Evaluation of Historical Museum Interior Lighting System Using Fully Immersive Virtual Luminous Environment

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ABSTRACT

Saint Rocco Museum, a historical building in Venice, Italy is used as a case study to explore the performance of its' lighting system and visible light impact on viewing the large size art works. The transition from three-dimensional architectural rendering to the three-dimensional virtual luminance mapping and visualization within a virtual environment is described as an integrated optical method for its application toward preservation of the cultural heritage of the space. Lighting simulation programs represent color as RGB triplets in a device-dependent color space such as ITU-R BT709. Prerequisite for this is a 3D-model which can be created within this computer aided virtual environment. The onsite measured surface luminance, chromaticity and spectral data were used as input to an established real-time indirect illumination and a physically based algorithms to produce the best approximation for RGB to be used as an input to generate the image of the objects. Conversion of RGB to and from spectra has been a major undertaking in order to match the infinite number of spectra to create the same colors that were defined by RGB in the program. The ability to simulate light intensity, candle power and spectral power distributions provide opportunity to examine the impact of color inter-reflections on historical paintings. VR offers an effective technique to quantify the visible light impact on human visual performance under precisely controlled representation of light spectrum that could be experienced in 3D format in a virtual environment as well as historical visual archives. The system can easily be expanded to include other measurements and stimuli.

Keywords: Virtual Luminous Environment, Integrated Optical Method, Chromaticity, Spectral Reflectance, Cultural Heritage, Immersive Virtual Environment, Human Visual Performance, Large Scale Historical Paintings, UV Hazard. *moji@umich.edu; phone 1 734-9360-228; fax 1 734-746-2322; http://um3d.dc.umich.edu/

1. INTRODUCTION

Current techniques on lighting simulation for building science are based on two decades of computer algorithm developments toward accurately representing common lighting simulation needs [1]. Some of these new techniques are making good progress to provide not only recreation of reality but also reproduction of stimuli within a virtual luminous environment [2]. Simulating complex scenes demand high accuracy for its simulation of colors and spectral characteristics of materials for psychophysics applications. Typically the outcome of such simulations is used as stimuli or alternative to physical simulation with better accuracy when combining freely available and commonly used software by lighting designers. Creation of physically accurate or relatively accurate visual stimuli is used to recreate an interior of Saint Rocco, a historical museum in Venice Italy.

Given the current technology, it is possible to create realistic image synthesis in the following categories.
1) Physical Realism: to create equal visual stimulation at the eye while viewing the image of the scene.
2) Photo Realism: to create equal image that is indistinguishable from the photograph of the scene.
3) Functional Realism: to create equal visual information at a scene about the properties of the object (e.g., shape, geometry, materials characteristic) that allows user to make an informed decision or reliable judgment.

It is possible to take a virtual walk through a virtual art museum while the interior space representing the same identical layout and lighting conditions as a real museum. If this is an acceptable method by the guardian of the cultural heritage therefore, it would be possible to document the conditions and archive such unique spaces through their accurate recreation within virtual environment [3]. This paper presents an integrated approach in application of such method that allows rendering caustic on non lambertian surfaces [4] while taking advantage of faster photon mapping of global illuminance [5]. This method provides an opportunity to use the new scalable technique and to estimates the indirect illuminantion or the reflected components contribution into a dynamic luminous scene in real time as generated within a virtual environments [6]. The algorithm allows rendering of each single bounce or reflection of light with higher degree of realism due its faster computation in real time. This particular technique in photo realism permits the application of the physical realism [7, 8 and 9].

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This integrated approach brings together various disciplines such as vision, optics, neurology, psychology, illuminating and computer engineering to work with researcher in history and archeology to work toward in historical preservation of cultural heritage of known buildings. The following sections will describe the steps toward this integrated approach and provide a path through a case study as an example of this method and its implementation.

Colour is a matter of perception and subjective interpretation. People have different references and experiences given 8 to 15 per cent of the people within the general population are colour blind. Most people even in their associated technical groups are not trained colorimetrically, and these days expect to get what they see through web base sources as electronically transmitted images of products. This is based on their eye colour sensitivity and past experiences. Colour as an interdisciplinary subject requires participation of researchers in electronics, computer science, chemistry, physiology, psychology fields and practitioners **[10, 11]**.

Typically, spaces designed by architects continue to evolve throughout the different stages of design. Designers have a need to view the same design option under many different scenarios such as changing lighting conditions, materials and surface colours etc. Each condition requires multiple inputs for activating the visual system. However; stimulating the viewer's eye does not include the optical filtering and light scattering within the eye. Combining photorealism with physically accurate simulation requires special algorithms for the use of the spectral data within rendering methods. The objective is to create an image that gives a visual stimulation such that the eye perceives the scene as if it were an actual stimulation from a spectral radiance source and or at some relative scale **[12-15]**.

Given the current capabilities of the display monitors to produce accurate display of such results, it is not fully possible to produce the spectral radiance stimulations at the eye. Photorealistic renderings are highly demanded by the advertising industry, and given the ever increasing ability of interactive computing power; there is a new growing need by architects. The goal is to provide a method for the evaluation of the virtual luminous environment and choices made during the design process on actual material samples. In this case the image of the interior space has to be believable and be perceived as equal to reality while producing similar physical sensations at the eye, although it should be noted that the spatial, temporal and the chromatics (hue, value as a relative brightness and saturation) characteristics are within the limits of the lighting systems. In order to be able to explain the phenomenon of colour to lighting professionals and their clients as relating to their architectural projects, the use of 3D Virtual Reality Laboratory (VRL) is found to be most useful **[16,17].**

2. METHODOLOGY

The following sections will describe the use of a 3D-VRL for its dynamic capabilities within architectural engineering field. After an overview of the system and related components, some specific applications as relate to colour appearance and the measurable domain in colour differences within the virtual reality environment are presented. The system limits and future development in software and the application of a new proposed method are discussed.

2.1 Virtual reality

The VR is the simultaneous simulation and perception of physical attributes of reality in an interactive, virtual, computer-generated environment in real-time. VR applications in architecture, music, computation, mechanical engineering and medicine have proven to be most beneficial to designers and researchers. The focus of these applications is mostly on the visual and aural aspect of the simulated scenes. The major spatial attributes such as surface colours and the lighting system spectral characteristic and its luminance distribution within a virtual environment are simulated and measured while the user is experiencing the space, and the perceived brightness of the light sources within the current limitation of the computing power within real time constraints. The post processed and analyzed lighting conditions are displayed in various visualization modes for lighting parametric studies. The data acquisition system allows for the simultaneous recording of the virtual environment and visual response of the users such as their pupil size change due to the lighting intensity and or spectral changes within a scene. The real time measuring capabilities using portable spectrometers allow one not only to record and analyze the conditions with users' reactions, but also to view the spectral characteristics of the light and associated colours reaching the users' eyes.

2.2 CAVE

A Computer Assisted Virtual Environment or the so called "CAVE" is an immersive display system for virtual reality environment. Virtual Reality (VR) is created within a cubicle space where at least three of the four walls depending on a given facility's capabilities; the floor and or the ceiling are all used as projection screens. Simultaneous use of all display systems outperform most other displays such as head mounted displays. It requires the use of 3D-glasses and a tracking system device which can locate the user within the space.

The system has obvious limitations given the typical 3.048 m2 or (10 ft2) size of the CAVE with rare projection screens. The stereoscopic format projected images at a known frequency through the lens of the 3D-glass as synchronized with the human eye or vision frequency response, provides the illusion of depth along with corrected perspective for a given viewing direction as a function of time. The tracking system combined with controller such as wand or joy-stick provides ease of navigation within a simulated scene.

2.3 UM 3D Lab

The UM 3D VR Laboratory includes an immersive virtual-reality CAVE-like environment, measuring 10 ft (3.048 m) in width, depth, and height. It runs on a cluster of six workstations, with one control computer, one motion-tracking computer, and four rendering computers. The renderers are Box Tech Workstations, with quad-core CPUs at 2.6 GHz, 8 GB RAM, and NVIDIA Quadro FX 5600 + GSync graphics cards. Four Christie Mirage S+4K projectors produce 3D images on the left, front, right, and floor surfaces. The resolution per surface is 1024 x 1024 pixels. The stereo mode is frame-sequential (alternating left-right) at 96 frames per second. Infrared emitters synchronize Stereo Graphics Crystal Eyes® liquid crystal shutter glasses with the projectors. A Vicon MX13 system with eight 1.3 megapixel cameras provides wireless (near infrared) motion-tracking of the shutter glasses and a Logitech Rumble Pad game controller. The sound system comprises four Klipsch speakers mounted in the upper corners, a Klipsch subwoofer on the floor a short distance away, and two amplifiers at 100 watts per channel. The software is an ongoing in-house development, named Jugular, which integrates several open-sources, proprietary, and custom-developed subsystems for graphics, sound, animation, physics, motion-tracking, data management, and networking. Figure 1 shows real and schematic views of the CAVE's back screen projectors, speaker and their locations including example of an output for this study.

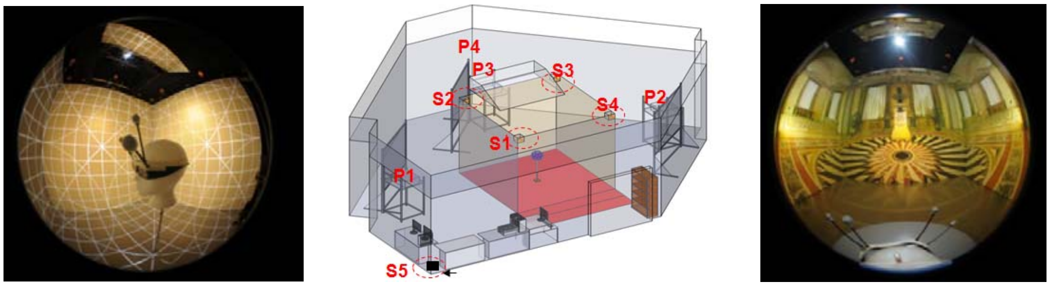


Figure 1 - Real and schematic views of the CAVE's projectors, speakers and example of an output

2.4 Visualization Software

The latest review on visualization software shows that major efforts are being made toward the use of 64-bit systems. The following software packages are the most used programs by architects and the industry given their capabilities and availability, regardless of the cost or affordability by individuals. These names are not listed in any hierarchy of use or cost: Radiance, Form Z Render Zone by Autodesk System, 3ds Max Design 2013 by Autodesk, Bentley Micro-station (luxology), Navis Works Simulate 2009 by Info Matrix software international, Pianesi 5, Modo 302, NuGraf and Poly Trans by Okino computer graphic [16,17]. They each provide an image and with some limited option, some provide WRL formatted files to be used within the CAVE system along with realistic visual information that helps users make design decisions. However, a detailed review of their unique capabilities is beyond the scope of this paper [1, 6 and 14].

2.5 The Virtual Reality Modeling Language

The VRML is representative of simulation capabilities in the CAVE. VRML version 2, also known as VRML97, was adopted as an International Standard ISO/IEC 14772 in 1997. The standards specify a file format, a content model, and algorithms for its interpretation. The model is a directed acyclic graph that includes nodes for geometry, colour, texture, and light, as well as sound. However, it provides for only one texture per shape and one pair of texture coordinates per vertex. Strict adherence to the “ideal VRML implementation” actually prohibits calculation of shadows and indirect lighting. The equations used within the standard do not accommodate such desired effects. VRML version 2 was amended in 2002 to add geospatial and NURBS support, but the shape, material, lighting, and sound specifications remain unchanged [20].

3. SIMULATING SCENES IN CAVE

The interior lighting conditions of the Saint Rocco Museum were measured and photographed using a calibrated digital camera for conversion to RGB and spectral reflectance data. The interior surface geometries were also scanned using 3D infrared scanners. The architectural records and the digital data were used to recreate the building in a 3D digital form. These procedures were documented for a historical heritage archiving of this building for future application.

The 3D model of specific interior spaces were then converted to 3D Max, Lightscape, Radiance and AGI32 formatted files for the best possible conversion to VRML formatted files to be used in a virtual reality setting within a 4-surface projection CAVE. The measured spectral power distribution of the source and surface reflectance provided the path to obtain the RGB signal levels for each of the interior surface characteristic. The simulated set up for the CAVE is achieved through use of Jugular, an in house software[16, 17] that allows the Omni or spot lights that can be positioned in the space with known light distribution and the following inputs such as cast shadows, intensity level, hotspot angle, cutoff angle, color (RGB), attenuation, rsm resolution and the following surface or materials characteristic as inputs such as ambient Intensity (0 to 1), diffuse Color (RGB), emissive color (RGB), shininess (0 to 1), specular color (RGB), transparency (0 to 1). The final outputs are 3D stereo projected scenes of interior spaces that are simultaneously tracked with motion trackers to provide the right perspective to the eyes of the user. The real time ability to calculate the color corrected scenes and display of their internal reflected component at the highest possible rate of display is one of the unique abilities of this system. The illuminance and luminance distribution in horizontal and vertical planes were measured using illuminance, luminance, chorma meters, spectrophotometer and spectroradiometers for both night and daytimes along with a digital camera as a luminance meter. The jugular software was used to create the colors and light sources in a given scene **[21, 22]**. The daylight as a source within simulation software differed only in its atmospheric condition settings. To establish the color of the illuminants, the measured color signals of the WHITE scene for each source were used. All images were rendered with the default values of software except for the number of light bounces, which was set to one within Jugular **[17]**. The objects or materials in the simulated scenes had lambertian surface properties; material type with specular surface to simulate reflective surfaces such as floor were also used for the complex illumination scenes though the application of Macbeth Color Checker sample because only one point in these scenes was measured at the site at the surface normal. The simulation of the simple Macbeth Color Checker allowed us to estimate and calibrate the RGB differences between measured and simulated scenes. Jugular software was used for simulation in the CAVE. The colors of objects and light sources are characterized by their RGB values. It is straightforward to calculate RGB values from a surface reflectance function $S(\lambda)$, which was derived from the measurements; the onsite measured values [W/ (sr. m^2)] are used as alternative color descriptors. When inter reflections are present in a scene, the representation of an object's color with three or any number of discrete samples will lead to an underestimation of the intensity of mutual illumination **[9]**. Computer graphics rendering software represents the spectral information for light source and surface as spectral coordinates [R, G, B] **[24]**. When a light is absorbed and or re-emitted by a surface with spectral coordinates [r, g, b], the reflected, transmitted light is assigned as Y [rR, gG, bB] where y is a scalar determined by the location of the light source, the surface, and the viewer. As demonstrated by **[22, 23]** such parameterizations of illuminated surface and associated interactions cannot be modeled by component-wise multiplication and be accurate representation of real scene or a stimuli for photo receptor excitations. Most of these programs represent color as RGB triplets in a device-dependent color space such as ITU-R BT.709. The underline assumption is that the human visual system; is broadly responsive to red, green, and blue light given the application of CIE's color matching functions. These algorithms represent the assumption that inter-reflections between colored surfaces can be accurately calculated using three separate color bands. The virtual reality simulation as part of this study shows that this assumption holds to be true for most architectural applications; however, for fully saturated colors it may produce varying results **[9]**. To overcome such limitation, an N-step algorithm proposed by **[22, 23]** was used to create hyperspectral imaging of the projected scenes using the Shafer model [24, 25] by increasing N to 9 steps. See **Figure 2** – Right.

This paper focuses on the differences in criteria between physically accurate or photo realistic images that could be utilized in architectural lighting design applications which are functionally realistic. 3DMax Design 2013 is used to simulate views of a building under day and nighttime conditions. The spectral properties of the building surface under real or controlled laboratory conditions are measured, along with a white reference sample. The CIE standards were followed to establish the colour of the illuminant and the spectral reflectance of the white sample used as a reference in the scenes **[15, 16 and 17]**. The available functions within 3D Max combined with all the VRML rendering graphic capabilities, were used to simulate the surface material optical properties along with photometric and radiometric characteristics of the light sources. The measured spectral data were sorted and used as an input to an established algorithm to produce the best approximation for RGB of each material sample. The calculated RGB were then used as an input to the software to generate the image of the objects. Conversion of RGB to and from spectra has been a major undertaking in order to match the infinite number of spectra needed to create the same colours that were defined by RGB in the program. The RGB colour space as defined by the standard XYZ matching functions and the matrix converting XYZ to RGB is described in many sources **[15, 21** and **22].**

The dynamic range of these colour matching functions is much wider than the range of 360 nm to 780 nm wavelengths which exist within computer rendering systems while maximizing for the eye focusing range. The use of the white sample during the spectral measurements provides an accurate match of RGB colours. Good attempts have been made in this study using spectral measurements under real sky conditions to match the composite colour of surface materials. The use of Spectral Scan, Ocean Optics spectroradiometers and spectrophotometers along with Minolta CS-200 Chroma Meter provided the simultaneous measurement of the computer generated scenes [8, 9 and 17]. Latest recommended procedure for better accuracy in modeling requires the N stepping algorithm. The N step rendering procedure recommended by [22] was used for N=3. This procedure requires the measured spectrum data to be divided into three consecutive, equally spaced ranges of wavelength bands ([380–510 nm], [515–645 nm], and [650–780 nm].) The average RGB values for each of the wavebands are calculated using the procedure described in section below, and then used as the corresponding colour descriptor. The outputs of each image for given ranges of wavelengths bands are rendered, each image accounting for a different part of the spectrum. Then images were combined into a standard three-channel RGB image similar to the creation of high dynamic range images within the VRML & Jugular 2 and 3 Scene files. **Figures 2 and 4** represent some of the results of this modeling effort.

3.1 RGB Conversion to Spectra

The following protocol or procedure for the conversion of the spectral data to RGB is directly extracted and followed step by step based on the recommendations provided in reference [2, 22]. A surface reflectance function S(λ) to X,Y,Z tristimulus values are converted using x(λ), y(λ), and z(λ) matching functions with the adjusted CIE 1931 matching function using equations 1, 2 and 3 as described in reference [21].

$$X = k \int S(\lambda)x(\lambda)d\lambda, \text{ (Eq. 1)}, \qquad Y = k \int S(\lambda)y(\lambda)d\lambda, \text{ (Eq. 2)}, \qquad Z = k \int S(\lambda)z(\lambda)d\lambda. \text{ (Eq. 3)}$$

The X, Y, Z tristimulus values are then converted to RGB with a conversion matrix T (3 by 3 matrix), which is based on the primaries of the display, as described in references [2, 15, 22 and 23]. The primaries are used to derive the conversion matrix T. Multiplying the XYZ tristimulus values with T produces the RGB triplets, to be used as the colour descriptor in the VRML material and Jugular 2 & 3 Scene files file [17, 20]. See Section 2.5 . The same procedure is used to code the colour of the illuminant, CIE x, y chromaticity values, from XYZ tristimulus values, CIE x, y chromaticity values as follows:

$$x = X/(X + Y + Z). \text{ (Eq. 4) and } y = Y/(X + Y + Z). \quad \text{(Eq. 5)}$$

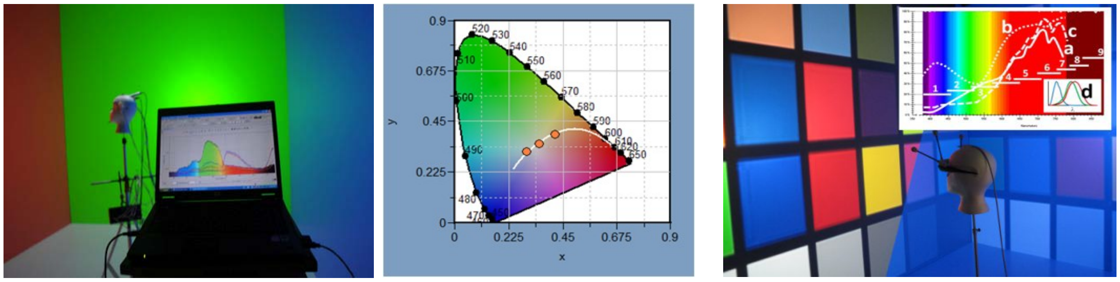


Figure 2 - Video 1 http://dx.doi.org/10.1117/12.2020535.1 Measuring RGB within a simulated scene in an immersive VR enclosure. **Left:** The manikin head is fitted with spectrometers behind the 3D stereoscopic-glass to account for the glasses' absorption and tint while measuring the SPD for a given viewing direction. **Center:** CIE 1931 x, y Chromaticity. **Right:** Macbeth color chart and blue glazing are simulated.

Figure 2 left shows light from a source with spectrum (a-solid line) is reflected by a surface with spectral reflectance (b-small dash line). The reflected light with new spectrum (c-large dash line) is absorbed by the eye's cone receptors with spectral sensitivities (d – color plot). Given the cones activities, the visual system has to estimate the surface reflectance (b). Note the changes in spectral shape from (b) to (c) are estimated using the proposed step functions (at least 9 steps, 1 to 9 solid lines) by references [22-25]. Photograph of the CAVE interior in which the Macbeth Color Chart is simulated and measurements were taken with a spectroradiometer in real time aiming at green and white with blue and red mixed colors. The Macbeth Color Checker was simulated and illuminated by a single spotlight and the color signal was measured at 45 deg (**Figure 2-center**).

3.2 Requirement for computer simulation

For a consistent and accurate analysis, it is necessary to keep the input quantities within a realistic range of real conditions. It is imperative that the input to the rendering models is clearly defined given the limits for each software rending engine and their required input variable, and that the possible range of predicted illuminance and or luminance levels along with associated RGB for a given scene is identified.

Some lighting applications require accurate levels of surface luminance to be simulated as the background in an image and not in the texture of the surface only. The images in **Figure 3** show the real lighting conditions as viewed under the museum lighting condition and **Figure 4** show the real time spectral reflection of the scenes as viewed by the viewers. Simple surfaces with known RGB are simulated as part of the calibration of the VRL projected light or scene passing through the back screen projection using diffuse translucent surfaces.

Figure 3 - Panoramic view of interior space

Figure 4 – Simulated scene as shown in a wide angle view of interior spaces created by the software using the average RGB combined with realistic textures and projected for measuring its SPD as viewed in the VR enclosure in real time.

3.3 VRML modeling of material including glazing

Major characteristics of surface materials and associated colour appearances are created based on their spectral reflectance and transmittance in the case of interior surfaces including glass. Reflection and transmission of the diffuse and specular components of surfaces are not actually or realistically modeled within some programs. RGB is often used as the basis of colour space and colour computation in computer graphics. The rendering software internally defines the CIE chromaticity coordinates of the RGB values. Simulation programs normally use an RGB averaging system while light source contains the full spectrum. RGB averaging as an input could affect the colour accuracy of the simulated scenes. However, the material's reflection and transmission in units of RGB is only for normal incident and not for the angular dependency. The VRML scene input requires the following variables to be specified for the appearance of the materials within a scene given their required metric, diffuse colour (R,G,B), ambient intensity (0,1), specular colour (R,G,B), shininess (0,1), transparency (0,1). [16, 17, 20]. Optical characteristics and angular dependence of various materials were measured and the conversions to RGB were used as an input following the earlier recommended procedures. Some of these metrics such as transparency are not available within the in-house written software.

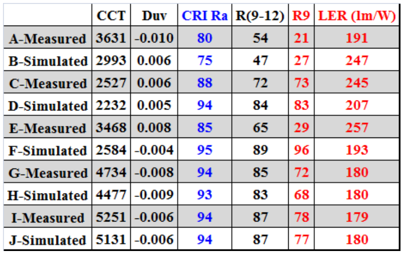
4. RESULTS

The colour Quality Scale (CQS) Program by NIST provides calculation of colour quantities of various lamp SPDs including CRI (CIE 13.3) and also the NIST CQS [12, 13]. The colours of the Munsell colour chips used in CIE 13.3 and the 15 samples used in CQS are presented on the screen or as shown in **Figure 2** for both reference and test illuminants. This capability provides a visual impression for the colour differences. The real time measured SPD and the simulated scenes projected on the CAVE wall surfaces are shown in **Figure 4.** The data for many simulated scenes was formatted and normalized to the peak wavelength within the range of 380 to 780 nm and used as input to the CQS program by Ohno and Davis [12] for colour quality analysis. SPD of a white colour scene viewed with and without the 3D stereoscopic-glass were also measured to examine the impact of the 3D glasses on the viewers' colour perceptions. The increase power in the range of 730 to 780 portion of the spectrum as shown in **Figure 4** is due to the random infra-red beam projections by the eye tracking system. The measured luminance results are shown in **Figure 5** for all lighting conditions within the ground level gallery. The associated measured SPD (see center of **Table 1**) were used as an input to CQS program to evaluate the lighting quality of the interior luminous environments under real and simulated conditions. The results show, it is possible to obtain close to quality of reality if the *N*-step algorithm is used.

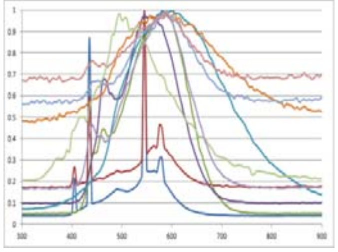
Currently-available rendering packages typically use 3-step approximations, but can be easily modeled to step function approximations with any number of steps. Scenes containing simulated Munsell chip surface spectral reflectance as shown in **Figure 2** and the spectral power distributions of the reference illuminants are not rendered accurately when 3-step approximations are used. Rendering is satisfactory when 9-step or 12-step approximations are used **[2, 16, 17 and 22]**. The CRI, CCT and the CQS calculations are summarized in **Table 1.** The simultaneous projections of the RGB for a given wall within the CAVE provide the opportunity to measure the impact on the viewers' eye due to simultaneous viewing of the RGB walls. The calculated COS and saturation factor show the degree of change due to these colour viewings. The observed differences in CRI, CQS and CCT for measured and simulated results indicate that these differences are due to parameter changes on the limitation of the light source (projectors) intensities and colours produced within this geometric lit environment**.**

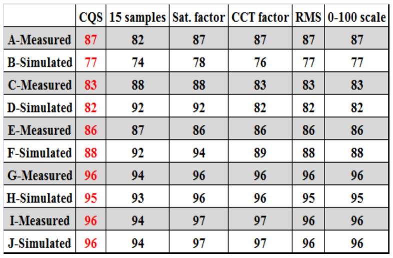
Figure 5 – Video 2 http://dx.doi.org/10,1117/12.2020535.2 Measured luminance of ground level gallery under real lighting condition given a viewing direction, **Video 3** http://dx.doi.org/10.1117/12/2020535.3

Table 1 - Summary of the colour index calculation using measured SPD within the museum luminous environment



	CCT	Duv	CRI Ra	R(9-12)	R9	LER (lm/W)
A-Measured	3631	-0.010	80	54	21	191
B-Simulated	2993	0.006	75	47	27	247
C-Measured	2527	0.006	88	72	73	245
D-Simulated	2232	0.005	94	84	83	207
E-Measured	3468	0.008	85	65	29	257
F-Simulated	2584	-0.004	95	89	96	193
G-Measured	4734	-0.008	94	85	72	180
H-Simulated	4477	-0.009	93	83	68	180
I-Measured	5251	-0.006	94	87	78	179
J-Simulated	5131	-0.006	94	87	77	180





	CQS	15 samples	Sat. factor	CCT factor	RMS	0-100 scale
A-Measured	87	82	87	87	87	87
B-Simulated	77	74	78	76	77	77
C-Measured	83	88	88	83	83	83
D-Simulated	82	92	92	82	82	82
E-Measured	86	87	86	86	86	86
F-Simulated	88	92	94	89	88	88
G-Measured	96	94	96	96	96	96
H-Simulated	95	93	96	96	95	95
I-Measured	96	94	97	97	96	96
J-Simulated	96	94	97	97	96	96

5. ANALYSIS AND DISCUSSION

The use of computer generated images within CAVE could be an alternative to the use of real or full mocked up space during the design concept or historical building evaluation. In the scene below, a red curtain was illuminated by sunlight as spotlights at 0 deg. The light bouncing off the red curtain while being animated within the VR scene created a red gradient on the white walls. The color signal of the bouncing red was measured. This particular scene was simulated utilizing an algorithm for visualization, including real-time shadows and massive lighting, a rendering engine that implements algorithms published by Anton Kaplanyan **[6],** and others **[17]** developed in-house, taking advantage of modern graphics hardware with GLSL shader programs.

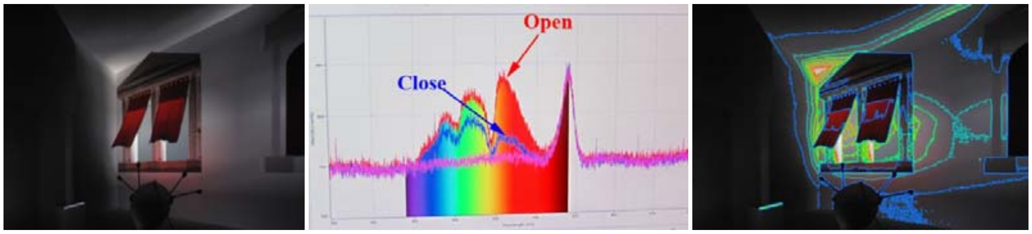


Figure 6 - Dynamic movement of a red curtain simulated **(left) Video 4** **http://dx.doi.org/10.1117/12.2020535.4** while measuring SPD in real time (**center**) **Video 5** **http://dx.doi.org/10.1117/12.2020535.5** and luminance distribution changes due to inter-reflection of light on the wall is shown at **right.** The blue and red lines within SPD plot (**center**) show closed and open curtain settings with its peak contribution in red part of the spectrum.

VR is no longer being viewed as an entertainment system but now is being used in scientific investigation for its visualization capabilities. Although, there are unique applications in which the design objectives demand high accuracy in simulated results, this method may not require absolute accuracy, in order to accelerate the decision making process. The information provided by these results and analysis could outline a set of future guidelines or requirements for simulation requiring high accuracy within a given dynamic range of spectrum **[2, 22-25].**

6. CONCLUSION

In many lighting applications, color preference is as important as color fidelity. Color preference is more than preference. It is strongly correlated with visual clarity and color discrimination. While, several indices may be useful for evaluating specific aspects of lighting; color fidelity, discrimination, preference, express general color quality of the interior environments. Application of immersive Virtual Environment (VE) technology for light and color perception is achieved through visualization of interior luminous environment of a historical museum. The lighting simulation procedure used for this space's existing conditions could be applied to evaluate real or virtual settings of historical buildings. This immersion capability allows stimulation of all human sensory subsystems in a natural way within this immersive environment. This paper has shown the implementation of an integrated method utilizing new scalable technique for approximating indirect illumination in fully dynamic scenes for real-time simulation in a fully immersive virtual luminous environment. Application of this method does not require any pre calculation to manage display of large scenes. It is primarily targeted at rendering single-bounce indirect illumination with occlusion. The application of such methods allows various scenes in combination with wide-spread real-time rendering techniques to be utilized for viewing historical heritage types of buildings under investigation. The collected results are used as archival records and might be a promising research direction.

REFERENCES

[1] Ochoa Morales, C.E., Aries, M.B.C. and Hensen, J.L.M. (2010) "Current perspectives on lighting simulation for building science", Proceedings IBPSA-NVL, Event, pp. 9. Eindhoven, 2010

[**2**] Alex I. Ruppertsberg and Mariana Bloj, "Rendering complex scenes for psychophysics using radiance: How accurate can you get?" Vol. 23, No. 4/April , J. Opt. Soc. Am. A759, 2006.

[3] Alex I. Ruppertsberg, Mariana Bloj, "Creating physically accurate visual stimuli for free: Spectral rendering with radiance" Behavior Research Methods, 40 (1), 304-308, doi:10.3758/BRM.40.1.304 , 2008.

[4] Henrik W., Jensen, "Rendering Caustics on Non-lambertian Surfaces", Proceeding of Graphics Interface", p116-121, 1996.

[5] Per H. Christensen "Faster Photon Map Global Illumination", Journal of Graphics Tools, 4(3):1–10. Association for Computing Machinery (ACM) 1999. .printed in April, 2000.

[6] Anton Kaplanyan, Carsten Dachsbacher, "Cascaded Light Propagation Volumes for Real-Time Indirect Illumination" Proceedings of the 2010 Symposium on Interactive 3D Graphics and Games and ACM, 2010.

[7] Alexa I. Ruppertsberg, Anya Hurlbert and Marina Bloj, "On seeing and rendering colour gradients", Association for Computing Machinery, Inc, 2007.

[8] Thomas Engelhardt, Carsten Dachsbacher, "Granular Visibility Queries on the GPU", Association for Computing Machinery, Inc.. http://doi.acm.org/10.1145/1507149.1507176, 2009.

[9] Ian Ashdown, "The Influence of Color Inter reflections on Lighting Simulations", IESNA, Leukos Vol7, no3, p159, 2011.

[10] Sik La´ nyi Cecilia, Zsolt Kosztya´ n, Bala´ zs Kra´ nicz, Ja´nos Schanda, and Mojtaba Navvab, "Using Multimedia Interactive E-teaching in colour Science", IESNA, Leukos Vol 4 NO 1, July, pp 71- 82, 2007.

[11] Navvab, M., "Modeling colour Appearance of Glazing Systems under Different Daylight Conditions", International Journal of Light and Engineering Vol:17, No# 3 92-101,30-04, ISSN 02362945, 2009.

[12] Davis W. , and Y. Ohno, "Toward an Improved colour Rendering Metric", Fifth International Conference on Solid State Lighting, edited by Ian T. Ferguson, etl, Proc. SPIE Vol. 5941, 59411G , 2005.

[13] Ohno Y.,. "Colour Rendering and Luminous Efficacy of White LED Spectra", Proc. SPIE Fourth International Conference on Solid State lighting, 5530: 88-98, 2004.

[14] Ritschel T., M. Ihrke, J. R. Frisvad, J. Coppens, K. Myszkowski and H.-P. Seidel, "Temporal Glare: Real-Time Dynamic Simulation of the Scattering in the Human Eye", Comp Graphics Forum, Vol 28, Issue 2, Apr, P183, 2009.

[15] Vos, J. J., "Colourimetric and photometric properties of a 2-deg fund.observer," colour Res. Appl. 3, 125–128,1978.

[16] Navvab, M., "Measureable Domain for Colour Differences within Virtual Environment", Jour. of Light and Engineering Vol.20, No. 3, pp. 71-81, 2012. http://um3d.dc.umich.edu/portfolio/virtual-reality-as-a-surrogate-sensory-environment/

[17] T.W. Hall, M. Navvab, E. Maslowski, and S. Petty, Book - Chapter 11 "Virtual Reality as a Surrogate Sensory Environment", Title of the Book: "Advances in Robotics and Virtual Reality", by Springer's Intelligent Systems, 2011. http://link.springer.com/chapter/10.1007%2F978-3-642-23363-0_11

[18] Inanici, M., Navvab, M., "The Virtual Lighting Laboratory: Per-pixel Luminance Data Analysis", IESNA, Leukos Vol 3, No 2 October, PP 89-104, 2006.

[19] CIE, "Colourimetry and Method of Measuring CRI", CIE 15 and CIE13.3 -1995,2004.

[20] ISO-IEC , " The Virtual Reality Modeling Language", (ISO/IEC 147721:1997). ISO, Geneva, 1997.

[21] Wyszecki, G., Stiles, W. S. "Colour Science", 2nd ed, Wiley, 2000.

[22] P. B. Delahunt and D. H. Brainard, "Does human color constancy incorporate the statistical regularity of natural daylight?" J. Vision 4 , p57–81, 2004.

[23] J. N. Yang and L. T. Maloney, "Illuminant cues in surface color perception: tests of three candidate cues," Vision Res. 41, p2581–2600, 2001.

[24] Cook, R., & Torrance, K. "A reflectance model for computer graphics" ACM Transactions on Graphics, 1, 7–24, 1982.

[25] Shafer, S. "Using color to separate reflection components", Color Research and Applications, 4(10), 210–218, 1985.

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