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Application of a modified evolutionary algorithm for the optimization of data acquisition to improve the accuracy of a video-polarimetric system

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ABSTRACT

The use of the polarimetry techniques for display and study of biological tissues has gained increasing interest in recent years. This interest is related mainly to the non-invasiveness, relatively low cost, and ease of application among other characteristics. However, for full use of these advantages, the calibration methods must ensure the minimization of the effects of uncertainties related to the optical element positioning and the noise in intensities measurements.

Keywords: evolutionary algorithm, tissue imaging, imaging polarimetry, error analysis

1. INTRODUCTION

The analysis of the polarization of light is usually carried out using modulation schemes. In this case, optical components rotate at a particular frequency and the unknown output state of polarization of light is determined by several measurements. One of the most widespread methods of modulation uses a rotation quarter-wave plate QWP, and a fixed linear polarizer LP. Such arrangement makes it important the advancement of efficient calibration techniques. The optimization of the set of measurements is closely related to the improvement of the quality of imaging and henceforth the likelihood of better diagnose.

2. ACTUALITY

Identification and treatment of cancer are still one of the biggest challenges and has received considerable attention of the researchers in modern medicine [1-3] and power management [4-5]. The probability of survival increases considerably with early detection. Hitherto, biopsy is the standard technique to diagnose potential lesions. However, this procedure may skip injuries when they are at an early stage. Polarimetry methods can improve diagnostic accuracy, on the one hand, and to reduce hardware costs at the other [6]. Analysis of video-polarimetry systems can be found in the literature [7], from which one can conclude that they are potentially powerful tools. However, it is very difficult to measure the polarization of light reflected from the samples. Calibration procedures provide an opportunity to minimize the effect of systematic and random errors that occur when moving the optical components [8-9]. Therefore, the determination of the optimal set of measurement angles is an important task in the development of calibration and measurement processes of video polarimetry devices.

3. AIM OF THE RESEARCH

The purpose of this paper is to increase the reliability of the diagnosis of skin injuries through the application of a sound technique of calibration of a video polarimetry device. For this purpose two objectives were distinguished: the selection of an optimization criterion and the development of a modified method based on a evolutionary algorithm to assess this criterion.

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4. SOLUTION

The Stokes parameters S and the level of polarization DOP depict the polarization of light. Mueller matrix M permits the description of effects of optical elements on the polarization of the light beam. The effect of a set of optical elements on the polarization of light is given by the product of individual matrices Mi, with matrices arranged in reverse order. Given this relationship, the Mueller matrix of the analyzer PSA, is written in equation (1).

$$S_{out} = M_{PSA} * S_{in} = M_{LP} * M_{RQWP} * S_{in}, \tag{1}$$

where, M_{PSA} is the Mueller matrix of the analyzer PSA, M_{PL} is the Mueller matrix of the linear polarizer, M_{RQWP} is the Mueller matrix of the rotating quarter-wave plate, and S_{in}, S_{out} are the Stokes vector of the incoming and outgoing light. A set of at least four measurements is required in order to perform image analysis. Formally, this is described by the following equation I=MA(Θ)*S$_{\text{in}}$, where I is a column vector formed with the intensities of each measurement, and MA is the modulation matrix formed by the first row of each M_{PSA}. The vector Θ consists of the phase shift δ of the QWP and the angles of rotation θ_i of the QWP; and the azimuth φ of the LP, Fig. 1. To consider systematic errors, a deviation dΘ from a given Θ_0 has to be introduced. In this case, the intensity is expressed by the equation (2):

$$I = MA(\Theta_0 + d\Theta) * S = MA_{err} * S, \tag{2}$$

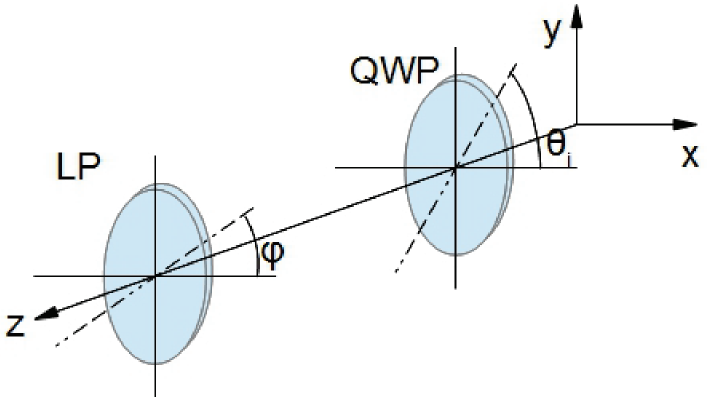

Figure 1. PSA scheme: Illustration of the angles for the calibration of the PSA with a rotating quarter-wave plate method. The angle of the LP transmission axis and the angle of the fast axis of the QWP are denoted by φ and θ, respectively.

The deviation of the vector Θ has a different effect on the error of each component of the Stokes vector measured. This difference is shown in Fig. 2. For this reason, it is advisable to look for the upper limit of the error instead of the error of each component of the Stokes vector.

If the difference is very small in comparison with Θ_0, then MA$_{\text{err}}$ can be expanded with a Taylor series to get

$$MA_{err} = MA(\Theta_0 + d\Theta) \approx MA(\Theta_0) + \frac{\partial MA(\Theta)}{\partial \Theta} d\Theta = MA + \Delta MA, \tag{3}$$

To evaluate the error on the measurement of Sin is necessary to determine the error of the modulation matrix $S_{in_{err}} = MA_{err}^{-1} * I$. In practical problems, it is advisable to use the condition number $\mu(X) = \| X \| \cdot \| X^{-1} \|$, where $\| X \|$, denotes the Euclidean norm [10].

The condition number allows quantitative assessment of the sensitivity of the solution due to errors in optics positioning. If vector Θ is such that the matrix MA is invertible and if MA^{-1}ΔMA<1 then

$$\frac{\| MA^{-1} - MA_{err}^{-1} \|}{\| MA^{-1} \|} \le \frac{\mu(MA)}{1 - \mu(MA)\frac{\| \Delta MA \|}{\| MA \|}} \frac{\| \Delta MA \|}{\| MA \|}. \tag{4}$$

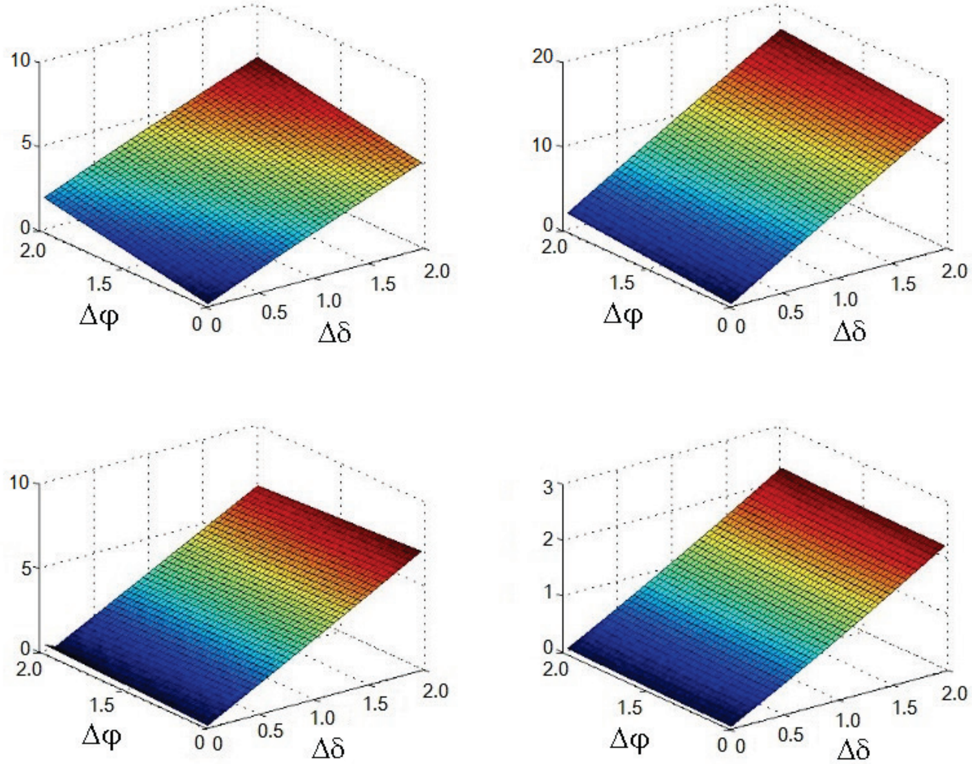

Figure 2. Comparison of the relative errors on the Stoke parameters due to different offset values.

Since $S_{in}=\mathrm{MA}^{-1}I$ equation (4) can be written in the following form

$$\frac{\| S - S_{err} \|}{\| S \|} \le \frac{\mu(MA)}{1-\mu(MA)\frac{\| \Delta MA \|}{\| MA \|}} \frac{\| \Delta MA \|}{\| MA \|}. \tag{5}$$

Equation (5) shows that the upper limit of the error depends on the conditioning of MA. If MA is a well-conditioned matrix, S will be relatively close to the actual value despite the presence of systematic errors. Therefore, the objective of the optimization process is to find the vector Θ that minimizes μ(MA). In addition to the systematic errors, it is necessary to consider the presence of noise in the image then, the equation (5) can be written:

$$\frac{\| S - S_{err} \|}{\| S \|} \le \frac{\mu(MA)}{1-\mu(MA)\frac{\| \Delta MA \|}{\| MA \|}} \left(\frac{\| \Delta MA \|}{\| MA \|} + \frac{\| \delta I \|}{\| I \|} \right). \tag{6}$$

where δI is the random noise of the measured intensity I. The previous equation shows that the upper limit of error is the sum of two separate terms. The first term is due to systematic errors in the system, and the second due to the noise in the image. Thus, it is important to optimize the conditioning of the matrix MA by finding the vector Θ, which minimizes μ and the effect of noise in the image. An evolutionary optimization strategy based on population allows finding Θ that ensures the proper conditioning of the matrix of modulation. The method operates on a population of potential solutions to the problem of optimizing μ. A mutation operator dictates the transitions of the population in the search space. In every generation, a certain number of the best individuals according to the evaluation of μ are selected. The mutation of a certain number of individuals, according to a probability factor, ensures the diversity over the search space. The best solution is selected and compared with the previous solution. The process is reiterated until the value of mu converges. Fig. 3 provides a description of the evolutionary mechanism.

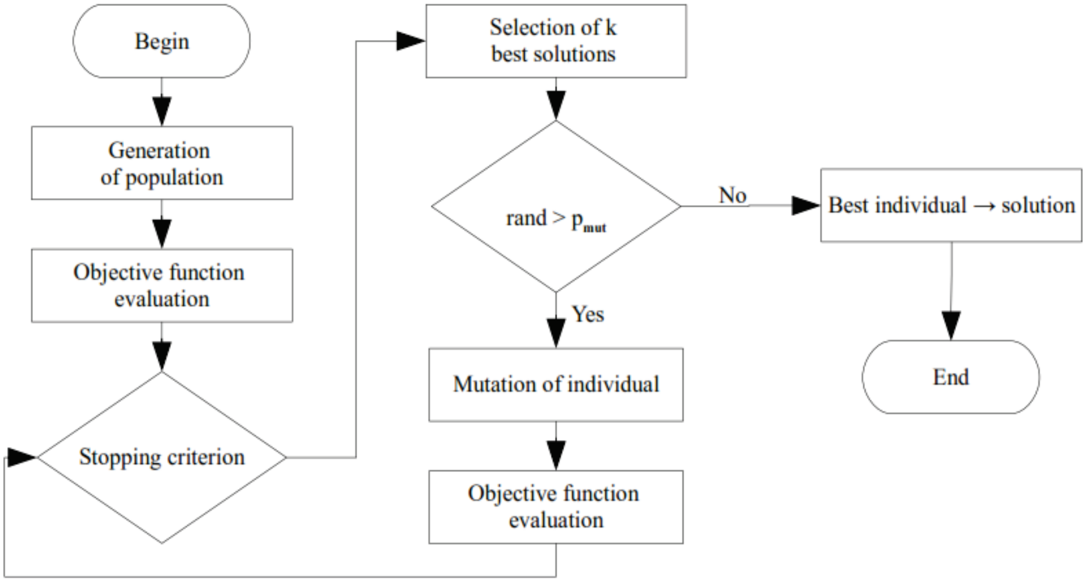

Figure 2. Evolutionary algorithm for the search of the optimal set of measurement angles.

The modulation matrix of the PSA was modeled considering two situations. First without offset of the azimuthal angle of the QWP, and second with a constant offset. The relative error obtained by the application of the proposed algorithm is shown in table 1 and Fig. 4 and Fig. 5.

Table 1. Maximum relative error of the Stokes parameters for an azimuth offset 1.5°

N	θ_1	θ_2	θ_3	θ_4	Max err%
1	72	155	171	245	0,05
2	20	120	150	247	0,17
3	192	229	231	292	0,39
4	70	152	184	38	1,45

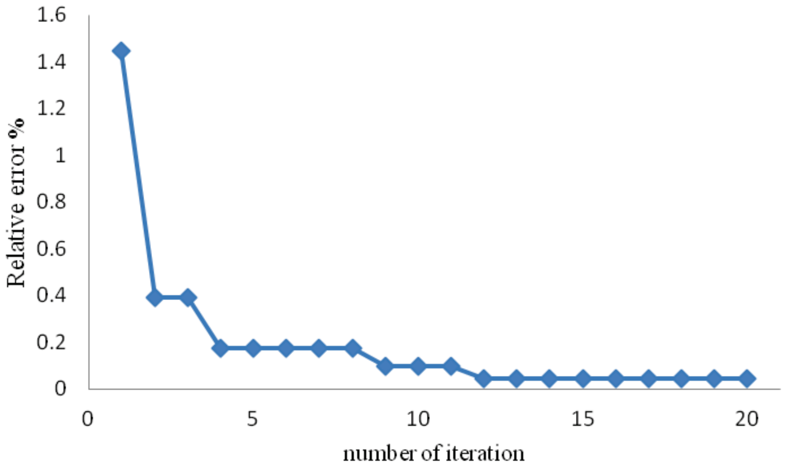

Figure 3. Evolution of relative Error with the number of iteration.

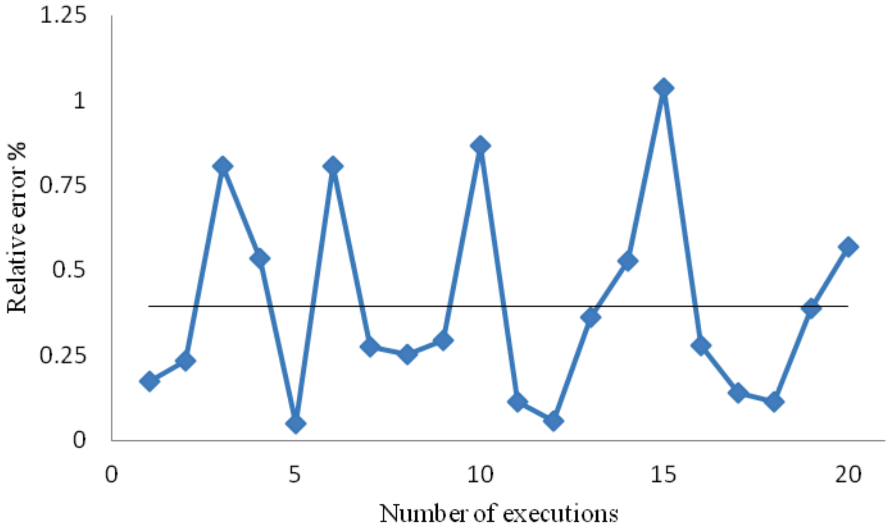

Figure 4. Variation of the results with the number of executions.

Table 1 and Fig. 4 show a set of positioning angles of the QWP. These angles provide the lowest value of the maximum relative error when establishing the parameters of the incoming to the PSA light. In the course of the simulation, it was found that the maximum relative error was as great as 26 for some values of the azimuth angles. This fact shows the positive effect of the application of the method has on the value of the measurements. In addition, Fig. 4 shows a rapid convergence to the final value. The robustness of the algorithm was carried out with a series of executions. At these executions the offset was kept constant and the maximum relative error was compared. The average value of the relative error was 0.39 and a standard deviation of 0.29

5. CONCLUSIONS

The proposed method of optimization of the image data acquisition in video polarimetry based on an evolutionary algorithm allows to minimize the maximum relative error of the parameters of the Stokes vector of the incoming light. The proposed technique can be applied in the assessment of both errors due to mechanical artifacts and image acquisition. The results might be employed to the calibration of imaging polarimetry devices for bio-tissue study.

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