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▶ To cite this version:

P. Marconnet, L. Gendre, A. Foulonneau, Laurent Bigué. Cancellation of motion artifacts caused by a division-of-time polarimeter. SPIE Optical Engineering + Applications, Aug 2011, San Diego, United States. pp.81600M, 10.1117/12.894050. hal-03604416

HAL Id: hal-03604416 https://hal.science/hal-03604416

Submitted on 10 Mar 2022

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Cancellation of motion artifacts caused by a division-of-time polarimeter

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ABSTRACT

For any kind of imaging polarimeter, at least four intensity images, named polarization state images, are needed to compute one full Stokes vector. When the polarimeter is designed according to the division-of-time principle, polarization state images are acquired sequentially. Consequently, the main issue is the systematic occurrence of artifacts as the scene is not static. Even though this is well known, little research has been done on this subject. Here a two-step motion-compensation-based method is proposed to fix it. The first step consists in estimating the motion between each image acquired according to the same polarization state. Then each image is warped according to a fraction of the previously estimated motion.

Due to their dense and accurately estimated motion field we have shown optical-flow techniques to be the most efficient for motion-estimation in this case. Compensating the motion using optical flow to estimate it actually leads to a strong correlation criterion between corrected and reference polarization images.

Our method allows the estimation of the polarization by post-processing the polarization state image sequence. It leads to a good estimation quality whether the scene is static or not, thus fixing the main issue of a division-of-time polarimeter.

Keywords: Imaging polarimeter, division-of-time, motion artifacts, stokes vector, optical flow

1. INTRODUCTION

Polarization of light may be analyzed by systems named imaging polarimeters which provide polarization information of a scene on a pixel basis. One way of fully characterizing the polarization of a ray of light is to use the Stokes formalism,^{1,2} in which light polarization is described by a four-component vector **S** named Stokes vector, which can be written:

$$\mathbf{S} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{-45} \\ I_R - I_L \end{bmatrix},$$
(1)

where s_0 , s_1 , s_2 and s_3 are named Stokes parameters, and I_0 , I_{90} , I_{45} , I-45, I_R and I_L are intensity images acquired according to different polarization modes, which are named "polarization state images" (PSIs). s_0 characterizes the total intensity of light, s_1 and s_2 the linearly polarized light and s_3 the circularly polarized light. I_0 and I_{90} are the intensities of horizontally and vertically polarized light, I_{45} and I_{-45} are the intensities of linearly polarized light at +45° and -45°, I_R and I_L are the intensity of right and left circularly polarized light.

Please notice that in eq. (1) six PSIs are used to compute the Stokes vector, whereas the Stokes vector can be computed with a minimum of four PSIs.

Each PSI has to bring different polarization information and thus has to be acquired by filtering the polarization differently. Ideally, each PSI has to represent the same scene, in the same time and according to the same field of view. In practice these requirements are rather hard to fulfill, and have led to design different kinds of polarimeter architectures, whose differences lie in the way of acquiring PSIs (see Ref. 3 for a description of polarimeter architectures). In the case of the division-of-time architecture, PSIs are acquired sequentially in

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time. An example of a synthetic PSI-sequence acquisition in case of linear Stokes vector estimation with four different polarization states is printed on Fig. 1.



Figure 1: Acquisition principle of a PSI-sequence performed by a division-of-time polarimeter with four different polarization states and in case of scene motion.

As pointed out by many authors in the literature³⁻⁶ the division-of-time scheme systematically leads to some motion artifacts when the scene is not static (cf. Fig. 2). Even though this issue is well known, to our knowledge, there are very few efforts which aim at fixing it.

Persons *et al.*⁴ proposed an approach to address the general problem of spatial misregistration of PSIs. The method is based on phase correlation and leads to a global rigid registration of the whole image. As a consequence, neither different objects displacements, nor motion amplitude differences resulting of the acquired scene perspective are properly corrected.

Guyot *et al.*⁵ proposed a first approach to fix this particular issue, but it was limited to sequences containing small motion amplitudes and whose raw images exhibit similar small scale patterns. As we thought this method was too restrictive, a technique which allows the attenuation of artifacts without doing any assumption neither on the features of the sequence nor on the motion characteristics was proposed.⁶ This technique consists in processing the computed Stokes vector sequence by a temporal median filter. Although the rendering of the Stokes vector images is improved, this processing can induce erroneous measure estimations at pixels where there were no artifacts.

The aim of the present work is to show how the Stokes vector can be recovered in the case of scene motion and therefore to demonstrate that a division-of-time polarimeter can be used to measure polarization in dynamic scenes.

The main idea of our method is to compensate for the apparent motion observable in PSI sequences and then to compute the Stokes vector using the compensated images. It means PSI-sequences are registered in order to correct artifacts on the sequence of Stokes vector images. Contrary to classical image sequences, we do not register pairs of consecutive images, but pairs of PSIs acquired according to the same polarization, so making our method insensitive to the kind of polarization analyzed. Our registration technique is composed of a motion field estimation supplied by an optical flow technique,⁷ then of the warping of each PSI according to a fraction of the previously estimated motion fields.

This two-step registration allows computing the genuine Stokes vector as if the PSIs were acquired simultaneously, thus canceling artifacts caused by the inherent motion of any dynamic sequence.

Since we have not yet analyzed the circular polarization (*i.e.* the s_3 parameter) in the case of motion, we restrain the study to the analysis of the linear polarization. Nevertheless we would like to emphasize that our method may be able to address the motion issue in the case of the full Stokes vector analysis.

To compute the full Stokes vector a minimum of four different PSIs are needed, whereas in the case of linear polarization analysis only three are needed. In order to be in the same conditions as if the full Stokes vector was analyzed, we decided to compute the three first Stokes parameters by combining four different PSIs $(I_{-45}, I_0, I_{45}, I_{00})$. The only differing characteristic of the fourth PSI needed to compute the full Stokes vector lies in using a circular polarizer instead of a linear polarizer. Replacing it by a PSI acquired using a linear polarizer changes the physical content of the image and the analyzable Stokes vector: s_3 cannot be analyzed anymore.

However, as our method is insensitive to the physical content of PSIs, it does not affect it.

In the second Section of this article the origin and the consequences of motion artifacts are explained and illustrated. Then, in the third Section the correction method is explained. The fourth Section aims at detailing the way our method has been evaluated. Finally, in the fifth Section results obtained by using the method are presented.

2. MOTION ARTIFACTS

Measuring the polarization with a division-of-time polarimeter involves that the PSIs are acquired sequentially in time (cf. Fig. 1). Acquisition can be performed by using a rotating waveplate² or liquid crystal cells.⁸ Because of the successive acquisitions, when there is a relative motion between the target and the sensor, gray levels of PSIs are not aligned anymore. As the successive PSIs are combined to compute the Stokes vector, it leads to erroneous values of the Stokes vector at pixels which do not represent the same object at the same relative position. These erroneous values are what we name "motion artifacts".



Figure 2: Consequence of scene motion during the acquisition: artifacts are occurring on the Stokes vector.

So artifacts occur systematically when there is motion. As they corrupt Stokes vector, useful quantities such as the degree of linear polarization (DOLP) or angle of polarization (AOP), which are function of the Stokes vector, are also corrupted (cf. Fig. 2):

$$\text{DOLP} = \frac{\sqrt{s_1^2 + s_2^2}}{s_0} \qquad \qquad \text{AOP} = \frac{1}{2} \cdot \arctan\left(\frac{s_2}{s_1}\right) \tag{2}$$

The DOLP is a quantity representing the proportion of linearly polarized light, and the AOP represents the major orientation of polarization. On those two quantities, due to the combination of every PSIs, artifacts are emphasized. Therefore we prefer showing the qualitative results on DOLP and AOP rather than on Stokes parameters.

An example of motion artifacts in the case of a real sequence is given on Fig. 3. These images were acquired with a division-of-time polarimeter which uses a liquid crystal cell to modulate the polarization. On picture (a) the luminance of the acquired scene is shown.⁹ One can distinguish in the foreground a tree, a walking pedestrian and four cars (one is hidden behind the leaves of the foreground tree). And in the background there is a building and several trees. One can see on the static DOLP image (b) that without motion the most polarizing elements are the windows and the hoods of the cars. However as the legs of the pedestrian are moving, one can see a few artifacts occurring on the edge of his legs. On DOLP image (c) the polarimeter has been slightly paned and thus has caused the occurrence of many artifacts. For example artifacts are clearly visible on the edge of the background, on the edge of the leaves of the tree and on the tires of the cars. In this case, they are so numerous that they prevent the user from detecting really polarizing elements.



(a) Total intensity, s_0 , without motion.

(b) DOLP without motion.

(c) DOLP with motion.

Figure 3: Consequence of motion on a real scene: artifacts are occurring.

3. CORRECTION METHOD

3.1 Registration Principle

As the artifacts are a consequence of the motion visible in the acquired PSI-sequence, the goal of our method is to compensate for the apparent motion in the PSI-sequence, before using it to compute the Stokes vector. In this way, if the motion was perfectly compensated, PSIs would appear as if they were acquired simultaneously. The principle is the following: an arbitrary reference time is chosen to estimate the Stokes vector. The aim is to warp the four nearest PSIs according to their motion, so that each one appears to have been acquired at the reference time. By placing the reference in correspondence with an instant where one PSI has been acquired, only three PSIs remain to be warped in order to have four simultaneous PSIs available. Consequently only three motions have to be estimated to compute the Stokes vector.

For example, on Fig. 4(a), the PSI I_{90} has been taken as a reference; then motion fields $\mathbf{w}_{I_0 \to I_{90}}, \mathbf{w}_{I_{45} \to I_{90}}$ $\mathbf{w}_{I_{-45} \to I_{90}}$ have to be estimated. But as each PSI may possess its own gray level dynamic, estimating these motion fields directly does not allow to obtain a good motion estimation. As a consequence, motion fields are estimated between pairs of PSIs acquired according to the same polarization (*e.g.* $\mathbf{w}_{I_0 \to I_0}$ on Fig. 4(b)). Then, assuming motion is linear, the desired motion fields are obtained by interpolating the estimated motion fields $(e.g. \mathbf{w}_{I_0 \to I_0})$.



Figure 4: Illustration of the registration principle. Blue arrows represent the desired motion fields and the black arrow represents one of the estimated motion fields. Here I_{90} has been chosen as the reference point. After warping I_{45} , I_{-45} and I_0 according to their respective motion fields, the Stokes vector can be estimated as if each of these PSIs was acquired simultaneously.

Motion estimation can be done using different techniques such as rigid registration, phase correlation, affine transformation, block matching, or optical flow. We implemented most of them, but in this article we will focus on the technique which leads to the best result quality, namely the optical flow. Obviously, the more accurate the estimated flow field is, the better the quality of the correction method will be. Today top of the art optical flow techniques allow the estimation of the displacement of each pixel with a very good accuracy (see Ref. 10 for an up-to-date benchmark of optical flow techniques).

Optical flow techniques aim at estimating the apparent motion of a brightness pattern between two images. In the same way, motion artifacts are the direct consequence of the mismatching between the gray levels of the PSIs. This makes a good match between the principle of optical flow and the motion issue of a division-of-time polarimeter.

Moreover, as stated before, due to their dense and accurately estimated flow fields, optical flow techniques allow a good registration quality. An example of an obtained flow field can be seen on Fig. 5.



Figure 5: Example of obtained motion field using an optical flow technique. (a) and (b): 5th and 6th I_{-45} image of the PSI-sequence. (c): motion field $\mathbf{w}_{I_{-45}\to I_{-45}}$ estimated between the 5th and the 6th I_{-45} images of the PSI-sequence. (d): motion field legend; intensity corresponds to motion amplitude $||\mathbf{w}||$ and hue corresponds to motion direction $\theta_{\mathbf{w}}$.

Middlebury benchmark offers four evaluation criteria¹¹ of developed optical flow techniques. Two of them evaluate the accuracy of the resulting optical flow field by comparing it with the exact motion field. The two others interpolation error and normalized interpolation error — quantify the gray level differences between the image warped according to the estimated motion field and the exact image. As the artifacts occur when the gray levels are not in phase, the two latter evaluation criteria directly evaluate the origin of the error of the division-of-time polarimeter. So, a well suited optical flow technique should be well ranked for the interpolation error criteria.

In year 2010, looking at the interpolation error criterion, one of the best ranked optical flow technique was the technique of Brox *et al.*¹²; therefore we implemented this technique. It improves the original technique of Horn and Schunck¹³ mainly by tackling the large displacements issue of their proposal. This has been done by postponing the linearization of the optical flow constraint equation to the numerical resolution and by implementing the multigrid approach proposed by Mémin and Pérez.¹⁴

3.2 Optical Flow Implementation

The implementation described here is a slightly modified version of the technique of Brox *et al.*^{7,12} For more information about the original method, the reader should refer to the corresponding articles.

The motion field estimation is here formulated as a variational minimization problem. The functional E to be minimized according to the motion field **w** consists of three terms in our case. The first one, named "gray value constancy assumption", conveys the hypothesis that brightness pattern of an object is not changed by displacement. The second one, the "gradient constancy assumption", completes the "gray value constancy assumption" by assuming gray level edges are not changed by displacement. The last one, the "smoothness constraint", conveys the hypothesis that neighboring pixels might have the same motion. This latter one is used to tackle the aperture problem¹⁵ which arises when evaluating the motion of an object locally (without taking into account the motion of neighboring pixels).

Thus the functional E can be written the following way:

$$E(\mathbf{w}) = \beta \cdot \oint \Psi \left(\|I(\mathbf{X} + \mathbf{w}) - I(\mathbf{X})\|^2 \right) d\mathbf{X} + \gamma \cdot \oint \Psi \left(\|\nabla I(\mathbf{X} + \mathbf{w}) - \nabla I(\mathbf{X})\|^2 \right) d\mathbf{X} + \alpha \cdot \oint \Psi \left(\|\nabla u\|^2 + \|\nabla v\|^2 \right) d\mathbf{X}$$
(3)

where α , β , γ are weights, **X** is the coordinate system of the image sequence I (with $\mathbf{X} = (x, y, t)$), **w** is the motion field to be estimated (with $\mathbf{w} = (u, v, 4)$). Thus $I(\mathbf{X})$ represents an image of the PSI-sequence and

 $I(\mathbf{X} + (0, 0, 4))$ the next image of the PSI-sequence whose polarization mode is the same as the $I(\mathbf{X})$ image. Consequently $I(\mathbf{X} + \mathbf{w})$ represents the image $I(\mathbf{X} + (0, 0, 4))$ which has been warped according to \mathbf{w} . Finally Ψ is a regularization function, which is defined by $\Psi(A^2) = \sqrt{A^2 + \epsilon}$, with $\epsilon = 10^{-3}$. Let us define the following notations, originally introduced by Brox *et al.*:

$$I_{x} = \partial_{x}I(\mathbf{X} + \mathbf{w}) \qquad I_{y} = \partial_{y}I(\mathbf{X} + \mathbf{w}) \qquad I_{z} = I(\mathbf{X} + \mathbf{w}) - I(\mathbf{X}) \qquad I_{xz} = \partial_{x}I_{z}$$

$$I_{xx} = \partial_{xx}I(\mathbf{X} + \mathbf{w}) \qquad I_{yy} = \partial_{yy}I(\mathbf{X} + \mathbf{w}) \qquad I_{xy} = \partial_{xy}I(\mathbf{X} + \mathbf{w}) \qquad I_{yz} = \partial_{y}I_{z}$$
(4)

In order to minimize the functional E according to \mathbf{w} , Euler-Lagrange theorem can be used, thus leading to the system of equations (5):

$$\begin{cases} \beta.\Psi'(I_z^2).I_x.I_z + \gamma.\Psi'(I_{xz}^2 + I_{yz}^2).(I_{xx}.I_{xz} + I_{xy}.I_{yz}) = \alpha.\operatorname{div}\left(\Psi'(\|\nabla u\|^2 + \|\nabla v\|^2).\nabla u\right) \\ \beta.\Psi'(I_z^2).I_y.I_z + \gamma.\Psi'(I_{xz}^2 + I_{yz}^2).(I_{xy}.I_{xz} + I_{yy}.I_{yz}) = \alpha.\operatorname{div}\left(\Psi'(\|\nabla u\|^2 + \|\nabla v\|^2).\nabla v\right) \end{cases}$$
(5)

Equations of the system (5) have to be linearized. Therefore two nested fixed point iterations loops (K and L) are used.¹² Motion field \mathbf{w} is linearized by the first fixed point iteration loop (K) and the usage of a first order Taylor expansion. That leads to define:

$$C^{k} = \sqrt{\|\nabla u^{k+1}\|^{2} + \|\nabla v^{k+1}\|^{2}} = \sqrt{\|\nabla (u^{k} + du^{k})\|^{2} + \|\nabla (v^{k} + dv^{k})\|^{2}}$$

$$A^{k} = I^{k+1}_{z} = I^{k}_{z} + I^{k}_{x}$$

$$G^{k}_{x} = I^{k+1}_{xz} = I^{k}_{xz} + I^{k}_{xx}.du^{k} + I^{k}_{xy}.dv^{k}$$

$$G^{k}_{y} = I^{k+1}_{yz} = I^{k}_{yz} + I^{k}_{xy}.du^{k} + I^{k}_{yy}.dv^{k}$$
(6)

with du^k and dv^k being increments of components u and v of the motion field \mathbf{w} to be estimated. Finally, remaining non-linear expressions contained in Ψ' are linearized by the second loop (L) thanks to the fixed point iterations method. This allows to obtain the partial differential equations system (7):

$$\begin{cases} 0 = \alpha \cdot \left(\frac{\Psi'(C^{k,l^2})_{i+1} - \Psi'(C^{k,l^2})_{i-1}}{2} \right) \cdot \nabla \left(u_i^{k,0} + du_i^{k,l+1} \right) + \alpha \cdot \Psi'(C^{k,l^2})_i \cdot \Delta \left(u_i^{k,0} + du_i^{k,l+1} \right) \\ - du_i^{k,l+1} \cdot \left[\beta \cdot \Psi'(A^{k,l^2})_i \cdot I_x^{k,0^2} + \gamma \cdot \Psi'(G_x^{k,l^2} + G_y^{k,l^2})_i \cdot \left(I_{xx}^{k,0^2} + I_{xy}^{k,0^2} \right) \right] \\ - \beta \cdot \Psi'(A^{k,l^2})_i \cdot I_x^{k,0} \cdot \left(I_x^{k,0} + I_y^{k,0} \cdot dv_i^{k,l+1} \right) \\ - \gamma \cdot \Psi'(G_x^{k,l^2} + G_y^{k,l^2})_i \cdot \left[I_{xx}^{k,0} \cdot \left(I_{xz}^{k,0} + I_{xy}^{k,0} \cdot dv_i^{k,l+1} \right) + I_{xy}^{k,0} \cdot \left(I_{yz}^{k,0} + I_{yy}^{k,0} \cdot dv_i^{k,l+1} \right) \right] \\ 0 = \alpha \cdot \left(\frac{\Psi'(C^{k,l^2})_{i+1} - \Psi'(C^{k,l^2})_{i-1}}{2} \right) \cdot \nabla \left(v_i^{k,0} + dv_i^{k,l+1} \right) + \alpha \cdot \Psi'(C^{k,l^2})_i \cdot \Delta \left(v_i^{k,0} + dv_i^{k,l+1} \right) \\ - dv_i^{k,l+1} \cdot \left[\beta \cdot \Psi'(A^{k,l^2})_i \cdot I_y^{k,0^2} + \gamma \cdot \Psi'(G_x^{k,l^2} + G_y^{k,l^2})_i \cdot \left(I_{xy}^{k,0^2} + I_{yy}^{k,0^2} \right) \right] \\ - \beta \cdot \Psi'(A^{k,l^2})_i \cdot I_y^{k,0} \cdot \left(I_{xz}^{k,0} + I_{xx}^{k,0} \cdot du_i^{k,l+1} \right) \\ - \gamma \cdot \Psi'(G_x^{k,l^2} + G_y^{k,l^2})_i \cdot \left[I_{xy}^{k,0} \cdot \left(I_{xz}^{k,0} + I_{xx}^{k,0} \cdot du_i^{k,l+1} \right) + I_{yy}^{k,0} \cdot \left(I_{yz}^{k,0} + I_{xy}^{k,0} \cdot du_i^{k,l+1} \right) \right] \end{cases}$$
(7)

where the index i represent a pixel of the image, and exponents k and l represent iteration indexes of K and L loops.

Then the system can be solved with respect to du and dv, using the successive over relaxation¹⁶ (SOR) method.

4. USED METHOD TO EVALUATE THE CORRECTION

4.1 Way of creating a genuine and a division-of-time like sequence

Division-of-time scheme is characterized by the successive acquisition of PSIs. To test our correction method on a PSI-sequence we assumed that the period between each acquisition is fixed, which is *a priori* often the case in such a scheme. In order to be able to compare our correction with a genuine sequence, two sequences of the same scene were created. The first one, named "asynchronous" sequence, corresponds to the case of acquisitions of PSIs using a division-of-time scheme. The second one, named "genuine" sequence, corresponds to an ideal polarimeter which acquires needed PSIs in the same time and with the same field of view.

As the genuine sequence is unrealizable in practice, we simulated the successive acquisition in time by controlling the position of moving objects. If the speed of an object is constant and the acquisition of the PSIs is periodic, then the displacement of this object in the scene is also constant. Thus, if the displacement of each object is constant between each PSI-acquisition, then PSIs look as if they were acquired with a fixed period of time. Moreover if the acquisition period is small enough compared to the acceleration of an object, then the speed of this object may be assumed as constant over the acquisition period. This enlarges the validity of the speed constancy assumption to the case of division-of-time polarimeters which have a high frame-rate.

The control of the position is realized by a micrometric-position-controlled motorized plate on which is fixed an aluminum plate (cf. Fig 6(a)). In order to create a second controlled displacement, a cardboard strip as been added. One of its extremity has been fixed on the chassis of the motorized plate, and the other extremity rests on the aluminum plate.

Thus two controlled displacements were created. One is the translation of the set of objects associated with the aluminum plate (in red on Fig. 6(b)) and the other one is a slight rotation of the cardboard strip (in dark yellow on Fig. 6(b)).



(a) Photography of the scene



(b) Segmentation of the two displacements of the scene

Figure 6: Presentation of the test scene. (a): photography of the scene, (b): segmentation of the two displacements of the scene. In fact, photography (a) is a reconstitution of the acquired scene, therefore the foreground polarizing strips are not exactly in the same position. The scene is composed of many different objects of different materials, having different polarization properties. On subfigure (b) the two created motions are depicted by superimposing two different colors to the set of objects moving the same way. One can notice that shadows are also moving, but were not segmented for readability reasons.

Finally, the genuine sequence and the "asynchronous" sequence (corresponding to the division-of-time scheme) were acquired according to the schemes represented on Fig. 7.



Figure 7: Acquisition method of the two sequences needed to evaluate the correction method.

In order to have an idea of what our PSIs look like, one PSI of each polarization state has been extracted of the genuine sequence and printed on Fig. 8(a)-(d). Their corresponding DOLP and AOP have also been printed on Fig. 8. It should be noticed that PSIs were acquired under an incident 90° linearly polarized light.



Figure 8: PSIs extracted from the genuine PSI-sequence and their corresponding DOLP and AOP. For a better visualization in this paper the luminance of the PSIs has been doubled.

4.2 Which evaluation criterion is best suited ?

In order to evaluate quantitatively the correction brought by our method, a suitable evaluation criterion has to be chosen. This criterion should be maximal when values of gray level of the reference image and the image to be evaluated are the same. This could simply be done by using the sum of absolute differences (SAD), as described on equation (8):

$$SAD(A,B) = \sum_{x,y} \left(\left| A(x,y) - B(x,y) \right| \right)$$
(8)

where A being the image to compare to the image B, x and y the spatial coordinates of images.

However, in practice, this criterion is minimal only if there is no noise in images. As our correction method aims to correct the motion artifacts but not the noise, we would like to minimize the noise influence on the criterion compared to the influence of motion artifacts on the criterion. Knowing artifacts leads to much more important amplitudes of gray value differences, squaring the SAD leads to minimize the relative importance of noise compare to that of artifacts. Therefore the sum of squared differences (SSD), equation (9) is preferred:

$$SSD(A,B) = \sum_{x,y} \left(A(x,y) - B(x,y) \right)^2$$
(9)

Finally, as we would like to have a criterion which is insensitive to the different features of the PSIs, the zero-mean normalized sum of squared difference (ZNSSD), equation (10) is preferred:

$$\operatorname{ZNSSD}(A,B) = \sum_{x,y} \left(\frac{A(x,y) - \overline{A}}{\sigma_A} - \frac{B(x,y) - \overline{B}}{\sigma_B} \right)^2$$
(10)

where \overline{A} (resp. \overline{B}) is the mean of A and σ_A (resp. σ_B) is its standard deviation.

As it may be known, this criterion has a direct relation with the zero-mean normalized cross correlation (ZNCC), as stated on equation (11):

$$\operatorname{ZNCC}(A,B) = 1 - \frac{1}{2} \cdot \operatorname{ZNSSD}(A,B) = \frac{1}{\sigma_A \cdot \sigma_B} \cdot \sum_{x,y} \left(\left(A(x,y) - \overline{A} \right) \cdot \left(B(x,y) - \overline{B} \right) \right)$$
(11)

To summarize, ZNCC, employed in a similar context by Guyot *et al.*,⁵ allows an objective evaluation of the quality of our correction method. This is done by using the criterion to compare our corrected sequence with the genuine sequence. This evaluation criterion has the advantages to be insensitive to gray level dynamics of images and to reduce the influence of noise compared to the influence of motion artifacts.

This criterion can be used to evaluate the similarity between gray level images such as PSIs, Stokes vector components or DOLP images. However, due to the periodicity of data, AOP can not be evaluated by this criterion. In counterpart, due to the larger range of colors of AOP images, artifacts are more visible, and so it is easier to see the effect of the correction on AOP images than on DOLP images. Therefore, the AOP is only visually and not quantitatively evaluated. Nevertheless, as the origin of motion artifacts is contained in the Stokes vector and its correction can be evaluated, one can have an idea about the quantitative evaluation of the AOP images.

5. RESULTS

The correction method has been applied to the whole sequence of asynchronous PSIs. Some qualitative results are given by extracting some DOLP (cf. Fig. 9) and AOP (cf. Fig. 10) images of the resulting sequence.



Figure 9: Qualitative result of the correction of the DOLP. DOLP images extracted from the sequence before (a) and after correction (b). Green squares define the enlarged areas on Fig. 11 and Fig. 12



Figure 10: Qualitative result of the correction of the AOP. AOP images extracted from the sequence before (a) and after correction (b). Due to the wide range of colors used to represent the polarization information, artifacts are more visible on AOP images than on DOLP images of Fig. 9. By comparing (b) with (a) and Fig. 8(g) it can be observed that most artifacts have been canceled.

As one can see on these two figures, almost every artifact has clearly disappeared. However, by comparing Fig. 10(b) with Fig. 8(g), a few artifacts are still visible; for example at the bottom center of the DOLP and AOP images (enlarged on Fig. 11 and Fig. 12 respectively). This area of the scene is subject to a strong motion

change: the cardboard on the bottom left corner and the polarizing strip are fixed, whereas the adhesive strip is translating to the right (see Fig. 6(b) for a visualization of the two motions). But the smoothness constraint imposed to the flow field in equation (3) prevents the flow field to match perfectly the apparent motion. Moreover there is a part of the adhesive strip which is occluded on some PSIs used to estimate the flow field. These two factors are causing the motion compensation not to be efficient enough on this part of the image.



Figure 11: Zooms on two parts of the frames #6 of the DOLP-sequences. (a) and (d): asynchronous DOLP, (b) and (e): corrected DOLP, (c) and (e): genuine DOLP. Values indicated as comments correspond to the ZNCC value evaluated between the cropped genuine DOLP image and the corresponding cropped images.



Figure 12: Zooms on two parts of the frames #6 of the AOP-sequences. (a) and (d): asynchronous AOP, (b) and (e): corrected AOP, (c) and (e): genuine AOP.

The whole DOLP sequences has been quantitatively compared to the genuine DOLP sequence by employing the ZNCC criterion. It can be noticed that the proposed method improves the quality of the DOLP estimation: asynchronous DOLP sequence has a ZNCC mean value of 0.9588, whereas correcting the PSI-sequence leads to a corrected DOLP sequence with a ZNCC mean value of 0.9977. The ZNCC values of the temporal median filter⁶ have also been plotted so that it can be quantitatively compared to this method.



Figure 13: Zero-mean normalized cross correlation (ZNCC) values for the sequence. The ZNCC has been computed between the genuine sequence and the tested ones (asynchronous, temporal median filter,⁶ and our correction by optical flow). Notice that ZNCC mean values of these three methods are 0.9588, 0.9750, and 0.9977 respectively.

It should be noticed that the qualitative improvement realized by this method has a cost. The temporal filter may be applied at a frame-rate of 50 frames per second, whereas this optical flow technique is time consuming and needs to be applied by postprocessing.

6. CONCLUSION

In the field of polarization, it is commonly admitted that motion artifacts occurrence makes the division-oftime scheme unusable in the case of dynamic scene acquisition.³ Here a registration method based on optical flow estimation is proposed to recover a polarization estimation which is not corrupted by motion artifacts. The motion estimation is realized between pairs of polarization state images acquired according to the same polarization state.

Obtained results on real sequences allow to consider using a division-of-time polarimeter in the scope of dynamic scenes, thus widely enlarging its usage and proposing a solution to its main issue. Nevertheless, due to the computational cost of the optical flow method used, the proposed method has to be used by postprocessing.

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