ABSTRACT

As architectural design methodologies focus increasingly on the production of dynamic form, the means to actuate these forms, the input that fuels parametric processes, analytical form-generating techniques and responsive controls is of primary concern. In the virtual test beds where systems are developed, inputs are often ad-hoc, based on crude assumptions of the environment, or disconnected from the physical environment entirely. Inverting a technique originally developed to illuminate virtual objects with light captured from real (physical) environments, this project explores image-based lighting as a means of detailed environmental light sensing. The objective of the project is to demonstrate the application of High Dynamic Range (HDR) image data acquired continuously in the physical world as signal input to inform, actuate and evaluate responsive solar control and daylighting systems. As a proof of concept, a virtual hemispherical dome consisting of 145 apertures is controlled to respond in real time to continuous image-based measurements of sky luminance, seeking a defined set of daylighting and solar control objectives. The paper concludes by discussing the implications of incorporating real-world environmental data in the development of dynamic form.
1. INTRODUCTION

There might be no more radical idea for our discipline than that of employing continuous measurement to produce works of architecture that can change autonomously. These works will bind measurement (in the form of analysis) directly into the fabric of our buildings. Such buildings will challenge not just the design methods we use, but also the very concept of what a building can be. In effect, this move translates building systems into robotic architectural media.—Tristan d’Estree Sterk, 2009.

1.1. FROM STATIC FORM TO DYNAMIC FORM

As architectural design methodologies focus increasingly on the production of dynamic form, the means to actuate these forms, the input that fuels parametric processes, analytical form-generating techniques and responsive controls is of primary concern. Put in an ecological context, dynamic forms are sought which can more effectively sense and respond to local environmental conditions to utilize environmental services available from natural systems such as daylight, solar thermal energy and natural ventilation. To mediate between the environment and building users, in order to minimize energy and enhance indoor comfort, building systems must develop the capability to continuously monitor and respond to the physical environment. However, environmental inputs are often ad-hoc, based on crude sensor data, crude models of the physical world, or disconnected from the world entirely. Developing environmentally responsive dynamic form first requires effectively capturing the detailed information available from the physical world.
1.2. FROM VIRTUAL ENVIRONMENTS TO PHYSICAL ENVIRONMENTS

In the virtual test beds where design processes are increasingly based, crude assumptions of the physical world are likely to lead to crude outcomes. This research seeks to bridge the divide between virtual environments and the physical world where designs are expected to perform. A number of efforts have emerged in the past several years to establish bridges between virtual and physical environments (Banzi and Cuartielles 2005; Payne and Johnson 2010). Efforts driven by cinematic arts have engaged in bringing the physical into the virtual through Image-based Lighting (IBL). Image-based lighting uses a High Dynamic Range (HDR) image of the physical environment as a light source to illuminate a virtual object or scene (Debevec 1996). Figure 1 and Figure 2 present examples of techniques for capturing physical lighting data for use in virtual environments. Figure 1 shows the use of a chrome sphere to generate a “light probe” image, an omnidirectional High Dynamic Range (HDR) image that captures the color and intensity of environmental light for a particular point in space (Debevec 1998). Figure 2 shows the use of a 180-degree equidistant fish-eye lens, which captures a hemispherical view oriented vertically. Figure 3 presents the application of four hemispherical light probe images used to illuminate a simple chrome sphere on a red plastic pedestal using the lighting software system Radiance (Ward 1994).

This project seeks to capture and present the often complex nature of environmental light as a means to enable the development of responsive forms carefully tuned to transient site-specific lighting conditions. A further objective is to enable a more representative virtual setting to test and evaluate environmental outcomes and system behaviors.

Rendering of a virtual object by four distinctly different physical light sources

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2. METHOD

2.1. WIRING TO THE SKY

Conceptually, the project presents a virtual hemispherical form wired to respond dynamically to a real, physical sky. Inverting the IBL technique originally developed to illuminate virtual objects with light captured from real (physical) environments, this project explores IBL not as a means to render a digital scene, but as a means of environmental sensing. The project demonstrates the application of HDR image data acquired continuously in the physical world as signal input to inform, actuate and evaluate responsive solar control and daylighting systems. As a proof of concept, a virtual hemispherical dome consisting of 145 unique apertures is controlled to respond in real time to continuous measurements of sky luminance and distribution, seeking a defined set of daylighting and solar control objectives. The behavior of the virtual space is presented in time-series images showing a view from within the dome over a subset of daily sky conditions.

2.2. SKY IMAGING

Recording physical lighting data from the sky is achieved in this project using an HDR-enabled camera combined with a hemispherical 180 degree fish-eye lens as a sky scanner. High Dynamic Range images store luminance data on a “per-pixel” scale, enabling the analysis of an arbitrary number of predefined regions within the camera’s field of view. In computer graphics, the original HDR format (Radiance RGBE) was developed for the lighting simulation engine Radiance to record the photometric conditions of synthetic lighting environments. In following years, techniques were developed to produce HDR images from real-world scenes (Debevec 1997, Mitsunaga and Nayar 1999) by compositing multiple exposure-bracketed Low Dynamic Range (LDR) images (for example, JPEG) into a single HDR image. Motivated by the possibility of using HDR in real spaces for photometric analysis, methods are now available to produce calibrated HDR images (Inanici 2004), referred to as luminance maps. To explore the applicability of environmental sensing using HDR, a physical site was selected that presented highly variable sky cover conditions. A rooftop site in Portland, Oregon (latitude = 45.5° N, longitude = 122.6° W) was used to monitor and record transient changes in sun and sky conditions vertically over the full sky hemisphere.

2.3. HDR IMAGE ACQUISITION AND POST-PROCESSING

Figure 4 presents a schematic view of the image acquisition procedure used to acquire and utilize HDR sky images. Exposure-bracketed sets of LDR images were acquired continuously from sunrise to sunset using an HDR-enabled digital CCD camera aimed vertically to view the celestial hemisphere. A firmware modification (SDM 2013) was used, enabling precise control over a wide range of camera features automatically. Each bracketed set of images was composited into a calibrated luminance map of the sky, where each pixel corresponds to a physically accurate measurement of sky luminance. Each luminance map was then post-processed using Radiance commands to reduce the data collected to a resolution suitable for signal input to a realistic number of individual apertures. As a first iteration, the celestial hemisphere was subdivided into 145 segments. Using HDR data enables the creation of an arbitrary number of apertures with arbitrary size and boundary. The number, size and boundaries chosen for development in this paper closely follows the concept of daylight coefficients (10), where the contribution of light from each sky segment to an interior point can be controlled to produce a specific lighting condition. The result of image processing is 145 unique luminance signals, which capture the variability in light intensity over the course of the day and enable granular control of an equal number of apertures to deliver a specific lighting condition at the center of the hemisphere. Discussion of the model used to control each aperture in response to the sky signal is provided in Section 3.2.

3. APPLICATION

3.1. DYNAMIC LIGHT

In application, dynamic form requires both appropriate environmental signals and established goals or objectives to seek within a range of possible outcomes. In many instances, projects with high spatial resolution across control surfaces lack the equivalent granularity in signal from the environment to operate individual controls independently or appropriately. For example, a façade with multiple windows may control all shading systems in response to input from a single exterior light sensor (for example, global vertical illuminance on the façade), despite the significant variation in sky luminances from each individual window view. Even with spatially and temporally rich environmental information, it still remains unclear what to do with this information to serve environmental performance objectives. Although daylighting design criteria and illumination engineering recommendations are plentiful, this guidance is primarily focused on establishing minimum illuminance thresholds or homogeneous lighting conditions throughout a space, and less applicable to guide control of light in response to instantaneous, daily or seasonal variation. Figure 5 presents a summary of sky-imaging data showing the overall change in the magnitude of sky luminance (cd/m2) as well as the dynamic range in sky luminances across the day (note log scale on y-axis). When considering continuous response to changing environmental conditions, the challenge is not only in creating the lighting condition but in establishing an intuition for how a condition or pattern should be allowed to vary over time in response to exterior signals and interior environmental needs or performance objectives.
3.2. RESPONSIVE APERTURES

The concept of a dynamically responsive enclosure was explored by constructing a hemispherical dome from 145 plant-like shading devices (Figure 6). Each device consists of a collection of multiple “petals,” each modeled as a translucent diffusing material (diffuse trans. = 0.21, specular trans. = 0.21, diffuse reflection = 0.2, specular reflection = 0.37). Apertures for direct transmission of beam radiation and diffuse light are created by the void area between adjacent apertures. The void area size is regulated by the number of petals deployed by adjacent apertures at a particular time. As sky luminance increases, an increasing number of petals are deployed, leading to a decrease in void size and an increase in translucent petal layers, which work to screen an increasing fraction of incident light.

3.3. SIGNAL PROCESSING AND CONTROL

Figure 6 presents a daily profile for all sky luminance signals for measurements taken on 10/19/2011 from 8:00 to 18:00 and demonstrates the response of a single shading device to threshold changes (red) in sky luminance (green line). The thresholds were chosen based on a simple control objective to limit view of the sky from within the dome to a maximum luminance of 7000 cd/m2. This assumption enables continuous view to blue sky (luminances consistently < 7000 cd/m2), while increasingly screening interior views to bright clouds (> 7000 cd/m2) and direct view of the solar disc. In concept, this simple control strategy enables maximum transmission of glare-free daylight to a specific interior zone, while maintaining solar control for visual comfort and to restrict solar overheating. The control strategy presents an interior view from the dome viewing the sky over a sub-set of daily changes in sun and sky conditions (Figure 7).

Determining the accuracy and precision of the control strategy is dependent on both the quantitative and subjective criteria established for evaluating performance. Future work for this project involves additional iterations to characterize the consistency of daylight illuminance delivered to the ground plane as well as the visual comfort conditions experienced from a range of interior viewpoints. Beyond assessing these quantitative outcomes, this work seeks to enable real-time user experience of (and feedback on) context-aware responsive architectural “performances,” visualized with photometrically accurate lighting conditions.
3.4. INFORMATION, ACTUATION, AND EVALUATION

The project presents a methodology for actuating a virtual object with continuous image-based physical lighting data. When implemented as a physical project, the methodology offers several benefits over systems where each aperture is controlled independently by a unique photosensor. The first is that a luminance map capturing the celestial hemisphere enables the response of dynamic systems to be informed from detailed awareness of patterns in sky cover, spectral quality, luminous intensity, and luminance distribution with per-pixel granularity. In contrast, a photosensor produces a single illuminance value and is incapable of discerning color or luminance distribution across its field of view. As a result, illuminance sensors are limited in applicability for sensing visual scenes that include the large luminance contrasts common in day-lit environments. Although a large number of photosensors can be deployed to improve the resolution of light sampling, the cost, maintenance, and calibration of photosensors capable of responding accurately to the broad dynamic range of outdoor lighting conditions is likely to be cost-prohibitive for many projects. Second, individual photosensors mounted on the exterior result in an “open-loop” control model, where façade apertures manage interior lighting conditions with no feedback on the actual conditions being produced by their actions or that of their peers. A luminance map describing the exterior luminous environment can be used in model predictive control as a light source to simulate and assess the indoor luminous environment experienced by building occupants in real time and issue coordinated actions among all apertures to refine these conditions without the need for any interior physical measurements. In other words, image data feeds the software simulation with context to evaluate and respond in real time.
4. CONCLUSIONS

What can be learned from this approach for exploring the development of dynamic form? Several topics are worth considering. First, from an environmental perspective, Image-based Lighting enables daylighting and solar control systems to be carefully tuned to site-specific lighting conditions during design, allowing for precise exploration and evaluation of the spectral, spatial, and transient nature of light. However, establishing appropriate assumptions for the control and distribution of light over dynamic daily and seasonal patterns presents a new set of design considerations emblematic of autonomous architecture. The need to respond to continuously changing information places the designer in the position of developing an interactive experience in parallel with a dynamic system. What are the appropriate internal lighting conditions? What physical thresholds should be established to achieve these conditions? Should the goal of responsive systems be to parse the dynamic attributes of natural phenomena to produce a homogeneous and predictable interior environment? These questions shed light on the need to develop rich descriptions of program and end-user experience to inform and establish boundaries and objectives for dynamic behavior. Establishing confidence in the interaction between environment and building, and building and user, is aided by the approach demonstrated through the feedback enabled from trialing behavior in response to environmental data that preserves the spatial detail, spectral richness, physical intensity, and transient nature of light from the sky. By bringing the transient physical conditions of the physical world into virtual test beds, the logic developed to drive dynamic form can be refined through a feedback loop between design and the physical environment.
WORKS CITED


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