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► To cite this version:

Michèle Atié, Toinon Vigier, François Eymond, Céline Drozd, Raphaël Labayrade, et al.. Towards a Calibrated 360° Stereoscopic HDR Image Dataset for Architectural Lighting Studies. MM '22: The 30th ACM International Conference on Multimedia, Oct 2022, Lisbonne, Portugal. pp.19-25, 10.1145/3552482.3556554 . hal-03880569

HAL Id: hal-03880569

<https://hal.science/hal-03880569v1>

Submitted on 15 Jun 2023

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TOWARDS A CALIBRATED 360° STEREOSCOPIC HDR IMAGE DATASET FOR ARCHITECTURAL LIGHTING STUDIES

A PREPRINT

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ABSTRACT

High fidelity 360° images enhance user experience and offer realistic representations for architectural design studies. Specifically, VR and hyper-realistic imaging technologies can be helpful tools to study daylight in architectural places thanks to the high level of immersion and its ability to create perceptually accurate and faithful scene representations.

In this paper, we present a novel method for collecting and processing physically calibrated 360° stereoscopic high-dynamic range images of daylight indoor places. The future dataset aims to provide a higher degree of realism, a wide range of various luminous interior spaces supplied with information on the physical characterization of the space. This paper presents the first applications of this method on different places and discusses challenges for assessing visual perception in these images. In the near future, this dataset will be publicly available for architectural as well as multimedia studies.

Keywords image dataset · high dynamic range · omnidirectional · light studies · architecture · visual perception · virtual reality

1 Introduction

In the past few decades, immersive and hyper-realistic imaging systems such as Virtual Reality (VR) have been widely used in various domains [Heydarian et al., 2014]. The ability of immersive content to reproduce real environments allows designers and architects to better perceive, create and assess spaces during the design process. In addition, immersive environments found applications for the built environment and have been employed as a support tool for designing architectural spatial experiences [Angulo, 2015], conception, rehabilitation, and construction site organization [Bellazzi

et al., 2021]. Lately, VR has been adopted for educational purposes and showed an impact on architectural design education. Angulo [2015] proved that this technology allows students to easily understand spaces and to learn to design through the projection or simulation of the real space. One aspect that immersive systems can be valuable for is daylight. The study of daylight has been a common subject among architects, and its importance is acknowledged in current design practices. However, teaching daylight to architectural students with the help of conventional tools can be complex. Daylight changes through time and space [Bellazzi et al., 2021] which makes it difficult to perceive differences in lighting conditions for the same scene. Moreover, accessing real spaces to understand light phenomena can be logistically difficult to visit. Thus, VR and hyper-realistic imaging technologies can be helpful tools to study daylight thanks to the high level of immersion and its ability to create infinite realistic scenarios.

In this context, our interdisciplinary research project Percilum aims to study the use of immersive and hyper-realistic imaging technologies for the study of daylight in architectural design studies and education, based on a consortium of experts from architecture, light engineering, multimedia, and visual perception. Specifically, we propose to improve the perception of daylight in interior architectural spaces by offering a wide range of high realistic images of interior luminous spaces for architecture students and educators. These images should be physically calibrated and should faithfully represent reality to allow better lighting and space perception, and finally, a better understanding of the role of daylight design in architecture. Towards that, we decided to build a physically calibrated 360° stereoscopic High-Dynamic Range (HDR) image dataset of architectural places. The main objective of this paper is to present a complete methodology for calibrating, capturing, and rendering hyper-realistic indoor scenes. We will also present the first collected images together with the challenges for their perceptual assessment. Beyond studies in light design and architecture, this dataset could be useful for research in multimedia (e.g., real-time tone mapping for 360 content), visual perception, and quality of experience. In addition, the described methodology can be applied to reproducing specific environments. Studies showed the importance of realistic environments in certain fields such as museums [Carrozzino and Bergamasco, 2010], heritage buildings [Debailleux et al., 2018], simulations for specific training [Sacks et al., 2013]. Thus, our study introduces a method of image collection and generation addressing the limitations of the other experimental methodologies.

2 Related Work

2.1 Immersive and realistic content for lighting design studies

Numerous studies have simulated immersive virtual environments as a surrogate environment to the real world for the study of daylight spaces. Chamilothon et al. [2019] implemented physically-based renderings into an immersive virtual environment which provides accurate photometric data (color and specularities of surfaces) of the real scene. The measurements of materials were conducted with a spectrophotometer and were translated to the 3D model in Radiance material properties. A series of 360° HDR images were then generated. This environment, representing a simple white room, was designed in order to assess five aspects of subjective perception of daylight spaces: pleasantness, interest, excitement, complexity, and satisfaction with the amount of view in the space. Hegazy et al. [2021] proposed an immersive virtual environment by simulating a 3D model and adding physical materials on the surfaces. Textures of the real space were captured, scanned, and stitched to resemble the appearance of the real space. For the daylight setup, a single directional light source was used to simulate the sun in Unreal Engine 4.22 and was linked to the sun position plugin. This environment was built to measure daylight perception for large-scale indoor environments and collect users' preferences in terms of light.

However, to our knowledge, few works introduce physically-based photography in virtual environments for the study of daylight spaces. Cauwerts [2013] studied the influence of representation mode on the perception of daylight scenes in virtual environments. Participants were asked to assess the scenes according to spatial and light attributes [Cauwerts and Bodart, 2013]. The author tested four presentation modes of images (2D, panoramic, 3D, and HDR) and compared them to real-world perception. The results show that panoramic mode is the only mode that allows studying the dimensions influencing the appearance of lighting. For this study, panoramic images were generated using conventional lenses, which require several shots. The camera was positioned vertically and was rotated every 30 degrees. For each exposure time, multiple images were stitched into several images using PTguiPro and then merged into a single HDR using Radiance software. The HDR images were calibrated using luminance values measured in the real room. The author worked with global and local operators, and the relative error between real-world luminances and tone-mapped luminances was determined at each pixel in order to minimize the mean relative error. This technique encountered some problems in merging some adjacent pictures due to software and technical limitations at that time. In addition, the image did not cover the total vertical field of view of the scene but only 66°. Rockcastle et al. [2021] compared the perception of a dimmable lighting system between real and virtual space. 360° HDR images were captured and calibrated. A luminance meter was used to take physical measurements of grey and white cards placed on the walls of the room. The HDR images were calibrated to the grey-card measurements using Photosphere software and calculated

the error between grey and white cards. The images were then tone-mapped using classical operators. However, given the nature of the camera and its rotational capture, the author couldn't create the stereoscopic mode for the visualization in the Head Mounted Display (HMD). In this study, the author evaluated the ratings of visual comfort, pleasantness, evenness, contrast, and glare of participants. They were asked to rate lighting conditions in real space or in HDR immersive photographs displayed in HMD. In the end, the author found that dim, high contrasted scenes or scenes with glare are not reproduced faithfully in the HMD. The author recommends improvement and optimization of (TMOs) for the headset. Other authors introduce a step-by-step procedure to generate 180° HDR imaging from a sequence of multiple exposures, selecting the useful images and merging them into an HDR by using the response function of the camera Pierson et al. [2021]. However, this study may not be adapted to 360° images and does not integrate the stereoscopic mode.

2.2 HDR and 360° image datasets in multimedia

Several 2D HDR image datasets have been published in the multimedia and image processing community [Fairchild, 2008, Emp, 2020, Narwaria et al., 2012]. However, most of them do not include any physical measurements for calibration. Fairchild's dataset is, to our knowledge, the only one with colorimetric or luminance points of reference in the 2D scene [Fairchild, 2008]. These datasets have been widely used for assessing the quality of the HDR and the tone-mapped images for multimedia applications which can differ in content and perceptual aspects to our goal [Yeganeh and Wang, 2013, Krasula et al., 2014, 2017].

To our knowledge, only one 360° HDR dataset has been published [EPFL, 2017]. This dataset has been used for assessing the quality of tone-mapped images [Perrin et al., 2017]. In this work, only static tone-mapping operators were used. More recently, real-time operators have been proposed with light adaptation to HMD viewports [Goudé et al., 2020].

Simulations have often been preferred for light studies in architecture. However, they are time-consuming, leading to very few represented spaces. The use of HDR photographs and, more specifically, HDR panoramas was proved to be efficient for this purpose. However, a larger variety of immersive, hyper-realistic content is still required. Moreover, the existing HDR datasets used in multimedia are too rarely calibrated. Therefore, we decided in this project to build a new calibrated 360° stereoscopic HDR dataset of daylight indoor scenes. To our knowledge, this dataset will be the first to combine all these new imaging technologies.

3 Method

This section aims to present the method used for collecting calibrated 360° stereoscopic HDR images of interior spaces. It mainly consists of three steps: the selection and physical characterization of iconic and ordinary interior spaces (Section 3.1), the content acquisition and calibration workflow (Section 3.2), and the rendering process (Section 3.3).

In this section, we describe our general method that can be replicated in different spaces. We will present the list of devices and built-in software that we use. However, this method can be replicated with different kinds of equipment.

3.1 Identifying daylight architectural places

3.1.1 Selection of places and points of view

Natural light is at the center of architectural concerns, and it does not receive the same attention from all architects. In order to focus on daylight design, the shot scenes must be nearly devoid of artificial light. We include two types of architecture in our study: remarkable buildings and ordinary places. Considering iconic architectural places, the chosen projects must be identified as architectural references. Specifically, we focus on architectural projects built by well-known architects that have made light one of their main topics and in which the treatment of natural light is an important and explicit concern. Ordinary places represent rooms or buildings constructed by less known architects but in which natural light plays a crucial role, mainly for specific activities (e.g., offices, classrooms,...).

At each place, one or several shooting points can be taken based on light and spatial properties (homogeneity, contrast...) as well as the usages of the place in question.

3.1.2 Physical characterization of places

We then physically characterize the natural lighting of each place. First, we conduct illuminance measurements on a regular grid on the floor level. These measurements are used to determine the daylight factor of the space. This factor is used by architects to assess the lighting levels in interior spaces, determine whether the light is sufficient for occupants

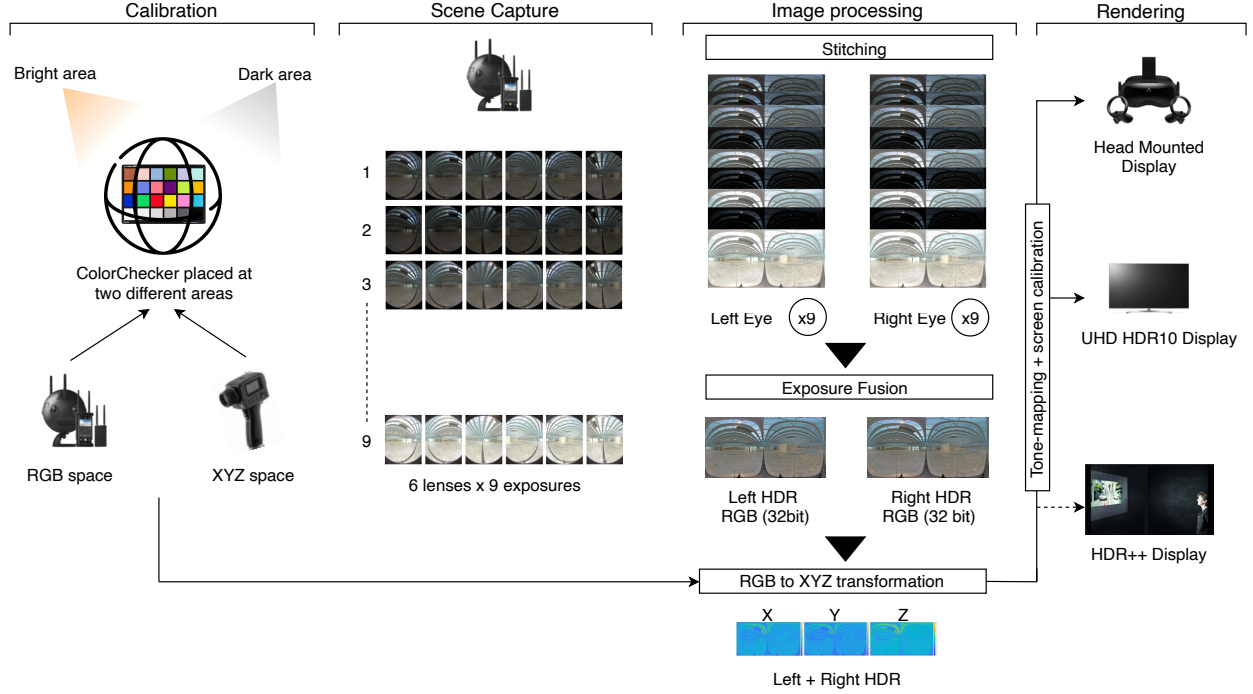


Figure 1: Content acquisition workflow of 360° stereoscopic HDR image

to carry out normal activities or not, and provide comfortable conditions. The transmission coefficients of the glazing surfaces and the reflection coefficient of the wall surfaces are also collected. This information characterizes the physical aspects of the light and helps researchers qualify the luminous atmosphere.

3.2 Content acquisition

In the second part of our method, we will present content acquisition. Figure 1 shows the summary and the process of content acquisition workflow.

3.2.1 Camera and 360° stereoscopic HDR image calibration

In order to achieve the best realism and to be able to assess physical and perceptual differences between real and rendered scenes, we conduct an accurate colorimetric calibration. In previous works, calibration of HDR photographs was mainly limited to brightness measurements, whereas color accuracy is also crucial in the visual perception of light scenes [Cauwerts et al., 2019]. In this study, the principle of the colorimetric calibration is based on color measurements, in XYZ and RGB spaces, of the cases of a ColorChecker directly in the final scene of the dataset. The ColorChecker must be placed under homogeneous illumination. Since the camera sensitivity and response can vary for different light levels, we run two steps of calibration in two different areas of the captured scene, a bright and a dark one, leading to 42 color points of reference.

In this study, we work with Insta360 Pro2¹, a professional 360° camera which integrates six fisheye lenses and a Konica Minolta Chroma Meter CS-160. The left image of Figure 4 presents the calibration in a bright area for one capture. In order to have a resolved image of the ColorChecker in the final 360° image and for the robustness of measurements, it is positioned approximately 2 meters away from the camera in front of the same lens. This calibration allows transforming the HDR RGB image into physical XYZ color space. This transformation is based on a barycentric interpolation inside RGB tetrahedrons obtained with a Delaunay triangulation of the complete RGB gamut for the 42 color points of reference. Figure 2 presents the Delaunay triangulation of the RGB space for one scene as well as the corresponding partition of the XYZ space.

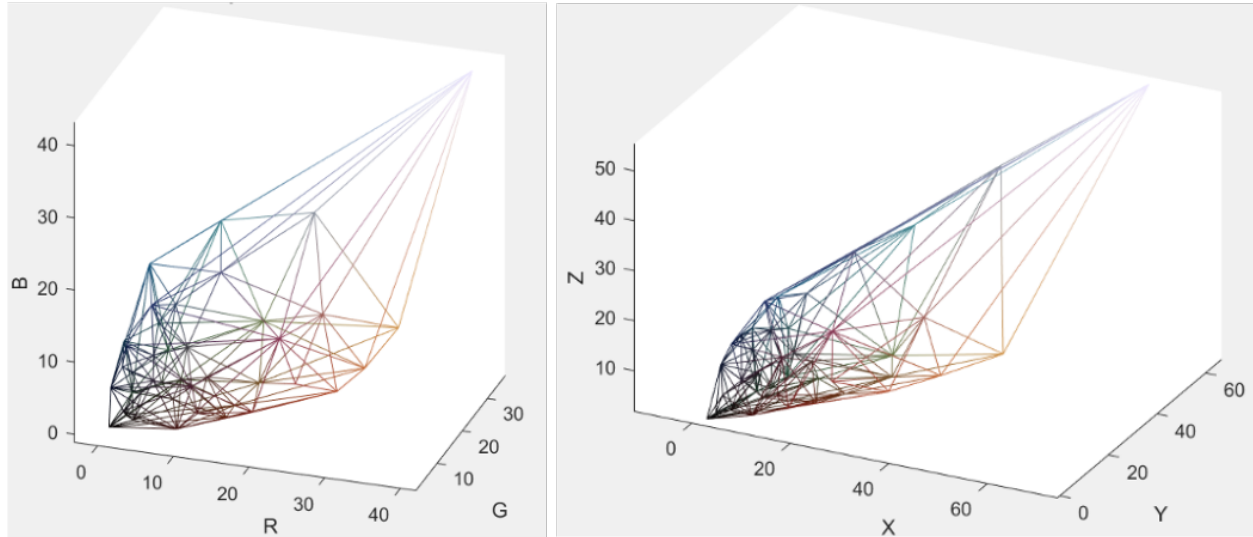


Figure 2: On the left figure, the RGB color space, on the right figure, the transformation of the image into XYZ space.



Figure 3: Application of two different tone-mapping operators on the same HDR reference (Reinhard TMO on the left image and Durand TMO on the right one).

3.2.2 360° stereoscopic HDR image captures

This next step consists in capturing 360° stereoscopic HDR image.

In our study, stereoscopic 360° images are captured by the Insta360 Pro2 camera. This camera captures stereoscopic equirectangular HDR images at 8K resolution with a 3D dynamic range of 30 f-stops. 9 different exposures are captured for each scene. The left and right equirectangular images for each exposure are generated offline with the embedded software of the camera, avoiding the necessity to acquire two viewpoints successively with possible light changes. In our setup, the camera is positioned approximately 1.7m from the ground level to simulate a standing visualization. In order to limit possible light changes during calibration and content acquisition, the shooting is done directly after the calibration phase.

3.2.3 Stitching and merging

For each exposure and each eye, we stitch the six fisheye images corresponding to the six lenses into a single 8K image in equirectangular projection format. The stitching can be done with the embedded software of the camera (Insta360 stitcher) or any other specific software. Then, for each eye, the nine low-dynamic range exposure photographs are merged into a single HDR picture. In this project, we test and compare different free and commercial software (e.g., Photosphere, Aurora) as well as Matlab function (e.g. *createhdr* in Image Processing toolbox) to fusion exposure images into HDR one. HDR images are originally stored in 32 bits .hdr format. They can also be exported in TIFF or JPEG 16 bits.

¹<https://www.insta360.com/fr/product/insta360-pro2>



Figure 4: 360° HDR images of "Le Pavillon de verre", Louvre-Lens, SANAA. On the left, colorimetric calibration; on the right, one final capture for a specific viewpoint.

3.3 Rendering

3.3.1 Display calibration

In this project, three main types of display are targeted. VR-HMD allows being completely immersed in the stereoscopic 360° environment leading to a better perception of the spatial quality of the architectural space. However, they have a low dynamic range and intermediate resolution, which can reduce the final perceived quality of light effects. UHD-HDR10 are consumer-grade TV screens with quite high quality of rendering and capable of displaying 10-bits HDR image until 1000 nits. Finally, a unique experimental HDR display with a high dynamic range of up to 30 000 nits is also tested in this study. For 2D screens, either a specific interesting viewport can be extracted from the 360° image, or users can freely choose where they look at with a mouse device.

In order to control the complete processing and rendering chain of the visual content, we calibrate the final displays with a colorimeter or color calibration device such as SpyderX. For HMD, we follow the methodology described in Mehrfard et al. [2019] which consists in applying the device directly at the center of each lens. A first test was conducted in an HTC Vive Focus 3, resulting in brightness measurements between 0.18 to 77.5 cd/m².

3.3.2 Tone-mapping

Tone-mapping is a crucial step in displaying HDR images on standard displays. In this study, we use different types of tone-mapping operators (TMO), such as classic (global or local) tone-mapping, real-time tone-mapping, and physical optimization of tone-mapping.

Classic TMOs can be applied directly on the complete 360° equirectangular images before rendering or on specific extracted viewport from these images (for 2D visualizations). Different tools can be used for tone-mapping, such as pfstools which integrate well-known tone-mappers from the literature or commercial photo editors (e.g., Aurora or Adobe Photoshop). In order to deal with stereoscopy while tone-mapping the content, different techniques can be tested, such as technique Akhavan and Kaufmann [2015]. Real-time tone-mapping operators are dedicated to the visualization of 360° HDR in HMD [Goudé et al., 2020]. This operator enhances the contrast of each viewport while preserving global coherency. Finally, thanks to the physical calibration of the scenes and displays, tone-mapping operators will be optimized in future work to preserve contrasts and brightness in the scene rendering in order to achieve the best perceptual fidelity.

Figure 3 represents the same HDR scene in Louvre-Lens museum tone-mapped with two different classic operators.

4 Results and future works

4.1 Preliminary results

In this section, we present the first images of the dataset obtained with the proposed method. It was firstly conducted in two spaces in the "Louvre-Lens Museum", France, and in different classrooms.

4.1.1 Louvre-Lens museum

This study was conducted in the "Galerie du temps" and "Pavillon de verre" of the Louvre-Lens Museum in France. This building was designed by SANAA agency, well-known for their specific treatment of natural light. The two places



Figure 5: 360° HDR images of a classroom for different lighting conditions.

deliver two different luminous atmospheres. "Galerie du temps" is a clear large area with zenithal lighting. The walls are coated with an aluminum skin leading to a fuzzy, blurry, and ethereal atmosphere. "Pavillon de verre" is a smaller area with a very large glazed window leading to a more contrasted atmosphere. Figures ?? and 4 shows the scenes captures in the "Galerie du temps" and in the "Pavillon de verre" respectively.

4.1.2 Classrooms

This method was also tested in a co-working ordinary building. Different rooms were selected, and scene captures and measurements were conducted over several days. One single room was captured for different daylight conditions as presented in Figure 5.

4.2 Challenges for Perceptual Evaluations

One of the challenges of this project is to assess visual perception and subjective impressions of daylit architectural places for different viewing conditions in order to optimize rendering considering physical and light characteristics of the spaces, architectural intentions, as well as subjective experiences lived in the real places. Indeed, TMO has a strong impact on the perception of the global scene in terms of visual quality but also on the aesthetic and natural aspects as well as on the visual attention [Aydin et al., 2015, Krasula et al., 2014, 2019, Narwaria et al., 2012]. Thus we intend to define criteria in order to deliver the most faithful visual experience in each scene and each display. To our knowledge, few studies [Yoshida et al., 2005] compared tone-mapped images with real-world references.

Towards that, different subjective experiments will be conducted in the near future to compare visual perception and subjective impressions of luminous atmospheres in real spaces and rendered images. In addition, the adequacy of the immersive tools will be tested on architecture students during their conceptual design process. Different methodologies of evaluation will be used based on qualitative interviews and quantitative questionnaires, and a comparison of visual behavior with head and eye tracking will be measured. One issue is to avoid light changes between subjective assessment of the real spaces and content acquisition.

5 Conclusion

We have presented a novel method for collecting and processing a large realistic dataset of indoor environments supplied by the physical characterization of these scenes. We provided preliminary results of the application of our method on an iconic architectural space, "Louvre-Lens Museum" in France, and ordinary classroom spaces. This work is an important step toward improving education and perception in architectural studies. In the future, we will continue to replicate this method on different architectural spaces. The final dataset will be publicly available for all researchers and will be tested for light perception experiments in future work.

Acknowledgments

The authors thank the "Agence Nationale de la Recherche- ANR-19-CE38-0010" for the financial support of this project. In addition, the authors wish to thank master students Léa Barthélémi and Rosa Olloghe Mandoukou for their help in the application of the method and the collection of the data.

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