Colorimetric Characterization of Augmented Reality Glasses Based on the Birdbath Optical Structure

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ABSTRACT

A new colorimetric characterization model is presented in this study for optical see-through augmented reality (AR) glasses based on the birdbath structure. The model employs an s-curve characterization approach for AR content, incorporating the spectral transmittance of the AR lens and the additive color mixing.

1 Introduction

Colorimetric characterization is an important process in color management. It establishes the conversion relationship between device-dependent color spaces (in terms of device RGB values) and device-independent color spaces (in terms of CIE XYZ values), enabling different devices to achieve accurate color reproduction [1]. AR glasses overlay its virtual images onto the real-world backgrounds behind the glasses. Thus, color characterization of AR glasses must consider the additive color mixing [2].

The present study demonstrates a new colorimetric characterization model for optical see-through augmented reality (AR) glasses based on the birdbath structure, a widely used optical design for AR glasses in recent years.

In the birdbath architecture, light from a display source is projected onto a beam splitter, which is a piece of teleprompter glass positioned at a 45-degree angle. The light reflects off the beam splitter onto a curved mirror. This curved mirror then reflects the light back through the beam splitter, directing it towards the user's eyes. The beam splitter also allows light from the real world to pass through, enabling the merging of virtual content with the real-world view and providing an immersive AR experience.

The proposed colorimetric characterization model for AR glasses based on the birdbath structure employs a conventional s-curve characterization approach for liquid crystal displays (LCDs), incorporating both the spectral transmittance of the AR glasses and additive color mixing. The model introduces a novel method for estimating single-value transmittance to be used with the CIE XYZ values. This method is particularly useful when the spectral data of the real-world background color behind the AR glasses is unavailable. The additive color mixing, serving as the foundation for the proposed model, was tested using projected color samples in this study to ensure good accuracy in color mixing.

2 Structure of the model

The proposed characterization model consists of two directions of calculations: forward and inverse.

Figure 1 shows the framework of the model in the forward direction, which predicts CIE XYZ values of the color viewed by the AR user. The input data includes the real-world background color, in terms of the XYZ values, and the virtual color of the AR content, in terms of the RGB values. This forward model is particularly useful for further investigations of color appearance for the AR user.

The inverse direction of the model, on the other hand, as Figure 2 demonstrates, predicts the RGB values of the virtual color of the AR content. The input data includes the real-world background color and the color viewed by the AR user, both in terms of the XYZ values. This inverse model is particularly useful for color selection and color reproduction based on a uniform color space such as CIELAB.

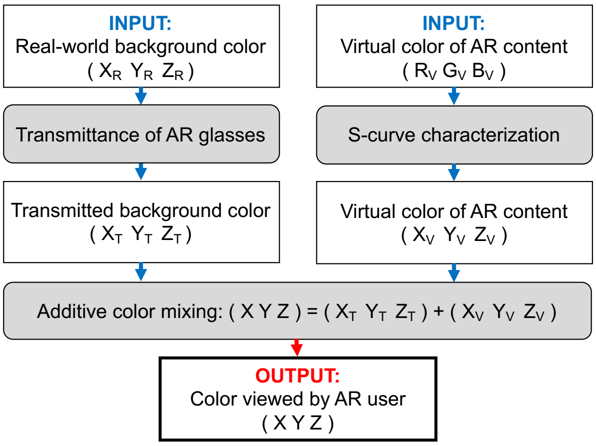


Fig. 1 Framework of the model for the forward direction

In both forward and inverse directions, the ideal input data for the real-world background color is its spectral power distribution (SPD), which ideally can be converted to the transmitted SPD using the spectral transmittance. In practice, however, the SPD of the real-world background color can only be obtained with instruments capable of measuring spectral radiance. This is a function normally lacking in typical AR glasses. Thus, it is desirable to have an estimated single-value transmittance for each tristimulus value, rather than the spectral transmittance, that can directly convert the XYZ values of the original real-world color ($X_R\ Y_R\ Z_R$) into transmitted color ($X_T\ Y_T\ Z_T$). The present study proposes a simple approach to estimating this single-value transmittance based on the spectral transmittance data, as will be described later in more detail.

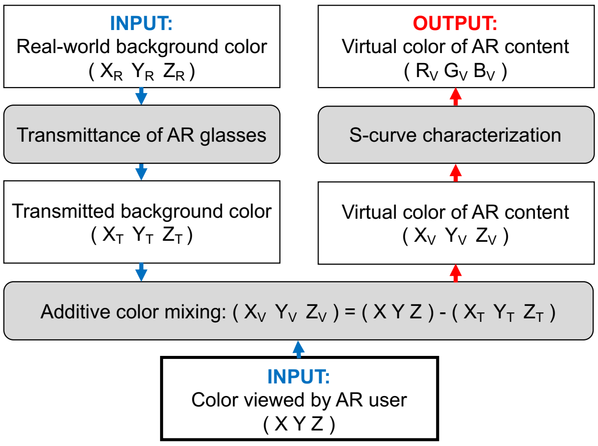


Fig. 2 Framework of the model for the inverse direction

Both the forward and the inverse directions employ a conventional s-curve characterization model for LCDs. This s-curve model is responsible for conversion between the display digital counts ($R_V\ G_V\ B_V$) and the CIE tristimulus values ($X_V\ Y_V\ Z_V$) for virtual color shown on the AR glasses, i.e. the AR content. The s-curve characterization is a common method used for LCDs that are not factory calibrated, such as those in birdbath-based AR glasses.

In the AR glasses, the virtual color of the AR content will merge with the transmitted color of the real world via the additive color mixing. The additive color mixing is referred to as the summation of two sets of SPD, representing two light colors to be mixed. This additivity also applies to CIE XYZ values. The additive color mixing serves as the foundation of the proposed characterization model.

The purpose of this article is to describe methodologies and performance of the colorimetric characterization model proposed in this study.

3 Methods

A pair of AR glasses, XReal Pro 2 Air, was characterized in this study. The device features birdbath optics with electrochromic dimmable lenses. The display type is Micro-OLED, with a peak luminance of 500 cd/m^2. Each eye gets a resolution of 1920x1080, and the refresh rate is 120 Hz. The glasses weigh 72g.

The AR glasses was set up in a darkened room in front of a 27-inch flat-panel BenQ LCD controlled by a computer. The LCD provided the real-world background colors behind the glasses.

A TOPCON SR-UL1R tele-spectroradiometer was used to measure colors shown on the AR glasses, representing the color viewed by the AR user (X Y Z), and colors shown on the LCD ($X_R\ Y_R\ Z_R$).

3.1 Single-value transmittance of the AR glasses

Ideally, CIE tristimulus values of any color on an LCD ($\boldsymbol{X_R\ Y_R\ Z_R}$) for absolute colorimetry (in the unit of cd/m^2) can be determined using Equation Set (1) when the SPD of the LCD color is available:

$$\begin{aligned} X_R &= 683 \int S(\lambda)\,\bar{x}(\lambda)d\lambda \\ Y_R &= 683 \int S(\lambda)\,\bar{y}(\lambda)d\lambda \\ Z_R &= 683 \int S(\lambda)\,\bar{z}(\lambda)d\lambda \end{aligned} \tag{1}$$

where $S(\lambda)$ is the SPD of the color shown on the LCD; $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are CIE 1931 color matching functions.

The transmitted tristimulus values ($X_T\ Y_T\ Z_T$) are then determined using Equation Set (2) when the spectral transmittance of the AR glasses is known:

$$\begin{aligned} X_T &= 683 \int S(\lambda)T(\lambda)\,\bar{x}(\lambda)d\lambda \\ Y_T &= 683 \int S(\lambda)T(\lambda)\,\bar{y}(\lambda)d\lambda \\ Z_T &= 683 \int S(\lambda)T(\lambda)\,\bar{z}(\lambda)d\lambda \end{aligned} \tag{2}$$

where $T(\lambda)$ is the spectral transmittance of the AR glasses.

In practice, particularly for applications of AR devices, a single-value transmittance for each tristimulus value is desirable. This can be done by calculating the integral of a product of a color matching function and the spectral transmittance, divided by the integral of the same color matching function, as described in Equation Set (3):

$$\begin{aligned} T_X(\%) &= \frac{\int \bar{x}(\lambda)T(\lambda)d\lambda}{\int \bar{x}(\lambda)d\lambda} \\ T_y(\%) &= \frac{\int \bar{y}(\lambda)T(\lambda)d\lambda}{\int \bar{y}(\lambda)d\lambda} \\ T_z(\%) &= \frac{\int \bar{z}(\lambda)T(\lambda)d\lambda}{\int \bar{z}(\lambda)d\lambda} \end{aligned} \tag{3}$$

where $T_X(\%)$, $T_Y(\%)$, and $T_Z(\%)$ are the single-value transmittance for the CIE tristimulus values X, Y and Z, respectively.

The transmitted tristimulus values ($X_T\ Y_T\ Z_T$) can then be estimated approximately by Equation Set (4):

$$\begin{aligned} X_T &\approx X_R \times T_X(\%) \\ Y_T &\approx Y_R \times T_Y(\%) \\ Z_T &\approx Z_R \times T_Z(\%) \end{aligned} \tag{4}$$

To test the single-value transmittance, as described above, we measured nine colors with and without the AR glasses placed between the LCD and the measuring instrument. The nine colors were selected randomly from CIELAB space.

3.2 AR-content characterization

The s-curve characterization model is commonly used for LCDs that are not factory calibrated. It is a two-stage model, consisting of a nonlinear conversion in the first stage and a linear transformation in the second stage. The present study utilized hyperbolic functions in the nonlinear conversion, as shown in Equation Set (5):

$$\begin{aligned} \mathrm{R}' &= k_{0,r} + k_{1,r} \cdot \tanh\left(k_{2,r} \cdot R_V - k_{3,r}\right) \\ \mathrm{G}' &= k_{0,g} + k_{1,g} \cdot \tanh\left(k_{2,g} \cdot G_V - k_{3,g}\right) \\ \mathrm{B}' &= k_{0,b} + k_{1,b} \cdot \tanh\left(k_{2,b} \cdot B_V - k_{3,b}\right) \end{aligned} \qquad (5)$$

where $(\mathrm{R}'\ \mathrm{G}'\ \mathrm{B}')$ are the output values for the three channels; $(R_V\ G_V\ B_V)$ are the normalized digital inputs of the three channels for the AR content only; k_0, k_1, k_2, k_3 are the constant and coefficients in the hyperbolic function of each channel.

The second stage is a linear transformation from $(\mathrm{R}'\ \mathrm{G}'\ \mathrm{B}')$ to corresponding tristimulus values $(X_V\ Y_V\ Z_V)$, as shown in Equation Set (6):

$$\begin{bmatrix} X_V \\ Y_V \\ Z_V \end{bmatrix} = \begin{bmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \qquad (6)$$

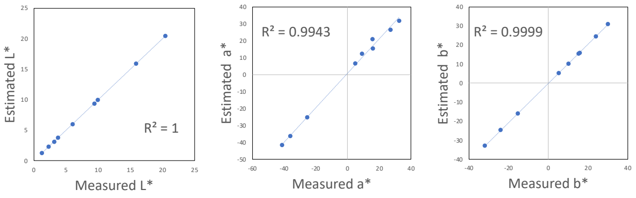
where the “max” subscript defines each channel’s maximum output after black correction.

To test the s-curve model, as described above, we measured 16 colors from digital inputs 8 to 255 with equal interval per channel and 8 neutral colors.

4 Results

4.1 Verification of the single-value transmittance

To verify the accuracy of the single-value transmittance algorithm as shown in Equation Set (3), we compared the estimated tristimulus values using the method described in Section 3.1 and those measured with the AR glasses placed in front of the LCD. All tristimulus values were converted to CIELAB color space for the comparisons. As Figures 3 (a) to (c) demonstrate, extremely high correlation was found between estimated and measured values, with coefficients of determination all higher than 0.99, indicating that the proposed algorithm is highly reliable and accurate.



(a) (b) (c)

Fig. 3 Estimated vs. measured values for single-value transmittance: (a) L*, (b) a* and (c) b* values in the right lens of the AR glasses

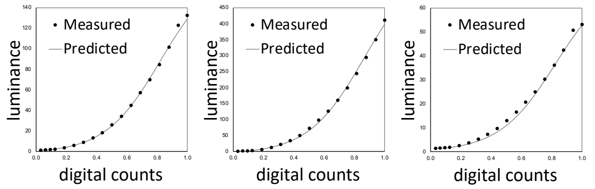
4.2 Verification of the AR content characterization

The s-curve characterization model for the AR content was derived using the measurement data as described at the end of Section 3.2. The resulting algorithms for the nonlinear and the linear stages are shown in Equations (7) and (8), respectively.

$$\begin{aligned} \mathrm{R}' &= 0.66 + 0.68 \cdot \tanh(2.74 \cdot R - 2.25) \\ \mathrm{G}' &= 0.71 + 0.73 \cdot \tanh(2.71 \cdot G - 2.35) \\ \mathrm{B}' &= 0.69 + 0.71 \cdot \tanh(2.69 \cdot B - 2.22) \end{aligned} \qquad (7)$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 267.08 & 201.33 & 102.02 \\ 131.67 & 412.90 & 51.53 \\ 4.55 & 72.06 & 563.39 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \qquad (8)$$

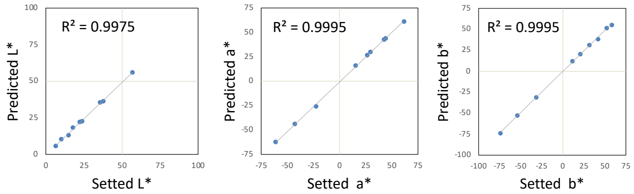
The optoelectronic transfer functions (OETFs) are shown in Figures 4 (a) to (c), all demonstrating s-shaped curves, particularly for the red and blue.



(a) (b) (c)

Fig. 4 The OETFs for (a) red, (b) green and (c) blue channels in the right lens of the AR glasses

We compared colors originally specified in terms of RGB values and the colors predicted by the s-curve model. As shown in Figures 5 (a) to (c), extremely high correlation was found between predicted and measured values, with coefficients of determination all higher than 0.99, indicating excellent accuracy of the s-curve model.



(a) (b) (c)

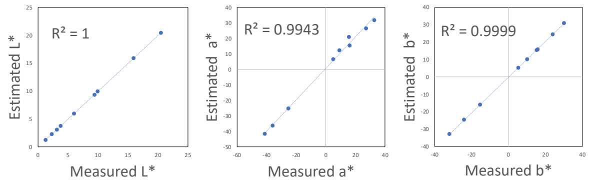
Fig. 5 Predicted vs. measured values for the s-curve model: (a) L*, (b) a* and (c) b* values in the right lens of the AR glasses

4.3 Predictive performance of the entire model for colorimetric characterization of AR glasses

The forward direction of the model predicts the color to be viewed by the AR user, in terms of tristimulus values. This requires the following input data:

1. CIE tristimulus values of the real-world background color $(X_R\ Y_R\ Z_R)$.
2. Digital inputs for AR content $(R_V\ G_V\ B_V)$.

To test the predictive performance of the model, we compared colors originally specified in terms of RGB values and the colors predicted by the entire model, consisting of the single-value transmittance and the AR-content characterization. As shown in Figures 6 (a) to (c), extremely high correlation was found between predicted and measured values, with coefficients of determination all higher than 0.99, indicating excellent accuracy of the proposed model in the forward direction.



(a) **(b)** **(c)**

Fig. 6 Estimated vs. measured values for the forward direction of the model: (a) L*, (b) a* and (c) b* values in the right lens of the AR glasses

The inverse direction of the model predicts the digital inputs for AR content. This requires the following input data for the model:

(1) CIE tristimulus values of the real-world background color ($X_R\ Y_R\ Z_R$).
(2) CIE tristimulus values of the color to be viewed by the AR user (X Y Z).

We compared colors originally specified in terms of RGB values and the colors predicted by the entire model, consisting of the single-value transmittance and the AR-content characterization. As shown in Figures 7 (a) to (c), extremely high correlation was found between predicted and measured values, with coefficients of determination all higher than 0.97, indicating satisfactory accuracy of the proposed model in the inverse direction.

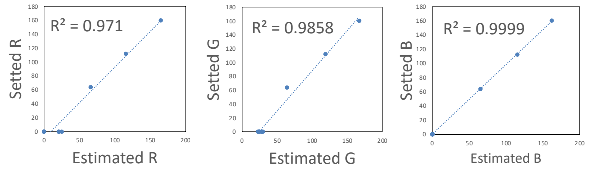


Fig. 7 Specified vs. estimated RGB values for the inverse direction of the model in the right lens of the AR glasses

5 Conclusion

A colorimetric characterization model for AR glasses was developed and verified in this study. The model includes two primary directions: one for predicting the necessary RGB inputs for desired color perception and the other for predicting the perceived color based on given RGB inputs. Both directions demonstrated high predictive performance, with extremely high coefficients of determination, validating the reliability of the model.

Future work will focus on incorporating the simultaneous contrast effect into the model. Considering this effect will further enhance the accuracy of color appearance in AR environments, accounting for the way colors perceived in relation to the real-world background color. This refinement will help ensure more precise and consistent visual experiences for AR users.

References

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