New developments at CAFADIS plenoptic camera

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***Abstract*— The CAFADIS camera project has consisted in building a camera to measure wave-front phases and distances under different scenarios (from microns to kilometres), using highly specialised electronic technology, namely Graphics Processing Units (GPUs) and Field Programmable Gate Arrays (FPGAs). It is a passive method of depth extraction, it uses incoherent light (natural light). In this paper we will present our new developments.**

Keywords: CAFADIS, plenoptic, wavefront, tomography, lightfield, adaptive optics, 3D, GPU, FPGA, underwater 3D.

I. INTRODUCTION

Plenoptic cameras have been developed over the last years as a passive method for the 3D understanding of a scene. A conventional camera makes use of a convergent lens in order to concentrate a bunch of rays coming from sharp points in the scene into a single pixel in the sensor. Focusing/defocusing is the price to pay to gather more light. A plenoptic camera separates part of those rays that were to be integrated into one pixel, in bunchs of rays that come from the same position of the scene, but with different angular directions by the use of a microlenses array. To record them a trade-off must be done to observe simultaneously the angular and positional structure of light coming from the scene.

Until now, the most common treatment for plenoptic images consists of applying multistereo computer vision techniques, considering that there are as many points of views as there are pixels behind each microlens. Nevertheless, an alternative procedure, that turns out to be efficient, as well as complementary in fields like Adaptive Optics for Astrophysics, employs plenoptic cameras as tomographic wavefront phase sensors. The double treatment we are proposing is in accordance with the wish of several authors who claim to use computer vision tools to solve wave optics problems and viceversa.

Within a plenoptic frame there is enough information to recreate *a posteriori* a volume of images covering a range of focusing distances, what is known as a focal stack. Attending to a measure of focusing through each ray that crosses that volume it is possible to estimate distances to objects. Algorithms have been developed to tackle all of these processes at video acquisition rate and nowadays it is possible to build around these methods a 3D camera, even one suitable to feed a glasses free 3D display. For the sake of speed parallel hardware is usually employed in the form of Graphics Processing Units and Field Programmable Gates Arrays.

Plenoptic methods, of course, have their inconveniences. The valid range of refocusing distances is constrained by the number of pixels that contribute to gather angular information. Moreover the specific placement of centres of depth of field of the resulting images is far from being linear, and is best suited for filming on close distances, which incidentally are a hard task when using stereo techniques. If we increment the number of angular pixels there are less remaining pixels to gather "positional" resolution. This sacrifice can not be fully overcome, but can be diminished by the use of superresolution methods. Also, when the microlenses array is placed close to the sensor, it is hard to avoid a certain tilt between them. This is the reason that explains the calibration stage that is mandatory previous to any further processing.

There are fields were the plenoptic sensor can be used in both senses: depth extraction and tomographic wavefront sensing. The terrestrial atmosphere degrades the telescope images due to the diffraction index changes associated to the turbulence. These changes require the high speed processing supplied by the GPUs and the FPGAs. Na artificial Laser Guide Stars (Na-LGS, 90km high) must be used to obtain the reference wavefront phase and the Optical Transfer Function of the system, but they are affected by defocus because of the finite distance to the telescope. Using the telescope as a plenoptic camera allows us to correct the defocus and to recover the wavefront phase tomographically (Rodríguez-Ramos *et al* [2])

CAFADIS, the plenoptic camera patented by the University of La Laguna (Rodríguez-Ramos *et al* [1]), brings several new developments at this workshop: a new calibration method for plenoptic frames that can be computed in real time, a construction design of plenoptic interchangeable objectives, a real time wavefront phase restoration at telescope pupil, and the first underwater plenoptic images.

II. PLENOPTIC FRAME CALIBRATION

The physical manufacturing of a plenoptic camera requires to locate the microlenses array somehow aligned with the imaging sensor. Perfect alignment is very difficult to obtain and pixel and microlens pitches will not be exact multiples in a general case, thus some sort of calibration is needed previous to any image rearrangement, in order to identify the relative position of every subpupil image on the detector.

Using the rather accurate nature of the manufacturing processes of both the imaging sensor and the microlenses array, we will consider them as "perfect", and thus uniquely identified by their respective pitches, i.e., 7.4 microns per pixel at the detector and 400 microns per microlens at the microlens array. Within this framework, the manufacturing process of the plenoptic camera will be modelled as a combination of a scale change, a rotation and a displacement, and quantitatively described by:

- The imaged microlens pitch: The combination of the microlens pitch and the scale change due to the imaging system. It can also be associated with the microlens pitch measured in pixels.
- The relative rotation: The angular orientation between the pixel and the microlens axes.
- The lateral displacement: Some sort of vertical and horizontal bias to be considered in order to obtain the relative position of the microlenses with respect to the imaging sensor.

These three parameters are considered the result of the calibration and completely describe the result of the manufacturing process under the written assumptions. A number of methods were used to obtain these parameters:

A. Aperture reduction

The aperture reduction method consists in the evaluation of a specifically obtained image with a reduced pupil size. The pupil is reduced by manually closing the iris in a way in which only the aperture centres are illuminated. Provided that the angular misalignment is less than one microlens at the edge of the imaging sensor, the algorithm can be used with very accurate results. It is also recommended to use a flat image scene, although not strictly necessary.

B. Two-dimensional Fourier Transform method

The aperture reduction method requires a specific setup for the camera and imposes a limit in the relative rotation. These are significant drawbacks that should be removed using alternative calibration methods for a general case, even accepting the compromise of less accuracy.

The direct estimation of both pitch and rotation from the two-dimensional Fourier transform is feasible provided that a Blackmann-Harris windowing is performed on the plenoptic image, and a four-times zero-padding scheme is used to interpolate in order to estimate the frequency peak with the required resolution. Rotation is estimated from the angle between positive and negative spikes of the two-dimensional Fourier transform.

Fourier transform method provides a very reasonable measurement for both the microlens pitch and angular rotation. However they are not very accurate when computing the lateral displacement or "phase" of the calibration.

C. Lateral displacement computation using linear correlation

Once that pitch and rotation have been measured, the lateral displacement identification aims to locate the centre of one of the microlenses, because doing so all of them can be obtained from the model. Three methods have been tested for this purpose. A first approach is to use the cross-correlation technique with only one line of the image, instead of using the whole image. This shortage greatly reduces the computational cost.

D. Lateral displacement computation using correlation

This method is based in the fact that the illumination at the centre of the microlens is, on average, greater than on the periphery. Under this assumption, a simulated plenoptic image can be generated using a sinusoidal profile in both vertical and horizontal axes, using the measured pitch and rotation.

The simulated image is cross-correlated with the original one, after suppression of the zero frequency component, and lower frequencies if needed, expecting to found a maximum at the lateral displacements in which both images better fit. Further quadratic interpolation may be used to precisely compute the displacement with sub-pixel resolution.

E. Lateral displacement computation using direct phase detection

The correlation method previously described unfortunately requires a high computational cost associated with the cross-correlation. A simpler method based on the direct detection of phase could also be used, especially when real-time calibrations will be needed. The algorithm is based on the trigonometric identity for the sum of two angles.

When the phases are very similar, the difference term will be very close to half that difference, and the adding term will generate twice the frequency that can be filtered out somehow, or be considered null provided that an integer number of wavelengths are involved

III. INTERCHANGEABLE PLENOPTIC OBJECTIVE

Until now, one of the greatest limitations to the use of plenoptic technology is the difficulties involved in its proper manufacturing. The manufacturing technique of the individual components is largely evolved: the objective lens, the detector even the microlenses array. But it is not easy to place, with the required accuracy, the microlenses array with respect to the sensor and the main lens. Sensors usually are protected with protective filters very close to them, in the order of a millimeter. To place the microlenses with a focal length within that range forces to use a very narrow field of view.

In order to get a wide field of view, f/numbers in the order of f/1.4 to f/2.8 should be chosen and therefore the microlenses array should be placed just micrometers apart from the sensor.

To avoid this limitation is why we have designed and implemented a plenoptic interchangeable objective that converts any conventional, single-body single-lens camera, into a 3 dimensional one.

This plenoptic objective system is composed by, at first stage, a refractive microlenses array; at a second stage, the images formed by such a multisystem are collected with an imaging optical vehicle, working in near field, once the incident beam is collimated; at last, it is collected by an optical element working conjugated to infinity that projects the set of images over the sensor.

The optic system has been miniaturized down to 10 centimeters and built as interchangeable using F-nikon mount, but a number of adapters allow to use it with different mounts: c-mount, micro 4/3,… Photographers or cameramen can continue to use their own objectives and cameras, and place our plenoptic objective in between to acquire plenoptic frames, then having access to the plenoptic technology: focal stack, 3D stereo focal stack, autostereoscopic images, depth maps and all-in focus images.

IV. Plenoptic Wavefront Sensor

In Adaptive Optics (AO) all the plenoptic capabilities can be exploited at the same time. The most salient feature of our CAFADIS camera is its ability to simultaneously measuring wavefront maps and distances to objects [3]. This makes of CAFADIS an interesting alternative for LGS-based AO systems as it is capable of measuring from an LGS-beacon the atmospheric turbulence wavefront and simultaneously the distance to the LGS beacon thus removing the need of a NGS defocus sensor to probe changes in distance to the LGS beacon due to drifts of the mesospheric Na layer. In principle, the concept can also be employed to recover 3D profiles of the Na Layer allowing for optimizations of the measurement of the distance to the LGS-beacon [4].

In case of solar obsevations, where the object covers the entire field of view and it is positioned at the infinity respect to the telescope, total wavefront phase tomography can be sense using the CAFADIS camera, because of the multiple points of view inherent to the plenoptic sensor structure. In that sense, we will show in this workshop a film where the wavefront phase at pupil is restored in real time using our FPGA implementation.

V. Underwater Plenoptic Images

As a result of the collaboration between Antinea expedition and the University of La Laguna, inside the ecological "7 islas conscientes" project, we have submerged our CAFADIS prototype in the Red Sea (Egypt). We used a Red One cinema camera as detector, and after adding our plenoptic objective, the housing needed a short expansion. This expansion was built using a passive bimetallic mechanical control in order to maintain the calibration after dilatation effects due to the 10 degrees temperature changes in the water between ship cabin and sea temperature, this produces undesiderable up to 11 microns of plenoptic array displacement. Nevertheless, many problems must be solved yet because of the refraction index changes between air and water.

Then, as far as we know, the first underwater plenoptic images have been taken thanks to this experience. A sample of them will be shown at this workshop.

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