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Polarization imaging with enhanced spatial resolution

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ABSTRACT

We present the design and the experimental implementation of a new imaging set-up, based on Liquid Crystal technology, able to obtain super-resolved polarimetric images of polarimetric samples when the resolution is detector limited. The proposed set-up is a combination of two modules. One of them is an imaging Stokes polarimeter, based on Ferroelectric Liquid Crystal cells, which is used to analyze the polarization spatial distribution of an incident beam. The other module is used to obtain high resolved intensity images of the sample in an optical system whose resolution is mainly limited by the CCD pixel geometry. It contains a calibrated Parallel Aligned Liquid Crystal on Silicon display employed to introduce controlled linear phases. As a result, a set of different low resolved intensity images with sub-pixel displacements are captured by the CCD. By properly combining these images and after applying a deconvolution process, a super-resolved intensity image of the object is obtained. Finally, the combination of the two different optical modules permits to employ super-resolved images during the polarimetric data reduction calculation, leading to a final polarization image with enhanced spatial resolution. The proposed optical set-up performance is implemented and experimentally validated by providing super-resolved images of an amplitude resolution test and a birefringent resolution test. A significant improvement in the spatial resolution (by a factor of 1.4) of the obtained polarimetric images, in comparison with the images obtained with the regular imaging system, is clearly observed when applying our proposed technique.

1. Introduction

Spatial resolution (SR) is a measure for the ability to distinguish two separated points in an image. SR is limited by diverse factors: numerical aperture of the imaging system, the wavelength of the employed light, misalignments and aberrations of the optical components, geometrical properties of the camera pixel (size, shape and pitch) among others [1]. High resolution devices are required for many purposes in imaging based applications, such as in remote sensing applications [2] or for medical purposes [3]. Different approaches have been reported to attempt to overcome the resolution of an imaging system. As well known, one of the main limitations for the SR is the diffraction limit of the optical system. To overcome this limitation different super-resolution methods have been presented in the literature, as for instance those based on the use of diffraction gratings [4], structured illumination [5,6] and time multiplexing super-resolution techniques [7]. In the case of modern imaging systems, they usually include Charged-Coupled Device (CCD) cameras as the main devices to capture the images. In such cases, the pixel dimension of the camera may also impose a geometrical limitation in resolution. In particular, many optical systems have detector pixels relatively large compared to the point spread function (PSF) of the optical system, resulting in a system that is undersampled. In such systems, the optical system passes higher spatial frequencies than those that the detector can correctly sense. Undersampled systems are used in some applications because they may present some interesting advantages, such as improved sensitivity leading to faster integration times and higher signal-to-noise ratio (SNR), larger fields-of-view, better image quality and less expensive [8,9]. When the SR is limited by the detector pixels, geometry multiframe super-resolution algorithms can be employed to improve the resolution of the imagery, as for instance sight-and-add, interlacing, Drizzle algorithm, [10] techniques based on the maximum likelihood [11,12], projection onto convex sets [13,14], non uniform interpolations [15,16], stochastic reconstruction method [17,18], code-division multiplexing [19], among others [9,20,21].

In general, imaging systems only analyze the intensity information of an object. However, extra image information, as an accurate knowledge of the light polarization content, may be of interest in some applications. For instance, in medical applications [22,23], polarimetric images provide valuable data for diagnosis, being this information hidden in regular intensity images of the

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sample. Imaging polarimeters are the basic devices to perform these polarization images, as those described in [24,25].

Moreover, the analysis of the polarimetric information collected in high numerical aperture imaging systems may help to resolve details of the object beyond the resolution limit. For instance, in [26] the position and orientation of nanostructures are resolved beyond the diffraction limit using the spatial distribution of the azimuth angle and the degree of polarization. Another example is provided in [27], where an instrument measuring scattering-angle-resolved Mueller matrix is described allowing for a high sensitivity to sub-resolution displacements of a sub-resolution scatterer.

In this work, we propose a new imaging system, based on Liquid Crystal (LC) technology, able to obtain polarization images with enhanced spatial resolution, when the main limitation in resolution is imposed by the pixel pitch of the Charged-Coupled Device (CCD) camera. As following detailed, the experimental set-up combines a super-resolution module (which reconstructs a single high resolution image of a scene from a set of regular images recorded at lower resolution) with an imaging Stokes polarimeter (which determines the polarization spatial distribution of a light beam from a set of super-resolved intensity images obtained with the super-resolution module).

2. Experimental set-up: combination of an imaging stokes polarimeter and an intensity super-resolution module

The proposed set-up sketched in Fig. 1 is implemented in the laboratory. A collimated red light emitting diode (LED, $\lambda_o = 625$ nm and $\Delta\lambda = 17$ nm) is used to illuminate the system. Then, a Polarizing State Generator (PSG), consisting of a linear polarizer (LP_1) and a quarter waveplate (QWP), is used to manipulate the polarization of the incident beam illuminating the scene. After the scene, the Stokes polarimeter is placed, working as a Polarization State Analyzer (PSA). This system is composed by two monopixel ferroelectric liquid crystal (FLC) cells and a second linear polarizer (LP_2). A convergent lens (L) images the scene onto the CCD plane, obtaining low resolved images due to the pixel size limitation of the CCD. Nevertheless, we include an extra module for enhancing the spatial resolution of the intensity images taken by the camera. In this module the light is transmitted by a 50/50 non polarizing beam splitter (B-S) towards a Parallel Aligned Liquid Crystal on Silicon (PA-LCoS) display. This device is a pure phase spatial light modulator (SLM) that allows the introduction of linear phases very precisely controlled. The reflected light goes back to the B-S and is redirected to the detector. The linear phases generate sub-pixel displacements of the low-resolution images at the CCD plane, and by combining them and applying an anti-aliasing algorithm it is possible to reconstruct a final super resolved intensity image. Finally, by combining 4 super-resolved intensity images, and conducting a polarimetric data reduction calculation later explained, a super-resolved polarimetric image is obtained.

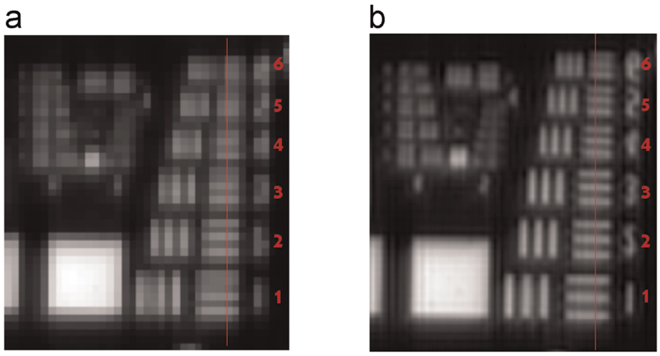

Fig. 2. S_0 Stokes element of USAF resolution test by applying (a) the regular technique and (b) the enhanced resolution technique. Cross sections of the red lines are plotted in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The PA-LCoS display used in this work is a PLUTO SLM distributed by HoloEye Systems with a diagonal display of 1.8 cm, a resolution of 1920 × 1080 pixels, with a pixel pitch of 8 μm and a fill factor of 87%. To operate with the PA-LCoS in the phase-only regime, the LP_2 is orientated at the same direction than the LC molecules extraordinary axis.

The ideal experimental set-up should use a transmissive liquid crystal display (LCD), avoiding the use of the B-S and its corresponding light losses. However, the available LCD in our laboratory is a PA-LCoS display working in reflection. So, a set-up configuration working in reflection is required. Under this scenario, two possible configurations could be used: a B-S based set-up or an off-axis illumination based set-up. However, the LCD phase modulation range decreases as the incidence angle increases [28], for this reason we have selected the layout of Fig. 1.

We are looking for the increase of resolution at the image plane, where the pixel size and point spread function (PSF) size are of concern. For the optical imaging system configuration employed, the PSF is about a quarter of the pixel size. Thus, the spatial

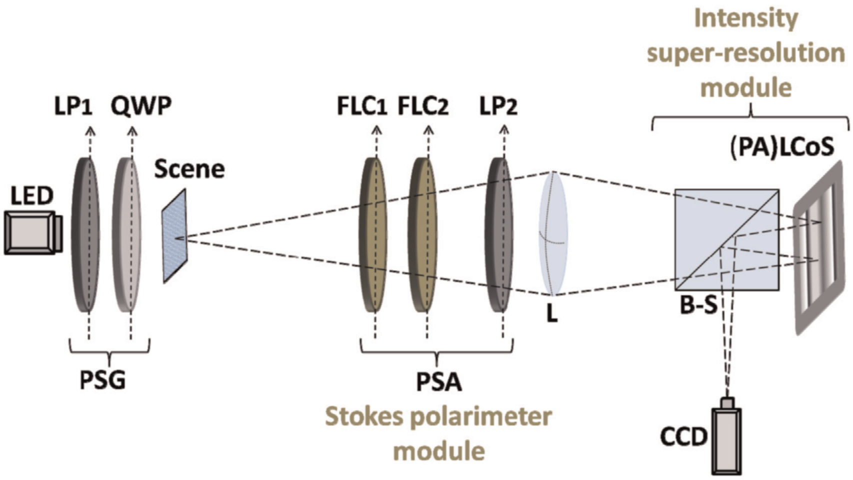

Fig. 1. Experimental set-up used to implement the polarization imaging system with enhanced spatial resolution. This consists of two parts: an imaging Stokes polarimeter (two Ferroelectric Liquid Crystal cells and a polarizer) and an intensity super-resolution module (LCoS spatial light modulator).