Color Constancy in virtual reality scenes. A first step toward a color appearance model in virtual reality

Pedro J. Pardo [1,*], Francisco Diaz-Barrancas [1] and Halina Cwierz [1]

[1] University of Extremadura; Centro Universitario de Mérida, Spain; pjpardo@unex.es, frdiaz@unex.es, hccwierz@unex.es

* Corresponding author: pjpardo@unex.es

Abstract

Due to the increase in the use of virtual reality systems, the requirement for quality in it has also increased. The most important factor may be the quality of the visual appearance of the scenes shown in it. One of the aspects that affects the visual appearance, among other things, is the color constancy or the ability of an object to be perceived with the same color under different types of illuminant. This means that even if the illuminant varies, the user can perceive the same color. In this paper we will prospectively discuss whether chromatic adaptation and color constancy should be considered different for a virtual reality device comparing with a 2D image shown in a display and comparing with real life. It could be a great first step toward establishing a color appearance model that can be applicable to devices in virtual scenarios.

Keywords: *Virtual reality, Head-mounted Display, Color constancy, Color Appearance*

INTRODUCTION

Classic colorimetry allows us to specify the color of a simple visual stimulus, using only three mathematical values. This is a huge dimensional reduction, from the infinite dimensions of the power spectral distribution of a physical stimulus to the tridimensional definition of a visual stimulus. This transformation is based on the trivariance of the human visual system. The validity of these tristimulus values is conditioned by its obtention conditions (luminance level, size of stimulus, surrounding field, adaptation degree) and by the validity of certain mathematical properties required for a Euclidean vectorial space (additivity, linearity, etc.). A detailed description of how color matching functions were obtained can be found at Wyszecki and Stiles (1967). However, the need of measure and represent mathematically a color in different branches of science, engineering and industry, has led to the recent development of fields such as color differences measurement (García et al. 2007; Oleari et al. 2009), applied colorimetry (Johnston 2009, Weatherall & Coombs 1992) or color management (Sharma 2018, Fraser et al. 2004) and more.

Color management in digital environments has been developing since the 1990s, sponsored by the leading companies of the computer sector (Has 1995). Color Management Systems (CMS) are based on color management modules (CMM) and the chromatic characterization of each digital device through an International Color Consortium (ICC) color profile. This system allows to obtain a reliable reproduction of the color between diverse digital media and to be able to manage it correctly. An example of usefulness of color management is color gamut mapping between different devices (Morovič 2008). In all cases, color management technics are applied to two-dimensional static images. Digital video has its own color management system based on several standards that must be followed by all video management stages (Poynton 2012).

However, the expansion and popularization of the 3D digital environments have brought new challenges in terms of color management and applied colorimetry. Previous solved problems such as, defining the RGB digital value of a light source from its power spectral distribution or computing the effect of the chromatic adaptation state of an observer when the illuminant is changed may have different solutions when we use virtual reality glasses. The mentioned change in the light source becomes even more critical for augmented reality because the virtual light source must match the real one in color, intensity and direction for the best experience. In this work we start a discussion if it is necessary or not to study known visual phenomenon like color adaptation and color constancy between others.

REAL-TIME 3D RENDERING IMAGES FOR VIRTUAL REALITY

There exist many differences between a digital image obtained from photographic techniques and a digital image obtained rendering of a 3D scene. In the first case, the image is captured by a sensor, typically CCD or CMOS, located at the image plane of the optical system of a photographic camera.

In the case of a digital image obtained by rendering a 3D scene, a ray tracing process is carried out based on the geometric definition of 3D objects, their position, the position of the camera and the position of the light sources (Glassner 1989). This ray tracing is done in reverse to the traditional optical systems, i.e. from the eye or camera to objects forming the scene. In this way, it is done for all rays that pass through a matrix of points that correspond to the future pixels of the final image

With the reversal in the ray tracing, it is possible to save computation time since the rays are only traced to the position in which they find an object that appears on the screen considering the location of the camera. It is made selecting objects in the scene from back to front to contemplate the possible interaction of rays bouncing off more than one opaque surface in the scene. Then, in order to handle the lighting and shading conditions, the graphic engine apply different mathematical models.

One of the most extended models of 3D rendering is the Physically-Based Rendering model (PBR) that apply a bidirectional reflectance distribution function (BRDF) as physical-law governing the interaction between light and matter (Pharr et al. 2016). The result of applying this model of rendering can be photo-realistic reproductions of real scenes.

This type of 3D rendering method enables the possibility of defining the spectral power distributions of light sources. In the same way, basic colorimetric calculations can be done and applied to the image in term of CIE 1931 XYZ tristimulus values. However, this type of 3D rendering needs long time of processing (typically hours) to produce one image. The problem arises when we need to apply these physical-law-based rendering techniques in virtual reality environments where human interaction with the environment is required in an active way, adapting the image shown to the position of the observer in a very short time.

For the immersion experience to be satisfactory in a virtual reality environment, it is necessary to generate at least 90 images per second, although the current trend is to achieve 120 images per second. In addition, it is necessary to generate two different images, one for each eye, in order to achieve the effect of stereoscopic vision. On the other hand, the response of the sensors of the virtual reality system to the movements of the head and body of the user must have a minimum latency to obtain a fluid image movement and a suitable feeling of immersion. This reduces the computation time per frame to about 10 ms or less (Pardo et al. 2018). With these restrictions it is not possible to apply a classical 3D physical-rendering method and it is necessary to apply more restrictions.

Currently, there are two main software platforms for developing virtual reality content: Unreal Engine (Epic Games Inc., USA) and Unity Game Engine (Unity Technologies, USA). In both platforms, new Graphics Processing Units (GPU) with high computing capabilities are employed to reflect in a greater or lesser extent the real world through physical laws. The geometry of the scene is supplied to the graphic card and this hardware projects the geometry and breaks it down into vertices. Then, the vertices are transformed and splitted into pixels, which get the final rendering treatment before they are passed to the screen using the frame buffer.

Specifically, Unity Game Engine applies inside this graphical pipeline a reduced BRDF model through the Standard Shader: a Physically Based Shading and Lighting engine based on four main components (diffuse, specular, normal, smoothness). These components are applied through bitmaps as texture files. The diffuse component corresponds to material color with a perfect Lambertian behavior following the Disney model (Burley 2018), the specular component including Smith Joint GGX visibility term (Walter et al. 2007) and Schlick Fresnel approximation (Heitz 2014), and normal and smoothness components correspond to surface texture. It is therefore possible to obtain rendered scenes with a high degree of visual appearance fidelity when treating the light–matter interaction this way. Figure 1 shows a comparison between a real and a virtual scenario employed in this work.

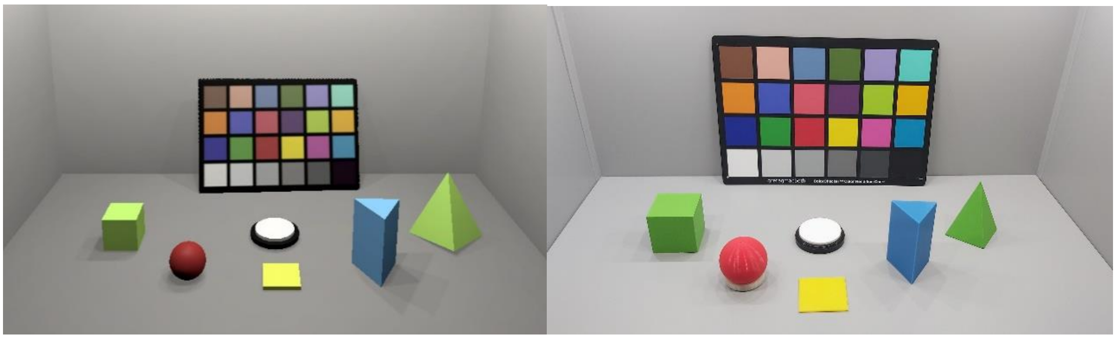

Figure 1: Synthetic image of a real scene shown in VR (left) and real image of a real scene (right).

However, the virtual reality scenes generated in this way has left out any color management technique, since color is processed from the beginning to the end in RGB values (8-bit digital values per channel). The only color correction that has been carried out is the calibration of the display setting up to a standard configuration (typically sRGB). Therefore, one of the challenges ahead for color scientists is to enable a color management system compatible with this type of Virtual Reality (VR) systems.

COLOR MANAGEMENT IN VR SYSTEMS

Several different levels of color management can be established on virtual reality devices. The first would refer to the processing of photographic images shown in VR systems in the same way that is done through Color Management Modules in a 2D environment. A second level would be to apply a color management system in VR not only to photographic images but also to the 3D objects that are part of the scene. A third possibility would be the spectral computation of both light source emission and surface reflection of 3D objects. Finally, there exists the possibility of applying color appearance models to the complete rendering of the scene. Each of these different proposals are described below.

Photographic color management inside VR

Virtual Reality environments can show all kinds of images. One type of images are photographic images. On this type of images, it is possible to apply a color correction using a Color Management System (CMS) in the same way as it is done in a two-dimensional environment, since the image is loaded on the scene and its RGB values do not change as long as the conditions of lighting do not change. In this way, it is only necessary to characterize chromatically the Head-Mounted Display (HMD) employed in the VR system, generating its ICC color profile. After this, it is necessary to incorporate a CMS that performs color management on that image when required by the VR system. Our research group has successfully conducted tests in this regard (Diaz-Barrancas 2018, Diaz-Barrancas et al. 2018).

Textured 3D Objects

The design of scenes in 3D environments requires the use of 3D objects. These 3D objects can define their external appearance by a texture file in the form of an RGB image that corresponds to the part of diffuse color or material color in the PBR model. This type of texture files can be obtained from the capture of a real object using a 3D scanner. The light used to capture the geometry and color of the object is usually a LED 5000K light source. On the contrary, the white point that is usually employed in displays corresponds to a D65 illuminant. Therefore, the default light source used in 3D design environments with 8-bit per channel RGB digital values = (255, 255, 255) would correspond to a D65 illuminant. With this premise, for a correct color reproduction of the scanned 3D object, it is necessary to perform a transformation to the digital RGB values of the texture captured with D50 to transform them to D65. We must consider that 3D graphics engines used in virtual reality only uses RGB values, and interaction between the light source and the object is calculated in real time. In order for this color transformation of the object's texture to be manageable at runtime, this transformation must be done prior to program execution or at time of loading (Díaz-Barrancas et al. 2020a).

Spectral computation of light and textures

The next step in the challenge of obtaining reliable color reproduction in virtual reality systems would be to apply spectral calculation to the entire scene in real time. This is not feasible today due to the large number of frames per second required to obtain a good feeling of immersion despite the great computing power of the nowadays GPUs. However, our research group is working to obtain a reliable reproduction of color in this type of environment by performing a spectral pre-computation of the light sources and the textures of the 3D objects. In this case it is necessary to have the hyperspectral texture of the 3D object, something that today is complex in objects with volume. In flat objects we have achieved the hyperspectral texture of the object using a hyperspectral camera and we have performed the spectral calculations of both the color of the source and the color of the texture with that source (Diaz-Barrancas et al. 2019, 2020b). It should be noted that the difficulty is to do it in such a way that the rendering of the scene corresponding to different positions of the HMD is sufficiently fluid and compatible with the PBR system based on 8-bit RGB values.

Color appearance models applied to rendered scenes

Finally, and from the point of view of basic research the most important point, it remains to check whether virtual reality systems based on physical rendering models need to integrate a color appearance model that improves the appearance of rendered scenes in 3D. All these types of models such as CIECAM (CIE 2004) or iCAM (Fairchild et al. 2004; Kuang et al. 2007) include a color adaptation stage to respond to changes in lighting. They also consider, in different way, the effect of the environment and a non-linear compression stage. In the case of iCAM, it also analyzes the details of the scene using a Contrast Sensitivity Function (CSF) and performing a contrast enhancement at certain points coinciding with the edges of the objects. The scientific question is to know if the stereoscopic 3D scenes generated for VR systems need to use the improvements provided by color appearance models or not. Last generation HMDs have a wide Field-Of-View (FOV), between 100° - 120°, that simulates quite well the natural FOV. Considering this wide FOV, the high frequency refresh and high-definition image rendered, it is necessary to check the behavior of human visual system in such conditions. Specifically, if light level and color adaptation occurs in the same way than in natural viewing conditions. We must study whether the spatial effects collected by appearance models such as iCAM are already generated by our own visual system when using a stereoscopic image system or, conversely, improve the appearance of the image. Another question to check is the compatibility with PBR rendering with any appearance correction.

RESULTS AND CONCLUSIONS

This is a prospective work, and it results can be analyzed as usual. Our research group is working in this research line and some quantitative results have been obtained related with the linearity of visual perception in HMDs (Diaz-Barrancas et al. 2021). Related with color adaptation and color constancy, preliminary qualitative results indicate that color adaptation could occur in the same way than in natural viewing conditions. In terms of Fairchild et al. (1995), there are a short-term and a long-term color adaptation effects. The sort-term is close to instantaneous and the long-term depends on the light source spectrum but needs around 1 minute to be significative.

There are many scientific challenges related with VR systems that color scientists must solve in the next future. Nowadays, we are designing a new experiment that let us to measure the time and the degree of adaptation for each simulate light source. In the current times in which the global pandemic of COVID 2019 has forced large numbers of people to telework, it is more urgent to know if this evolution in visual appearance is possible.

ACKNOWLEDGEMENTS

Thanks are due to Prof. João Linhares from University of Minho (Portugal) for his support. This work was supported by grants GR21148 and IB20094 of the Regional Government of the Junta de Extremadura and was partially financed by the European Regional Development Fund.

REFERENCES

Burley, B., and W. D. A. Studios. 2012. Physically-based shading at Disney. In: *ACM SIGGRAPH, 2012,* 1-7.

CIE TC 8-01. 2004. *A Color appearance model for color management systems*. Publication 159. Vienna: CIE Central Bureau.

Díaz-Barrancas, F. 2018a. *Estudio de la fidelidad de la reproducción cromática en dispositivos de realidad virtual* (Master's thesis). Mérida: University of Extremadura.

Díaz-Barrancas, F., P. J. Pardo, M. I. Suero, and A. L. Pérez. 2018b. Is it possible to apply colour management technics in Virtual Reality devices? In: *Proceedings of XIV Conferenza del Colore*. Associazione Italiana del Colore: Firenze.

Díaz-Barrancas, F., H. Cwierz, P. J. Pardo, A. L. Pérez, and M.I. Suero. 2019. Hyperspectral textures for a better colour reproduction in virtual reality. In: *Proceedings of XV Conferenza del Colore* Associazione Italiana del Colore: Macerata.

Díaz-Barrancas, F., H.C. Cwierz, P.J. Pardo, A.L. Pérez, and M.I. Suero. 2020a. Spectral Color Management in Virtual Reality Scenes. *Sensors* 19: 5658.

Díaz-Barrancas, F., H.C. Cwierz, P.J. Pardo, A.L. Pérez, and M.I. Suero.. 2020b. Visual fidelity improvement in virtual reality through spectral textures applied to lighting simulations. *Electronic Imaging* 15:259-1

Diaz-Barrancas, F., H.C. Cwierz, and P.J. Pardo. 2021. A study of physical and perceived linearity in a virtual reality environment. In: *Proceedings of the International Colour Association (AIC) Conference 2021*. AIC: Milan.

Fairchild, M. D., and L. Reniff. 1995. Time Course of Chromatic Adaptation for Color-Appearance Judgments. *Journal of the Optical Society of America A* 12: 824.

Fairchild, M. D., and G.M. Johnson. 2004. iCAM framework for image appearance, differences, and quality. *Journal of Electronic Imaging*, 13: 126-139.

Fraser, B., C. Murphy, and F. Bunting. 2004. *Real world color management*. United States of America: Peachpit press.

Garcia, P. A., R. Huertas, M. Melgosa, and G. Cui. 2007. Measurement of the relationship between perceived and computed color differences. *Journal of the Optical Society of America A* 24: 1823-1829.

Glassner, A. S. (Ed.). 1989. *An introduction to ray tracing*. Academic Press: London.

Has, M. 1995. Color Management-Current Practice and The Adoption of a New Standard. In: *TAGA* 2: 748-771.

Heitz, E. 2014. Understanding the masking-shadowing function in microfacet-based BRDFs. *Journal of Computer Graphics Techniques* 3: 32-91.

Johnston, W. M. 2009. Color measurement in dentistry. *Journal of dentistry*, 37: e2-e6.

Kuang, J., G.M. Johnson, and M.D. Fairchild. 2007. iCAM06: A refined image appearance model for HDR image rendering. *Journal of Visual Communication and Image Representation* 18: 406-414.

Morovič, J. 2008. *Color gamut mapping*. New York: John Wiley and Sons.

Oleari, C., M. Melgosa, and R. Huertas. 2009. Euclidean color-difference formula for small-medium color differences in log-compressed OSA-UCS space. JOSA A, 26(1), 121-134.

Pardo, P. J., M.I. Suero, and A. Perez. 2018. Correlation between perception of color, shadows, and surface textures and the realism of a scene in virtual reality. *Journal of the Optical Society of America A* 35: B130-B135.

Pharr, M., W. Jakob, and G. Humphreys. 2016. *Physically based rendering: From theory to implementation*. Burlington, Massachusetts: Morgan Kaufmann.

Poynton, C. 2012. *Digital video and HD: Algorithms and Interfaces*. Amsterdam: Elsevier.

Sharma, A. 2018. *Understanding color management.* New York: John Wiley and Sons.

Walter, B., S. R. Marschner, H. Li, and K.E. Torrance. 2007. Microfacet Models for Refraction through Rough Surfaces. In: *Eurographics Symposium on Rendering*. ed. Geneva: The Eurographics Association, 1-12.

Weatherall, I. L., and B.D. Coombs. 1992. Skin color measurements in terms of CIELAB color space values. *Journal of investigative dermatology*, 99: 468-473.

Wyszecki, G., and W. S. Stiles. 1967. *Color science, concepts and methods, quantitative data and formulae*. New York: John Wiley and Sons.