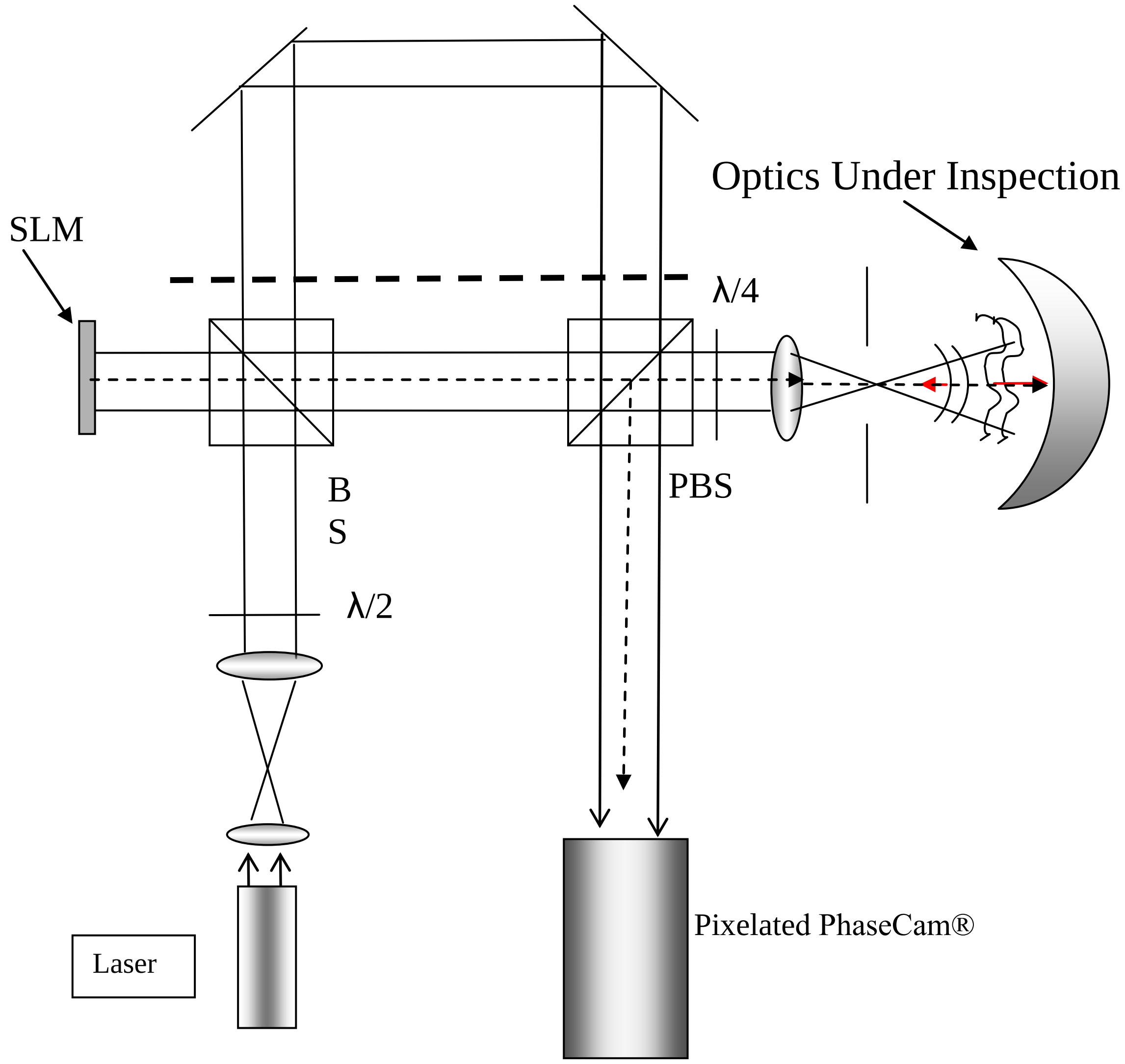
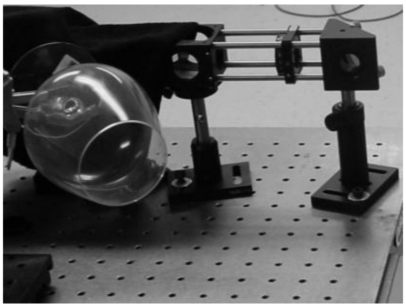


Fig. 2. Hybrid inspection system. To convert the system from interferometry to Shack-Hartmann sensing, the optics above the dashed line are blocked, the SLM scans a light pencil over the optics, and the PhaseCam is used simply as an imaging device to track the focused light pencil.

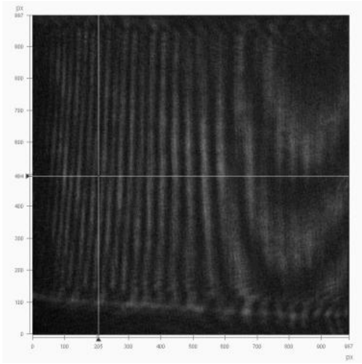
As a measurement exercise of an unknown aspheric Fig. 3 shows the system employed to characterize the optical properties of a wineglass. In this case, the system was able to compensate for a very sharp, near discontinuity in the wavefront. Still some error still remains in the final interferogram and this conversion of the PhaseCam data for programming the SLM is still being refined.

5. Conclusion

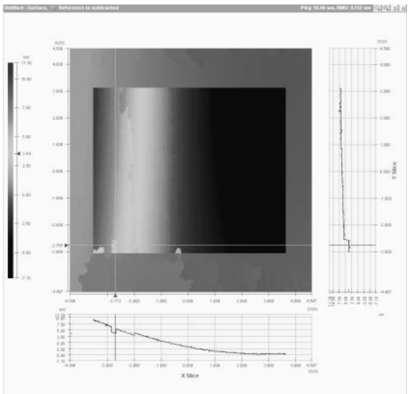
The foregoing presents a series of concepts for employing now commercially available SLM's as programmable holographic optical elements to enhance the performance of digital phase shift interferometry. The dynamic range of an inspection system can be extended by orders of magnitude by wavefront preconditioning and by hybrid operation of the system between Hartmann sensing and interferometery. The work has shown that optical components that cannot be inspected in conventional interferometers will be measurable with such a system.



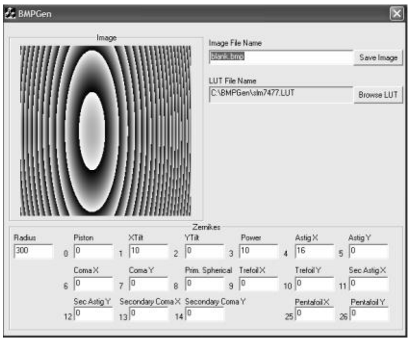
a) Wineglass



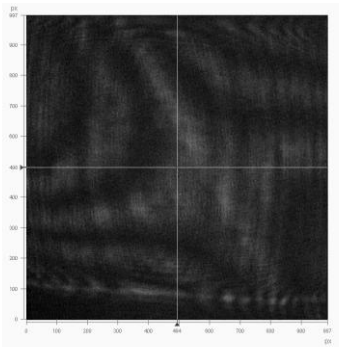
b) Measured by PhaseCam



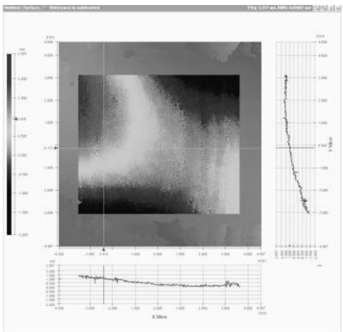
c) Wavefront error



d) Wavefront applied to SLM



e) Interferogram with preconditioned wavefront



f) Compensated wavefront

Fig. 3. Measuring the optical quality of a wineglass.

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