Available online at www.sciencedirect.com

SCIENCE DIRECT®

Sensors and Actuators A 109 (2004) 220–230

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

High-speed wavefront sensor compatible with standard CMOS technology

D.W. de Lima Monteiro[*], G. Vdovin, P.M. Sarro

Electronic Instrumentation Laboratory, EEMCS/DIMES—Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands

Received 22 January 2003; received in revised form 6 October 2003; accepted 20 October 2003

Abstract

This paper addresses the design, implementation and performance of an integrated Hartmann (–Shack) wavefront sensor suitable for real-time operation and compatible with standard CMOS technology.

A wavefront sensor can be used to detect distortions in the profile of a light beam or indirectly in that of an optical component. Such a sensor can also be coupled to a deformable mirror to enable the compensation of the detected distortions in a light beam. These adaptive optical systems find more and more applications in astronomy, industry and have recently been introduced in medical setups.

We use the Hartmann wavefront-sensing method, in which a light beam is sampled into a number of sub-beams, which are projected on a plane. The displacements of the light spots on this plane are used to estimate the profile of the associated arbitrary wavefront. Usually, a conventional image sensor registers the light spots and an image-processing algorithm computes their displacements from a reference grid. However, this approach restricts the operational speed of the sensor because it relies on the frame-transfer rate of the imager and on the rather slow data-reduction algorithm.

The novel contribution of this work is that, to render faster operation, we introduce a Hartmann wavefront sensor that uses an addressable matrix of CMOS integrated position-sensitive detectors, namely quad cells. Each sampled light spot is associated with a quad cell such that direct information about the spot-centroid displacement is available.

Each particular application has its own requirements and the developed sensor, which should be used with light sources in the visible spectrum, shall perform well for applications involving enough light (>0.5 mW beams), and there where lower-order wavefront aberrations are expected (<30 Zernike terms). However, this sensor can be modified in a variety of ways to attend to particular applications. The fabricated sensor allows operation at rates higher than 3 kHz.

Keywords: Wavefront sensor; Adaptive optics; Position-sensitive detector; Quad cell; CMOS

1. Introduction

Deviations from the optimal profile of an optical component can severely affect the component's performance. Over the years, optical profile tests have evolved from the work of craftsman to systematic test procedures and the profile analysis ranges from that of micrometric components to that of components which are several meters large. The demand for a combination of three test features, namely accuracy, capability of real-time analysis and low cost, has been steadily increasing. To date, several test methods and setups are available [1], but there is still a lack of an inexpensive compact real-time device capable of quantitative analysis.

This paper addresses the proposition, design and implementation of an integrated device, a wavefront sensor, suitable for real-time optical-profile analysis. This sensor was also coupled to a deformable mirror resulting in a system able to dynamically detect and correct optical aberrations.

In wave optics, a wavefront is a hypothetical surface defined as the loci of all points of a given wave featuring the same phase. In geometrical optics, a wavefront is defined as a continuous surface having normals parallel to the light rays, where the rays represent the direction of energy propagation.

When a light beam passes through an optical component, or is reflected by it, its shape becomes imprinted on the wavefront, whose subsequent detection reveals the profile under test. Although interferometric methods are the leading solutions in optical-profile testing, they have several inherent limitations, such as the need of highly coherent sources, sensitivity to vibration and the ill-posed mathematical problem

---

[*] Corresponding author. Tel.: +31-15-278-6285; fax: +31-15-278-5755.
E-mail address: davies@titus.et.tudelft.nl (D.W. de Lima Monteiro).

0924-4247/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2003.10.039

associated with interpreting an interferogram. These drawbacks favored the implementation of alternative optical tests based on either irradiance measurements or geometrical optics, e.g. the Hartmann technique explained in the next section.

As a diagnostic tool a wavefront sensor can be used, for instance, in optical shop testing, analysis of fluid dynamics and ophtalmology [2–4]. When the sensor is part of a closed-loop adaptive-optical-system, the sensor is coupled to an adaptive mirror to improve the quality of a light beam or that of an image; the sensor measures the wavefront distortions and the flexible mirror adjusts its surface to compensate for them [5]. This might be useful in astronomical imaging, ground-based free-space optical communications and retinal imaging, for example. Dynamic operation at high refresh rates is demanded there where the propagation media, or surfaces, affecting the wavefront change rapidly.

2. Hartmann wavefront sensor

The conventional Hartmann sensor consists of an opaque mask with a grid of sub-apertures placed parallel to an image sensor, and at a distance D from it. A light beam at the mask is sampled into individual light beams at the sub-apertures. The displacement of each spot on the imager plane is proportional to the respective sub-beam tilt, which is associated with a local tilt (slope) of the wavefront. When a perfectly collimated light beam impinges perpendicularly on the mask, each spot on the imager plane is located under the center of the respective sub-aperture. On the other hand, any aberrated wavefront causes the spots to depart from their reference positions, as can be seen in Fig. 1. In practice, the spot displacement is proportional to the average tilt over the sub-aperture. An arbitrary tilt can be decomposed in x and y components, as in Eq. (1).

$$\frac{\mathrm{d}W}{\mathrm{d}x} = \tan\theta_x = \frac{\Delta x}{D}, \qquad \frac{\mathrm{d}W}{\mathrm{d}y} = \tan\theta_y = \frac{\Delta y}{D}, \tag{1}$$

where Δx and Δy are the spot-centroid displacements in the x and y directions, respectively. The registered displacement on the detector plane is that of the centroid of the spot intensity distribution $H(x,y)$, as given by Eq. (2).

$$\Delta x = \frac{\iint H(x, y)x\,\mathrm{d}x\,\mathrm{d}y}{\iint H(x, y)\,\mathrm{d}x\,\mathrm{d}y}, \qquad \Delta y = \frac{\iint H(x, y)y\,\mathrm{d}x\,\mathrm{d}y}{\iint H(x, y)\,\mathrm{d}x\,\mathrm{d}y}. \tag{2}$$

As the sampling plane, an advantageous alternative to the Hartmann mask is a close-packed microlens array, in which case the sensor is referred to as a Hartmann–Shack sensor. The main advantages of substituting a perforated opaque mask with a microlens array are its higher light-power collection efficiency and the reduction of aliasing. This latter effect is associated with sampling high wavefront spatial frequencies with an insufficient number of sub-apertures.

3. The concept of a custom wavefront sensor

For a Hartmann wavefront sensor, the detector part can be in principle a conventional charge-coupled device (CCD) or a CMOS imager, however often none of these features frame rates higher than 75 Hz, unless costly specialized imagers are meant. Furthermore, their output is a bitmap which must be processed to yield the positions of the centroids of the light spots.

We propose the implementation of a chip with an integrated matrix of CMOS optical position-sensitive detectors (CMOS PSDs) instead of a conventional imager [6–9]. In this configuration, each sampled light spot falls on the surface of a particular PSD, whose output is directly proportional to the spot position. In contrast to an imager, the matrix of PSDs yields nearly direct information about the spots displacements rendering image processing unnecessary, which favors a much faster operation of the sensor. A diagram depicting the conventional and proposed approaches is shown in Fig. 2.

Simultaneous work in this direction has been reported by Droste and Bille [10] and Nirmaier et al. [11]. Both CMOS chips feature multiple-pixel PSDs and adjoining winner-take-all circuitry to determine the positions of the spots [12]. The first chip determines each spot position based on its intensity maximum, and the second has also a virtual-centroiding feature embedded in addition to the maximum-intensity circuit. Although these two sensors

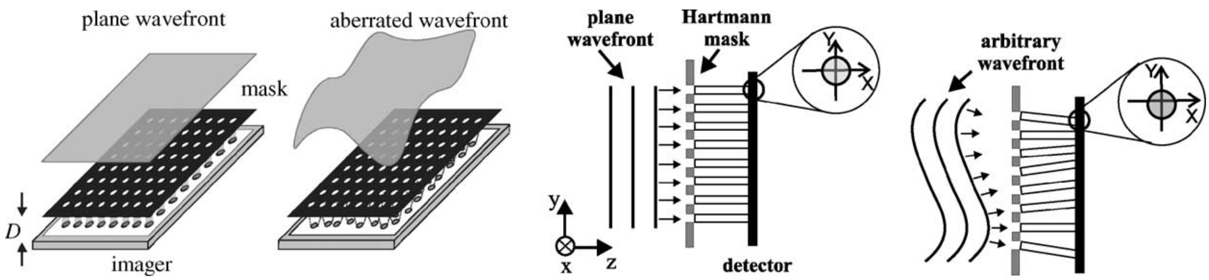

Fig. 1. Schematics of the Hartmann setup for an incident plane wavefront and an aberrated one.