Optimization of a polarization imaging system for 3D measurements of transparent objects.

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Abstract: This paper presents a multispectral imaging system for 3D reconstruction of transparent objects based on "shape from polarization" technique. The originality of this work relies on a multispectral active lighting system which enables to cope with the two ambiguities on the zenith angle and azimuth angle. A calibration step allows optimising the polarimetric measurements. Example of a reconstructed transparent object is presented.

OCIS codes: (110.0110) Imaging systems; (110.5405) Polarimetric imaging.

References and links

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1. Introduction

Competitiveness requires industrial to manufacture zero default products. To ensure this, visual inspection is often required to sort out defective products. Whereas technology now enables to inspect 3D opaque products, mainly trough active triangulation based systems, transparent objects are still challenging to inspect. Indeed, classical laser triangulation approach fails to reconstruct the surface of transparent object and the only solution to overcome this problem, requires applying an opaque coating onto the surface to be inspected. 3D inspection of unknown transparent objects is still an open problem and two techniques have been lately investigated:

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The first technique, “shape from heating” is based on the heat released by the object after being exposed to a heat front. Maldague and associates were among the pioneers to work on this idea of using thermal infrared. Their techniques “shape from heating” [1] and recently “shape from amplitude” [2] require a pre-segmentation of the image to isolate linear patches and non linear patches, which are afterwards used to lead to “extraction of relative depth” and “extraction of surface orientation”. This technique led to crude results (various assumptions) and was not applied to transparent objects. Recently Eren and al [3,4]. proposed an active triangulation method inspired from the shape from heating technique where results are quite promising but involved the use of expensive (IR camera) and cumbersome (CO_2 laser) equipments which prevent for an easy implementation within the industry.

The second technique exploits the polarization information contained in the reflected Electrical Field and is sometimes called “shape from polarization”. Techniques based on polarization imaging [5] are intended to use the Stokes vector model in order to get the needed parameters of the light wave: the degree of polarization and the angle of polarization. In the case of 3D shape recovery only a simplified model is required. Miyazaki [6] and Sato [7,8] proposed different set-ups to obtain 3D information, but the systems are still to cumbersome to be installed in the industrial context.

The approach presented in this paper, is based on the work of Miyasaki [8], later applied with a simpler experimental configuration by Morel [9] for metallic objects, with the use of a multispectral system [10] which after thorough characterization enables to release the ambiguity of the zenithal angle.

The rest of the paper is organized as follows: the first part presents the basis related to the principle of polarization imaging, the second part, is related to our 3D experimental set-up and is followed by a part describing our calibration technique. The last part is dedicated to our results showing the efficiency of our method. The paper ends with a short conclusion which presents our contribution as well as some insights for future contributions.

2. Principle of polarization imaging

The principle of polarization imaging that we will consider is: on reflection, a non-polarized light wave becomes partially linearly polarized according to the normal to the surface and the optical index of the material at the point of incidence. A partially linearly polarized wave may be defined by three parameters which are: the light intensity I, the degree of polarization ρ and angle of polarization φ.

The study of the state of polarization of a light wave requires a rotating polarizer placed in front of a camera. The relationship between amplitude Ip transmission of a light wave partially linearly polarized and the angle α of the polarization filter is given by:

$$\mathrm{I}_P(\alpha)=\frac{\mathrm{I}}{2}(\rho\cos(2\alpha\text{-}2\varphi)+1) \quad (1)$$

The purpose of the polarization imaging is to calculate I, ρ and φ through this formula.

The degree of polarization is defined by

$$\rho=\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}} \quad (2)$$

It is equal to zero when the light is not polarized and equal to 1 when the light is linearly polarized which corresponds to the incident angle θ_b equals to the Brewster angle.

However, even for the Brewster angle, the degree of polarization is less than 1, this can be compensated by introducing a complex index $\hat{n}=n(1+ik)$, where n is the real index and k the coefficient of extinction of the material being studied.

As pointed out earlier by Myasaki [8] and Morel [9], the measures of degree of polarization ρ and of the angle of polarization φ do not allow a straightforward evaluation of the normal vector defined by zenithal angle θ and azimuthal angle ϕ.

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Indeed, both the degree of polarization ρ and the angle of polarization φ provide two candidates for each measure. These two ambiguities are presented in the next-subsection.

1.1 Ambiguity in the azimuth angle ϕ related to the polarization angle φ

Wolff [5] has shown how to determine the normals to the surface using the Fresnel reflectance model and showed that the azimuth angle ϕ can be connected to the angle of polarization φ by the following equation:

$$\phi=\varphi\pm\frac{\pi}{2} \quad (3)$$

To remove this ambiguity and select the right candidate, we used an active lighting system based on Morel approach [9].

1.2 Ambiguity in the zenithal angle θ related to the degree of polarization ρ

One can express the degree of polarization ρ from Fresnel coefficients and Snell Descarte's law as a function of the zenithal angle θ for a dielectric object as:

$$\rho=\frac{2\sin(\theta)\tan(\theta)\sqrt{n^2-\sin^2(\theta)}}{n^2-2\sin^2(\theta)+\tan^2(\theta)} \quad (4)$$

When dealing with absorbing media (complex coefficient), using the approximation usually used in the visible region, $n^2\left(1+k^2\right)\gg 1$, this relation can then be expressed as

$$\rho=\frac{2n\sin(\theta)\tan(\theta)}{\sin^2(\theta)\tan^2(\theta)+n^2\left(1+k^2\right)} \quad (5)$$

where n is the real index and k the absorption coefficient.

Introducing a complex index provides a curve having a degree of polarization less than 1 for the Brewster angle and a shape which best fits the experimental data as will be presented later.

3. Experimental system

The polarization state of the reflected light is studied through the use of a prototype composed of several elements: a color dome light wavelengths (472nm, 513nm and 655nm) to control the lighting conditions and illuminate the object with a non polarized light; on optical analyzer composed of a combination of an electrically controlled liquid crystal variable retarder (LCVR), a polarizer and a quarter wave plate (Fig. 1). All of these combined elements act as a rotating polarizer automatically controlled by a computer.

All these elements must be able to meet the requirements for working under the three wavelengths used for visible light.

The choice of a multispectral lighting (three wavelengths) was guided by the fact that, for the same material, the index of refraction varies with the wavelength providing an opportunity to remove the ambiguity on the zenith angle θ. However, to take advantage of this, a thorough calibration (polarization rotation vs voltage) of the whole system is required for each of the three wavelengths.

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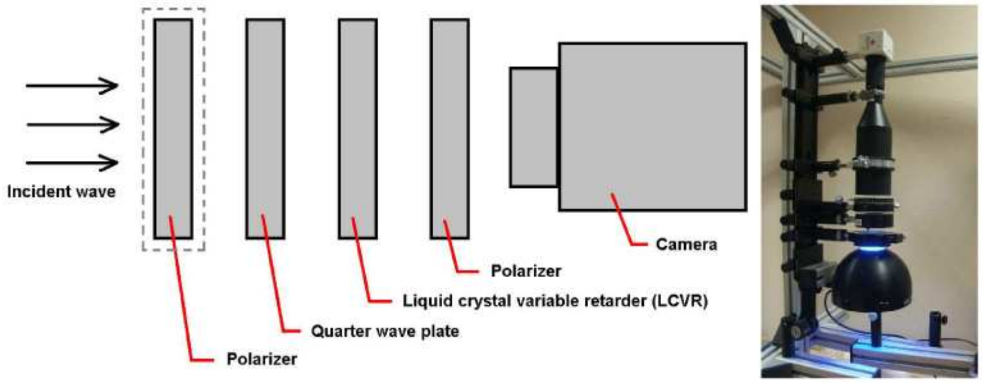

Fig. 1. Optical system for calibration, the polarizer on the left is only used for the calibration.

4. Calibration procedure

First of all, noise acquisition effects are reduced by both a temporal filtering (averaged over three acquisitions) and a spatial filtering (averaged over a mask 3x3 pixel).

To perform the calibration, a polarizing filter is inserted between the light source and the polarization state analyzer (Fig. 1). Then, the voltage applied to the LCVR is changed so as to obtain a maximum intensity. In order to automatically process the data and locate the maximum, a salient operator [11] was used. It consists of a sweep of the curve by a disk, and on evaluation of relationship between the disc surface intersected by the curve and the total surface of the disc. The degree of saliency is bounded between 0 and 1, for a curved plate will be 0.5, for a cavity it will be between 0.5 and 1 and for a peak it will be between 0 and 0.5. The closest the value is from the boundaries, the highest is the saliency of the curve. The maximum is found as the point where the saliency is the minimum (see Fig. 2). This point corresponds to the right voltage to be applied.

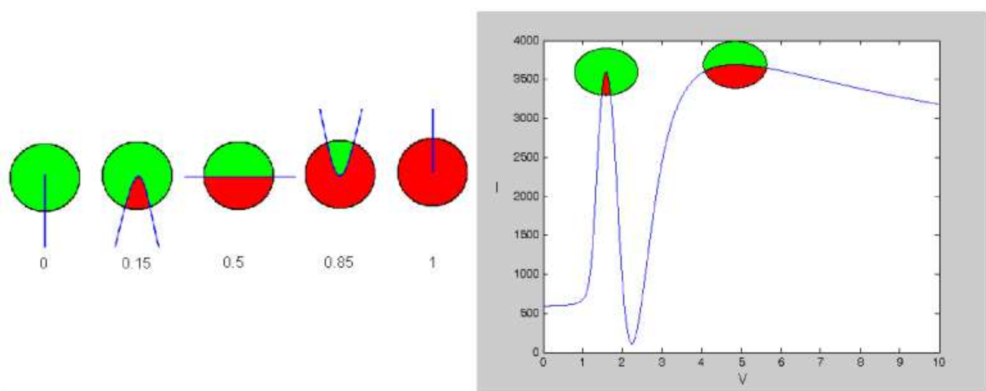

Fig. 2. Automatic detection of the maximum based on a saliency detector.

The polarizer is rotated from 0 to 180° for each wavelength in order to fully characterize the LVCR.

5. Experimental results

A first experiment, which consists in rotating a semi-reflecting plate under our acquisition system, was performed. This experiment (see Fig. 3) clearly illustrates that the ambiguity (lower or higher than the Brewster angle) can be solved by our multispectral system (curves are crossing near the Brewster angle).

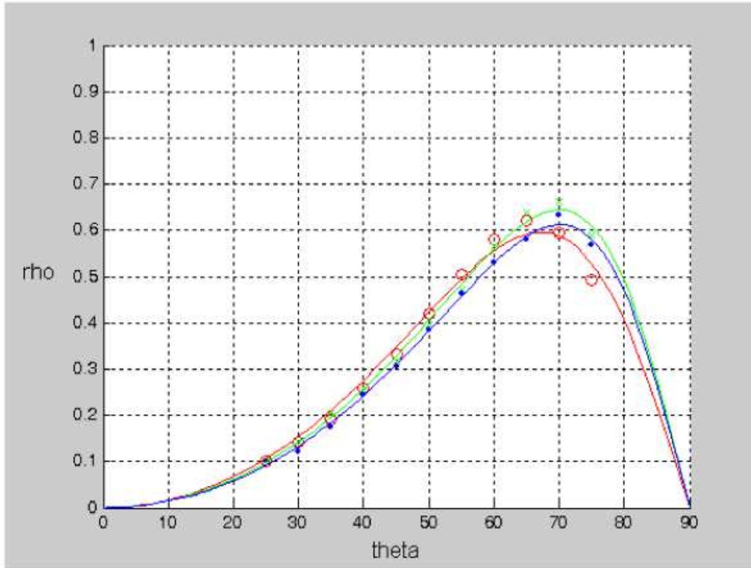

Fig. 3. Average degree of polarization recorded for different plate tilt for the three wavelengths and complex index estimation

The plate was rotating at 11 different angles and the index of refraction values (n and k) were estimated from Eq. (5), for each of the three wavelength. These values are later used to extract the zenithal angle from the degree of polarization.

The calibrated system was then used to reconstruct the 3D surface of transparent dielectric sphere. A simple difference of the average (spatial and temporal) of the degree of polarization obtained for each wavelength is realized (see Fig. 4) and remove the ambiguity on the zenithal angle. The ambiguity on the azimuth angle is obtained by using the active system developed by Morel and al [9].

Then knowing θ and ϕ the normal gradients can be determined and recovery of the height is obtained by the global method in the Fourier space as described by Frankot and Chellapa [12].

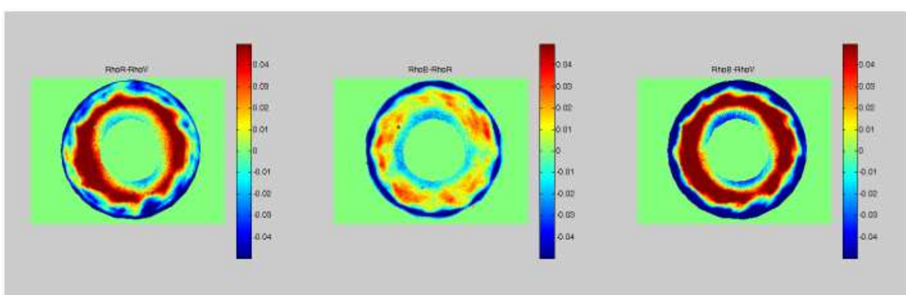

Fig. 4. Degree of polarization difference (negative value in blue, positive value in red).

Figure 5 is an example of the obtained result with an error map evaluated through comparison of an ideal sphere of known radius.

The standard deviation error is less than 90 µm corresponding to the tolerances announced by the manufacturer. However the symmetrical error results which can be seen on Fig. 5 were investigated by mean of a MMT 3D scanner and show that the differences arising from the fact than the sphere hasn't been perfectly machine milled.

This shows that our system can automatically recover 3D shape of transparent object and could be used for defect detection (shape variation) of 3D transparent object.

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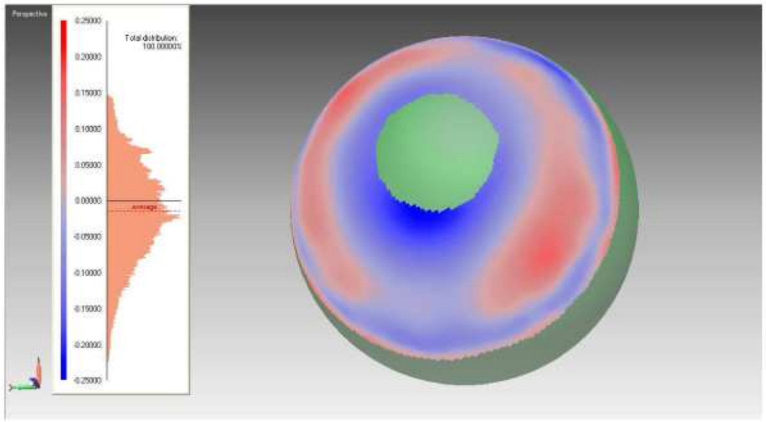

Fig. 5. 3D reconstruction and error map.

6. Conclusion

This paper presents recent results in reconstruction of 3D transparent object. The system uses an active multispectral system which enables removing the two ambiguities inherent to the technique of “shape from polarization”.

The technique proved to be very accurate and could be used for quality control inspection of 3D transparent object and could be extended to metallic object where redundancy in the data acquired, offered by the three wavelength system would provide more accurate results.

The problem of concave object which will lead to inter-reflections will be further investigated in our next work.

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