Image Based Objects' Transparency Measurement by a Polarization Camera

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ABSTRACT

In this paper, we propose an image-based method to quantify the transparency of objects based on a polarization camera. By controlling the status of the backlight, we can obtain the light intensity of penetration in four different phases, and can observe the difference to quantify the haze and transmittance. It is worth mentioning that our method can measure objects' transparency as small as a pixel, and it benefits to quantify the transparency of compound as well mixed materials.

1 Introduction

Transparent and translucent materials, such as display panels, glass, acrylic, plastics, films, etc., are widely used and visible in daily life. It not only meets people's pursuit of beauty but also meets the need for privacy and security. The issue of how to precisely obtain a material's transparency is always important. Transparency measurements are often carried out with optical instruments and in accordance with the procedures suggested in International Standard documents like ASTM D 1003, JIS K 7361, and ISO 14782 [1]. However, those instruments suffer from inconvenient use and difficult measurement on mixed materials.

1.1 Background

In the theory, transparency as a physical property refers to the ability of a material to allow light to pass through without extensive scattering [2]. There are many indicators used to evaluate transparency, including transmittance, haze, reflectivity and clarity, etc. In order to quantify transparency more comprehensively, at least two independent indicators are required to evaluate. Therefore, we can choose the appropriate index according to the characteristics and properties of the material [3].

1.2 Purpose

In this paper, we propsed a novel method for quantifying transmittance and haze to the level of pixel which is capable to identify an object with more than 2 materials. By using a polarization camera, we are able to collect the data from a single image consisting of four phases (0°, 45°, 90°, 135°). Compared with color cameras, polarization cameras can detect and filter polarized light generated by reflection, refraction, and scattering, helping us discover hidden material properties [4][5].

1.3 Target

In this study, we verified and tested 7 plastic samples with known material transmittance and haze. The feasibility of our system is assessed by comparison with the traditional architecture, as shown in Fig. 1. The color space and reflectance of the samples are measured in front of a standard black and white background. Our proposed architecture is shown in Fig. 2. The system consists of a polarization camera, white LED light, and flat backlight.

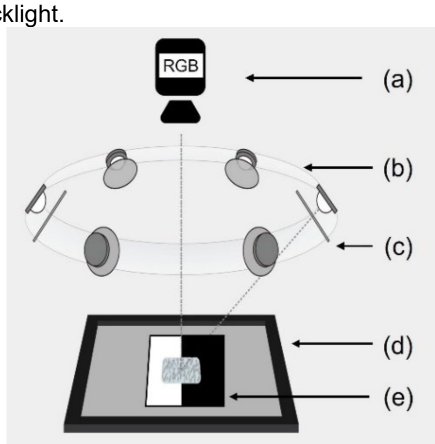

Fig. 1 Traditional architecture: a) Color camera, b) White LED, c) Polarizer, d) Stage, and e) Black and white brick

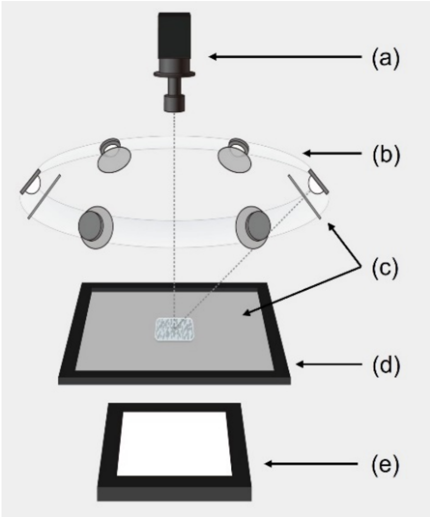

Fig. 2 Proposed method: a) Polarization camera, b) White LED, c) Polarizer, d) Stage, and e) Flat backlight

2 Experiment

In experimental setup, we desired to evaluate transmittance, and haze by comparing the difference in translucency parameter (TP), contrast ratio (CR), and degree of linear polarization (DoLP).

2.1 Materials

We used 3 methyl methacrylate ("PMMA") sheets (1.5 mm thick) with transmittance rates of 92%, 87%, 78%, and haze of 60%, 90%, 90%; and 4 polystyrene-based plastic ("PS") sheets (1.8 mm thick) with transmittance rates of 90 %, 74 %, 63 %, 57 %, and haze is all 90 %. These two materials have good optical properties, homogeneous effects, and superior thermophysical properties, so they are frequently utilized in a variety of applications to replace glass [6].

2.2 Optical Design

In order to capture the image information, we use a polarization camera, 6 white LEDs and a polarized flat backlight. By controlling the status of the flat backlight, different levels of transmitted light intensity can be observed under the same phases. In addition, we added a diffuser in front of the white LEDs to provide uniform illumination which allows consistent lighting distribution in the measurement area.

The polarization image information is shown in Fig. 3(a). After the p-polarized backlight is irradiated into a translucent object, that does not change its original path can be used to estimate the transmittance, and if the passing light is redirected by the internal particles to change the direction of the original light incidence, it is used to estimate the haze, as shown in Fig. 3(b).

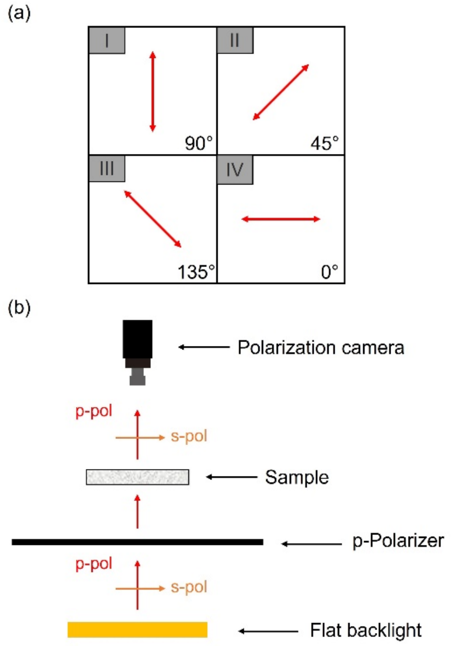

Fig. 3 Separation of transmitted light and scattered light by polarized backlighting

2.3 System Calibration

System calibration is an indispensable part for obtaining accurate measurement results. The calibration process is divided into three steps: hardware calibration, parameter calibration, and image calibration. As shown in Fig. 4, after focusing distance and aperture of the lens are fixed, the exposure time of the camera can be locked to avoid errors in subsequent color calculations caused under different exposure conditions.

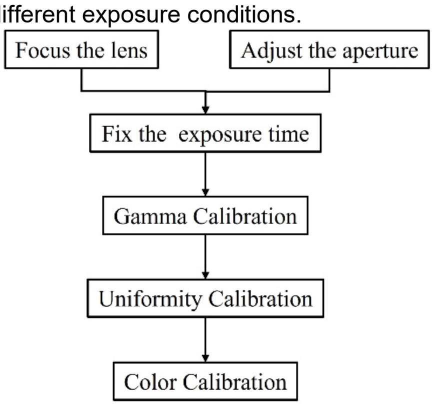

Fig. 4 System calibration flowchart

Through color space conversion, the RGB signal of the image obtained by the polarization camera can be converted into the CIE XYZ tristimulus values which is perceived by the human eye. The color space conversion process is shown in Fig. 5. The RGB signal is initially normalized, then linearly transformed by TRC, and finally calculated by a calibration matrix (we utilized a 3x10 matrix for a better result). Human vision is nonlinear for the natural brightness, as known from Weber-law Fechner's [7]. To make the images from the polarization camera as similar as perceived by the human vision, the Gamma correction needs to be performed during the linear conversion of TRC to solve the problem.

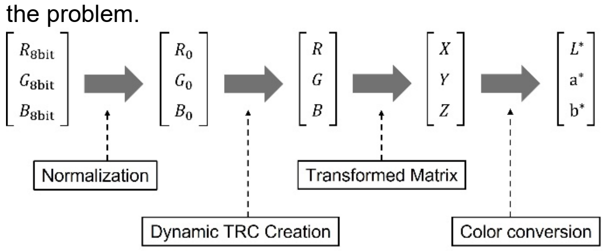

Fig. 5 Color space conversion

2.4 Parameter calculation

We use TP and CR as the eveluation parameters. Based on the definition of the traditional method, TP value refers to the color difference of the sample in front of black and white background. The formula is known as $TP = [(L_B-L_W)^2 + (a_B-a_W)^2 + (b_B-b_W)^2]^{1/2}$, where the subscripts B and W refer to the black and white backgrounds. The CR value refers to the ratio of the reflectance (Y_B) of the sample in front of the black background to the reflectance (Y_W) in front of the white background. The formula is known as $CR=Y_B$ / Y_W, where the reflectance is the Y of XYZ defined by CIE in 1931 [8][9].

Moreover, we can also identify particles inside the material and scratches on the surface by calculate its DoLP [10]. The calculation of DoLP is obtained through three Stokes vectors, the formula is DoLP= $\sqrt{(S_1^2+S_2^2)/S_0^2}$, where S_0, S_1, S_2 are obtained by the light intensity of the four phases, and the calculation formula is as follows:

$$S_0 = \frac{1}{2}(I_0 + I_{45} + I_{90} + I_{135}), \quad (1)$$

$$S_1 = I_0 - I_{90}, \quad (2)$$

$$S_2 = I_{45} - I_{135}, \quad (3)$$

And, to visualize the values, we convert all DoLP data into pseudo-color images for analysis.

3 Results and Discussion

We measured the color space and reflectance of 7 plastic samples with known material transmittance and haze under the traditional architecture and proposed architecture respectively. At the same time, we also compared the DoLP images.

3.1 Proposed architecture versus traditional architecture

For the first phase of polarization cameras, as the left-top sub-figure of Fig. 3(a), we observed that the TP values increase and the CR values decrease as T rises. And the TP and CR values obtained from proposed architecture and the traditional architecture have the same trend, although they are different; while for the fourth phase of polarization cameras, it can be seen that the TP and CR values are almost the same for the remaining T except when T is 92%, as shown in Fig. 6.

And Fig. 7 shows that in the first phase, even though the haze is the same, the TP and CR values are still variable. However, in the fourth phase, it can be seen that when the haze is 90 %, the TP values are almost at the same point. This confirms our previous assumption that the Information of the polarization camera received in the first phase is related to the transmittance and in the fourth phase is very likely related to the haze.

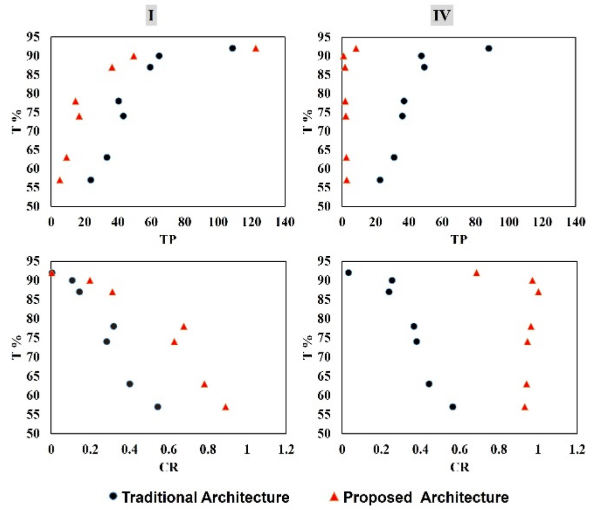

Fig. 6 Relationship between T and TP, T and CR in phases I and IV of the polarization camera

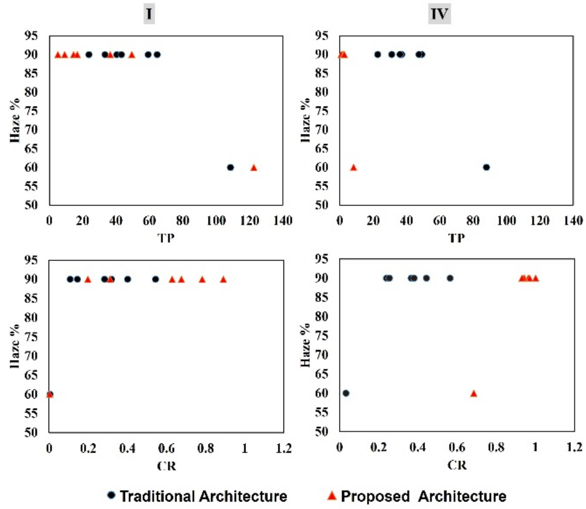

Fig. 7 Relationship between Haze and TP, Haze and CR in phases I and IV of the polarization camera

3.2 Variance between different R

In addition, we generated different R by adjusting the brightness of the flat light ($R = \frac{\text{illuminance of flat light}}{\text{illuminance of white LED}}$), and observe the difference.

As shown in Fig. 8. In the first phase, it can be observed that when the R is larger, the TP value is larger, and the CR value is smaller, while in the fourth phase, the CR value is inversely proportional to R, and the TP value is not affected by R. We think it makes sense, since the reduced brightness of the flat light is equivalent to the reduced reflectivity on a white background.

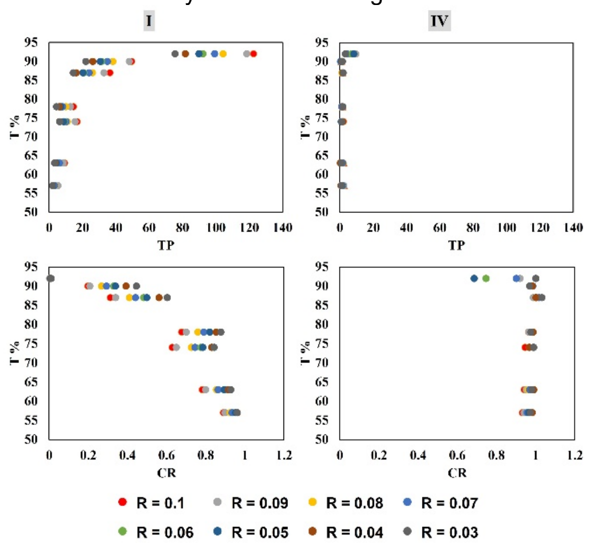

Fig. 8 Relationship between T and TP, T and CR in different R

3.3 Degree of linear polarization (DoLP)

DoLP, which involve the range of a value from 0 to 1, is the value that indicates how much light is actually polarized to a particular angle. A higher DoLP value shows more perfectly linearly polarized light. This is the main reason we generated polarized illumination.

As shown in Fig. 9, it can be found that DoLP is proportional to the T value, and haze is inversely proportional.

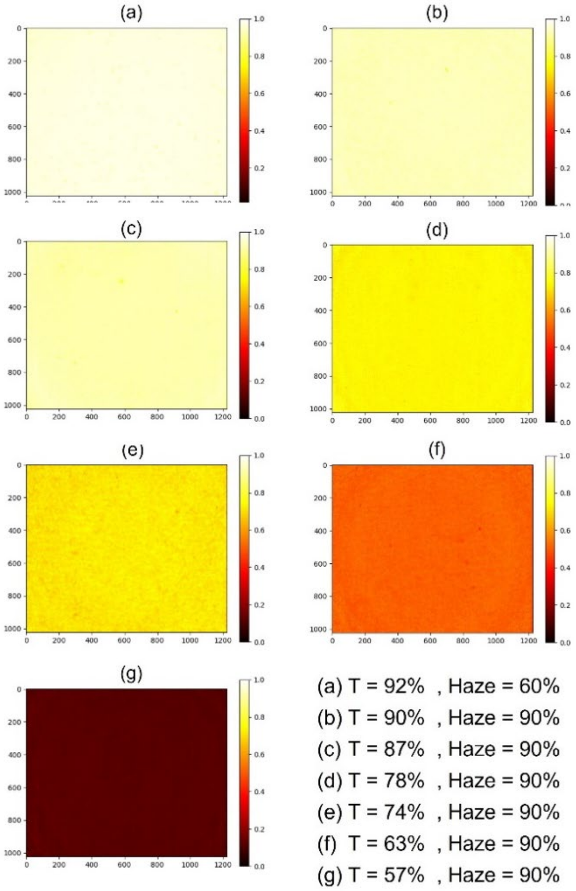

Fig. 9 DoLP of different sample

3.4 Measurement of mixed materials

Based on the outcomes of previous experiments, we analyze the non-uniform material, which consists of at least two different translucent materials, using the CR value as an example, and the results are shown in Fig. 10. When the CR is smaller, the T is larger, the Haze is smaller. It proved that our proposed method is capable to measure mixed materials with different translucency at the same time.

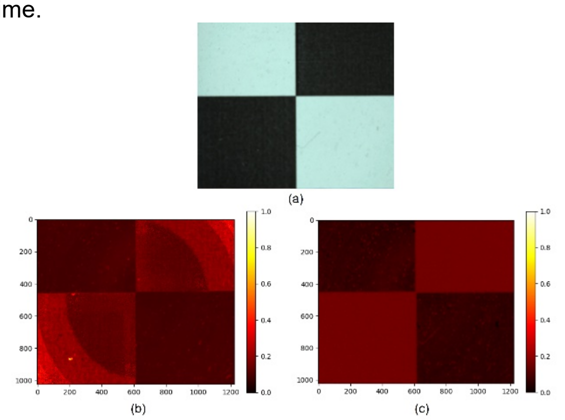

Fig. 10 Using CR to analyze non-uniform materials: a) Color image of non-uniform material, b) CR in phases I, c) CR in phases IV

4 Conclusions

This paper proposed a method for evaluating a material's transparency based on polarization images, which overcomes some limitations of optical measurement and enables the evaluation of transparency even for multiple transparency conditions of mixed materials. In the future, this method can be further improved to analyze with haze and transmittance of materials more accurately, and extend in various applications and researches.

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