A Binned-Profile Approach to the Color Blending Problem

in Transparent See-Through Displays

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Abstract

See-through displays allow users to view both digital content and physical objects at once. In such displays, light coming from background objects mixes with the light originated in the display, causing what is known as the color blending problem. Color blending is an important issue for the wider adoption of see-through displays and AR in general as it affect the legibility and color encodings of digital content, with a negative impact on the general usability of such displays. Color preservation aims at reducing the impact of color blending by finding an alternative color which, once blended with the background, would result in the original color. At the heart of color preservation is the capacity to predict how digital and background colors blend for a particular display.

In this paper we propose the binned-profile model for color prediction and preservation in see-through displays. The binned-profile model is based on the observations that each display renders colors differently and that background colors are changed by the display medium before blending. For a given display the model uses a colorimetric profile of how such display shows colors; with colors binned to a small set of “noticeably different” colors. We validate our model by measuring the accuracy of the predictions against other prediction models (direct model and chromatic adaptation transformations). Then, we introduce a color correction algorithm and measure the accuracy of the corrections. We investigated our approach with an extensive set of digital and background colors and different hardware configurations (projector-based and OLED displays). Finally, we elaborate on the usability and design implications of our approach for color preservation.

**Keywords**: Color Blending, Optical See-through Displays, Color Binning, Color Correction, Color Perception.

**Index Terms**: H.5 [Information Interfaces and Presentation]: H.5.1: Multimedia Information Systems — Artificial, Augmented, and Virtual Realities; H.5.2: User Interfaces — Ergonomics, Evaluation / Methodology, Screen Design, Style Guides

# Introduction

Optical see-through displays allow users to view both digital content and physical objects at once. They come in multiple form factors (e.g. head mounted displays or projection-based) and are used in augmented reality (AR) as a way to enhance the real world with digital information. Although other technologies can also be used for AR (e.g. video see-through displays), optical see-through displays have the advantage of letting users see the real world with their own eyes, without reducing its fidelity and preserving properties like lighting, texture, color, age and wear. Researchers investigate optical see-through displays for a wide range of applications including medical, maintenance, education and training (see [1][2][3] for a comprehensive list of applications); with a few consumer electronics have started to adopt them [5][Android glasses]. We can expect wider adoption of such technologies with the introduction of novel mobile AR platforms like Google Glass [], and the continuous development of transparent LCD (Samsung NL22B [[link](http://www.samsung.com/us/business/commercial-display-solutions/LH22NLBVLVC/ZA)], Eyevis [[link](http://www.eyevis.de/index.php?article_id=163&clang=1)], RichTech [[link](http://www.richtechsystem.com/html/transparent-video-showcase.html)]) and OLED displays (Futaba Corporation [[link](http://www.oled-info.com/futabas-oled-road-map-amoleds-2014-transparent-and-flexible-oleds-cars-2015)], Fujitsu [[link](http://www.fujitsu.com/be/Images/Workplace_of_the_Future.pdf)], Winstar [[link](http://www.winstar.com.tw/newspaper_ov.php?lang=en&ID=153)]).



Figure 1. Color blending including the screen distortions for background and digital colors.

An important aspect of optical see-through displays is that background light coming from real-world object mixes with the light emitted by the display, something that has been described as color blending [1]. Color blending is an important issue as it can affect the legibility and color-encoding of digital information, and compromise the general usability of such devices. Despite being a widely acknowledge problem for the adoption of optical see-through displays and general AR applications, little research exists on how to preserve digital colors exposed to color blending. To preserve a digital color a system should find an alternative digital color which, upon blending with such background, comes closest to the desired digital color. Existing solutions include blocking background light, and iterative correction and measuring of the digital content. PROBLEMS WITH THIS APPROACH.

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An effective approach to preserve digital color in see-through displays relies on its *prediction* accuracy, i.e. the capacity to estimate the blend resulting from a given background and digital colors and for a particular display. In this paper we argue that high prediction accuracy requires taking into account two distortions introduced by the display and shown in Figure 1: (1) the way a particular display renders colors, and (2) the effect of the display media on the background color. To address the first distortion we propose the binned profile prediction model: a model that divides the continuous universe of colors into discrete and finite bins and measures how the display actually renders each bin. To address the second distortion we measure the background color only after passing through the display. We compared our model with other approaches to the *direct model*, the *chromatic adaptation transformation* (*CAT) model*. The direct model ignores the effect of the display on the digital colors; the CAT model uses known transformation matrices to determine the way a display shows particular colors.

We used a colorimeter to measure the accuracy of the different prediction models on three transparent see-through displays. Results showed that prediction with the binned-profiled model and background display distortion outperforms other combinations. We compared the accuracy of color preservation using the binned-profile model against using the direct model, with and without the background display distortion. Results showed our model outperforms the direct model correcting a wider range of colors and with higher accuracy.

This paper contributes to the field of augmented reality in several ways: 1) we propose a novel approach to color prediction and preservation for optical-see through displays; 2) we validate our approach against other possible solutions; 3) we discuss the implications of color blending for situations where color preservation is not possible or contrast preservation is preferred; and finally 4) we discuss the challenges associated to incorporating our algorithm into everyday optical see-through display platforms.

# Background [1 column]

Color blending is the phenomenon where background light coming from real-world object mixes with the light emitted by the display and changes it. Figure 2-top shows examples of color blending for a yellow text over three different background conditions: no background (black), red and blue. Figure 2-bottom shows the corresponding shift in color: the yellow text shifts toward orange when the background is red, while the green text shifts toward green when the background is blue. Field studies of AR applications with optical see-through displays reveal that the clarity and legibility of digital colors are affected by such changes in normal outdoors conditions; i.e. the colors in text and icons are altered (change in hue) or washed out (de-saturation) [Pingel and Clarke 2005]. Such changes affect the user interface and can render it useless: e.g. text might turn unreadable when washed out, or color encoded information such as red warning icons might lose their visual meaning.

Gabbard et al. studied such color changes in optical see-through displays [4] by building an experimental test-bed and examining foreground (27 colors on the edge of the RBG gamut) and background colors (6 common outdoor colors – foliage, brick, sidewalk, pavement, white and no background) of different lighting level and hues. His results showed how light background colors affect all other colors by pulling them towards white; while background colors of different hues pull all colors toward them. They defined the color blended and perceived by a user (CP) as a function of the light source (L1), the reflectance (RF) of background object (B), the light emitted by the display (L3), the interaction of both L1 and L3 in the display (ARD), and the human perception (HP). Equation 1 describes the interactions:

(1)



Figure 2. Examples of color blending

Our goal in this paper is to offer a solution to the color blending problem by means of colorimetric compensation: carefully selecting the color shown by the display so that the resulting blend comes close to the color originally intended. At the core of color compensation is the capacity to estimate how two colors blend; or more specifically, how any color showed by the display blends with a particular background color. To do so we take equation 1 as our starting point and unravel the interaction of colors on the display (ARD) to account for two externally observable distortions. The first distortion is due by the fact that each display represents digital colors differently, and that it is such representation the one to consider when estimating color blending. Figure 1 illustrates this condition as the difference in hues between the “digital color” (DC) and the “color shown” (CS): for a given digital color, different displays produce light of different hues. The second distortion is due to the display medium changing the background color before blending (BCD). In our formulation we simplify the light and reflectance of the background (the RF(L1,B) component of equation 1) into the single entity “background color” (BC), so that our formulation can be expressed as:

(2)

with and

Key to our understanding of color blending is the characterization of the fdDC and fdBC functions. The fdDC function describes the way a particular display shows a given digital color. The fdBC function describes the way a background color is altered by the display medium.

# Related Work [1 Column]

## Field-studies of augmented reality.

Relocation of content,

Using the hand to create contrast

## Color Compensation

Colorimetric compensation in projector-based see-through displays.

Color correction in projector-based spatial augmented reality

## Occlusion

1. Increase the intensity of the digital content (mentioned by Koyikawa)
2. Use LCD to block background light: B/W LCD (Koyikawa – optical s-t display for mutual occlusion), Grayscale LCD (Zhou et al. Novel Optical S-T HMD), spatial light modulator - SML (Cakmakci et al. a compact OST HMD)
3. Illuminating only the parts of the real objects that will not mix with the digital content (requires dark room) [Noda el at – rangefinder, Bimber et al.’s occlusion shadows]
4. Screens behind the real objects [Inami – visio-haptic display]

# Experimental Test-Bed

Box

Colorimenter

LCD as a background generator (discuss image)



Figure 3. Background color set in the experimental set-up.

Projector display 1

Projector display 2

OLED display

Software

# Color Prediction

Direct Model (show the binned-color space)



Figure 4. Left: The digital color #FF0000 and as displayed by different optical see-through displays. Right: The background color, and as it is seen through different optical see-through displays.

However, the colors involved in the blending differ from the “pure” ones assumed by the direct model. Figure 3-left shows

Show the new conception of color blending as presented in figure 4.

Say that to investigate this effect we took two approaches: cat and binned profile.

CAT (show image with the three cats for each display 3x3)

Binned-profile (show image with the binned-profile of each display), say that we are interested in this given the high variation of the CAT profiles. Tell hw we built each profile. Say that a limitation of this approach is the memory overhead (bytes per color pair).

## Data Collection

Describe how we collected data for each display

Describe how we computed the blending prediction for each model.



Figure 5. Examples of Euclidian distances and their corresponding just-noticeable difference.

## Results

Show one sample 3D image for a given display with the direct model and the binned profile to demonstrate the differences in the blue dots.

Show the BIG bar charts image (5 models X 3 displays X 27 backgrounds)



Figure 6. Single prediction result

# Color Preservation

Correctable range (by bg color)

# Discussion

Colors that can be corrected regardless of the background

Camera-based color correction



Figure 7. Prediction results

# Conclusions

References

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