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Color theory perception of steady wide band liquid crystal thermometry

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ABSTRACT

A color theory perspective to steady wide-band thermochromic liquid crystals (TLCs) is presented towards application in surface temperature measurements. In this regard, TLC color response experiments are conducted on an ex situ calibration plate under various illuminant spectra, and for a broad range of camera angle and white balance configurations.

The findings indicate that by color theory guided application of eligible background image subtraction technique, in conjunction with appropriate camera white balance selection, accurate, illuminant and viewing angle invariant hue-temperature relations can be established. This yields more practical, robust and generalized calibration methodologies. The importance of an adequate processing technique, along with its implications in color theory and consequences on hue-temperature relation is addressed in detail towards applicability in a broad spectrum of experimental arrangements.

1. Introduction

Development of accurate surface temperature measurement techniques is essential for improvement of the current physical understanding of various heat transfer phenomena. Where intrusive techniques, such as thermocouples and thin films, suffer from decreased applicability due to poor resolution, high accuracy full-field surface temperature measurements can be performed by thermochromic liquid crystals. Despite being among the most common means to experimentally acquire surface temperature distributions in convective heat transfer applications, the present study provides an original in-depth color theory based perception of the steady wide band liquid crystal thermometry technique.

One of the crucial aspects inherent to liquid crystal thermography investigations is the formulation of the unique hue-temperature calibration curves. In order to ensure highly resolved monotonous hue relationships, the selection of favorable experimental conditions, in terms of lighting and viewing arrangements, are imperative [1,2].

Color information retrieved by the observation camera is highly sensitive to the primary illumination source and the accompanying camera white balance (WB) configuration. Several comparative studies in prior thermochromic liquid crystal thermography literature focused on the effect of lighting and viewing arrangements in terms of relative camera angle and light source incidence, including on and off-axis configurations [2–8].

The current research effort conducts systematic studies on multiple combinations of fluorescent primary illuminants and camera white balance settings. It attempts to indicate the significance of such a match on the recorded color responses, as well as on the subsequent hue-temperature calibration curves. In this case, the roles of lighting and viewing arrangements are analyzed in an off-axis configuration. The importance of adequate background image subtraction routines, along with the theoretical implications and effects on hue-temperature relation, is addressed in detail.

In order to provide the reader with comprehensive insight to the underlying principles of surface liquid crystal thermometry measurements, the first two chapters of the present paper are devoted to the relevant fundamentals of color theory. Special emphasis is placed upon the eligible colorimetric processing of the data, in terms of color spaces and tristimulus values. Further discussion provides a broad overview of the well established liquid crystal thermometry routines, paving the basis for highlighting the role of adequate data processing.

2. Theoretical background

2.1. Liquid crystals

Liquid crystals (LCs) are organic substances which behave, from a mechanical point of view, as liquids while they simultaneously exhibit optical properties similar to crystalline materials. A mesomorphic phase appears as an intermediate state of aggregation between a true crystalline solid and an amorphous liquid [9]. As molecules lose their positional order, they simultaneously establish an orientational order, responsible for the optical properties.

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Nomenclature

B	blue primary in RGB color system	R	red primary in RGB color system
CCT	correlated color temperature	S	saturation
G	green primary in RGB color system	TLC	thermochromic liquid crystal
H	hue	WB	white balance
I	intensity	X, Y, Z	orthogonal components of XYZ space
LC	liquid crystal		

Among different types of liquid crystals, cholesteric liquid crystals exhibit characteristics favorable to heat transfer studies [10]. Specifically, composed of different parallel layers, the rotational molecular orientation is different in each layer and results in a characteristic twisted arrangement. Reflections from the symmetric molecular planes interfere at a predominant wavelength, known as selective light reflection. Since the re-orientation of the lattice structure is temperature dependent, liquid crystal substances are known to reflect incident light of different wavelengths selectively and in different directions when subjected to temperature changes [11–14].

2.2. Liquid crystals in heat transfer applications

Pure, unencapsulated (neat) liquid crystals are known for their color brilliance; however, they suffer from rapid deterioration due to ultraviolet radiation exposure and sensitivity to moisture and dust [2]. To overcome these drawbacks in heat transfer measurements, liquid crystals are commonly micro-encapsulated in protective 5–50 μm, clear, polymer spheres, suspended in a sprayable binder material [2,6,10]. In surface thermography applications, the liquid crystal layer is typically deposited as a thin film on an underlying black substrate. The latter is a thin coating beneath the LC layer utilized to absorb the transmitted light [15,16].

Based on the active temperature bandwidth, in which a color response is observed, liquid crystals are subdivided into the so-called narrow-band and wide-band TLCs. The narrow-band TLCs have an activation interval typically equal to 1 K or less [1], which indicates a distinct event temperature. In contrast, the wide-band technique utilizes the entire color interval to map the surface temperature distribution on a single image [1,2,17–22]. Favorable in the case of complex heat transfer problems, where a detailed temperature distribution of high spatial resolution is desired, the wide-band technique requires an accurate color-temperature calibration that has to be performed over the full color play interval with a significant number of points.

2.3. Color theory

2.3.1. Colorimetry and color spaces

Colorimetry refers to the measurement of color and is the fundamental basis of color appearance specification standardized by the Commission Internationale de l'Eclairage (CIE) in 1931 [23,24]. Unique colorimetric data demand for information on the illuminant; otherwise, depending on the light spectrum, different tristimulus values can be obtained for the same object color. Beyond the spectral power distribution, another means of quantifying a light source is the associated correlated color temperature (CCT). It is based on the reference of the spectral power distribution of a Planckian radiator, indicating the predominant wavelength correlated to the temperature. Associated with the power weighted light spectrum averaging, the CCT of a light source is directly related to the relative warmth of the "white light". While a color temperature of around 5000 K produces neutral light, low color temperatures imply warmer (yellowish/reddish) and high color temperatures imply colder (bluish) light.

Since the visual color perception of the human eye is dependent on the observer field of view, the CIE defines a norm based on historical color matching data from Wright [25] and Guild [26,27] (referred to as the *CIE 1931 2° Standard Observer*), and which represents all perceivable colors. It is a three-component additive model where all colors can be expressed in terms of positive values of the X, Y and Z primaries; each one being artificially defined, they do not correspond to any physical light wavelength, Fig. 1.

The geometrical representation of the tristimulus values constitutes a three-dimensional space, which is less illustrative since the spatial relationship is harder to perceive. The CIE chromaticity concept is in principle based on the assumption that color can be expressed in terms of two dimensions, luminance and chromaticity, where the normalized chromaticity coordinates x, y and z are:

$$x = X/(X + Y + Z) \tag{1}$$

$$y = Y/(X + Y + Z) \tag{2}$$

$$x + y + z = 1 \tag{3}$$

The derived color space is known as CIE xyY, within which the two normalized independent coordinates x, y indicate chromaticity and Y signifies luminance of color. Although illuminant and observer dependent, this representation of all visible colors is referred to as the gamut of human vision. Within the gamut, the projective chromaticity coordinates x and y occupy a region of the real plane, where in turn, all colors outside the gamut are solely imaginary, Fig. 2. The solid line connecting the extreme red and violet ends of the spectrum at the lower end of the gamut is referred as the line of purples, which are non-spectral colors and do not exhibit a counterpart in monochromatic light. Representing achromatic color, the white point (WP) is situated in the center of the chromaticity diagram, with its exact position varying according to the type of illuminant. The hue quantity in the chromaticity diagram, corresponding to the dominant wavelength in the physical domain, can be uniquely identified by the angle between a line joining the point to the WP with respect to a chosen reference line, Fig. 2. In turn, a numerical description of the saturation/purity of a sample is determined by the relative radial distance between the color point and the origin, with respect to that of the respective spectral color, Fig. 2. Situated on the spectral locus, the spectral colors are characterized by a maximum saturation while non-monochromatic or less saturated colors fall within the horse-shoe. Hence, lights resulting in color perception of approximately identical hue but varying saturation are projected on radial lines from the center point to the periphery of the gamut.

A commonly employed color space which mimics the physiology of the human eye is represented by the RGB model. It is an additive color model and utilizes the three primary colors red, green and blue, located near the beginning, middle and end of the visible spectrum, spanning a triangle inside the CIE chromaticity diagram. Both trichromatic color spaces, RGB and XYZ, are related by a linear transformation of the respective tristimulus