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Natural Rhythms and Temporal Perception: Visualization of Sunlight Patterns with Energy Monitoring

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Abstract

The research merges architectural design, lighting technology and BIPV to demonstrate a proof-of-concept for the reintroduction of natural rhythms into built environments. My design proposes skylights that combine PV-integrated glazing with indirect skylight well LED lighting to achieve conditions that stimulate the occupants of a selected space while connecting inside to out. Expanding on preset protocols used in recent dynamic lighting research, I created natural protocols with variable light intensity and color generated from recorded building integrated photovoltaic (BIPV) monitoring data. The generated protocols were used to control an interior dynamic lighting system introducing a temporal stimulus into the space. The effect of the LED skylight well lighting was compared with the sunlight entering through the skylights using quantitative numeric analysis methods and qualitative visual comparison tools including time lapse photos and videos. A long term study is proposed to better understand and confirm the results and also gather additional user feedback evaluating the intended effect of the dynamic lighting system.

Keywords: *Dynamic lighting, natural rhythms, PV-integrated glazing, Energy monitoring*

1. Introduction

In his book *Ritual House*, Ralph Knowles states, "The houses we inhabit, the cities surrounding our houses, even the clothes we wear – all are shelters we erect against the elements. But they are also manifestations of ancient rituals, developed in response to nature's rhythms." (2006) Implicit within this quote is the importance of nature's rhythms in our lives, particularly those related to the movement of the sun. Many built environments have no daylight or connection to the exterior. Those who work in these spaces are disconnected from these natural rhythms and often experience detrimental physiological effects, particularly if they work irregular hours or at night. However, technologies such as LED lighting and building integrated photovoltaic (BIPV) panels have the potential to reintroduce aspects of natural rhythms into built environments. In addition to collecting renewable energy, a BIPV panel can be considered a recorder of variations in solar radiation.

My research crosses disciplinary boundaries separating architecture, engineering, psychology, and building science. My findings inform the design of an architectural intervention for a multidisciplinary workspace at Virginia Tech, called the Sandbox. I propose to introduce skylights with PV-integrated glazing and indirect LED well lighting. During the day, I used BIPV energy monitoring to record variations in solar radiation which at night play back through intensity and color variations of LED lighting to reestablish a connection to natural rhythms. Instead of preset protocols used in recent dynamic lighting research, I created varied natural protocols for interior lighting controls using recorded data. In this way, the skylight glazing becomes a sensory skin. The research merges architectural design, lighting technology and BIPV to demonstrate a proof-of-concept for the reintroduction of natural rhythms into built environments.

2. Dynamic Lighting

The positive effects of daylight on spaces for working and learning are widely acknowledged and designers have access to comprehensive design strategies for proper daylighting in a space. Although there has been research conducted on potential positive effects of dynamic electric space lighting, variation in intensity and color temperature similar to daylight is much less recognized and comprehensive (De Kort & Smolders, 2010). However, research in the field indicates that a balanced combination of daylight and dynamic artificial light contributes to the physical and psychological well-being of human beings in work and learning environments (Begemann, Van den Beld, & Tenner, 1997).

Even though De Kort's and Smolders' study did not find the desired measurable positive effects related to office workers' performance and health, the participants of the study expressed a significantly higher satisfaction with a dynamic lighting scenario with variable illuminance and color temperature. This points to a perceived positive phenomenological effect of the dynamic lighting condition. The goal is to examine the potential of dynamic lighting as a tangible phenomenon by replacing the pre-set protocol of the mentioned study's dynamic lighting with a protocol generated by a natural pattern in an immersive case study.

3. Immersive Case Study

3.1. Documentation of the Sandbox workspace at Virginia Tech

The Sandbox is a student project workspace used by the Institute of Creativity, Arts, and Technology (ICAT). I selected this space for the intervention and documented it by creating a 3-dimensional CAD model (dimensions of space, location of mechanical equipment) which was generated from available construction documents in PDF format, diagrams mapping light levels and estimated surface reflectance levels (established using Extech LT300 light meters), and an estimate of the light color temperature (using a color temperature meter app), as well as photo documentation of the surface textures. The illumination in the center of the room and the color temperature of the space lighting were measured at 540 lx and 4100K respectively.

Fig. 1: Lighting condition in the Sandbox workspace at ICAT

3.2. Project Design

The case study includes three project components designed to record natural sunlight patterns, translate the recorded patterns to lighting protocols, and visualize the protocols for evaluation.

Recording unit - To record sunlight intensity patterns I installed an experimental setup at Virginia Tech's Research and Demonstration Facility. The sunlight recorder included a 77W photovoltaic panel mounted on an adjustable substructure, a dynamic resistive load drawing the maximum available power depending on solar radiation, and a modified monitoring system to record the energy production over time.

Translation unit - The recorded intensity patterns were translated to protocols for the dynamic lighting system considering perception (variation in brightness and color temperature) and climate (sunny and cloudy days, steady and volatile light intensity variation). A parametric design tool (Grasshopper) was used to generate intensity and color maps for dynamic lighting protocols. I created a Python program which translates this information into color and intensity protocols to control the skylight's integrated electric lighting.

Playback unit - I used a physical model of the Sandbox to create visualizations of the daylight entering through the skylight and the electric light patterns created by the color and intensity protocols. The current space lighting of the Sandbox was simulated with warm and cool white 5mm flat top LEDs. The skylight wells were illuminated with 5mm RGB LEDs which are connected to a Raspberry Pi computer and dimmed via pulse width modulation (PWM).

The purpose of the project is to use BIPV as a solar insolation recorder throughout the day, process the recorded data, and "play it back" through temporal LED light intensity and color variations in the Sandbox.

Fig. 2: Sandbox study model (scale 1:32)

3.3 Time Lapse Studies

For the purpose of this thesis project I selected a method which allows me to quickly evaluate the visual effect of daylight and LED light patterns and use the feedback to update the design of the dynamic lighting protocols. I placed a small digital camera in the physical model to record time lapse photos and videos. The camera's white balance is set to a fixed value of 4000K matching the color temperature of the current lighting in the real space. First I placed the model next to the PV panel on the roof of the test cell building to record photos for a full-day sunlight time lapse study. The translated monitoring information of the PV panel from the same day was then used for a second recording where the model was placed in a dark space. This recording created photos for a time lapse study of the LED lighting protocol. The photos were used to compare the sunlight patterns with the LED lighting patterns applying quantitative and qualitative methods.

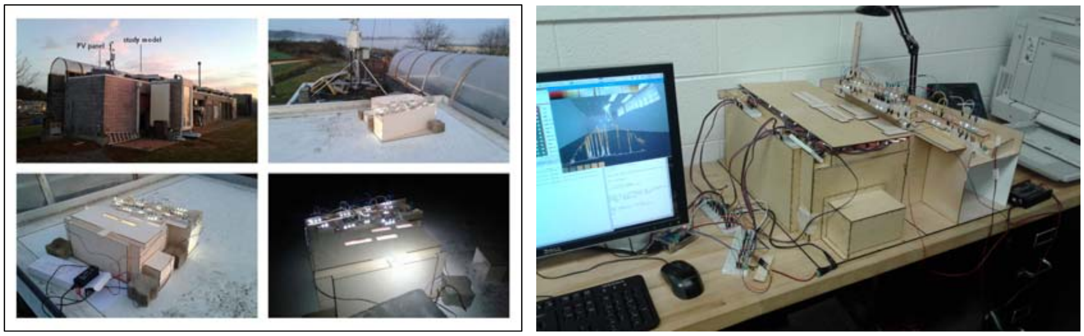

Fig. 3: Time lapse setups for sunlight studies (left) and dynamic LED lighting studies (right)

4. Results and Evaluation

To verify that a BIPV panel can be considered a recorder of variations in solar radiation I compared the power levels of the PV panel with the light intensity levels of a pyranometer by plotting the levels as graphs over time. The curve characteristics of the graphs were very different for various weather conditions. The comparison showed a very close correlation between the PV current and voltage levels (blue & red) and the light levels recorded by the pyranometer (black).

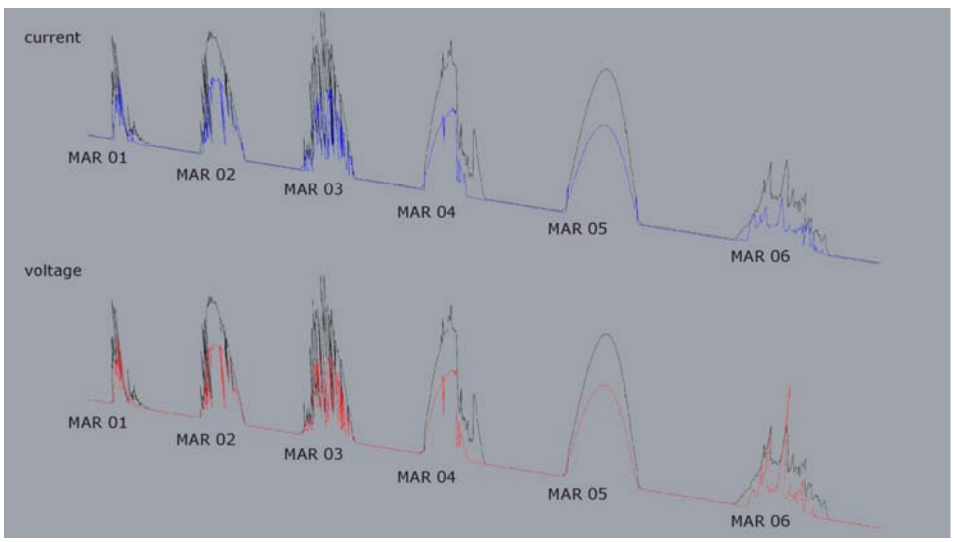

Fig. 4: Curve characteristics dependent on different weather conditions

The quantitative evaluation of the sunlight and LED light patterns was carried out by an automated RGB value analysis of selected pixels in the recorded photos. The analysis program compared the pixels' RGB values of the selected area in each photo with the values of the same pixels in the successive photo and saves all values as a list of "pixel variations" which indicate magnitudes of difference in color, brightness, or a combination of the two. The list values are then plotted as a graph. There were two important findings: the fluctuation of the PV power correlated with the fluctuation of the sunlight, and the magnitude of the LED lighting pixel variation was only slightly lower than the magnitude of the pixel variation caused by the sunlight. This can be adjusted by changing the LED lighting control protocol via increased light color and brightness.

The fluctuation correlation (PV power and sunlight) and the similarity in magnitude (LED light and sunlight) can be observed in Fig. 5.

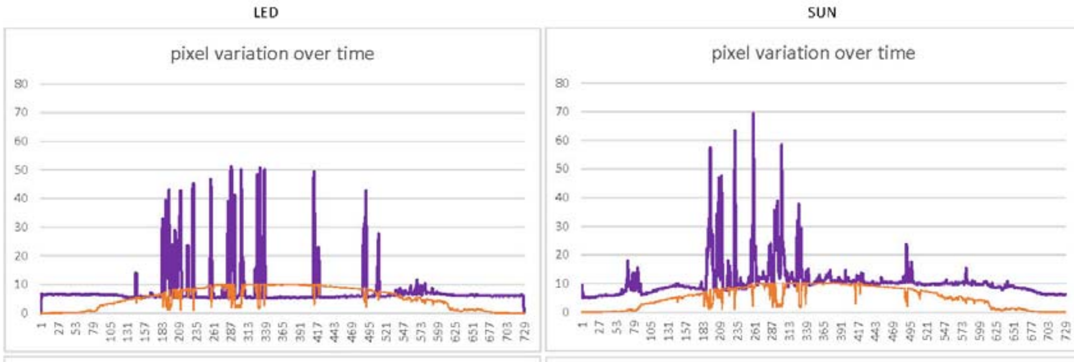

Fig. 5: Plotted pixel variation values (purple) and PV power levels (orange)

For the qualitative evaluation, I created time lapse videos using the recorded photos. The videos of the LED lighting recording and the sunlight recording were played on the screen side by side simultaneously. The eye of the researcher was used as a measuring instrument for a visual comparison. The visual evaluation revealed a close correlation between the time based fluctuation of the daylight and the LED light which can also be observed quantitatively in the plotted graphs. The visual comparison of different color patterns showed that the visual effect of a sky color scheme (cool colors for low PV power and warm colors for high PV power) was similar to the effect of direct sunlight entering through the skylight. The visual effect of a sunlight color scheme (warm colors for low PV power and cool colors for high PV power) which is meant to simulate the light colors during sunrise and sunset was not similar to the direct sunlight's effect. The reason why the LED color scheme based on the sunlight color temperature was not similar to the observed direct sunlight falling into the model might be caused by the design of the skylights. The depth of the skylight well is large enough to prevent low direct morning and evening sunlight. This reduced the impact of the direct sunlight and raised the impact of the diffuse light from the portion of the sky above the skylights. The color temperature of the sky's diffuse light is cooler in the mornings than during the day. This observation could not be made quantitatively.

A selected demonstrative time lapse video can be viewed online: https://youtu.be/Nj_KqhQdGbA

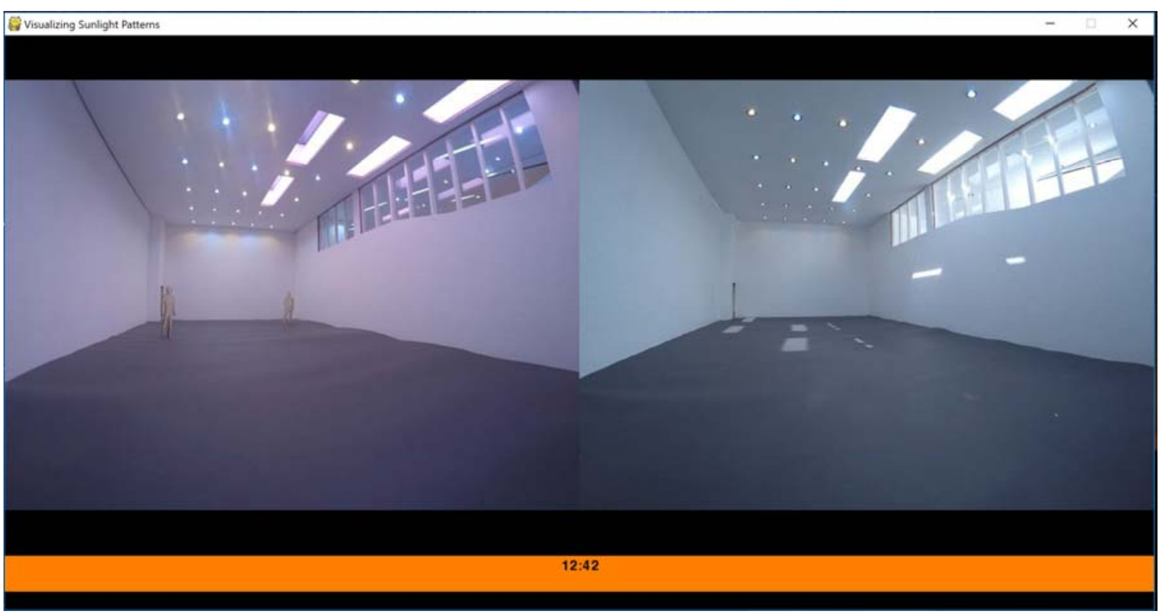

Fig. 6: LED lighting and sunlight videos played side by side

5. Discussion

The current findings of the study are based on a limited number of recording days. Additional recordings of sunlight and corresponding LED lighting patterns are required to further verify the observed correlation between the PV power levels and the readings of the pyranometer.

This project's results are based on the numeric analysis of RGB pixel values and the visual evaluation of time lapse photos and videos. A scaled model of the studied space and a small action camera were used to capture images visualizing the effect of sunlight entering the space and also of LED lighting patterns based on the recorded variations in solar radiation. To improve our understanding of the effect of these natural patterns in real time I will conduct a long-term study in the Sandbox in collaboration with ICAT which has provided a grant for this purpose. Dynamic RGB LED wall washing lighting will be installed in a selected section of the space. Brightness and color of the light will be set according to interpreted power values of a PV panel located outside in close proximity to the Sandbox. The users of the space will be asked for feedback on the perceived effect of the dynamic lighting on the space. I hope to find that the dynamic lighting will reintroduce a natural rhythm in the Sandbox and give presence to the passing of time.

During my work on the immersive case study I identified potential application scenarios for the project. The ideal scenario for the project's application is the combination of sunlight through a skylight (day mode) with dynamic LED lighting (night mode). On overcast days with low daylight the LED lighting could be used to complement the sunlight. Using only the PV power monitoring and LED components there are additional applications for the project in spaces with very little or no potential access to daylight where the properties of the dynamic LED lighting could reintroduce natural rhythms and stimulate the users' circadian rhythms during the day.

6. Conclusion

Working on the case study I immersed myself in the aspects of designing skylights that combine PV-integrated glazing with indirect skylight well LED lighting to gain a better understanding of the interactions between quantitative and qualitative design measures and evaluation methods. Using a scaled model of the case study space I was able to document that energy monitoring values can be translated to lighting protocols for LED lighting which reflect the natural variation in solar radiation. Future work will expand on the documentation of the skylights' visual impact in the scaled model to improve my understanding of the dynamic lighting's real time impact as it would be perceived by the users of the case study space and also to assess my findings and conclusions so far. The identified potential application scenarios need to be worked out in more detail considering the findings of the long-term study.

7. References

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