Dynamic polarimetric imaging: overview and implementation using liquid crystal cells

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Abstract. This paper gives an overview of dynamic polarimetric imaging techniques. Various methods are reviewed. Techniques using liquid crystal devices, incepted in the late 1990’s, are emphasized. Practical implementations are presented. We particularly focus on high-speed techniques (ie faster than 200 Hz).

1. Introduction
Whereas basics of modern polarimetry were incepted in the mid-19th century by Stokes [1], practical imaging solutions allowing real-time measurements have only been implemented for a dozen years. These realizations have already enlarged the field of polarimetry to medical diagnosis [2], remote sensing [3], surveillance [4] or robotics [5]. Nevertheless, these solutions either remain slow or prove rather cumbersome to implement. In this paper, we propose the implementations of imaging polarimeters using a single ferroelectric liquid crystal cell. A laboratory implementation which gives full linear polarization information is considered, as well as a portable implementation which only gives polarization information for two crossed linear polarization states.

Section 2 sums up very basics of polarization. Section 3 gives a brief state of the art in imaging polarimetry. Section 4 describes the imaging polarimeters we implemented. Section 5 reports experimental data obtained with our systems. Finally, Section 6 proposes techniques to enhance the images we obtained.

2. Polarization basics
Polarization of a light wave can be fully characterized with a 4-component vector named Stokes vector [1, 6]. The first parameter \( s_0 \) describes the total light intensity. Information about polarization is contained in the other three parameters \( s_1, s_2 \) and \( s_3 \). \( s_1 \) describes the horizontal and vertical polarizations, \( s_2 \) the components at \( \pm 45^\circ \) and \( s_3 \) the right and left circular polarizations. The following relations between all parameters of Stokes vector can be established [6]:

\[
s_0^2 \geq s_1^2 + s_2^2 + s_3^2 \tag{1}
\]

\[
DOP = \frac{\sqrt{s_1^2 + s_2^2 + s_3^2}}{s_0} \tag{2}
\]
If \( s_1, s_2 \) and \( s_3 \) are zero, the beam is totally unpolarized and the Degree Of Polarization (\( DOP \)) is zero. In most cases, the beam is partially polarized, therefore the inequality (1) is strict and \( DOP \) is smaller than one. In the case of a fully polarized beam, (1) tends to a strict equality and \( DOP \) is equal to unity.

When studying linear polarization, \( s_3 \) is not considered or considered to be nil. In this case, the Stokes vector is partial and is defined as:

\[
S = \begin{pmatrix}
  s_0 \\
  s_1 \\
  s_2 \\
  0
\end{pmatrix}
\]  

Therefore, the \( DOP \) becomes the linear degree of polarization \( DOP_L \) defined by:

\[
DOP_L = \sqrt{s_1^2 + s_2^2} / s_0
\]

\( DOP_L \) permits evaluation of depolarization \([7]\), distinction between materials like metallic or scattering surfaces \([8, 9]\), painted surfaces \([10]\) or some most natural or man-made objects \([11]\). It should be noticed that \( DOP_L \) is of course smaller than \( DOP \) and not considering \( s_3 \) comes down to consider circular polarization like an unpolarized component.

A further parameter, the polarization angle (\( \Psi \)), can be evaluated with the partial Stokes vector:

\[
tan(2\Psi) = \frac{s_2}{s_1}
\]

The polarization angle allows the user to evaluate the orientation of linear polarization. With some implementations, only two crossed polarization states are available. In this case, it has been shown that provided the incident beam is linearly polarized and normal to the scene, and that the scene does not include any birefringent nor dichroic material, \( DOP \) comes down to \([12]\):

\[
DOP = \frac{|s_1|}{s_0} = \frac{|I_0 - I_{90}|}{I_0 + I_{90}}
\]

where \( I_0 \) represents the intensity of the light which is parallely polarized to the input and \( I_{90} \) the intensity in the crossed direction.

3. State of the art in imaging polarimetry
Imaging polarimetry is a field of growing interest and more or less general reviews may be found in the literature \([3, 6]\). In this Section, we will sum up and compare the basic principles that can be implemented for dynamic operation.

3.1. Division-of-time polarimeters
The simplest solution for the implementation of polarimetric imaging consists in performing successive acquisitions of the considered polarization states with a rotating polarizing element. Of course, this basic solution no longer holds in the case of evolving phenomena, because accurate rotation angles cannot be obtained with a sufficient precision even at reduced speeds. A solution incepted by Wolff et al. in the 1990s consists in using a polarizing element whose rotation is virtual: liquid crystal (LC) cells which act as polarizing elements can classically be operated at few tens of Hz. The use of twisted nematic and parallel-aligned nematic liquid crystal cells was reported by several authors \([13, 14]\). Their implementations were able to capture polarimetric data at a few tens of fps, but cannot be used for high-speed operation. On the contrary, ferroelectric LC cells can operate at the kHz rate, but at present the reported implementations used binary controlled modulators, which results either in a rather simple
system, using a single cell but only providing a reduced polarimetric information (see Subsection 4.1), or a more complicated setup, using several cells but providing more information [15]. Implementations using other electro-optic materials were also reported, for instance with PLZT modulators, but they seem to be less effective than implementations using LCs [16].

3.2. Division-of-wavefront polarimeters
This technique is very popular in the infrared domain, using wire-grid polarizers in a focal plane array [17]. It consists in implementing a scheme similar to Bayer’s scheme for RGB cameras: each pixel acquires a given polarization state, different from its neighbours. Subsequent interpolation and registration allow the user to estimate the full polarimetric interpolation at each pixel. This technique leads to compact and robust implementations and is only limited by the speed of the camera and of the interpolating calculus.

3.3. Division-of-amplitude polarimeters
This technique consists in decomposing the wavefront to be analyzed into as many beams as parameters to be analyzed. In practice, in order to determine the full Stokes vector, four beams should be analyzed simultaneously, corresponding to four arms in the optical setup [18]. Therefore, four identical cameras are required and have to be synchronized and registered with micrometric precision. This implementation is extremely heavy, but is only limited by the speed of the cameras.

4. Implementation of ferroelectric-liquid-crystal-based high speed imaging polarimeters
In setups inspired by Wolff’s dynamic system described in Section 3.1, we propose to replace the two liquid crystal modulators by a single ferroelectric liquid crystal (FLC) modulator capable of reaching up to at least 1 kHz [19]. We both experimented with a transmissive bistable modulator and with a reflective modulator able to be continuously controlled. Each implementation uses a cost-effective CCD camera.

4.1. Implementation with a transmissive bistable modulator
We experimented with a transmissive FLC which led to a simplified, portable implementation (Fig. 1). Operation was demonstrated at up to 360 fps, but at present the modulator control does not allow the user to get anything but two crossed polarization states.

Figure 1. Our portable high-speed polarimetric camera. The AVT CCD camera is equipped with an objective lens and a 1-inch clear aperture FLC modulator.

4.2. Implementation with a reflective tunable modulator
This modulator, manufactured by BNS Inc., is supposed to act as a half-wave plate whose axis is continuously tunable from 0° to 45° [19, 20]. Ferroelectric liquid crystal cells can be operated at several tens of kHz, but this device is pixelated (512x512 pixels) and the electronic addressing scheme limits its frame rate to 1015 Hz [21, 22]. The modulator can be controlled with eight bits and exhibits a response
(versus grey level) which is varying according to the frame rate [23]. Evaluating the first three Stokes components requires at least three measurements in order to produce three polarization rotations (for instance resp. $0^\circ$, $45^\circ$ and $90^\circ$). Due to the modulator nonlinear response, the intermediate control corresponding to $45^\circ$ has been determined thanks to a full Mueller matrix characterization.

5. Experimental results
Experimental data were obtained either in the lab, with the reflective SLM-based system with known illumination, or outdoor, with the portable system, under uncontrolled lighting conditions.

5.1. DOP evaluation
In this first series of experiments, we were only interested in evaluating DOP as expressed in (6). In order to prove the ability of our device to capture dynamic phenomena, we used a rotating scene and studied it with our portable system described in Subsection 4.1. It is composed of an aluminium plate on which several objects are placed: a polystyrene chip, a one euro cent coin which is fixed with a piece of double-sided adhesive tape and several layers of translucent adhesive tape which have been superimposed.

![Figure 2. Images produced by our polarimetric camera under laser illumination at 360 fps with a 8-bit resolution. The two top sub-images are intensity images grabbed in two crossed polarization directions. The bottom left image represents the total intensity (luminance) with a logarithmic greyscale. The bottom right image describes the DOP image.](image)

The scene has been illuminated by a vertically polarized laser. Despite noise, good quality images have been obtained for DOP (Fig. 2) at up to 360 fps. DOP is clearly an interesting way to retrieve information, either in lit or dark zones. In our case, we can clearly see that the coin and the aluminium background do not depolarize, but the double sided adhesive tape and polystyrene chip depolarize strongly.

5.2. Linear polarization evaluation
In addition to the first two Stokes parameters, the reflective-based SLM allows the user to evaluate the third Stokes parameter, and consequently the angle of polarization. We experimented with a translucent scene consisting of three stripes of polarizing film oriented at $0^\circ$, $45^\circ$ and $90^\circ$ (Fig. 3). Since the scene is moving, artifacts are noticeable at the edges of the polarizers, as mentioned in the next Section.

6. Discussion
Despite minor accuracy issues, whose origin may be noise or a lack of precision in characterization or calibration of the system, the previous results clearly assess that FLC-based imaging polarimeters can be an interesting solution for the evaluation of polarization data in dynamic situations. Nevertheless, like all other division-of-time polarimeters, our systems fail in correcting evaluating polarization data when objects in the scene are rapidly moving, or similarly when the camera is in motion (Fig. 4). Several images, acquired with a slight time shift, are required to get back to polarimetric data, and since these
Figure 3. Polarization images of samples obtained with SLM-based polarimeter for transmissive scene. We report Stokes images $s_0$ (a), $s_1$ (b) and $s_2$ (c), $DOP_L$ (d) and polarization angle $\Psi$ (e). Our scene consists of polarizers respectively aligned at $0^\circ$ (left), $45^\circ$ (center) and $90^\circ$ (right).

Figure 4. Correction of DOP in a natural scene. Intensity image (a). Erroneous DOP without any correction (b). DOP computed when the camera is static (c). Result of median filtering (d). Result of the registration (e).

images or these objects are spatially shifted, our system proves to act as an edge detector. A classic solution to this problem consists in registering the images prior to polarimetric data extraction. Another solution, less computer intensive, consists in performing a temporal median filtering on each pixel of DOP images. We report Fig. 4 the implementation of both techniques to data we acquired outdoor, with uncontrolled lighting conditions. Whereas giving less accurate results [24], median filtering can seem an interesting solution compared to image registration since it is so little computer intensive that it can be implemented at 50 fps with a PC.

7. Conclusion
Dynamic implementations of imaging polarimeters have been proposed for a dozen years. Among them, implementations using liquid crystal cells proved of interest. We particularly assessed the interest in using ferroelectric liquid crystal cells. They allowed us to obtain polarimetric data to 360 fps, which
opens a wide range of applications.

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