COLOR MANAGEMENT FOR CINEMATIC IMMERSIVE EXPERIENCES

T. Pouli[1], P. Morvan[1], S. Thiebaud[1], A. Orhand[1] and N. Mitchell[2]

[1]Technicolor, France & [2]Technicolor Experience Center, Culver City

ABSTRACT

Immersive technologies offer new approaches for engaging audiences and providing visual information, whether for entertainment or more practical applications. To ensure that the content maintains the intended appearance across different devices and environments, one of the key challenges is that of accurate color management. In this paper, we discuss the challenges that have to be overcome to create color-accurate immersive experiences at a cinematic quality level. We propose workflows for efficiently characterizing different virtual and augmented reality devices and review their color reproduction capabilities against current display standards.

Figure 1 - Illustration of different immersive technologies.

INTRODUCTION

Immersive technologies are attracting a growing consumer interest, with proposed solutions offering different tradeoffs in terms of budget, comfort and quality. Such technologies can span the range from virtual reality (VR), where the viewer is isolated from their surrounding environment, to mixed reality (MR), where digital content should be indistinguishable and fully blend with the real scene (see Figure 1 for an illustration of key immersive technologies).

The increasing availability and sheer variety of different devices has inspired a multitude of applications. While gaming remains the main attractor towards VR, applications are being explored in fields such as virtual tourism (1), health (2) or education (3). Creative professionals are also taking advantage of the unique capabilities of this new medium to create cinematic experiences that place the viewer in the middle of the action or offer unusual viewpoints that cannot be achieved with traditional film. Augmented and mixed reality applications go even further, spanning applications as diverse as entertainment, manufacturing, surgery, telecommunications or e-commerce (4). Although in this case commercial availability is more limited, the possibilities offered by the prospect of seamless combination of synthetic or virtual objects and the real world seem limitless.

Despite the capabilities of immersive technologies and the buzz surrounding them though, widespread adoption is still elusive. Many reasons may be considered as responsible, but a key issue is that of the visual quality[1], meaning that current headsets are not yet able to produce images that are indistinguishable from reality.

Many of the challenges relating to image quality in immersive devices fall in the remit of color reproduction. To ensure that the content preserves the intended appearance across different devices and environments, color management needs to be taken into consideration at many steps of the imaging pipeline. In the case of immersive technologies, traditional approaches for achieving this may not be applicable or may require considerable extensions.

In this work, we focus on color management as it applies to immersive content creation and consumption. Specifically, we focus on the display devices used for viewing immersive content and we provide an overview of practical workflows that may be used to improve the color accuracy of such devices. We review the color reproduction quality offered by several key devices, focusing both on VR and AR OST scenarios.

COLOR MANAGEMENT CHALLENGES IN IMMERSIVE TECHNOLOGIES

Color management includes all the steps and processes necessary such that the representation of color remains constant and predictable within the content production and consumption pipeline. On the acquisition end, for instance, 360° content acquisition typically involves rigs with multiple cameras and requires a complex series of optical and geometric correction steps. To facilitate these processes and ensure homogeneity, color correction and calibration steps are necessary.

Moving into post-production, and specifically the color grading phase, where artists modify images to impart a creative look, may need to be rethought to better adapt to 360° content (5). Similar to traditional content production, any devices used in the studio for visualizing content – be it monitors, projectors or immersive devices – need to be precisely measured to ensure that they can reproduce colors accurately (6). Finally, at the user's end, a similar correction may be desirable to maintain a degree of color accuracy and to ensure that content is experienced by the user as the director intended it.

Characterization and Calibration of Display Devices

Digital images are typically represented using RGB *display-referred* values, meaning that the color produced for a given value will vary depending on the display characteristics, and

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[1] https://techcrunch.com/2015/03/26/the-biggest-challenges-left-in-virtual-reality-according-to-oculus/, https://tech.cornell.edu/news/the-challenges-and-possibilities-of-virtual-reality-startups

therefore different devices might represent the same RGB values in different ways. This is easy to visualize – it suffices to observe the same image on your PC monitor and your phone next to it, and you are likely to see that colors show up differently.

So, to be able to accurately reproduce color on devices, a *scene-referred* representation is necessary, where color is encoded as a physical quantity – the wavelength of light the display should emit given a particular RGB value. To obtain this, we need to measure the device through a process known as *display characterization*, which allows us to construct a mapping between RGB display-referred values and the corresponding scene-referred quantities for that display, typically encoded as CIE XYZ tristimulus values (7).

Using this information, we can compare the performance of the measured device against a predefined target and evaluate whether it needs to be corrected or *calibrated.* If this is the case, a transformation may be determined between the scene-referred values obtained for our device, and those that it should emit, which in turn can be used to modify the RGB pixel values to the desired effect.

Depending on the viewing scenario, other factors relating to the viewing environment and device may need to be considered as well. The illumination of the real environment where the user is located can have an important effect in how colors appear on a display. Further, optical properties and characteristics, for example the material of lenses used in VR headsets or the visors in AR Optical See-Through (OST) glasses, can influence color reproduction. In the following sections, we will review color management workflows for VR devices first, as they represent a simpler scenario, followed by AR OST devices, where the environment can have a stronger effect.

VR COLOR MANAGEMENT

When experiencing VR content, viewers are isolated within the virtual environment and minimal to no ambient light reaches their eyes. Content in this case is shown on a standard display, which may be integrated in the device, as is the case with headsets such as the Oculus Rift or HTC Vive, or it may be provided by a smartphone that can be attached to a separate optical element, as is the case with the Samsung Gear FR and Google Daydream devices.

In either case, the characterization and calibration process described in the previous section is sufficient to ensure accurate color reproduction. In an ideal case, all possible RGB values reproducible by the display should be measured, and corresponding XYZ values should be determined, obtaining a complete model of the display behavior. Of course, in practice this would lead to an intractable number of measurements, necessitating a sparser sampling of the display color space.

Different applications may have different requirements, but in practice, for many existing VR headsets, we find that a *Piecewise Linear assuming Chromaticity Constancy (PLCC)* model provides a good trade-off between accuracy and complexity (8). According to the PLCC model, two key pieces of information are necessary. The *display EOTF* (electro-optical transfer function) encodes the transfer function of the display between incoming (pixel) values and emitted light. It is modelled as a piece-wise linear function and stored in a 1D look-up table (LUT).

In addition, the *color transformation* between display-referred RGB values and scene-referred XYZ values needs to be determined. After accounting for the EOTF, a linear relationship is assumed between them, allowing us to encode this transformation into a 3x3 matrix, where each component of XYZ is computed as a weighted combination of the input RGB values.

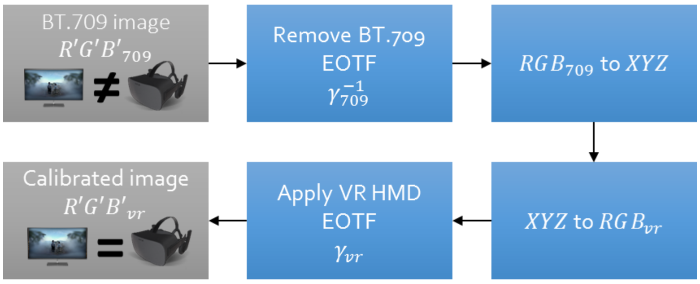

Figure 2 - Core steps for calibrating a VR headset

Given this information, as well as the target EOTF and color transformation model, which could be defined according to a standard such as BT.709 for example (9), the VR headset display can be calibrated, following the steps shown in Figure 2.

Display Measurements

To determine the EOTF and color transformation matrix, RGB color samples should be shown on the headset display and measured with a spectrophotometer. In our work, we rely on the X-rite i1 Pro 2[2] as it provides a good tradeoff between its small form factor and the accuracy of its measurements. Each RGB sample is shown as a single-color image filling the display of the headset. Measurements obtained from the i1 can be used to directly determine the EOTF and the color transformation matrix of the headset. We rely on a series of 86 color samples for this procedure, consisting of 27-step ramps for red, green and blue components, pure black and white as well as secondaries (yellow, cyan, magenta).

As it is not currently possible to incorporate the computed correction model directly in the devices, we opt for encoding the calibration model into a 3D LUT, which can be used in many content creation platforms (e.g. Nuke, Adobe Premiere etc). Through exchanges with creative professionals working on VR content production, we determined that a 33^3 resolution for the resulting LUT provided sufficient accuracy for their purposes.

VR Headset Examples

Using the above procedure, we calibrated key consumer devices, focusing in particular on wired headsets. Specifically, we measure the Oculus Rift, HTC Vive and Playstation VR devices as are the best represented VR devices in terms of market share currently (10). Our calibration target in this case was the BT.709 standard (9).

Figure 3 shows the color gamut of the three devices, compared against the BT.709 gamut, as well as their respective white points before and after calibration. In all cases, we observe that the devices natively offer a color gamut considerably larger than BT.709, particularly in the green and blue hues. Using our proposed procedure, all three devices can be successfully calibrated to the target gamut (average CIE DeltaE color difference of **1.83** for

[2] www.xrite.com/categories/calibration-profiling/i1basic-pro-2

the Oculus, **1.07** for the HTC Vive and **1.04** for the Playstation VR). Looking at the device EOTF before and after our calibration (Figure 4), we see that all devices approach the target EOTF of a 2.4 gamma after calibration, although the Playstation VR starts with an EOTF that is further away. Visual experiments indicate that these corrections lead to easily perceivable differences when applied to images.

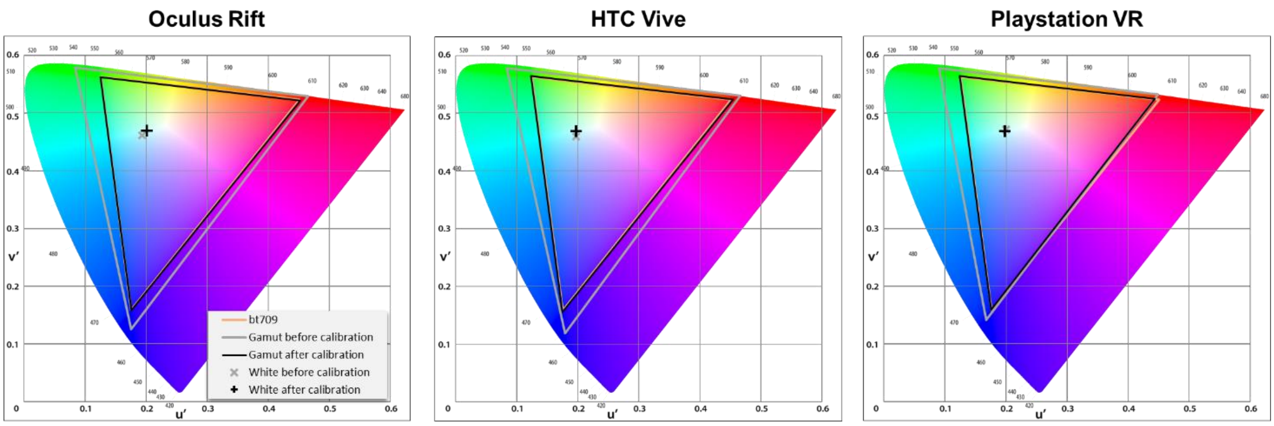

Figure 3 - Gamut measurements before and after calibration to BT.709 for key devices.

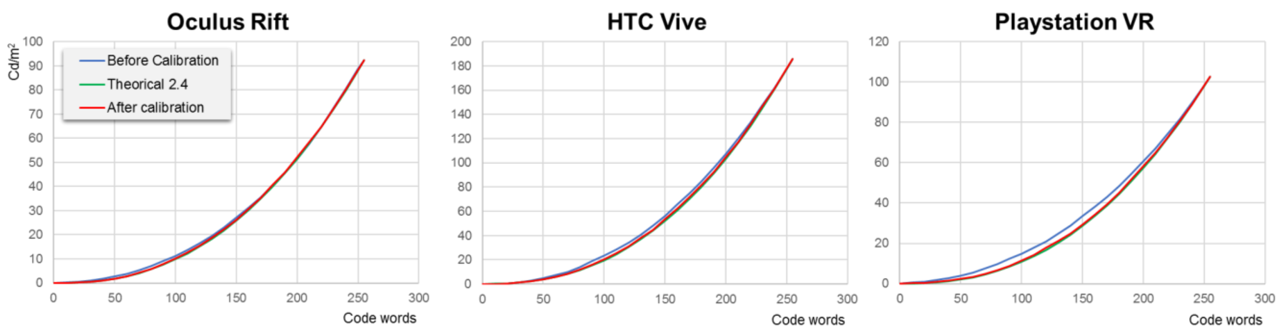

Figure 4 - Device EOTF before and after calibration compared to target 2.4 gamma.

AR & MR COLOR MANAGEMENT

Augmented reality can take two general forms. In the simpler case, the real environment is reproduced on a standard display, where synthetic objects may be added. Alternatively, optical systems may be constructed and integrated into glasses or headsets, allowing the real light of the scene to directly reach the observer's eyes, while synthetic objects can be superimposed through an optical (e.g. Meta, Microsoft Hololens and Magic Leap AR glasses). Here we focus on the latter type of devices, which introduce additional challenges compared to the VR scenario we have seen so far, since the environment surrounding the user can interact with the image being displayed.

Irrespective of the image formation technology used, the color V_c observed by a viewer in an OST configuration can be expressed as an additive relation between the displayed light and the light reaching the eye from the real environment, according to $V_c = f_{display}(D_c) + f_{material}(B_c)$ (11) (12), where D_c denotes the input pixel color sent to the display, $f_{display}$ is the display model itself, B_c encodes the background color due to the surrounding environment materials and illumination, and finally $f_{material}$ models the potential distortion of the background colors as they pass through the visor of the OST headset.

Similar to VR displays, $f_{display}$ can be defined through a characterization process as described previously, while $f_{material}$ can be defined using a controllable light source (or calibrated display), allowing us to sample the different possible values of background color B_c and measure how the visor material transforms them. Unfortunately, this only allows us to characterize the device. When calibrating such a device, we only have control of the displayed values (D_c), but not the environment colors and illumination (B_c). As such, the transformation applied to the content should account simultaneously for the display characteristics and the light from the scene.

To achieve that, an inverse look-up is necessary. Assuming BT.709 content, we consider that the target color T_c is obtained by transforming the image colors D_c using the BT.709 model $f_{BT.709}$. What we observe instead is V_c as described above (see Figure 5), which can be computed using the predefined display and material models ($f_{display}$ and $f_{material}$ respectively). To obtain a corrected V_c that better matches our target T_c, we can modify the image values either by exhaustive search (11) or by limiting the search space according to certain assumptions (12), until an acceptable error is achieved between the observed and target colors.

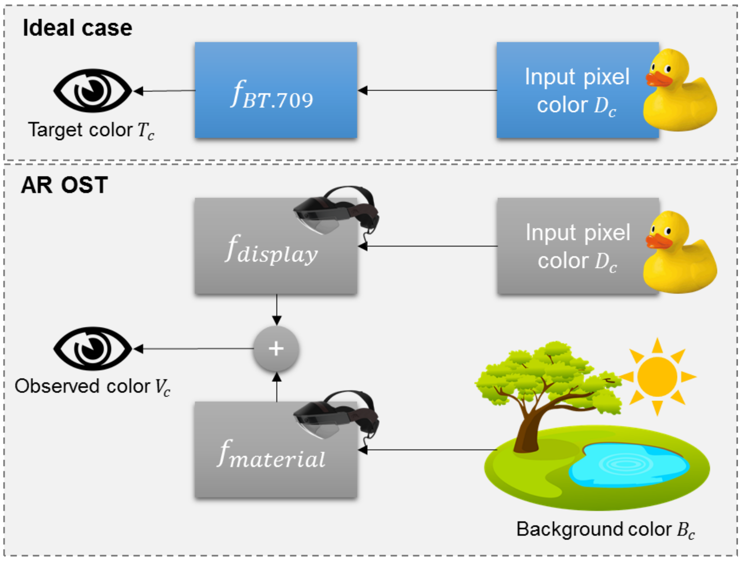

Figure 5 - AR OST model

Although the display and material models can be precomputed and encoded in a LUT, the challenge in such a correction procedure is that it depends not only on the image color D_c, but also on the background scene color B_c, which changes dynamically according to the environment and the viewpoint of the user. Using a head-mounted camera with known characteristics, it may be possible to obtain an estimation of B_c in real time. Still, to correct each pixel of the image, a precise optical alignment is necessary between the image captured by the camera and the viewpoint from the user's eyes, which is currently not addressed by existing approaches (13).

Some of the discussed models have been evaluated in limited and controlled setups in the literature, but currently available technologies do not allow for such a correction to be implemented in practice. Further, the limited gamut and dynamic range of AR headset displays mean that the environment lighting is likely to overwhelm the display capabilities in many cases, since, as we saw, their combination is additive. This, combined with the optical challenges discussed, mean that significant hardware improvements would be necessary to allow on-the-fly calibration of AR OST devices. In the meantime though, calibration of the display element of the device can already improve the image quality of content, especially in controlled viewing situations, such as installations in exhibitions or business applications.

Characterization of META2 AR OST Headset

Although a complete calibration of AR OST devices is not yet feasible in practice, here, we study the display component ($f_{display}$) of a currently available AR OST headset, namely the Meta2, as well as its visor characteristics ($f_{material}$) to understand how incoming background illumination is likely to affect the displayed image.

For this analysis, two series of measurements were performed. First, the display was measured with the headset placed in a dark environment, so that the background color component B_c could be ignored, effectively measuring $f_{display}$ in isolation. Then, a white reflective surface was placed behind the visor to measure the color shift due to the white reflection going through the visor material. Measurements for the two cases relative to the target colors are shown in Figure 6.

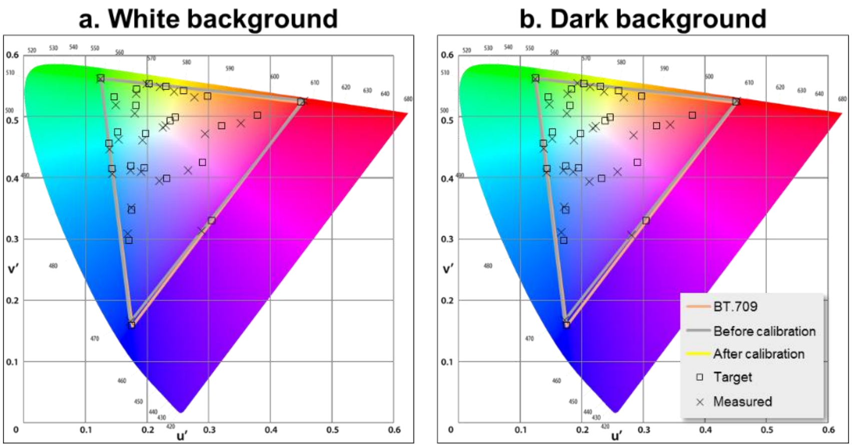

Figure 6 - Measurements for the Meta2 AR OST headset using a white reflective background or a dark background.

Although overall the display was found to be easy to calibrate with our proposed model, achieving an average CIE DeltaE value of 1.34 after calibration, a distinct shift was observed when measuring with the white reflective surface in place, showing that the visor itself has an influence in observed colors, even without considering background illumination, suggesting that more complex corrections are likely to be necessary for AR OST devices.

CONCLUSIONS

Immersive technologies are gaining traction in the consumer market, offering new creative avenues to content creators. Nevertheless, to fully take advantage of the possibilities that VR and AR devices offer and to accurately reproduce the creative intent of content, image quality plays a crucial role. In this work, we focused on the color management aspect of image quality, presenting workflows for characterizing and calibrating different devices. Looking at real measurements from a range of devices, we observe that even with simple color calibration models, good accuracy is achievable. Nevertheless, hardware limitations and the influence of the surrounding environment in the case of AR OST applications, make this case more challenging, necessitating further research to ensure accurate color reproduction and really open the doors for creative, cinematic content in this exciting field.

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