Activities in imaging through fog at CD6: polarimetric imaging

Sara Peña-Gutiérrez
Centre for Sensors, Instruments and Systems Development (CD6)
Universitat Politècnica de Catalunya (UPC)
Terrassa, Spain
sara.pena.gutierrez@upc.edu

Maria Ballesta-García
Centre for Sensors, Instruments and Systems Development (CD6)
Universitat Politècnica de Catalunya (UPC)
Terrassa, Spain
maria.ballesta.garcia@upc.edu

Santiago Royo
Centre for Sensors, Instruments and Systems Development (CD6)
Universitat Politècnica de Catalunya (UPC)
Terrassa, Spain
santiago.royo@upc.edu

***Abstract*— The CD6 has recently developed a powerful line of research on polarimetric imaging. This field covers several applications in which the addition of polarization properties enables to enhance the contrast in detection. Moreover, recent literature states the possibility of using polarization illumination and detection to improve the range detection in turbid media such as fog, dust or smoke. This paper addresses the optical engineering behind the detection of polarization imaging and sets the basis of using polarization as a tool in detecting through fog.**

Keywords—polarization, polarimetric imaging, turbid media, fog, remote sensing.

I. INTRODUCTION

Polarization is one of the basic properties of light, together with the intensity, the wavelength and coherence. By definition, it represents the relation of the electric field vector components at each time and point of the space [1]. This inherent vectorial dependence differentiates polarization among the other properties becoming a potential new type of detection and imaging since it provides uncorrelated information with the intensity and spectral ones [2]. The immediate contribution comparing to common intensity measurements when detecting is the improvement of contrast. Therefore, these last thirty years polarimetry has arose as a potential tool in several and very different fields such as remote sensing [2], industry, medicine [3], etc.

Recently there has been a growing interest in applying polarization imaging to enhance the target detection in poor-visibility conditions such as scattering environments. Theoretical models and experimental data indicate that using polarization to image through scattering media such as fog, dust and smoke, greatly increases contrast versus intensity imaging. This statement relies on the polarization persistence of light, known as polarization memory, where the backscattered light tends to preserve the original polarization state, especially when circular instead of linear polarization is used [4,5]. This effect is of interest in transport, in specific in autonomous vehicles, and in surveillance applications to increase the sensing range in this type of environments.

In CD6, one main field of research dedicated to polarization in turbid media has recently being developed. Two main lines of research are separated. First, the general study of polarization and development of polarimetric cameras in order to improve detection. Secondly, the study of turbid media by means of Monte Carlo simulations employed to track the polarization evolution trough different turbid media to study the environment under controlled parameters and look for solutions applying the previous polarimetric cameras and other acquisition systems.

This paper is structured as follows. Firstly, a brief introduction of the importance of polarization applied to turbid media inside the CD6 is presented. In Section 2, the experimental methods to prove the polarization performance over intensity in poor-visibility conditions are described. Section 3 shows the results of polarization measurements regarding polarimetric calibration and its application to imaging in fog. Finally, some conclusions and further work are exposed in Section 4.

II. METHODS: POLARIMETRIC IMAGING

Polarimetric imaging is a specific application of polarimetry, which consists in measuring the polarization state of a scene as a 2D map. These types of images let us detect different signals of polarization depending on the shape and type of the surfaces that interact with the detected light. In addition, one can measure the change that an incident light polarization suffers when crossing the scene using active illumination, especially helpful when dealing with scattering media. As stated in the introduction, polarimetric imaging expands the "common" intensity measurement and allows exploring new applications based on this vectorial measurement such as measuring the roughness and shape of the objects, 3D reconstruction [6], and even the differentiation between dielectric and metal materials [7].

The Stokes vector represents the polarization information of a beam light and is composed by four parameters, as follows [1]:

$$S = [S_0, S_1, S_2, S_3]^T \qquad (1)$$

where S_0 stands for the intensity of the detected light, S_1, S_2 and S_3 represent, respectively, the prevalence of linear polarization state at 0° over 90°, the prevalence of linear polarization state at 45° over 135°, and the prevalence of right circular (RC) over left circular (LC) polarization state.

Because of polarization nature, the components of the Stokes vector cannot be measured directly; they must be recovered from a set of intensity measurements. Hence, the basis of polarimetric imaging lies in acquiring at least four intensity measurements using different combinations of the polarization optical elements.

The camera is based on the architecture of division of time, where the intensity measurements are performed at a different time. This involves to measure four intensity images in order to have polarimetric images at a rate of 1fps, restricting the dynamics of the detection.

Its design is based on a quarter-wave plate followed by a linear polarizer mounted on a rotating stage, which compose the polarimeter set up. A telescope lens is added to focus the

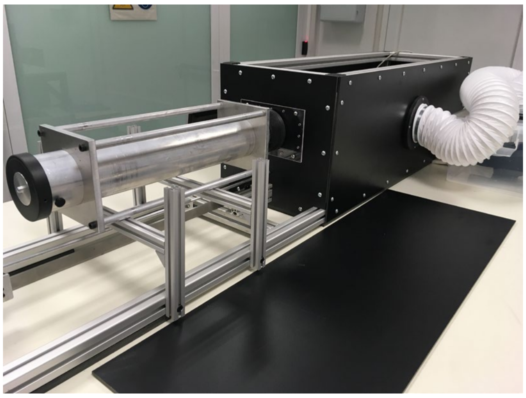

Fig. 1: Self-developed fog chamber to perform the polarization experiments in turbid media under controlled conditions.

scene on the CCD sensor of a commercial Canon EOS1000 camera. In order to reconstruct an accurate Stokes vector with this economical setup, the system must be calibrated both radiometrically and polarimetrically. The measured intensities at the different polarization states can be expressed in matrix form as:

$$I = A \cdot S \qquad (1)$$

where S is the input Stokes vector and A is the measurement matrix. The aim of the polarimetric calibration is to determine the W matrix, known as the reduction matrix, from the intensity measurements I in order to evaluate the Stokes vector:

$$S = A^{-1} \cdot I = W \cdot I \qquad (2)$$

Here we directly measured the data reduction matrix W by following the procedure described in [8]. The recovered Stokes vector can be obtained by solving equation (2) pixel by pixel once it is calibrated.

In CD6, several experiments have been designed and developed to improve the detection of light based on active detection of polarization through turbid media, such as fog, This has potential impact on transport and surveillance applications. Using our lab fog chamber (Fig.1) in order to control the conditions of the artificial fog, we seek to do polarimetric imaging using a self-developed polarimetric camera. This camera is conceived to be able to measure any state of polarization, the so-called full Stokes system, which would not restrict the active illumination to a determined polarization and thus, allowing us to demonstrate experimentally what is the optimum state to enhance the detectivity through several types of turbid media, already done by means of Monte Carlo simulations.

III. RESULTS

A. Polarimetric device

In the experiment related to the polarimetric camera, we use a fibre laser of 632nm coupled to an integrating sphere, in order to erase any portion of polarization of the light beam and assuring a uniform distribution of the light falling on the sensor, and a magnifying lens used to magnify the light source. Then, to perform the polarimetric calibration different polarizers are located in turn just at the exit port of the integrating sphere. To generate linearly polarized light a standard linear polarizer is rotated from 0º to 180º at steps of 10º. To produce circularly polarized light, the linear polarizer is replaced with the standard LC and RC polarizers.

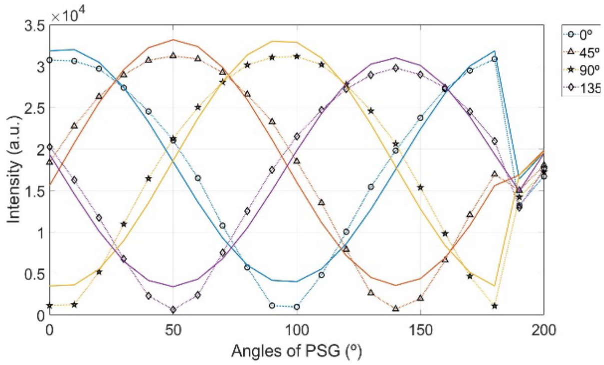

Fig. 2: Mean value intensity of the different states of the measurement calibration set. The dashed lines with symbols represent the measured data at the different RPS. The solid lines represent the recovered intensity from calculated W matrix.

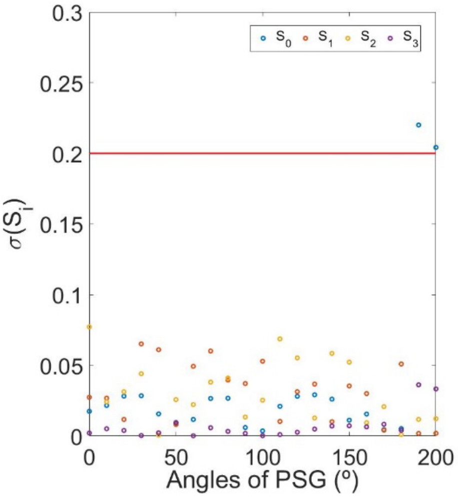

Fig. 3: RMS error between the recovered and the theoretical parameters. Angles 190º and 200º correspond to the RC and LC states.

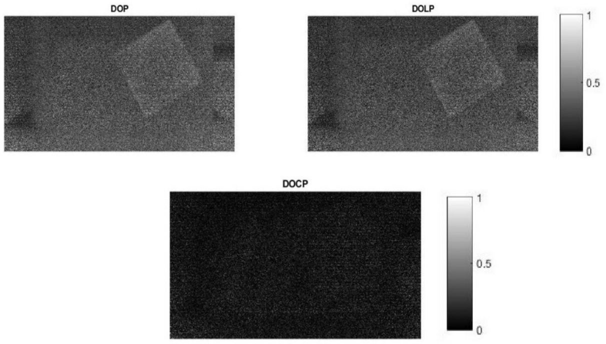

Fig. 4: Maps of the recovered DOP, DOLP and DOCP for an image in reflection of a random linear state.

Fig. 2 shows the measured intensity and the recovered data produced by the determined data reduction matrix W at the six reference polarization states (RPS): 0º, 45º, 90º, 135º, RC and LC. Fig. 3 shows the root mean square (RMS) errors of the recovered Stokes parameters after calibration, The RMS are less than the 10% that is a very good result taking into account the simplicity of the set up. Hence, we see the system can

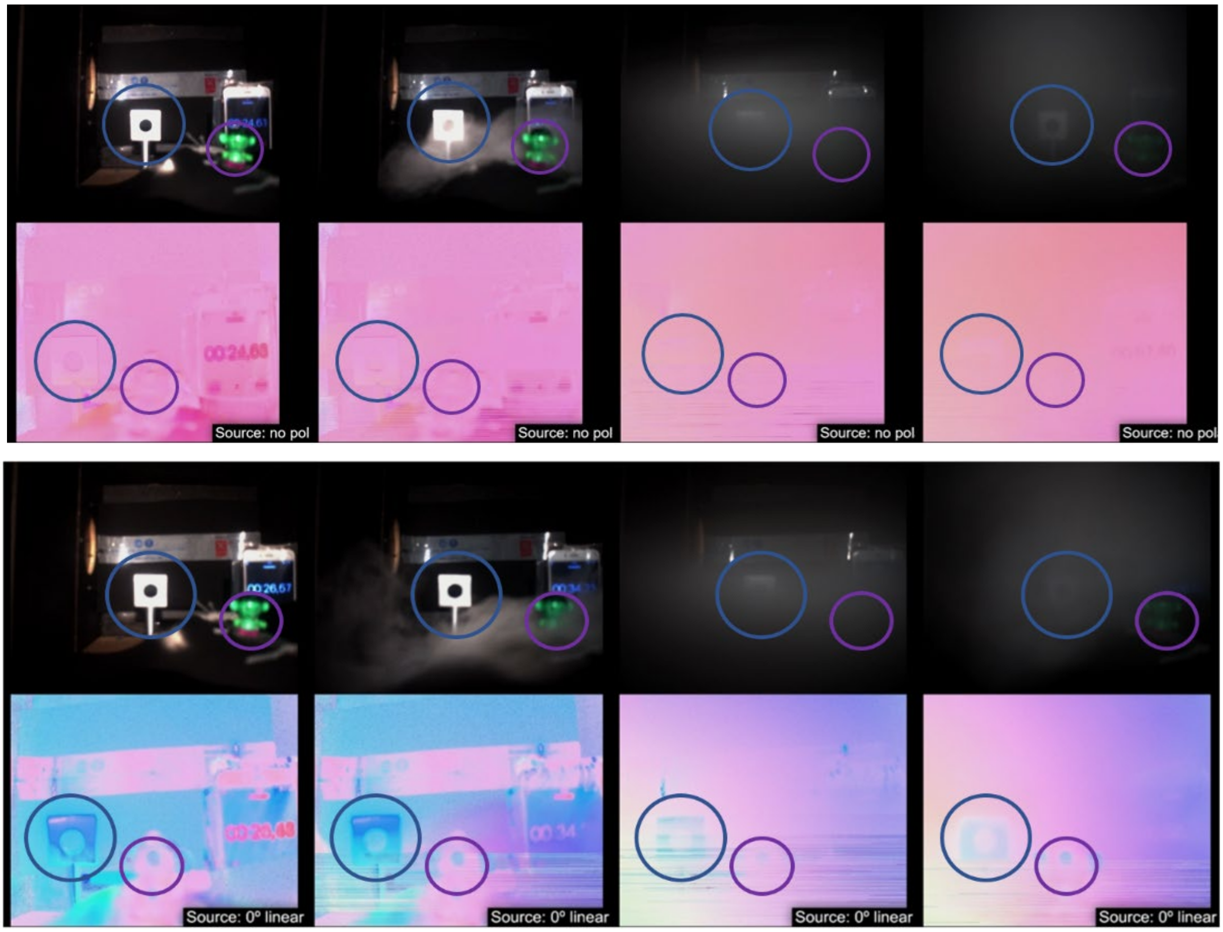

Fig. 5: (Top) Intensity measurements (first row) and polarization measurements (second row) of an object embedded in a lab fog chamber under unpolarized illumination. (Bottom) Intensity measurements (first row) and polarization measurements (second row) of an object embedded in a lab fog chamber under linear polarization illumination.

provide a well-conditioned data reduction matrix for noise immunity and the bandwidth can be widen by using white light and a monochrome camera.

The next step is to use the characterized matrix in order to capture polarimetric images and test the usability of the system. To do so, we measure the polarization of a controlled scene using the reflected light, using ambient illumination. A linear sheet polarizer located at an oblique azimuth angle is imaged through the system, as seen in Fig.4. The degree of polarization (DOP) expresses the amount of polarized light in the scene. It is also defined the degree of linear polarization (DOLP) and degree of circular polarization (DOCP) regarding the amount of linear/circular polarization in the scene. When generating DOP maps, as it can be appreciated in Fig. 4, a remarkable presence of a whiter area in the DOP and DOLP plots appears, corresponding to the position of the oblique polarizer within the scene.

B. *Intensity and polarization comparison*

To make sense of our approach of using polarization in imaging through turbid media, a proof of concept experiment is carried out. The self-built fog chamber, presented in Fig.1, was employed to mimic objects embedded in a foggy media and study quantitatively the performance of two types of detection: conventional imaging vs polarimetric imaging.

In Fig. 5 (top), it is shown the acquisition of a polarimetric camera and a RGB camera at different moments of fog stabilization illuminating with no polarized light. As it can be seen, both sensors are not capable to distinguish the object under moderate fog environment. In contrast, in Fig. 5 (bottom) the same measurement is performed but illuminating the scene with linear polarization light. It must be highlighted the improvement in detection in the polarimetric image when the fog obscures the object in the RGB camera (Fig. 5 (bottom))

IV. CONCLUSIONS AND FUTURE WORK

The presented results correspond to a DoT polarimetric camera able to measure any state of polarization with a low relative error using COTS elements and a commercial camera. Moreover, we have been able to demonstrate the initial hypothesis that polarimetric measurements outperform in turbid media conditions.

However, one of the main drawbacks of this camera is the acquisition of the polarimetric images at different temporal frames, thus not allowing the detection of highly dynamic scenes, as the case of turbid media conditions. Therefore, a snapshot polarimetric camera is being currently under development to acquire in a single shot the polarimetric image, widening current dynamic range. It will be applied to the validation experiments of the Monte Carlo simulations using the lab fog chamber, as well as, measuring light propagation in real fog facilities.

It is worth mentioning that this design will also take into account the possible errors present in any experimental measurement (signal independent noise and signal dependent noise) being optimized to have noise immunity leading to a further improvement in detection under turbid conditions. Furthermore, general polarization measurements for other applications are meant to be done such as imaging tissue properties or material detection with this high performance device.

ACKNOWLEDGMENT

This work was supported by the Secretary of Universities and Research from the Generalitat of Catalunya and the European Social Fund under the grant 2018FI-B-00868 and partially supported by the Spanish Ministry of Economy and Competitiveness (MINECO) under the project FIS2017-89850R.

REFERENCES

[1] D. L. Goldstein, Polarized light. 3rd Ed Taylor and Francis, 2011.

[2] J. S. Tyo, D. L. Golsdtein, D. B. Chenault and J. A. Shaw, “Review of passive imaging polarimetry for remote sensing applications” Appl. Opt. vol. 45, 2006, pp. 5456-69.

[3] T Novikova, A. Pierangelo, and A. D. Martino, “Polarimetric imaging for cancer diagnosis and staging," Opt. Photonics News vol. 23, 2012, pp.26-33.

[4] J. D. van der Laan, D. A. Scrymgeour, S. A. Kemme, E.LJ. Dereniak, “Detection range enhancement using circularly polarized light in scattering environments for infrared wavelengths”, Appl. Opt. vol.54, 2015, pp. 2266-2274.

[5] Fade *et al.* “Long-range polarimetric imaging through fog," Appl. Opt. vol. 53, 2014, pp.3854-3865

[6] M. N. Garcia, I. de Erausquin, C. Edmiston and V. Gruev, “Surface normal reconstruction using circularly polarized light”, Opt. Exp. vol. 23, 2015, pp. 14391-14406

[7] H. Chen, L. Wolff, “Polarization phase-based method for material classification and object recognition in computer vision” International Journal of Computer Vision vol.28, 1998, pp. 73–83.

[8] B Boulbry, J C Ramella-Roman and T A Germer, “Imporved method for calibrating a Stokes polarimeter” Appl. Opt. vol. 46, 2007, pp. 8533-41.