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4D Light Field Ophthalmoscope: a study of plenoptic imaging of the human retina

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Abstract: The application of 4D Light Field technique to retinal imaging is proposed as a multi-modality imaging device. A feasibility study developed with numerical simulations is presented
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1. Introduction

The retina in the human eye is a complex three-dimensional (3D) structure consisting of distinct layers. There are a number of challenges faced when imaging the retina in-vivo. The retina is an organ whose function is to absorb light and hence the illuminating light levels should be high enough to get sufficient backscattered light, but not too high in order not to damage it. Another issue is the presence of non-negligible levels of aberrations that change dynamically due to the fact that the eye is a living organ constantly in motion [1,2] These aberrations should be corrected in order to get the best possible resolution. The voluntary and involuntary saccadic eye movements results a target constantly in motion during the imaging process, therefore a rapid image acquisition would be preferable.

The four dimensional (4D) Light Field Ophthalmoscope (LFO) addresses these issues. Acquiring the 4D Light Field, as discussed below, yields significantly more information carried by the light reflected by the retina and enables numerous post processing operations leading to a multi-modality retinal imaging device capable of 3D imaging, especially topographic imaging, stereo imaging, aberration correction and with the potential of further capabilities. Imaging the eye is a new application of a 4D Light Field device, and poses new challenges to this technique due to the complexity of the anatomy of the object of study.

2. 4D Light Field and its application to retinal imaging

The 4D Light Field is defined as a four dimensional function, also known as plenoptic function, representing radiance along rays as a function of position and direction in space [3]. Therefore a device that is capable of recording the light field will not only give a two dimensional irradiance pattern of the object, but will also contain more information about the path travelled by light to reach the image plane. It follows that through post processing of the 4D Light Field a number of applications are feasible, such as 3D topographic rendering, synthetic refocusing and aberration correction.

The Light Field is recorded by placing a micro-lenses array on the conjugate plane of the object plane, in our case the retina [4,5]. The photo sensor will be placed at the conjugate plane of the main lens as shown in figure 1. The microlens plane gives the spatial coordinates of the image plane. Each micro lens could be considered as a macro pixel of the final image whose coordinates are s and t while each sub-image under each microlens gives directional coordinates u' and v'. Under each microlens there will be a sub image of the principal lens, subsequently directional coordinates u' and v' are correlated with coordinates u and v on the main lens. Rays of light coming from the same region of the main lens will fall on the same pixel relative to each microlens [5]. This set of four coordinates gives the Light Field, or plenoptic, function $L(s,t,u,v)$ [4]. The presence of two additional directional coordinates gives information about the origin of the rays. One of the most important features of a 4D Light Field application to the eye is that in one snapshot, information regarding the 3D topography and the different layers of the retina are captured and this minimizes the issue of eye movements during the imaging process.

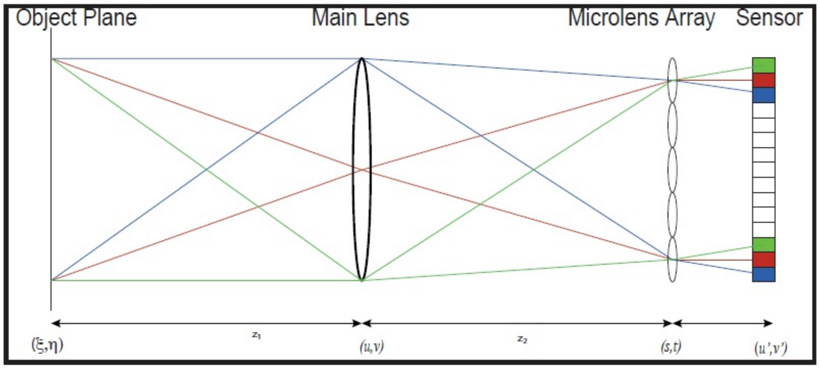

Fig. 1: Recording of the Light Field: rays originating at the same point (ξ,η) in the object plane fall on the same microlens *(s,t)*. Rays passing through the same region of the main lens *(u,v)*, shown in the same color, fall on the same pixel of the sensor relative to each microlens *(u',v')*.

Conventional instruments like the Scanning Laser Ophthalmoscope (SLO) and Optical Coherence Tomography (OCT) require several scans in order to get a comparable amount of information, taking more time and are subject to artifacts due to eye movements. In addition with synthetic focusing imaging different layers of this complex 3D structure is possible, within a single snapshot.

3. Simulation platform to assess feasibility and optimize design of the 4D LFO

In its original form as proposed by Adelson and Wang [4] and Ng *et al.* [5], 4D Light Field acquisition using a microlenses array requires a tradeoff between lateral and directional resolution. Further research has proposed modifications in order to restore some of the lost lateral resolution [6, 7]. In order to study these various modalities for the purposes of retinal imaging, numerical simulations of light propagation in a Light Field imaging system have been developed. In particular a Light Field system has been simulated using Fresnel wave propagation. This represents a novel approach to Light Field Simulation.

Two are the main purposes of this early study:

1. Understanding how a light field is acquired by the system under a wave analysis approach.
2. Studying the feasibility of Light Field imaging for retinal imaging.

Simulations are performed in MATLAB (The Mathworks, Inc.), where a set of functions simulating Fresnel wave propagation of light have been written. The Fresnel propagation toolbox consists of two main function: free space propagation and phase transformation performed by a lens. Both coherent and incoherent illumination cases have been investigated. In particular incoherent illumination seems more suitable for capturing the Light Field. The Fresnel free space propagation integral is considered as an operator which when applied to the optical field in at the object plane $U(\xi,\eta)$ gives the field after a propagation of z, $U(x,y)$ [8]

$$U(x,y) = \frac{e^{jkz}}{j\lambda z} e^{j\frac{k}{2z}(x^2+y^2)} \iint_{-\infty}^{+\infty} \left\{U(\xi,\eta) e^{j\frac{k}{2z}(\xi^2+\eta^2)}\right\} e^{-j\frac{2\pi}{\lambda z}(x\xi+y\eta)} d\xi d\eta \quad (1)$$

To minimize the long computational time and memory requirement that Fresnel propagation requires, an iterative method has been developed, similar to the modified convolution approach algorithm proposed by Sypek [9]. It consists in subdividing the full propagation distance into steps and propagating the field step by step. This method improves computational time considerably.

The lens operator adds a spherical phase factor

$$\Phi(x,y) = e^{j\frac{k}{2f}(x^2+y^2)} \quad (2)$$

The code had been verified comparing simulation to real images of a propagating laser. The incoherent light case has been simulated by creating a random phase pattern to be added at the object field and generating N such random phase patterns. The resultant fields intensities are then summed to give the incoherent output. Following validation of the code, simulations of a simple light field system have been performed in order to understand lateral resolution limits, diffraction limits and computational limits. The first results which confirm the feasibility of using Fresnel wave analysis to study plenoptic systems is shown in figure 2.

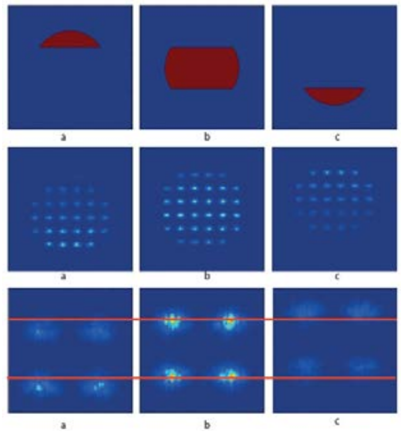

Fig. 2: Simulation of Light Field system shown in figure 1. Top: Aperture in the main lens plane. Center: Image produced by the microlens array. Bottom: Enlarged area of center images showing the output behind four microlenses (red line shown for reference)

In this case a plane wave of incoherent light is illuminating the main lens, which was divided into three sections (Top: a, b, and c). Spatial coordinates s and t are shown in the central part of figure 2. Each micro lens could be considered as a macropixel of the original image, and gives a couple of spatial coordinates. Under each microlens, as show in the bottom part of figure 2, directional coordinates *u'* and *v'* are recorded. Light coming from the upper part of the main lens falls in the lower part of the sensor under each micro lens, while light coming from the bottom part of the main lens falls on the upper part of the sensor under the microlens, as shown by the presence of the reference line. Light coming from the central part of the main lens falls on the central part under each microlens.

The simulation platform developed will enable detailed study of the application of 4D Light Field imaging to retinal imaging.

4. References

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