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GPU-based processing of Hartmann–Shack images for accurate and high-speed ocular wavefront sensing

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HIGHLIGHTS

- GPU-based high-speed processing of Hartmann–Shack wavefront sensor images.
- A robust and accurate centroid detection algorithm based on dynamic pyramidal search.
- A highly-parallel pupil tracking algorithm for Hartmann–Shack wavefront sensor images.
- Parallel high-speed wavefront map calculation.

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ABSTRACT

Hartmann–Shack aberrometry is a widely used technique in the field of visual optics but, high-speed and accurate processing of Hartmann–Shack images can be a computationally expensive/resource intensive task. While some advancements have been made in achieving high-performance processing units, they have not been specifically designed for processing Hartmann–Shack images of the human eye with Graphics Processing Units. In this work, we present the first full-Graphics Processing Unit implementation of a Hartmann–Shack sensor algorithm aimed at accurately measuring ocular aberrations at a high speed from high-resolution spot pattern images. The proposed algorithm, called PaPyCS (*Parallel Pyramidal Centroid Search*), is inherently parallel and performs a very robust centroid search to avoid image noise and other artifacts. This is a field where the use of Graphics Processing Units have not been exploited despite the fact that they can boost Adaptive Optics systems and related closed-loop approaches. Our proposed implementation achieves processing speeds of 380 frames per second for high resolution (1280x1280 pixels) images, in addition to showing a high resilience to system and image artifacts that appear in Hartmann–Shack images from human eyes: more than 98% of the Hartmann–Shack images, with aberrations of up to 4 μ m Root Mean Square for a 5.12mm pupil diameter, were measured with less than 0.05 μ m Root Mean Square Error, which is basically negligible for ocular aberrations.

1. Introduction

Optical aberrations are defined as the difference between the perfect (flat or spherical) wavefront for an ideal optical system and the bumpy wavefront generated by a real optical system. Optical aberrations (defocus, astigmatism, coma, etc.) cause deviations to the rays of the light beam, therefore preventing them from converging to a single focusing point and blurring the image. Wavefront sensing, i.e., optical aberration measurement, is routinely performed in a wide range of fields (e.g., Astronomy, Microscopy, Communications) for different purposes (e.g., optical quality determination, instrument calibration, optical design) [1]. Wavefront sensing is also pivotal in most Adaptive Optics (AO) systems, widely used in astronomy and vision science. AO aims to dynamically correct the fluctuating aberrations of a system in *real time* by means of a wavefront corrector (deformable mirror or liquid-crystal modulator) whose shape or refractive index distribution can be modified point-by-point to reshape the wavefront [2]. Due to the dynamics of the aberrations, an AO system requires very fast wavefront sensing and image processing, therefore, being a computationally intensive process. As wavefront sensing involves heavy image analysis and processing, it is an intrinsically parallelizable task which makes the use of General Purpose Graphic Processing Units (GPGPUs) a perfect candidate to achieve real time processing speeds.

The Hartmann–Shack (H–S) wavefront sensor, described in 1971 [3], which is based in the sensor proposed by Hartmann

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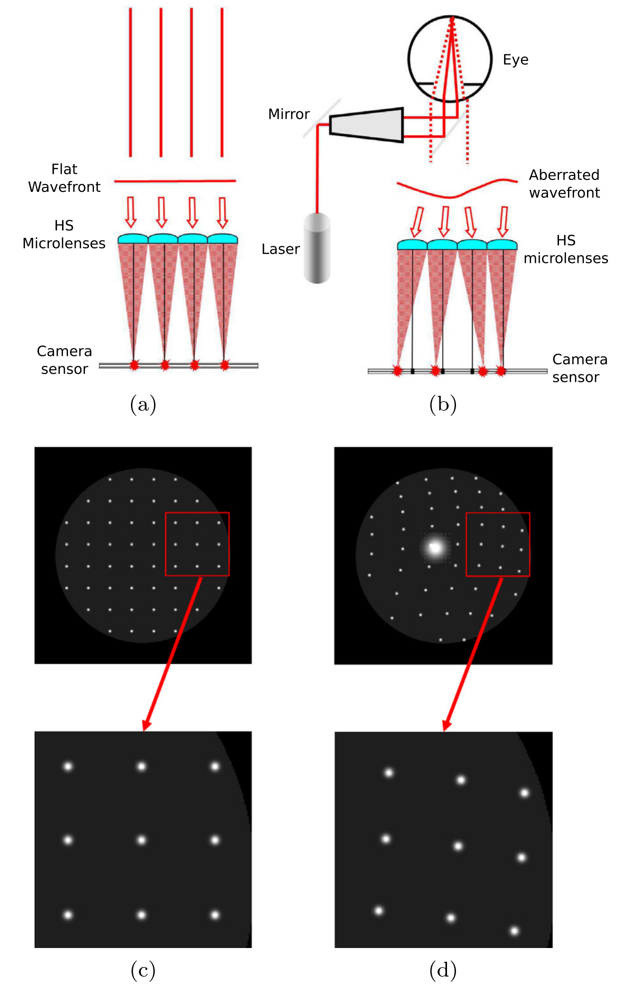

Fig. 1. (a) H–S wavefront sensor diagram registering a flat wavefront. (b) H–S wavefront sensor diagram registering an aberrated wavefront. (c) Obtained H–S spot image for the perfect wavefront. The whole eye is shown on top and a zoomed area below. (d) Obtained H–S spot image for the aberrated wavefront, including a corneal reflection. Whole eye is shown on top, zoomed area below.

in 1900 [4], is the most widely used aberration measurement approach nowadays. The H–S sensor consists of an array of microlenses, which sample the aperture of the optical system, and an image detector that records the spot pattern generated (commonly called the H–S image). For an ideal system, each microlens focuses the collected wavefront into its focal point and a regular spot pattern is recorded (Fig. 1(a) and (c)). For a real system, the wavefront irregularities cause local slopes over each microlens, resulting in a distorted spot pattern (Fig. 1(b) and (d)). The displacement of each spot with respect to its ideal location (i.e., the focal point of each microlens) is related to the wavefront's local tilt, which in turn is related to the wavefront's local derivative. The H–S wavefront sensing operation, therefore, consists of recording the spot pattern, calculating the position of each spot (i.e., its center of mass or *centroid*), computing each centroid displacement in x and y directions and, finally, integrating these set of local derivatives to finally obtain the wavefront shape or aberration map (as that depicted in Fig. 5).

In this paper, our main focus is on measuring the aberrations of the human eye. Considering this special optical system is far from perfect, which results in a limited visual quality, measurement of the eye's aberrations, also known as *ocular aberrometry*, is a very important field of study. Over the last two decades, Ophthalmology and Vision Science applications have been a catalyst for wavefront sensor development [5]. There are several commercially available aberrometers for clinical use, most of them based on the H–S principle, and many other research apparatuses and prototypes, recently including binocular and open-view configurations [6]. In many cases, ocular aberrations are used for diagnosis and/or prescription of corrective optics but there are also Adaptive Optics systems for ocular applications [7,8]. It is important to note that, given the fact that the human eye is a living system – closed, mobile, and fragile – *ocular aberrometry* is somewhat idiosyncratic and not completely interchangeable with other optics areas that deal with artificial systems (e.g., telescopes, microscopes, camera lenses). For example, H–S images from living human eyes suffer from corneal reflections (which severely degrade the spot images, as displayed in Fig. 1, right) and brightness irregularities due to crystalline lens reduced transparency as an effect of aging, in addition to temporal fluctuations in spot intensity across the pupil due to the tear film and other factors.

In this paper we present a parallel Hartmann–Shack wavefront sensing algorithm for accurate yet high-speed ocular aberrometry. The proposed core algorithm, called PaPyCS (*Parallel Pyramidal Centroid Search*) parallelizes the centroid detection phase while performing a very robust centroid search, to make the algorithm immune to the aforementioned issues that degrade ocular H–S spot images. PaPyCS has been parallelized and optimized for GPGPUs as it will be detailed in Section 3. In addition to the spot detection and centroid search phase, polynomial fitting of the aberration and wavefront map calculation have been parallelized using the GPU as well. The pupil tracking algorithm, which is another crucial component in the process, as we will discuss later, has also been parallelized in the GPU. Experimental results show that our full approach achieves a speedup above 100× compared to its corresponding sequential implementation. This enables a high speed processing (up to 380 frames per second on 1280 × 1280 pixel images), while not sacrificing detection accuracy (more than 98% of the H–S images with aberrations up to 4 μm were measured with RMS-Error lower than 0.05 μm).

The key contributions of this paper are: developing a GPU-based high-speed implementation capable of processing H–S wavefront sensor images; creating a robust and accurate centroid detection algorithm based on dynamic pyramidal search; implementing a highly-parallel pupil tracking algorithm for Hartmann–Shack wavefront sensor images; and developing a parallel high-speed wavefront map calculation.

The remainder of this paper is organized as follows. Section 2 provides some background on H–S wavefront sensing and further motivates this work. In addition, Section 2 reviews the most relevant literature on real-time H–S image processing. Section 3 describes our parallel GPU-based implementation. In Section 4 we evaluate and report its performance and accuracy. Finally, Section 5 summarizes the main conclusions of the work.

2. Motivation and related work

2.1. Background and motivation

When measuring the wavefront and aberrations of a living optical system such as the human eye, H–S images must be processed to first detect the centroid of each spot of the microlens array, and then the wavefront aberration can be reconstructed from the set of spot displacements — similarly to other artificial optical systems such as telescopes.

However, as mentioned in the previous section, H–S spot images from a living human eye suffer from an important number of inherent problems that can seriously jeopardize the accuracy of the measured aberration. For example, instead of the typical single-pass arrangement, an *ocular* H–S always works in double-pass