Motivation for a coherence gated wavefront sensor (CG)-SH/WFS

1. Introduction

Due to the limited numerical aperture in the beams associated with each microlenses in the lenslet array, a Shack – Hartmann wavefront sensor (SH/WFS) has little sensitivity to the position in depth in the object where the signal comes from. This makes the SH/WFS insensitive to depth variations of aberrations, and stray reflections from the interface optics cannot be rejected and therefore supplementary spatial filters need to be employed in the interface optics.

2. Method

Elimination of stray reflections and operation as a depth resolved WFS can be achieved by incorporating principles of coherence gating. We are evaluating solutions using a physical lenslet array in opposition to a virtual lenslet array proposed earlier [1].

3. Two procedures have been evaluated [2] which are still subject of ongoing research, operating in time domain and spectral domain: phase shifting interferometry and swept source based interferometry respectively.


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A coherence gated wavefront sensor is built based on a Shack-Hartmann wavefront sensor and a Mach-Zehnder Interferometer. A broadband light source is employed as the light source. A 500 fps CMOS camera is used as the detector to provide a high operating speed. The time-domain coherence gating is applied using phase shifting interferometry method. 125 wavefront measurement per second is achieved using this method. Depth resolved wavefront measurements are performed to test the capability of rejecting stray light and selecting depth-related aberration. A 5-layer target is fabricated with 2 piece of thin microscope slides and a piece of silver-coated mirror. Deliberated tilts and defocus was created by inserting the 5-layer target, which allows the system to measure the depth-related aberrations from each individual surface of the target. The results are published in J. Wang and A. Gh. Podoleanu, "Demonstration of real-time depth-resolved Shack-Hartmann measurements," Opt. Lett. 37, 4862-4864 (2012). DOI: 10.1364/OL.37.004862 (Open access).

Abstract: Shak–Hartmann wavefront sensors (SH-WFS) have little sensitivity in depth and hence are unsuitable for microscopy and are limited for retinal imaging. We demonstrate the first direct Shack–Hartmann measurement of wavefront originating from a multiple-layer target, in the presence of significant stray reflections that render a standard SH-WFS inoperable. A coherence-gate SH-WFS is implemented by adding time-domain low-coherence reflectometry gating to an SH-WFS configuration. The depth resolution is determined by the operational depth selection of the coherence gate, much narrower than the depth range of the SH-WFS. Five distinctive wavefronts are measured from five layers of a multiple-layer target. This paves the way toward depth-resolved wavefront sensing, which can significantly improve adaptive optics closed loops applied to microscopy and imaging of the retina.

Details of the setup and the method were previous described in "Time-domain coherence-gated Shack-Hartmann wavefront sensor," in Optical Coherence Tomography and Coherence Techniques V, R. Leitgeb and B. Bouma, eds., Vol. 8091 of Proceedings of SPIE-OSA Biomedical Optics, OSA, 2011. DOI:10.1117/12.889567

Abstract: In the present paper we investigate the possibility of narrowing the depth range of a physical Shack-Hartmann wavefront sensor (SH-WFS) by using coherence gating. We have already demonstrated a low coherence interferometry (LCI) set-up, capable of generating similar spots patterns as a conventional SH-WFS and also capable of eliminating stray reflections. Here, we evaluate the accuracy of wavefront measurements using a coherence-gated (CG)/SH-WFS. This is based on a Mach-Zehnder interferometer combined with a SH-WFS, that implements time-domain (TD)-LCI acquisition. The wavefront measurement errors introduced by the non-uniform distribution of the reference power over the photo-detector array were investigated. The effect on the centroid nodes accuracy due to different numbers of phaseshifting interferometry (PSI) steps applied was also evaluated. This novel technique has the potential of providing depth resolved aberration information,
which can guide better correction in adaptive optics assisted OCT and confocal imaging instruments.

The coherence gated wavefront sensor is a very sensitive device not only on wavefront aberration but also on the axial variation of reflective index change inside the target. We performed more experiments using the setup by changing the parameters of the wavefront sensor and applying a technique of dynamic centroiding. The performance of the coherence-gated wavefront sensor is compared with a commercial SH-WFS in measuring a reflective surface. These together with real-time wavefront measurements from a scattering sample are also presented in Jingyu Wang; Adrian G. Podoleanu; Tuning parameters and performance of a real-time depth-resolved wavefront sensor. Proc. SPIE 8914, International Symposium on Photoelectronic Detection and Imaging 2013: Fiber Optic Sensors and Optical Coherence Tomography, 89141G (August 29, 2013); doi:10.1117/12.2035314.

Abstract: In this report, we demonstrate characteristics and parameters of a coherence-gated Shack-Hartmann wavefront sensor (CG/SH-WFS) that is capable of measuring depth-resolved wavefront aberrations. A technique of dynamic centroiding is applied to CG/SH-WFS images and its precision is evaluated. The performance of the CG/SH-WFS system is compared with a commercial SH-WFS measuring a reflective surface. Real-time wavefront measurements from a scattering sample are also presented. The experiments demonstrate that the performance of CG/SH-WFS can replace conventional SHWFS and also provide its unique advantages. © (2013) COPYRIGHT Society of Photo-Optical Instrumentation Engineers (SPIE). Downloading of the abstract is permitted for personal use only.

The same optical setup is also capable of doing spectral-domain acquisition using a wavelength tunable light source and a fast camera. As the wavelength of the light source is tuning, the camera records a sequence of spectrum-indexed images of SH spots. The images are then processed by applying Fourier transform to spectral-indexed image data pixel by pixel. The result is a 3D image volume that contains SH spot from consecutive depths, which are used to access the depth-resolved aberrations. This method was demonstrated in Jingyu Wang; Adrian G. Podoleanu; Real-time depth-resolved Shack-Hartmann measurements. Proc. SPIE 8802, Optical Coherence Tomography and Coherence Techniques VI, 88020B (June 18, 2013); doi:10.1117/12.2032507.

abstract

We demonstrate a direct Shack-Hartmann wavefront sensing method that allows depth-resolved measurements. A coherence-gate Shack-Hartmann wavefront sensor (CG/SH-WFS) is implemented by adding low coherence reflectometry gating to a SH-WFS. The depth resolution is determined by the coherence gate, much narrower than the depth range of the SH-WFS. Distinctive wavefronts are measured from five layers in a multiple-layer target. This paves the way towards depth-resolved closed-loop adaptive optics assisted microscopy and imaging of the retina.

Abstract: In this report we demonstrate results of measuring wavefront aberrations from different depths in a fabricated phantom using a coherence-gated Shack-Hartman wavefront sensing technique (CG-SH/WFS). The SH/WFS is equipped with a Mach-Zehnder interferometer and the coherence gate operates on principles of swept source (SS) interferometry. The CG-SH/WFS is able to differentiate wavefront signals from different depths separated by a depth resolution of 7.1 micron. The CG-SH/WFS delivers a similar SH spot pattern as that provided by a conventional SH/WFS. Due to the coherence gate, the sensor is capable of eliminating stray reflections. Hereby we present the results of measuring depth-resolved wavefront aberrations. The method is robust and all depth-resolved aberrations are recorded simultaneously without any mechanical movement. This technique has the potential of providing depth resolved correction in adaptive optics assisted ophthalmology imaging and in nonlinear microscopy.