Inspection of plant pathologies through pseudocolored images based on polarimetric basis

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Abstract.
The study of the interaction of biological tissue with polarized light leads to relevant information of physical properties (dichroism, retardance and depolarization) of samples. Polarimetric analysis of different characteristics in tissues is useful for applications such us tissue classification, contrast enhancement or pathology detection. By means of polarimetric imaging techniques we can characterize the polarimetric signature of biological samples in a noninvasive and nondestructive way. We have found that depolarization information is of special interest in turbid media such as plant tissue. In this manuscript we use polarimetric observables for plant inspection. In particular, we provide enhanced visualization of certain plant pathologies by constructing depolarization based pseudocolored images of pathological leaves where the pathological areas are revealed.

1 Introduction

Polarimetry has proved to be a very suitable tool for visualization and classification of biological structures. In botanical applications, two main characteristics are commonly inspected, dichroism and retardance, specially by using polarimetric microscopes. However, the depolarization channels have been usually understood as noisily characteristics that degrade dichroism and retardance information. Recent publications have demonstrated that depolarizing behaviour of vegetal tissues provides important and meaningful information of plants structures, and they are very precious for plant characterization and pathogen detection [1].

In this work we want to provide the suitability of two different sets of depolarizing metrics: the Components of Purity (CP; inspecting physical properties originating depolarization) and the Indices of Polarimetric Purity (IPP; inspecting the entropic properties of samples leading to depolarization) [2]. We take profit of these metrics to obtain polarimetric images enhancing the visualization of certain structures and pathogens in plants, as well as to reveal some information hidden in standard (non-polarimetric) images. These tools are applied to different plants specimens and pathogens. Finally, the best results in terms of image visualization are applied to construct pseudocolored images of plants diseases for an improved visualization.

The results provided in this work can be of interest in biophotonics for the early detection of pathogens. This can have some socio-economic impact, as these polarimetric-based methods could be applied for crops inspection, preventing harvest losses, as well as, reducing the use of pesticides, with the associated environmental impact.

2 Mathematical Background

The compact form of a general Mueller matrix (M) describing a polarizing system can be written as [2],

$$M = M_{00} \begin{pmatrix} 1 & \mathbf{D}^T \\ \mathbf{P} & m \end{pmatrix}, \qquad (1)$$

where $\mathbf{P}$ is the polarizance vector, $\mathbf{D}$ is the diattenuator vector and M_{00} is the irradiance value.

The modulus of $\mathbf{D}$ and $\mathbf{P}$, lead to the diattenuation and polarizance parameters. Whereas the former gives the dependence of the transmitted (reflected and scattered) light as a function of the incident state of polarization, the latter describes the capability of a polarimetric system to depolarize an incident fully polarized beam. Both characteristis are related with the dichroic properties of the media. Another interesting parameter can be deduced from the submatrix m, the so-called spherical purity paramterer, which can be written as a function of the M coefficients as $P_S = \|m\|_2 / \sqrt{3}$, where $\| \|_2$ is the Frobenius norm. This parameter is related with the depolarizing properties of a sample not originated by dichroic responses [2].

These three parameteres, D, P, and Ps conform the Components of Purity, providing a description of the physical origin of depolarization.

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On the other hand, we are also interested in the IPP, which can be calculated from the eigenvalues, λ_i, of the covariance matrix $H(M)$ (which is an unitary transformation of M). The IPP can be obtained by [2]:

$$P_n = \sum_{k=1}^{n} k\Delta\lambda_k, \qquad (2)$$

where $\Delta\lambda_k = \lambda_k - \Delta\lambda_{k+1}$, with $\sum_{i=1}^{4} \lambda_i = 1$. These IPP metrics, i.e, P_1, P_2 and P_3, give a description of the randomness processes leading to depolarization in a sample [2]. Importantly, combinations of IPP are the weights of the so-called characteristic decomposition of a Mueller matrix, which describes a general M as the addition of different matrices with physical interpretation [2]:

$$\hat{M} = P_1\hat{M}_{J0} + \sum_{k=1}^{2}(P_{k+1} - P_k)\hat{M}_k + (1 - P_3)\hat{M}_3, \qquad (3)$$

where the symbol ˆ indicates normalization, $\hat{M}_{J0}$ is a pure component, $\hat{M}_1$ and $\hat{M}_2$ are two non-pure components and, $\hat{M}_3$ represents an ideal depolarizer.

3 Experimental results and discussion

The experimental M image of the studied sample was obtain by means of the complete Mueller image polarimeter described in Ref.[1]. From these experimental images, the polarimetric observables described in previous section are calculated. The best metrics in terms of image contrast of different vegetal structures were selected to implement pseudo-colored images. Different depolarization sets were tested: IPP, CP, weights of the characteristic decomposition (Eq. (3)), among others.

To construct the pseudo-colored images, different strategies were used, but in all cases, different tissue classes or metrics were associated to different colors of the RGB color space. In particular, linear combination of polarimetric observables [3], the Euclidiean based approach or the probabilistic Gaussian approach [4] were tested. These techniques were applied on a collection of different vegetal leaves and common infections, they being of socio-economical interest.

As an example, in Fig.1 we show an *Hedera helix* leaf sample which was infected with Ascomycete fungus *Mycosphaerella hedericola*, causal agent of the leaf spot disease of ivy. The figure provides the comparison between the intensity image (M_{00}; Fig. 1 (a)) and a pseudo-colored image based on combinations of IPP channels (Fig. 1(b)).

The pseudo-colored image in Fig.1 (b) was constructed by associating the three first weights of the characteristic decomposition (Eq. (3)), i.e., P_1, $P_2 - P_1$ and $P_3 - P_2$ images of the leaf. Each one of these three parameters is associated to a main color RGB, with a given weight ($\alpha = 2$ for red, $\beta = 3$ for green and $\gamma = 3$ for blue), and linearly added to implement the final pseudo-colored image of the leaf.

In Fig.1 we observe a clear improvement on the pathology visualization thanks to the pseudo-coloration.

In this sense, note how the darkened necrotic spot and their bounds visualization are significantly enhanced (see necrotic bound highlighted with the dashed white line in Fig.1), when compared with the standard intensity image (Fig.1 (a)), where this transition between healthy and necrotic regions is not well defined.
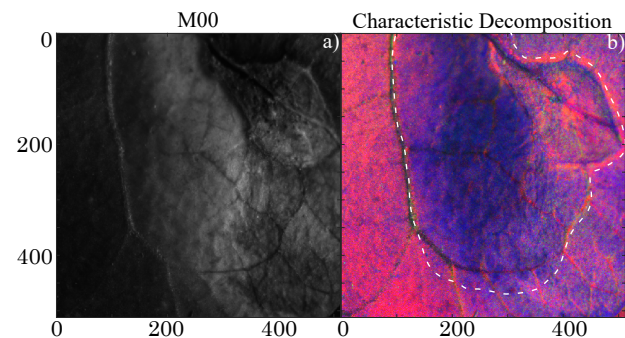

Figure 1. Intensity (a) and (b) depolarization based pseudo-colored images of the *Hedera helix*, the dashed line delimits the necrotic region caused by the Ascomycete fungus *Mycosphaerella hedericola*.

4 Conclusions

In this work we have provided the interest of polarimetric methods for the enhanced visualization of pathogens in plants. From two particular sets of polarimetric observables suitable for depolarizing description of samples, the Components of Purity and the Indices of Polarimetric Purity, we have constructed pseudo-colored functions improving the visualization of certain pathogens in plants. In particular, pseudo-colored images were constructed by associating one of the primary colors of the RGB color space to the polarimetric observables providing larger visualization between certain structures of interest. This was conducted for a collection of different plants and associated pathogens. As an example, we provided the pseudo-colored image, based on the weights of the characteristic decomposition, applied on the *Hedera helix* leaf infected by the Ascomycete fungus *Mycosphaerella hedericola*. Obtained results provide a clear improvement in the visualization and localization of necrotic spots compared with non-polarimetric intensity images.

References

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