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A framework outlining a daylight responsive model for smart buildings

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A framework outlining a daylight responsive model for smart buildings

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Abstract. The intensity of daylight varies due to periodical changes in the sun's position, changing cloud-cover over the region, and other weather-related phenomena. Thus, artificial lighting remains a major component of the overall energy consumed in smart buildings. This necessitates corrections for maintaining optimum lighting levels in these buildings, by enhancing the positioning of artificial lighting sources with respect to outdoor lighting conditions. In this paper, a methodological framework is proposed for developing a daylight responsive model to minimize energy consumption for artificial lighting. This could be achieved by optimizing the usage of natural lighting in the built-environment, with the aid of Geo-location and sun-path tracking in a simulated model using *Unity* software. This smart daylight responsive model integrated with Virtual Reality (VR) would aid in designing an efficient lighting system utilizing Building Information Modelling (BIM). Further, this framework would help architects, engineers, and other stakeholders to collaborate, and virtually visualize the lighting conditions in smart buildings. In conclusion, an energy-efficient model for lighting can optimize the energy usage pattern in smart buildings, effectively increasing the usage of natural lighting.

1. Introduction

A building may be categorised as traditional, intelligent or smart. The naming depends upon the extent of information gathered by the building under the umbrella of intelligence gathering, the level of control possible in the building, the architecture used in the design phase, and the integration of IoT devices with BMS (Building Management Systems). Smart buildings are subtly different from an intelligent building because smart buildings employ the concepts of adaptability as a fundamental principle in contrast to intelligent buildings that react to situations [1]. The energy consumption aspect of buildings is a significant parameter that is used to design and operate smart buildings. Buildings consume a major portion of all electric energy produced and it reaches 66% in states like California of the USA [2]. Energy usage for lighting is a major portion of the overall energy consumed by buildings, but due to faster adoption of new technologies in lighting solutions, such as Light Emitting Diodes (LEDs) and better energy policies adopted by nations, energy usage for lighting has come down to 7% of the total energy consumed. This has the potential to further increase energy savings of up to 3.611×10^{11} kWh annually by the year 2040 [3]. Therefore, further progress needs to be made in order to reduce energy consumption on lighting. This can be achieved by making use of natual daylighting coupled with efficient control of artificial lighting within the building [2]. Savings in energy for lighting also helps to reduce the carbon footprint [4], thereby helping the world to progress towards a sustainable future.

Smart cities are predicted to be an intergral part of modern human civilization in the near future, this includes smart buildings along with the key industrial and service sectors, smart utilities, smart governance, and smart environment [5]. IoT devices, which are an interconnected network of sensors and actuators working in tandem to achieve a common objective, are used extensively in smart buildings. In an IoT environment, all devices and appliances including safety and security services will be communicating with each other through a cloud network. The rapid rise in adoption of Radio Frequency IDentification (RFID) and sensor networks integrating information systems with communication systems will make the field of IoT grow by leaps and bounds [5]. Using IoT based systems optimal lightings solutions can be effectively integrated into a smart building environment.

Also, a smart building should be able to predict and adjust the temperature, humidity, air quality and maintain optimum lighting conditions inside the building, which would provide enhanced comfort, better health, and improved productivity for the inhabitants of the building [6]. This paper is an attempt to build a methodological framework for providing an optimum lighting solution in smart buildings by enhancing the positioning/installation of artificial lighting sources with respect to outdoor lighting conditions, thus improving the fenestration ratio and daylight factor. The advantage of this approach is the use of the virtual model in predicting optimum fenestration ratio during the design and development phase of the building, as well as in optimising the installation of artificial lighting in an existing building scenario.

2. Methodology

2.1. Development of the virtual model

Placing the sun in the 3D model is made possible with the calculation of the solar altitude angle and the solar azimuth angle, with respect to the location coordinates of the building (Figure 1). The solar altitude angle is the angle the sun makes with respect to the earth's horizon (horizontal plane) measured in degrees such that the altitude angle is zero during sunrise and can reach a maximum of 90 degrees at noon when the sun is directly overhead [7].

$$Azimuth\ of\ sun = tan^{-1}\frac{sin(H)}{cos(H)\times sin(L) - tan(D)\times cos(L)} \tag{1}$$

$$Altitude\ of\ sun = sin^{-1}(sin(L)\times sin(D) + cos(L)\times cos(H)\times cos(D)) \tag{2}$$

Where H is the *Hour Angle,* L is the *Latitude*, and D is the *Declination* [7].

The azimuth angle is the angle measured in degrees clockwise around the observer's horizon (reference plane) due south (true south) for the Northern Hemisphere or due north for the Southern Hemisphere [8]. These two angles are used together to give the directions of celestial objects (in this case, the sun) in the topocentric coordinate system. The data for these angles are calculated using the formula based on the Julian date (Equation 1). The location coordinates can be sourced manually from the user or alternatively sourced from the time-stamp and GPS location of the smartphone or computer. Also, the sunrise angle for the location is fetched from '*www.timeanddate.com',* which is a trusted website for keeping clocks, time, and calendars [9]. With these inputs, Unity software can perform realtime rendering of the 3D model with the light settings set as Directional light.

2.2. Development of the virtual lux measuring model

Light sensing in the virtual model is done with the help of a '*3D object with camera'* that can be placed in various locations inside the virtual building to determine the light intensities (Figure 3). Calibration of the camera model is necessary to determine light intensity in relative lux. The camera object takes in light from reflected surfaces in the form of RGB (Red, Green, Blue) values. These values of reflected light are combined to determine the relative lux values (Figure 3).

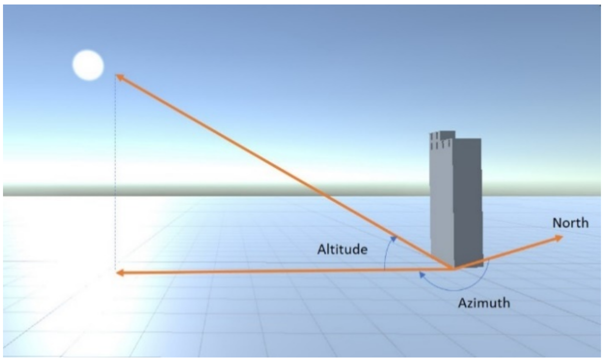

Figure 1. Solar altitude and azimuth angle

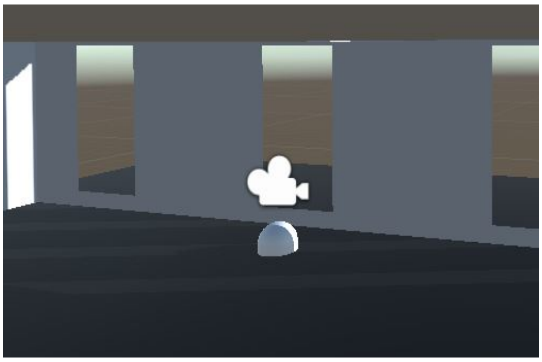

Figure 2. Virtual lux measurement in the model

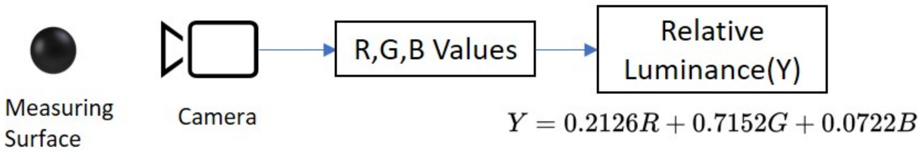

Figure 3. Virtual lux measurement in the unity software

The relative luminance is calculated using the formula $Y = 0.2126R+0.7152G+0.0722B$, where Y represents the relative luminance; and R, G, B represents the intensities of red, green, and blue light intensities [10]. A virtual model was developed in unity software to simulate the built environment. A software code was written in C# to position the sun in the virtual model [11]. This simulated model is used to predict the placement of windows, air vents, and doors to maximize daylight usage.

Acutal values of light intensities measured from various positions inside the building are compared to the virtual values generated from the Unity software model. The lux-meter (HTC LX - 101A) used has an accuracy of $\pm 5\%$. The readings are tabulated (Table 1) and a graph of real values is plotted against virtual values (Figure 4).

3. Results and discussions

An android based mobile application is developed using the android build feature in the Unity software (Figure 4). The virtual reality (VR) is enabled in the app using the XR (Extended Reality) in the player settings. Unity is a computer game development software which is used to model elements for the gameplay [12]. In contrast, this paper attempts to use this software as a modelling tool for modelling buildings and supporting infrastructures. For this, a virtual model was developed in unity to simulate the built environment (Figure 5). This simulated model is used to predict the placement of windows, air vents and doors to maximize daylight usage. Moreover, it also predicts the direction of sunlight and its intensity and thereby helps in positioning of electrical luminaires in rooms, semi-enclosed spaces and transition spaces within a smart building.

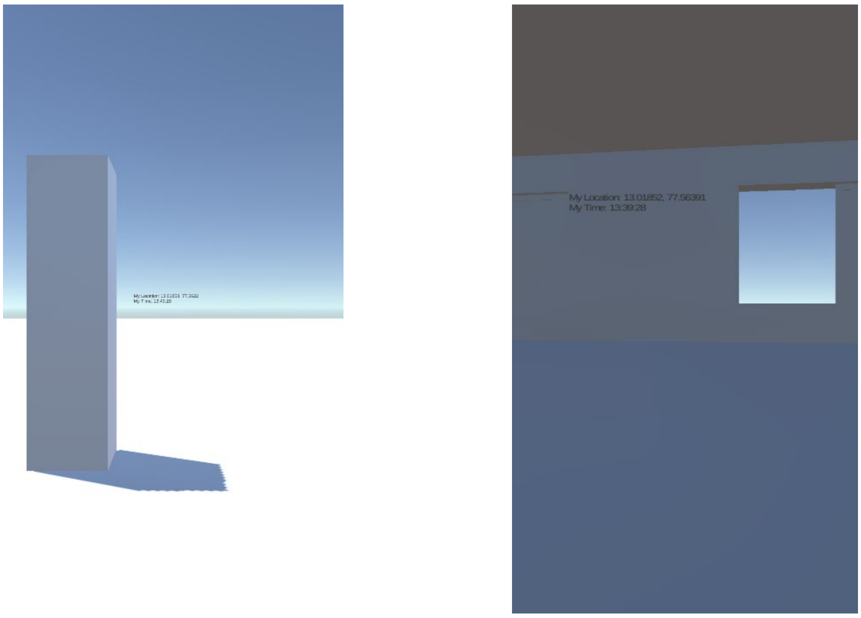

Figure 4. Screenshots of the developed mobile application (outside view, inside view through window)

Thus, this method is able to determine an accurate orientation of the building so as to maximise daylight usage in its design and planning phase. Also, the placement of windows and doors can be altered in the model according to the architectural necessities and asthetics required by the professionals concerned. These alterations can be remodelled and redered in Unity, to check for the optimum illuminance inside the space of interest within the buiding. This technique allows the designer of the building to come up with a design that best suits the needs of the persons concerned (with the design and construction of the buildings).

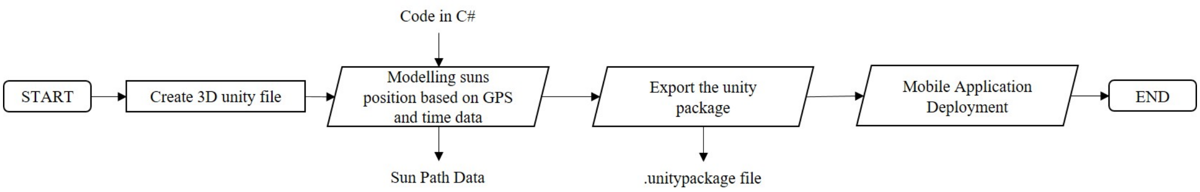

Figure 5. Flowchart for the creation of virtual model of the building

3.1. Validation of the model

Real-Time measurement of daylight intensity is performed, using a digital lux-meter positioned at various spaces within the building. This is compared with the data generated from the simulated model in the unity software for validation. The calibration of the model is done from real-time values obtained from the lux-meter placed near the window. For the real-time rendering of the model, while in the development phase of the building simulation, the baking feature in the Unity software is used. This will help the designers or other stakeholders to visualise the natural lighting pattern in real-time, with the choice of setting the rendering interval. The positioning of the building is done according to the actual directional coordinates.

Table 1. Observed values and virtual values near the window

Time (in ISO 8601)	Real Values (in lux)	Virtual Values (in relative lux)
11:30	1300	1619
12:00	1480	1628
12:30	1400	1629
13:30	1560	1600
14:00	1450	1565
15:00	1030	1432
16:00	782	1197
16:30	992	1037
18:00	110	418
18:30	20	137

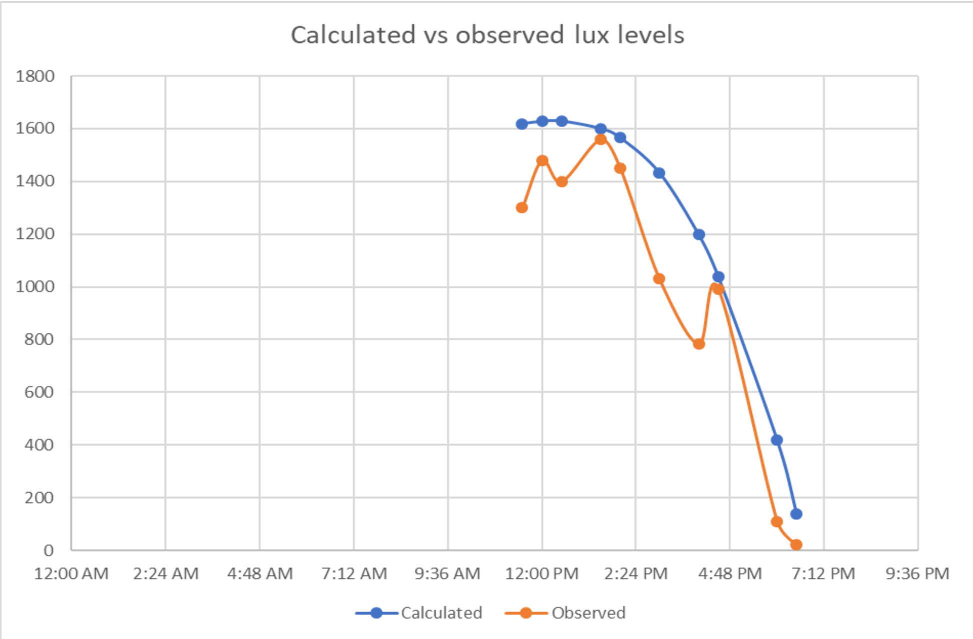

Figure 6. Observed values of lux and virtual values of relative lux plotted against time of the day

The root mean square (RMS) value of the error was found to be in the range of 252 lux (Table 1), which indicates the presence of cloud cover over the region during the observation phase. The intensity of daylight varies throughout the day, due to variation in the sun's position over the sky, cloud-cover over the region and other weather related phenomena. Therefore, corrections are needed to maintain optimum lighting conditions within the built environment. These levels of variations in light intensities can be compensated with controllable artificial luminaries integrated with daylight sensors, which forms a crucial component of the IoT based smart building systems.

4. Conclusion

The development of a virtual model for efficient lighting solutions, for maximium usage of daylight and optimum use of artificial lighting results in a sustainable smart building. Such a model for lighting in smart buildings can optimize their energy usage patterns. Also, the integration of virtual reality (VR) in the existing BIM models can help designers, engineers and other stakeholders to visualise and validate the designs in real-time. This method could also help the designers and architects to optimise the fenestration ratio of the buildings in the designing or planning phase. Therefore, it can benefit all the stakeholders involved such as the construction companies, contractors, and consumers make better decisions in view of the energy consumption pattern of the built environment. This can effectively contribute to significant energy savings in larger spatial scenarios such as smart cities or smart districts. Moreover, this would help to effectively increase the usage of natural lighting available, thereby decreasing the dependence on artificial lighting resulting in reduced energy usage and carbon footprint.

5. References

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