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ORIGINAL ARTICLE

Coloration Technology

Colour appearance in immersive three-dimensional virtual environments

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Abstract

Technology is constantly evolving and, consequently, all the technological advances taking place are regularly integrated into the daily life of society. During recent years, there has been a trend towards virtual resources such as teleworking, telemedicine and e-commerce. In many countries, this virtualisation process has been accelerated by the changing circumstances caused by the COVID-19 pandemic. In any case, there is a growing demand for virtual systems, and virtual reality is a suitable field for the application of a multitude of solutions. However, advances in virtual reality occur without any regard to colour science, and there are several challenges to be overcome to improve the visual appearance and fidelity of colour reproduction in all types of related devices. This paper discusses three open issues related to the visual appearance and visual fidelity of virtual reality systems. We believe it is necessary to direct future research efforts in each of these directions to secure improvements in the visual fidelity of virtual reality systems.

1 | INTRODUCTION

The ultimate purpose of virtual reality (VR) is for users to experience a situation of total immersion that makes it difficult for them to distinguish between a virtual world and the real world.[1] Starting with the sense of sight, this feeling of immersion is achieved if the visual appearance of the objects appearing in a virtual scene is the same as the visual appearance of the corresponding real objects. Visual appearance is defined as the perception of objects in which the spectral and geometrical aspects of the objects are integrated with the lighting and the observation environment. The International Commission on Illumination (CIE) Technical Committee 1-65 agreed to define appearance as the visual sensation through which an object is perceived with attributes of size, shape, colour, texture, brightness, transparency and opacity. Subsequently, as a result of this work, in 2006 the CIE published Technical Report 175:2006:*A framework for the measurement of visual appearance*, which indicates how to measure visual appearance (as defined above).[2] The final aim was to correlate human perception with physical properties; therefore, because the visual aspect is one of the most important parts in perception, the first step was to characterise all materials from an optical viewpoint. As a starting point for measuring visual appearance, four optical properties (colour, gloss, translucency and texture) and two physical properties (size and shape) were defined and measured.

The measurement of physical properties, such as the shape and size of three-dimensional (3D) objects, is performed by 3D scanners and using photogrammetric techniques. The difficulty arises when these physical properties have to be linked to optical properties such as the colour at a particular point of 3D space. Classic colorimetry allows us to specify the colour of a simple visual stimulus using only three mathematical values. This represents a huge dimensional reduction from the infinite dimensions of the power spectral distribution of a physical stimulus. This transformation is based on the tri-variance of the human visual system. The validity of these tri-stimulus values is determined by the conditions under which they are obtained (level of luminance, size of the stimulus, surrounding field, degree of adaptation) and by the validity of certain mathematical properties necessary for a Euclidean vector space (eg, additivity, linearity).[3] Although colorimetry can be a good starting point for studying the visual appearance of objects and their correlation with optical measurements, this approach is insufficient; this is why, for several years now, visual appearance in general, and the appearance of colour in particular, have been studied from a more global perspective, using colour appearance models that contemplate all the variables that influence it, including adaptation phenomena, the visual environment and spatial properties.

The expansion and popularisation of 3D digital environments like virtual reality systems (VRSs) have brought new challenges in terms of visual appearance and visual fidelity. Problems such as calculating the colour appearance of a virtual 3D object shown to wearers of VR glasses when changing the illuminant and/or the surrounding objects are open issues for colour researchers. In this paper we discuss three examples of unresolved problems related to VR and the colour appearance of 3D virtual scenes.

2 | MEASUREMENT OF OPTICAL PROPERTIES RELATED TO COLOUR APPEARANCE

As discussed in the Introduction, the road travelled to measure the physical properties of a 3D object such as its size and shape is a very long one; currently, devices such as 3D scanners enable a fairly detailed measurement of these properties. A typical result of one of these measurements is a dots cloud, with the spatial coordinates (X, Y, Z) of each point defining the surface of the 3D object. If the scanner is of high resolution then the number of dots defining a particular 3D object could be tens of thousands or even millions. If the 3D scanner is a colour scanner then a standard red green blue (sRGB) colour value is associated with each dot in the cloud. This RGB value is obtained using RGB charge-coupled device sensors that process the images using multiview photogrammetric algorithms. The colour coordinates obtained by a 3D colour scanner are device-dependent because they rely on the light source used by the 3D scanner. Colour researchers have been making device-independent colour measurements for a long time using spectroradiometers or spectrophotometers, but the measurement consists of one point each time. Commercial two-dimensional (2D) colorimeters have recently been launched, but for each type the measurement is always in one, fixed direction. However, there are modern materials with complex surface structures (eg, gonio-apparent) that produce very different colour perceptions at different angles of incidence and observation.[4] This means that it is no longer sufficient to specify only one colour measurement for a given geometry. The reflectance or transmittance of a 3D object must be measured at various angles of incidence and observation to properly describe its visual appearance.

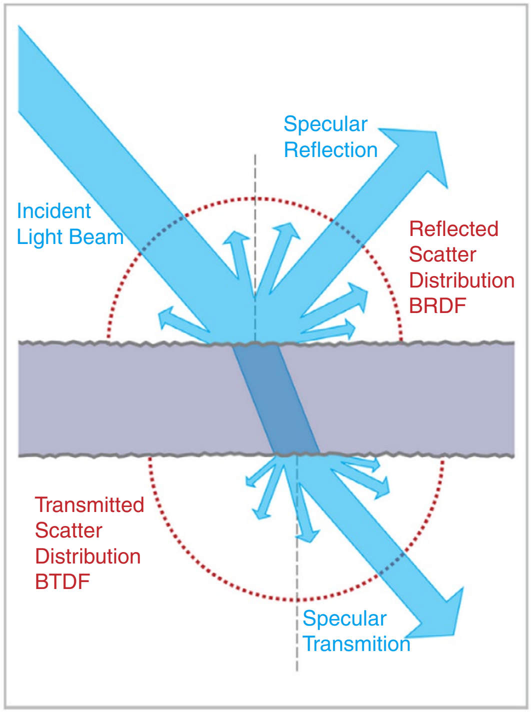

FIGURE 1 Graphical representation of BSDF = BRDF + BTDF,[5] where BSDF is the bidirectional scattering distribution function, BRDF is the bidirectional reflectance distribution function, and BTDF is the bidirectional transmittance distribution function

The solution to the problems outlined above can be found by measuring the bidirectional scattering distribution function (BSDF) using a goniospectrophotometer. The BSDF is defined as the ratio of the radiance of an object in each direction of space in relation to the irradiance it receives. It indicates, therefore, how an object spatially distributes the light it reflects or transmits; thus it is the basic characteristic with which to determine the visual appearance of an object's colour, gloss, texture and translucency (Figure 1).

The two-way function of diffusion distribution (ie, BSDF) expresses how a given object diffuses radiant energy in each direction of space, that is, it indicates the amount of radiance per unit irradiance that is reflected in each direction as a function of the direction of incidence. Its definition is:

$$\mathrm{BSDF}\left(\theta_i, \phi_i ; \theta_s, \phi_s\right) = \frac{dL\left(\theta_i, \phi_i ; \theta_s, \phi_s\right)}{dE\left(\theta_i, \phi_i\right)}, \tag{1}$$

where dL is the radiance differential element and dE is the irradiance differential element.

BSDF is the sum of two terms: one relating to transmittance (bidirectional transmittance distribution function [BTDF]) and the other taking into account the properties of reflectance (bidirectional reflectance distribution function [BRDF]). In the case of opaque objects, BSDF is reduced to BRDF. From the BRDF it is possible to calculate the reflectance and the factor of reflectance for any geometry at one point, that is, with any solid angle of observation ω_s when the object is irradiated from any solid angle ω_i.

$$R\left(\omega_i;\omega_s\right)=\left(\frac{\pi}{\Omega_i.\,\Omega_s}\right).\int_{\omega_i}\int_{\omega_s}\mathrm{BRDF}\left(\theta_i,\phi_i;\theta_s,\phi_s\right).\,d\Omega_s.\,d\Omega_i \tag{2}$$

However, within the framework of 3D computer graphics, use of the BRDF does not resolve the problem because it does not capture the spatial structure of textured materials. For this reason, the BRDF concept has been extended to a more generic definition of bidirectional texture function (BTF), which aims to capture all the variations of textured materials, including non-local effects in rough material structures such as occlusions, masking, subsurface spreading and inter-reflections.[6,7]

A monospectral BTF is a six-dimensional function BTF (x, y, θ_i, φ_i, θ_v, φ_v) that represents the appearance of a material sample at a surface point with coordinates (x, y) for the variable illumination I (θ_i, φ_i) and the point of view V (θ_v, φ_v), and where θ and φ are the elevation and azimuth angles, respectively. The spectral version of the BTF can introduce the photorealistic visual appearance of materials into 3D computer graphics. The open issue lies in how to measure the BTF function of a real 3D object at all its points and manage the huge set of data generated in real time for use as part of a VRS.

3 | REAL-TIME 3D RENDERING IMAGES FOR VR

When ray tracing is used to render a 3D scene, a process is carried out based on the geometrical definition of 3D objects, their position, the position of the camera and the position of the light sources. One of the most extended models of 3D rendering is the physically based rendering model (PBR) that applies a BRDF as a physical law governing the interaction between light and matter.[8] The result of applying this rendering model can be a photorealistic reproduction of real scenes, like the one shown in Figure 2.

FIGURE 2 Example of a photorealistic reproduction of a real scene produced with POV-Ray 3.6[9]

BRDF introduces a large amount of data to 3D rendering, improving the final result but providing the scene with a great complexity of calculation.

This type of 3D rendering method theoretically enables the possibility of defining the spectral power distributions of light sources. In the same way, basic colorimetric calculations can be performed and applied to the image in terms of CIE 1931 XYZ tri-stimulus values. However, this type of 3D rendering needs a long processing time (typically hours) to produce one image. The problem arises when we need to apply these physical law-based rendering techniques in VR environments where active human interaction with the environment is required, adapting the image shown to the position of the observer in a very short time. The VR device must be able to detect the movements of the head and generate different views of the same scene with sufficient frequency (90-120 Hz) and very little delay to obtain a good experience of virtual immersion. This concept is known as low latency. The VRS must be able to change the image generated according to the movements performed by the observer's head as much as continuously possible for a better immersive experience. This reduces the computation time per frame to *ca*. 10 ms or less. With these restrictions, it is not possible to apply a classical 3D physical rendering method and it is necessary to apply more restrictions.

Currently, new graphics processing units (GPUs) with high computing capabilities are employed by 3D game engine software platforms to reflect, to a greater or lesser extent, the real world through physical laws. Some graphics engines apply a reduced BRDF model based on four main components (diffuse, specular, normal, smoothness). These components are applied through bitmaps as 2D texture files associated with each 3D object. The diffuse component corresponds to material colour with perfect Lambertian behaviour following the Disney model[10]; the specular component includes the Smith joint GGX visibility term[11] as well as Schlick Fresnel approximation[12,13]; and both the 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 in this way.

However, colour management has been left out of this type of technique, since colour is processed from the beginning to the end in RGB values (eight-bit digital values per channel). The only colour correction that has been carried out to date has been the calibration of the display setting up a standard configuration that allows a similar appearance on all displays (typically sRGB). Considering this, it is possible to apply colour management techniques using scripts that let us modify the colour of the virtual light sources inside a VR scene in real time. Starting from the spectral power distribution of a real light source it is possible to calculate the RGB values of the virtual light sources inside the scene to simulate any other light source. This method fails when the light source to simulate has a spectral distribution that is very different to the reference illuminant D65. Figure 3 (left) shows the results of simulating the appearance of the ColorChecker illuminated with a light-emitting diode (LED) source composed of only two spectral peaks (spectral blue and spectral yellow), chosen in such a way that the chromaticity *xy* of this source over a diffuse reflectance target coincides exactly with the chromaticity of the D65 illuminant. The appearance of the ColorChecker is very close to the appearance when it is illuminated with a D65 simulator. However, Figure 3 (right) shows a real picture of the ColorChecker obtained in a six-peak LED light booth tuned to match the two peaks of spectral light source theoretically defined before. Although the colour match is not complete in neutral patches because the real light booth does not have a yellow spectral peak and we have employed a green-yellow peak instead, the absence of red colours in the image can clearly be appreciated. This represents its real behaviour because this spectral light source can only render colours whose chromaticity lies on a straight line between the chromaticity of both spectral peaks (blue and yellow).

Therefore, the next step in the challenge to obtain VR scenes with a higher degree of visual fidelity is to apply spectral calculation to the entire scene in real time. As we have shown above, this is not currently feasible because we have not characterised any 3D object with the spectral BTF function, due to the large number of frames per second required to obtain a good feeling of immersion, despite the great computing power of GPUs these days. The open issue consists of finding a compromise solution between visual fidelity and feasibility with a data reduction based on perceptive criteria.

4 | COLOUR APPEARANCE MODELS APPLIED TO RENDERED SCENES

At the beginning of this paper we established that a good feeling of immersion in a VRS is achieved if the visual appearance of the objects appearing in the scene is the same as the visual appearance of the real object, which we call visual fidelity. To obtain that visual fidelity in the reproduction of the real world inside the virtual world, a good physical characterisation of real objects through spectral BTF measurements is needed, and a suitable supply of the capabilities for spectral processing of 3D objects by VR software is required. These two steps would be sufficient if human perception was perfectly linear, but the reality is that seeing sight is not linear in many cases. In other colour-imaging fields different to 3D computer graphics, the solution to these non-linearities was to define then apply colour appearance models. These mathematical models were mainly developed for non-complex scenes like CIECAM02 or CAM16[14,15] or were created considering only 2D images, although they covered spatial phenomena like image Color Appearance Model (iCAM).[16,17] From the point of view of basic research, it remains to be seen whether VR systems are capable of integrating a colour appearance model that improves the colour appearance of rendered scenes in 3D.

All these types of appearance models include a colour adaptation stage to respond to changes in lighting. They also consider, in a different way, the effect of the environment and a non-linear compression stage. In the case of iCAM, it also analyses the details of the scene using a contrast sensitivity function and performs a contrast enhancement at certain points coinciding with the edges of the objects. The key issue is to know if the stereoscopic 3D scenes generated for VRSs can make use of these improvements provided by colour appearance models. On one hand it is necessary to check compatibility with PBR rendering. On the other hand, we must

FIGURE 3 (Left) ColorChecker simulation using a two spectral peaks light source in a virtual reality system and (right) a real picture of the ColorChecker using a two spectral peaks light source

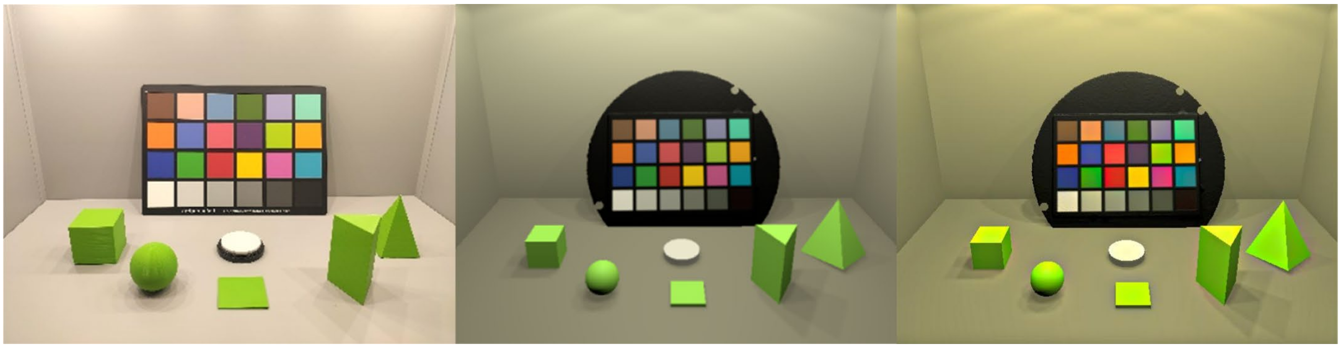

FIGURE 4 (Left) Real picture of a real scene inside a light booth, (centre) screen capture of the simulation of a real scene in a virtual reality system (VRS) without any post-processing, and (right) screen capture of the simulation of a real scene in a VRS processed with an iCAM06 appearance model

study whether the spatial effects collected by appearance models such as iCAM have already been generated by our own visual systems when using a stereoscopic image system, or conversely, if they improve the appearance of the image.[18]

As an example, Figure 4 (left) shows a real picture of a compound scene of a ColorChecker chart, a white diffuse reference and several geometrical pieces printed with a 3D printer from the same material, all inside a light booth. A simulation of the same scene using a 3D game engine typically used in VRSs without any post-processing can be seen in the centre of Figure 4, and on the right the same image processed with an iCAM06 colour appearance model.

The images in Figure 4 are only shown for the purposes of explanation because the open issue consists of assessing the visual fidelity between the real and virtual scenes with and without CAM models using real observers under real conditions, and not by using 2D images. Under such conditions, stereoscopic vision and perception of depth can have a major influence. Future visual fidelity research should focus on topics like chromatic adaptation, hue appearance in complex scenes, the contrast enhancement of 3D objects and other spatial effects.

5 | CONCLUSIONS

There are several challenges that colour scientists must surmount in the near future. Because of the evolution of technology, as we head towards a more interconnected society with greater possibilities of virtualisation, it is essential to start improving colour rendering and visual appearance in VR environments. Currently, because the COVID-19 pandemic has forced large numbers of employees to telework from home, it is important to discover if improvements in visual appearance and fidelity are possible. In this paper we have discussed three open issues related to capturing the real world through physical measurements, introducing spectral computation in lighting and objects as well as assessing the efficiency of appearance models applied to VRSs.

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REFERENCES

1. Pardo P, Suero M, Pérez Á. Correlation between perception of color, shadows, and surface textures and the realism of a scene in virtual reality. *J Opt Soc Am A*. 2018;35(4):130-135.
2. CIE 175:2006. *A Framework for the Measurement of Visual Appearance*. Vienna: Central Bureau of CIE; 2006.
3. Wyszecki G, Stiles W. *Color Science*. New York: Wiley; 1982:985.
4. Ferrero A, Rabal A, Campos J, Pons A, Hernanz M. Variables separation of the spectral BRDF for better understanding color variation in special effect pigment coatings. *J Opt Soc Am A*. 2012;29(6):842-847.
5. Wikimedia. BSDF. https://upload.wikimedia.org/wikipedia/en/d/d8/BSDF05_800.png. Accessed October 4, 2020
6. Filip J, Vávra R, Krupička M. Rapid material appearance acquisition using consumer hardware. *Sensors*. 2014;14(10):19785-19805.
7. Wu J, Chen H, Liu X, Cao L, Peng X, Jin G. Unsupervised texture reconstruction method using bidirectional similarity function for 3-D measurements. *Opt Commun*. 2019;439:85-93.
8. Pharr M, Jakob W, Humphreys G. *Physically Based Rendering: From Theory to Implementation*. Burlington, MA: Morgan Kaufmann; 2016. 1266.
9. Oyonale-3D art and graphic experiments. POV-Ray. http://www.oyonale.com/modeles.php?lang=en&page=40. Accessed October 4, 2020
10. Burley B, Animation Studios W. Physically based shading at disney. In *Proceedings, ACM SIGGRAPH*. Los Ángeles, CA, USA; 2012;1-7.
11. Walter B, Marschner S, Li H, Torrance K. Microfacet Models for Refraction through Rough Surfaces. In *Proceedings, Eurographics Symposium on Rendering*. Grenoble, France; 2007;195-206.
12. Heitz E. Understanding the masking-shadowing function in microfacet-based BRDFs. *JCGT*. 2014;3(2):48-107.

13. Schlick C. An inexpensive BRDF model for physically-based rendering. In *Proceedings, Computer Graphics Forum*. 1994;13(3):233-246.
14. CIE 159:2004. A Colour Appearance Model for Colour Management Systems. CIECAM02. Vienna: Central Bureau of CIE; 2004.
15. Li C, Li Z, Wang Z, et al. Comprehensive color solutions: CAM16, CAT16, and CAM16-UCS. *Color Res Appl*. 2017;42(6):703-718.
16. Fairchild M, Johnson G. iCAM framework for image appearance, differences, and quality. *J Electron Imaging*. 2004;13(1):126-138.
17. Kuang J, Johnson G, Fairchild M. iCAM06: A refined image appearance model for HDR image rendering. *JVCIR*. 2007;18(5):406-414.
18. McCann J, Parraman C, Rizzi A. Reflectance, illumination, and appearance in color constancy. *Front Psychol*. 2014;5:5.

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