Simple Book Example

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thesis

Introduction

The information contained in the light surrounding the environment we live in is captured by the different living being according to the structure and the nature of their visual systems. The human eye is a single lens imaging system whose retina is composed by three different types of photosensitive cells [6]. For this reasons cameras have always been designed to capture light in the same way the human eye works, single lens with three colour pixels producing two dimensional images based on three colours [5]. This way of designing cameras produce a loss of information respect the all sets of information included into the light reaching the imaging system. Adelson *et al.* in 1991 proposed a to describe the whole set of information contained in the light defining the plenoptic function [7], ray based a seven dimension function describing intensity, direction and wavelength of rays propagating in the space. According to Adelson a conventional imaging device captured projections of this function. For example a photo is obtained integrating along the directional variables the function, obtaining a two dimensional intensity pattern of the object imaged loosing information on its three dimensional structure. If the integration in performed also along the wavelength the image will be in black and white and also the information on the wavelength will be lost, while adding a polariser we can obtain information on the state of polarization of the optical field coming from the object. [8, 2]. The reality we see and measure with the instruments and the senses we have is just a projection of a more complex reality and great part of the information carried by the electromagnetic field is lost. This situation is similar to the one described in Plato's "Allegory of the cave" where a group of people are being chained for all their life inside a cave and facing a blank wall on which shadows of different objects are projected. For them the shadows produced by the objects passing in front of the fire are the only reality they know since they are limited in their perception by their situation[9] . The same happen with human perception and with the camera that imitates human visual system. All conventional imaging instruments are limited and the images they produce is a projection of a more complex quantity containing all information that light carries. Even the most advanced imaging instrument will always produce data that are close to reality, but that does not reach it, both for intrinsic properties of light, such as diffraction, and because they have been designed to collect only a small set the reality. The role of scientific research is to push further this limit and understand how close to reality an measuring instrument can go. In this work will be described a new set of instruments that are able to sample the plenoptic function and the post processing methods to access all the information it carries. The character of this thesis will be mostly computational, and numerical simulations will be used as an instrument to explore the potential and define the limitations of this class of instruments.

The first idea that more information were carried by the light contained in a scene was made by Leonardo da Vinci who understood that described the volume contining the light as filled by a dense array of light rays, called by him "radiant pyramids" [7]. The plenoptic function described by Adelson and Wang *et al.* is the formalization of this concepts of "radiant pyramids" adding to the directions and positions of the rays information on the wavelength. The problem now, once it has been defined the extra information contained in the scene, is to define a method to measure it. The first work about capturing the plenoptic function was done by Yves in 1903 on his works on parallax panorama-grams [10, 11] and by Lippmann in 1908 [12] who proposed an array of pinhole cameras. The key to capture the plenoptic function is to have multiple views of the object to image. This can be done translating a single camera to different positions over a spherical or planar surface[13, 14, 15], method known as time sequential sampling, or by using an array of cameras [16, 17, 18] that is the multi-sensor sampling. Multi -sensor techniques give high performances in term of resolution but are extremely complicated and expensive, while time-sequential techniques suffer the loss of the capability to capture dynamic scenes [5]. The solution between costs and resolution is given by single-shot plenoptic sampling techniques based on a space multiplexing of the plenoptic function [5], as proposed by Ives [11] and Lippmann [12]. This single-shot space multiplexing method produces an array of elemental images on the sensor and this introduces several trade-offs between spatial and directional resolution [5, 19] as well optical resolution trade-offs [20]. Several families of devices has been developed. In this work will be described those who sample the plenoptic function using an array of micro lenses in front of the sensor as described by Adelson and Wang *et.al* [8], Ng *et al.* [21, 2], Ueda *et al.* [22] and Georgiev *et al.* [3]. In particular Ng *et al.* developed the first generations of plenoptic imaging systems, known as plenoptic 1.0, then improved by Georgiev *et al.* who modified them giving birth to the second generations, or plenoptic 2.0. This two class of instruments will be treated in this work. Other methods to capture the plenoptic function are based on creating a mask patterns that enables frequency domain multiplexing of the plenoptic function [23, 24], compressive imaging techniques [25] or exotic solution such as a slit camera [26]. The resulting image obtained with all this different methods contains all the extra information contained in the plenoptic function, but they are codified. Therefore the final image is obtained implementing post processing algorithms in order to decode these information. For this reason the process of capturing plenoptic images is also called computational photography [5, 1]. Along with the image rendering several post processing features can be performed once the information captured are decoded. This features includes digital refocus [2], changing the point of view, estimating depth [26, 5, 27, 28] and super-resolution imaging [29, 30, 31, 32].

The purpose of this work is to analyse the optical performances of micro lens array based plenoptic imaging systems. When this project started all existing work on this kind of instruments has been done using a ray optics approach. This work uses a wave optics approach so the behaviour of a plenoptic imaging system at its diffraction limit. This is the first work that quantifies the effects of diffraction on the quality of raw sensor images and rendered images, defining a new trade-off between spatio-angular resolution and optical resolution. This facts has not been investigated in other work because they most of the applications of plenoptic imaging regards photography and imaging of macroscopic objects. When the attention is moved to the microscopic world, diffraction effects become important. The first thing that has been done was to develop an home made simulation platform for wave propagation in a generic optical system. Existing method to implement free space propagation has been investigated and a variant of one of the existing methods has been proposed in order to make it more efficient. It has also defined a new empirical method to simulate light in any state of coherence based on the true physical nature of coherence and it has been proven to give realistic results. Once the simulation platform has been properly tested it has been used to simulate a plenoptic imaging system. Different parameters have been changed in order to investigate their influence on the optical properties of the system. At the same time post processing algorithms to extract information from the raw sensor data have been developed following the guidelines present in literature. Some innovative custom made solutions have been also applied. Different configurations of plenoptic setup have been compared, with particular attention to the optical performances of plenoptic 2.0 imaging systems. The information collected have then been used to build an home made plenoptic microscope.

In the first chapter an introduction of plenoptic imaging will be given. It will be explained in a rigorous way how to pass from a seven dimensional plenoptic function to a four dimensional function called light field. A definition of light field will be given and it will be explained how the light field carries information regarding the 3D structure of the scene imaged properties and how it is sampled by the two different configurations, plenoptic 1.0 and plenoptic 2.0. A rigorous theoretical description of both class of system will be given using geometrical optics, with particular attention to the post processing methods to decode the information in it.

The second chapter is a description of the home made simulation platform developed. The platform has been written in MATLAB and implements wave propagation of light under the Fresnel approximation. It has been designed to be a versatile and modular platform composed by operators that applied to an input optical field give an output field. The first operator to be described is the free space propagation based on Fresnel approximation of diffraction. The scalar theory of diffraction will be treated from a theoretical point of view starting from Maxwell equations to end with the expression of Fresnel diffraction integral. Then different method to implement Fresnel propagation will be analysed highlighting advantages and disadvantages of each one of them in term of resolution, signal to noise ratio and computational effort. These methods are: the direct Fresnel integral application, the multi step propagation, the angular spectrum method and the band-limited angular spectrum method. It will also be presented an original variation of the band limited angular spectrum method to optimize the trade-off between the signal to noise ratio and digital aliasing. Then the lens operator will be described. Once the lens has been defined there will be shown some results of simulation of simple optical systems with the purpose of comparing the performances of the five different free space propagation operators. This chapter is concluded by the exposition of the method to simulate partially coherent light.

The third chapter is a complete description of a plenoptic 1.0 system. It will be explained how to design and run simulations and how the to implement in

MATLAB existing post processing algorithms to render the final image from the raw sensor data. Digital refocus principles and methods will be described as well as the change the point of view. An original home made method to estimate the depth of point sources will be also proposed.

Chapter four is about the simulations performed to define the optical properties of a plenoptic 2.0 system. It will be calculated the impulse response of the system together with its modulation transfer function. A frequency analysis of the system will be done as well, and it will be explained how the different parameters of the system influence the optical resolution of the final rendered image. Such a detailed optical analysis of a plenoptic system has never be done using wave optics simulations.

Chapter five contains the description of the real setup built in the laboratory to verify the conclusions achieved with the simulations. A full description of the system will be given, as well as a description of the protocol to follow to capture light field images. Few results will be presented.

The final chapter is about the conclusions and the future possibilities of development of plenoptic imaging systems.

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