Electronically-Controlled Artificial Sky Dome @ OSU … in Progress

Khaled Mansy, Steven O'Hara / Thomas Gedra, Qamar Arsalan

School of Architecture / School of Electrical and Computer Engineering
Oklahoma State University, Stillwater, OK 74078

Abstract

Indeed, design of daylighting systems is increasingly becoming an integral part of the design of energy-efficient buildings. In order to accurately design, test, and analyze daylighting systems, a controlled luminous environment is required to simulate different sky conditions, under which a physical model can be tested. An artificial sky dome is needed.

This paper reports on the ongoing effort to build an Artificial Sky Dome for the School of Architecture at Oklahoma State University. The paper discusses the technical challenges faced by the team in charge of designing the Artificial Sky Dome. Challenges that relate to the structure of the dome, uniform distribution of light sources, avoiding the star effect, effect of internal reflections, models of different sky conditions, control of sky luminance, and the need for a post-construction calibration of the lighting control system. The construction of the Artificial Sky Dome is expected to be completed by the end of summer 2005. This laboratory is funded by the National Science Foundation, Division of Undergraduate Education, (CCLI) Course, Curriculum, and Laboratory Improvement-Adaptation and Implementation. This new laboratory will help integrate the engineering of daylighting systems into the school's curriculum, with the anticipation that this will nurture the scientific background and design skills of undergraduate students. The secondary mission of the laboratory is to disseminate the same knowledge and/or skills between graduate students, faculty, and practicing professionals. The laboratory will also be an effective venue to integrate teaching and research.

1. Design of Daylighting Systems in Buildings

Integration between daylighting and electric lighting systems in commercial buildings may result in a significant reduction in the annual energy consumption and operating cost. Indeed, daylight is a free source of energy. Moreover, it is rather a cool source of light that reduces space cooling load. Despite of this fact, the majority of building designers still does not use accurate design tools to design daylighting systems in buildings. Currently, design of daylighting systems relies on the use of rules of thumb, which are not accurate because they only offer general guidance that is not case-specific. The use of inaccurate design tools results in losing the opportunity of saving energy. Currently used daylighting design tools include, but not limited to, simple formulas, daylighting nomographs, and graphical methods. Each of these design-assisting tools has its own limitations, and they are not flexible enough to allow for innovation in the design of daylighting systems [1]. The use of computer programs does not suit beginning undergraduate students as a learning tool. An accurate and a user-friendly design tool to design daylighting systems is testing physical scale models under a simulated sky dome.

2. The Need for an Artificial Sky Dome Laboratory

To overcome current design limitations, a special laboratory is needed to test these physical scale models. This laboratory should be able to simulate a variety of sky conditions in different locations (Latitudes), in different months in the year, in different hours in the day. The answer was to build an Artificial Sky Dome. With the support of the National Science Foundation (NSF), OSU is currently in the process of designing and building a cutting-edge daylighting laboratory, i.e., the Artificial Sky Dome. In this pursuit, the team in charge of designing and building this new laboratory was faced with many technical challenges that are worth-sharing with the engineering education community. These challenges, if all to be once overcome, will make this new laboratory a role model to follow in designing similar laboratories for other educational and/or research institutions. This paper will discuss these challenges in detail.

3. Technical Challenges

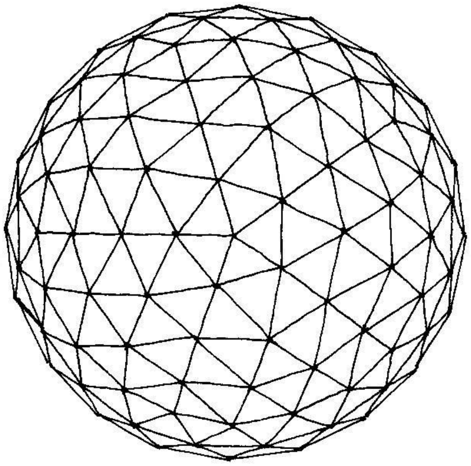
The essential part of the design of this new laboratory was to overcome a number of technical challenges. These challenges added to the complexity of the design process and lead to certain design choices that will ultimately result in the creation of a cutting-edge flexible facility that will help students to explore advanced designs of daylighting systems in buildings. These technical challenges can be presented as follows:

3.1. Structure of the Dome

Construction method of the sky dome was the first question. The determinant criterion was that the selected structural model should allow for a uniform distribution of light fixtures on the internal surface of the dome. Although there is no perfect answer, the most appropriate answer was the use of a geodesic dome as a means to mount the light fixtures. The geodesic dome is made of a number of triangles that, in turn, compose five identical sectors (in plan), see (Figure 1). Although not all triangles are exactly identical in size, the geodesic dome provided the best close-to-uniform distribution of vertices. Differences in the length of different struts can be ignored. Because the geodesic structure is a special open form, its selection eliminated the need for a ventilation system to exhaust heat generated from the light fixtures.

The frequency number of the geodesic geometry was selected to be an even number. Even frequency numbers result in a complete hemisphere, i.e., a complete dome (Figure 2). On the other hand, odd frequency numbers create a dome plus or minus a half triangle, which makes it harder to adjust the height of the horizon. A raised floor is used to protect wires running under the floor and to adjust the height of the physical model in relation to the horizon circle (Figure 5).

Live loads on the dome are estimated at 50-60 pounds per square foot, and/or 300 pounds concentrated load, in order to carry at least a person climbing on the structure. A movable door is required to allow students and models in and out. The door is located where it can rotate upwards around a horizontal axis, does not compromise the structural integrity of the dome, and to be wide enough to fit a single student at a time.



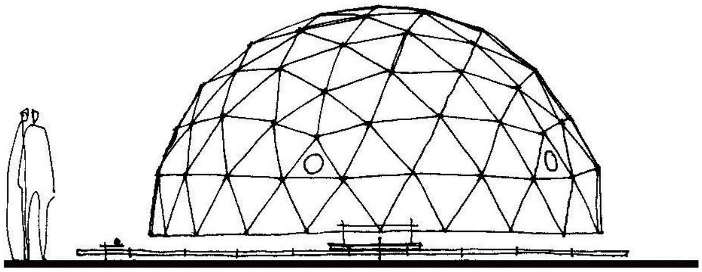


Figure 2: Geodesic Dome (elevation)

Figure 1: Geodesic Dome (plan)

3.2. Star Effect & Internal Reflections

Accurate control of the distribution of sky luminance requires a large number of light fixtures to be mounted on the internal surface of the geodesic dome (341 fixtures with the 4 frequency dome in this case). However, experiments have shown that even a large number of point source lights will create a star effect (Figure 3). This star effect causes inaccurate readings by the light sensor inside scale models (Figure 4). When the light sensor is moved inside the scale model, it may see a different number of point source lights, which causes unrealistic jumps in the reading of internal illumination levels. To overcome the challenge of the star effect, the solution was to diffuse the light on the sky dome in order to reach a smooth gradation of sky luminance. A smaller translucent dome installed inside the geodesic dome is used as a diffusing media (Figure 5). The smaller translucent dome is suggested to be made of translucent polycarbonate lexan sheets. The use of a smaller solid translucent dome as a diffusing media is expected to cause internal reflections, a phenomenon that can be adjusted for by post-construction calibration of the lighting control system.

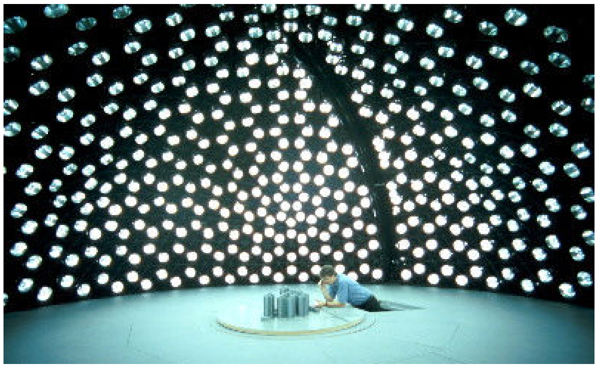


Figure 3:
The Star Effect as seen in the Daylighting Laboratory in Cardiff University, UK.

Figure 4:
The light sensor inside a scale physical model while measuring internal illumination levels.

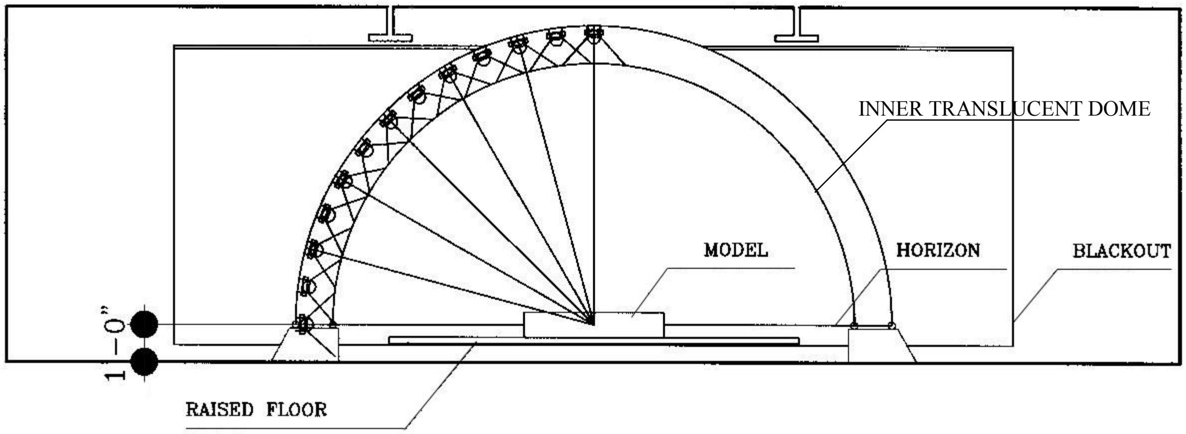


Figure 5: Laboratory setup, showing outer and inner concentric domes.

3.3. Sky Conditions and CIE Standards

In the design process of daylighting systems the worst case condition, i.e., design condition, is assumed to be the overcast sky condition [2]. However, for students to build a better understanding of the performance of daylighting systems, testing models under clear sky conditions is a must. Furthermore, testing daylighting models under clear sky conditions is essential in order to evaluate the distribution of illumination levels in different months, and to evaluate the possible effect of glare in case of very high interior illumination levels. Testing models under both overcast and clear sky conditions will help design any automated control system that may adjust the seasonal amount of admitted daylight into the space under consideration.

The artificial sky laboratory will simulate both overcast sky (Figure 6) and clear sky conditions (Figure 7), which represent the two ends of the spectrum of sky conditions. It is worth mentioning that: although used in some daylighting design-assisting methods, the uniform sky condition is excluded because it is a hypothetical case that never occurs in nature. Sky models to be simulated will follow the most recent internationally-recognized CIE (Commission Internationale De L'eclairage) standard: ISO (International Organization for Standardization) 15469:2004 (E) / CIE S 011/E:2003 [3].

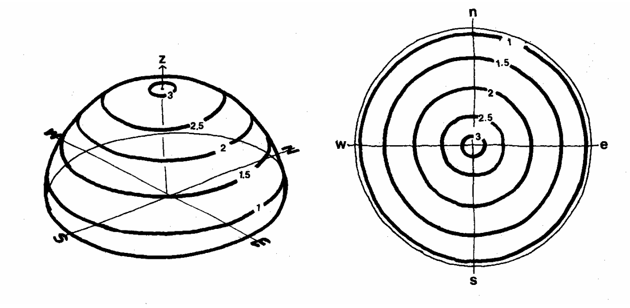


Figure 6: Overcast Sky Conditions

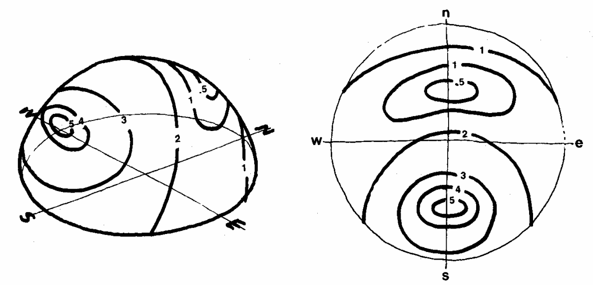


Figure 7: Clear Sky Conditions

3.4. Direct Solar vs. Sky Component

In fact, internal illumination levels inside spaces (due to daylight) occur due to three different components, which are: direct solar, diffuse sky, and ground-reflected components. In this design, the artificial sky dome represents the diffuse sky component. A heliodon, which is a movable point source light, represents direct solar component. The reflection off the raised floor represents the ground-reflected component. The raised floor can be covered with different colors of carpet.

3.5. Luminosity Control System

The design of lighting control system turned out to be quite challenging. Incandescent halogen lamps, which have tungsten filaments, will be used as light sources. When the voltage across a lamp is changed, the current will change correspondingly. But the bulb does not behave as a linear resistor. Also the fraction of power consumed in production of light as opposed to heat, varies with the applied voltage. Consider a basic light dimmer shown in figure 8. By controlling the operation of the switch, the effective or root-mean-square (RMS) value of the voltage seen by the load can be changed.

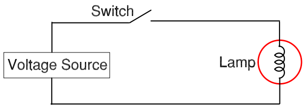


Figure 8: Basic Light Dimmer

The performance of tungsten-filament lamps can be expressed by equation 1.

$$L = L_0 \left(\frac{V}{V_0} \right)^k , \qquad (1)$$

where L and V represent luminance and effective voltage respectively. The rated quantities are denoted by L_0 and V_0. The value of the exponent k determined experimentally [4], is approximately k = 3.38. The voltage source in figure 8 may be an AC (Alternating Current) or DC (Direct Current) source. It is possible to control the illumination in both of these cases.

In the case of an AC supply, the RMS value of the lamp terminal voltage can be controlled by detecting the zero crossing of the AC waveform and turning on the switch after introducing a delay. This delay, represented as a portion of one period of the AC waveform, is called the firing angle and it can vary from 0 to π radians (often expressed in degrees). A larger firing angle results in smaller RMS voltage and *vice versa*. The RMS voltage value of the light bulb terminal voltage as expressed as

$$V(\alpha) = V_0 \sqrt{\pi - \alpha - \frac{\sin(2\alpha)}{2}}, \qquad (2)$$

where α is the firing angle. To control the firing angle we use a triac as the switch of figure 8 as shown in figure 9(a). The triac triggering pulses are generated by a peripheral interface controller (PIC). In order for the PIC to determine at which point of the AC half cycle it should turn on an individual channel, it needs a reference for AC zero crossing as well as a clock signal to count down until the commanded firing angle is reached. For zero-crossing detection and clock signal generation, circuits have been developed as shown in figure 10. The external clock signal is provided by the phase-locked loop (PLL) which is a feedback system that included a phase detector a low-pass filter and a voltage-controlled oscillator (VCO) in its loop. The PLL design employs the widely-used integrated circuit (LM565). The firing angle α is discretized at a resolution of 8 bits. Since each half cycle of the AC line voltage is discretized by $2^8 = 256$, the free-running frequency of the LM565 is chosen to be close to 30.720 kHz. To generate this frequency from 60 Hz reference signal, the VCO output is divided by 512 before it is returned to the feedback input. To facilitate the generation of clock signal, PLL is provided with a clock 60 Hz reference signal *Vref* from the zero-crossing detector. The zero crossing and clock signals are sent to the external interrupt and external clock inputs of the PIC.

Figure 9: Basic Lamp Driver Circuits

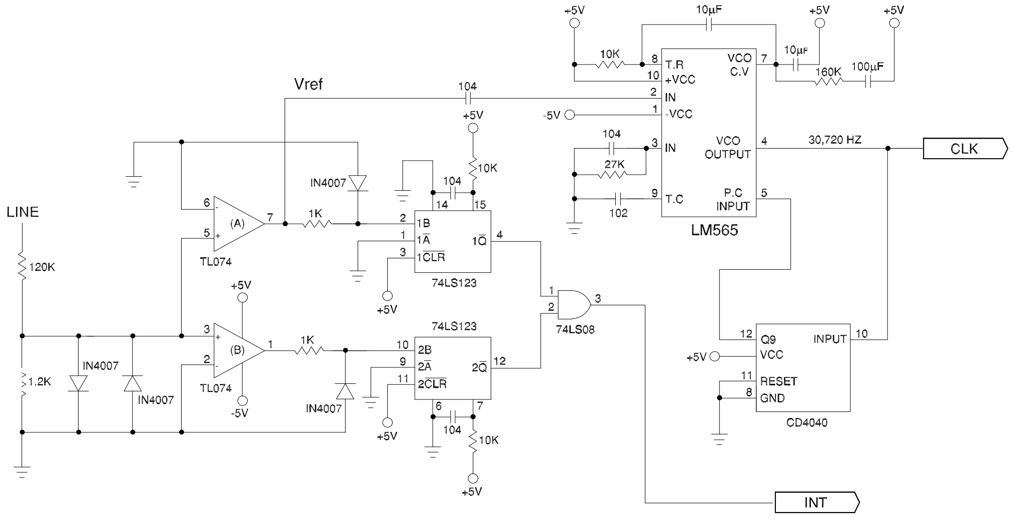


Figure 10: Zero-Crossing Detection and Phase-Locked Loop Circuit

In the case of DC we can use a MOSFET (metal oxide semiconductor field effect transistor), an IGBT (integrated gate bipolar transistor) or a BJT (bipolar junction transistor) as the switch in figure 8. Pulse width modulation (PWM) could be used instead of firing angle control as shown in figure 9. The time of PWM signal in which the output remains high is called the duty cycle. In this case the RMS value of the light bulb terminal voltage can be expressed as

$$V(d) = V_0 \cdot d, \qquad (3)$$

where d is the duty cycle of PWM signal. This means that by controlling the duty cycle we can control the RMS value of the voltage across the bulb and hence the luminosity, according to equation 1.

The internal surface of the sky dome will be illuminated by hundreds of light sources. The luminosity of these light sources will be individually controlled. The user will control all the sky conditions through the use of a LABVIEW program (or "virtual instrument"), which will provide a simple and user-friendly interface to the sky dome. The LABVIEW interface will in turn communicate with the master PIC, through a serial (RS232) interface, which will coordinate the operation of slave PICs which ultimately control individual light sources. The inter-integrated circuit (I^2C) protocol is used for the communication between master and slave PICs. This is a synchronous protocol using two wires: the serial data line (SDA) and the serial clock line (SCL) as shown in figure 11.

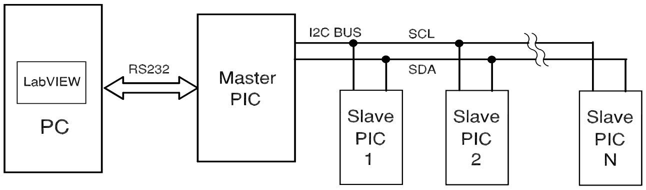


Figure 11: Block Diagram of Communication Network

Each of the slave PICs, shown in figure 11, can independently control up to16 light sources. The slave PIC handles two functions. First, it communicates with the master PIC using the I2C protocol so that it can receive firing-angle data in the case of AC and duty-cycle data in the case of DC for the lamps it controls. Second, it controls the firing time of the power triacs for its lamps in the case of AC or the duty cycle in case of DC using PWM. Therefore the luminance of each light source is under the control of the slave PICs. The slave boards are designed to be identical in hardware as well as in software. Therefore, it is possible to interchange any two slave boards, or replace a defective board, with great ease. Each slave PIC will be informed of its address by one of several methods, for example by using dual in-line package the (DIP) switches on each slave board.

We have successfully created the basic architecture for an electronic luminosity control system, which is able to control the individual luminosity of all the light sources of the sky dome. Some minor design details, like the exact luminance and distance of diffusive material from the light sources, are being worked out.

4. Conclusion

In conclusion, the design of this new Artificial Sky Laboratory is still ongoing. 90% of technical challenges were overcome. Purchase of some components is underway. Another challenge the design team faced is to locate the appropriate components in the market that can be put together to create this new laboratory according to its final design.

The Design team intends to publish the detailed final design after the actual construction of the laboratory. Results of research done using the laboratory should be published as well.

5. Bibliography

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6. Biography

Khaled A. Mansy is an Assistant Professor in the Architectural Engineering Program, School of Architecture, Oklahoma State University. He earned his Ph.D. from Illinois Institute of Technology, Chicago, 2001, and has 15 years of teaching experience in professional programs in the USA and Egypt. Dr. Mansy is the PI of the NSF grant awarded to build this artificial sky dome.

Steven O'Hara is a Professor of Architectural Engineering, School of Architecture, Oklahoma State University. He received his Bachelor of Architectural Studies and Master of Architectural Engineering from Oklahoma State University, 1982 and 1985 respectively. Professor O'Hara is also a registered Professional Engineer. He has been teaching structural design since 1988.

Thomas W. Gedra received his B.E.S. and M.S.E. degrees from The Johns Hopkins University in Baltimore, Maryland. He worked at Westinghouse Electric Corporation on algorithms for synthetic aperture radar before attending U.C. Berkeley, where he received a Ph.D. in Electrical Engineering. He is now an associate professor in the School of Electrical & Computer Engineering at Oklahoma State University in Stillwater, where his current research interests include power systems, power system economics, and stochastic systems and control. Dr. Gedra is a past recipient of the National Science Foundation (NSF) Research Initiation Award and an NSF Early Career Development (CAREER) award.

Qamar H. Arsalan received his B.S.E. degree from NWFP University of Engineering & Technology, Peshawar, Pakistan, and M.S.E. degree from Oklahoma State University, Stillwater in 2002. He is currently working on his Ph.D. in Electrical Engineering at Oklahoma State University, Stillwater. He was electrical engineer with Ideya Co. Ltd, Kyoto, Japan.