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DESIGN AND PERFORMANCE OF AN INTEGRATED ENVELOPE/ LIGHTING SYSTEM

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ABSTRACT

Dynamic envelope/ lighting systems offer the potential to achieve a near optimum energy-efficient environment meeting occupant needs throughout the year by adapting to dynamic meteorological conditions and changing occupant preferences in real time. With the dramatic increased functionality of the microprocessor, there is an untapped potential to make dynamic envelope/lighting systems easier to use, diagnose, and monitor, and to integrate them as part of a sophisticated building-wide control system. This study addresses the complex relationship between this energy-efficiency technology and many of the non-energy issues related to its potential acceptance by the building industry, architects, owners, and users. We demonstrate the concept of integrated dynamic systems with a prototype motorized venetian blind operated in synchronization with electric lighting and daylighting controls via an intelligent control system. Research work conducted with simulation software and reduced-scale and full-scale field tests is summarized. Much of this work is directly relevant to other active shading and daylighting systems on the market today and to state-of-the-art window systems yet to come (i.e., electrochromics).

INTRODUCTION

Historically, building envelope design has addressed the combination of various materials and components needed to produce a building skin that would act primarily as a static barrier to control or moderate the extremes of the exterior climate. In contrast, the human body utilizes an interface between internal and external environments that is dynamically controlled through complex interactions between internal loads of the body, thermal resistance of clothing, activity level, and conditions of the external environment (i.e., air temperature, mean radiant temperature, air velocity). Human beings have several means at their disposal to dynamically modify their comfort, either through conscious thermoregulatory control (e.g., removing clothing layers or changing locations) and/or through involuntary responses (e.g., sweat secretion or vasoconstriction). Our ability to dynamically use a variety of regulatory tools enables us to function effectively over a wide range of adverse conditions.

Because buildings are subjected to an even wider range of internal and external conditions, with the additional handicap of being unable to relocate themselves to more favorable environments, they too should ideally possess dynamic thermoregulatory capabilities at the building envelope. These dynamic qualities could yield improved comfort, satisfaction, and productivity to its occupants while minimizing the energy costs and environmental impact to maintain that comfort. The dynamic control might be triggered by occupants' needs within a room, at a building-wide scale in response to an integrated building automation system, or perhaps at a local or regional scale based on wide area utility system needs. The future design of building envelopes should address a careful balance between internal requirements and loads, mechanical system, the materials and properties of the building skin, and the external environment. This new model assumes that this balance is a dynamic function, not a static solution, so that optimal building performance is established continuously under changing conditions in real-time. For example, a dynamic facade may be able to respond to an increase in solar heat gain by altering its thermal conductance, by operating a series of shading devices or altering glazing properties, and by converting incident solar radiation into electricity for use in other parts of the building, all in coordination with the building mechanical and lighting systems while meeting any remaining cooling and illumination requirements.

There are a wide array of existing products on the market today that provide relatively simple solutions within a specific and limited market niche. Generally, these products have not captured a significant market share despite their availability over many years. Existing candidate dynamic fenestration products include mechanically driven devices designed to mitigate the thermal or daylighting environment with a shading device (roller shade, louver, venetian blind) via input by the occupant or automated controls. These systems control daylight illuminance levels (particularly for museums and galleries) or control cooling loads from direct sun, and indirectly control view and glare. Newer products are venturing across traditional building trade lines to include such features as preset architectural theatrical lighting "scenes" (audio/visual blackout, conference) with coordinated window and electric lighting operation. Air flow windows, double envelope systems, electrically heated glass, and water flow window grid systems are variants on dynamic systems that have all been used in Europe in specialized applications and even less frequently in the United States. While many dynamic systems focus on sun control and daylight control, several of these systems also work well in cold climates where thermal effects from a cold window causes significant thermal discomfort.

One of the reasons the markets move slowly in accepting these systems is a concern for maintenance requirements and costs of mechanically based systems. There are exciting new optical materials that are emerging from research labs with the potential to change the picture dramatically. New building materials are being developed with the capacity to change thermophysical properties (such as thermal conductivity), optical properties (absorptivity, reflectivity, and transmissivity within various wavelength ranges), direction of light (diffraction, reflection, refraction) and visual appearance (such as opacity and transparency). Passive and active electro-optic devices (e.g. thermochromic, photochromic, electrochromic materials) are under extensive development around the world, with first significant commercial products likely to be available by the turn of the century. These have the potential to profoundly change architectural design as well as building performance, in ways that we are only now beginning to explore and understand.

Architectural and engineering design in the United States is based upon a series of implicit and explicit engineering, practical and legal assumptions that result in most building services being vastly overdesigned. Even though average building performance might be within expectations, the assumption behind peak sizing of HVAC systems is that any operable devices, e.g. window blinds, will not be operated properly. Control hardware and strategies in U.S. building are slowly undergoing change. Building control systems are slowly changing from closed, proprietary black box systems to more open systems with interoperable components. Two traditional control models predominate in the U.S. market. Local control assumes that each building zone is autonomous and dictated by the desires of the occupants immediately residing in that zone. Centralized control systems, typically energy management control systems (EMCS) for mechanical systems, are single point decisionmakers for all building zones. A state-of-the art control solution would build on a distributed systems computer architecture that accommodates non-hierarchical control of multiple building subsystems (mechanical, lighting, fire, and security) and imbues local zone nodes with richer device models by providing feedback from a central monitoring/ diagnostics/ control system. This emerging trend in turn has driven the market toward open standardized communications protocols (i.e., BACnet, CORBA), flexible physical media (twisted pair, R12, wireless), and interoperability/ interchangeability of sensors, actuators, and building components (Bushby & Newman 1991).

The stimuli or inputs to the local zones and the EMCS are multiple and can be conflicting. From the perspective of the occupant, assurance of a comfortable work environment is of paramount importance for satisfaction and productivity. Comfort can be defined by physiological (thermal, visual, glare, luminance distribution, direct solar, mean radiant temperature), psychological (view, privacy, connection to the outdoors, visual interest, design aesthetics) and health (vitamin D, pupil dilation, focal distance, fresh air) considerations. The building owner and operator must balance a fine line between operating costs and providing a satisfactory interior environment for the tenants within the context of variable weather, utility pricing schedules, and assured operation of all building subsystems. With increased utility deregulation occurring throughout the U.S., building owners may wish to demonstrate their ability to shed loads during critical peak periods or, for those owners with substantial building stock, seek utility rate price breaks by brokering their controllable aggregate load of multiple buildings. Pressure on utilities to mitigate environmental impacts (greenhouse gas emissions, deferring power plant growth) affects rates and puts pressure on building owners to determine the threshold of "comfort" provided to occupants without unduly compromising satisfaction.

PROJECT DESCRIPTION

This context of change in some aspects of the commercial buildings market has set the stage for a multiyear research project supported by the California Institute for Energy Efficiency and the United States Department of Energy. The R&D project addresses the vision of energy-efficient building systems integration with two parallel approaches:

(1) by acknowledging the current ineffective piecemeal approach to lighting and window design at the perimeter zone of the building and laying the groundwork for a more "integrated" approach through design guidelines, improved computerized tools, and showcase demonstrations; and

(2) by developing a working dynamic system prototype that integrates daylighting and thermal performance and provides a database of supporting performance evidence that demonstrates its ability to yield a satisfactory work environment, reduce operating costs through improved energy efficiency, and is responsive to broader environmental concerns.

We describe the performance results to date from the second approach. Much of this work is directly relevant to the most prevalent dynamic fenestration type commercially available today—active shading systems—and to more elegant solid-state fenestration solutions (i.e., electrochromics[1]) yet to come. Dynamic window components are operated in synchronization with electric lighting and daylight controls via an intelligent control system. Supporting evidence has been provided in the form of building energy simulations, reduced scale field tests (control system design, thermal tests), and a full-scale testbed building demonstration. While our primary focus has been energy performance, we are increasingly interested in addressing the comfort and productivity dimensions to these design problems so as to create a more robust economic basis for pursuing these new building design solutions.

PERFORMANCE RESULTS

Annual energy use predictions were made using the DOE-2 building energy simulation program for a prototypical commercial office building module in the Los Angeles, California climate (Lee & Selkowitz 1995). Results were calculated as a function of glazing area for the south, east and west perimeter zones and for conventional static glazing designs, an automated venetian blind, an absorptive broadband electrochromic, and an idealized narrowband reflective electrochromic. All dynamic systems (venetian blind and electrochromics) were controlled in a similar manner—to provide sufficient daylight to meet the design illuminance level at the workplane. When compared to a low-E spectrally selective glazing with daylighting controls, the automated venetian blind system achieved a 16-26% reduction in total electricity consumption (lighting energy and cooling load reductions) over unshaded glazing, with the electrochromic glazings achieving a 23-47% reduction. Peak demand reductions were roughly of the same magnitude: 17-40% compared to the same base case system. These predictive calculations established that annual energy and peak demand savings were substantial and that further development of the concept of integrated dynamic envelope/lighting systems was worthy of further development. Further work was conducted with the automated venetian blind because electrochromic devices were not yet available.

The simulated results were corroborated with short term reduced-scale field tests. A dual-chamber calorimeter outdoor window test facility was outfitted with a conventional bronze-tinted glazing and an early prototype automated venetian blind system, then tested for a six week period with a southwest orientation in Reno, Nevada. Results showed that peak heat gain reductions of ~50% were achieved, principally by controlling solar radiation while still providing sufficient useful daylight. This peak cooling load reduction can be tied to a potential reduction in HVAC cooling system capacity and ultimately a deferment of utility peak load growth.

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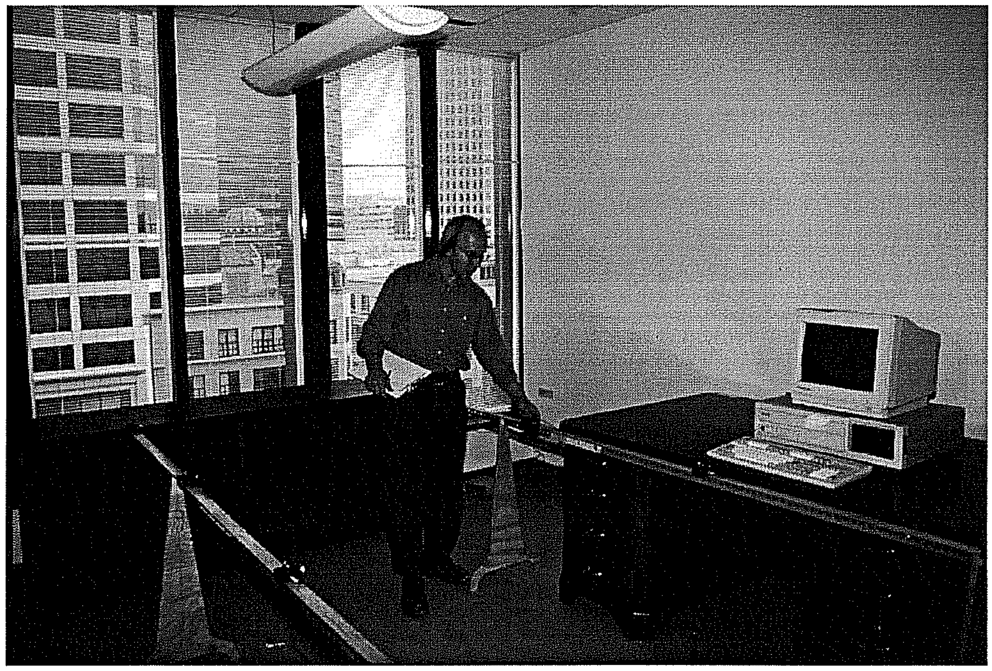
[1] The electrochromic is a thin multi-layer coating on glass that switches from a clear to colored state with a small applied voltage.

Figure 1.
Interior view of the full-scale test room outfitted with the prototype automated venetian blind and an indirect/ direct lighting system. The two rows of workplane illuminance sensors are used for monitoring purposes. The 12 mm (0.5 in) wide blinds are difficult to detect in this photograph.



A second, year-long daylighting performance field test was conducted in a 1:3 reduced scale model of a 3.05 by 4.57 m (10x15 ft) office facility to develop hardware and software solutions for the dynamic envelope/lighting system and to monitor the resultant electric lighting energy savings under real weather conditions. Results showed that for south to southwest orientations with minimal exterior obstructions for the climate of Berkeley, California that 37 to 71% lighting energy savings could be achieved by the dynamic blind system when compared to a fixed blind positioned to block direct sun throughout clear sunny days (DiBartolomeo et. al. 1996). The control system was refined iteratively over the year to improve energy efficiency and the logistical design. Note that all lighting energy savings calculated in the simulations and measured in the reduced scale model tests requires the use of daylight dimming controls in perimeter zones. At the present time, this technology is only rarely used and occurs in less than 1% of the commercial office buildings in the U.S. However, improved electronic ballasts and photocell sensors are now available at much lower cost, thus increasing the likelihood that this technology can be effectively used in the future.

The next and final step was to move to a full scale testbed demonstration within a 0.11 Mm^2 (1.2 Mft^2) Federal Office building, located in the fairly dense urban context of downtown Oakland, California (approximately the same climate as Berkeley). Two side-by-side, full-sized 3.66 by 4.57 m (12x15 ft) testbed offices oriented southeast were constructed on the fifth floor of this 18-story building and outfitted with the prototype automated venetian blind/ lighting system (Figure 1). The offices were fully furnished and instrumented. Daily lighting energy savings of 22 to 86% were obtained compared to a nondaylit space throughout the year. Daily cooling load reductions of 22-24% were attained with the dynamic blind compared to a daylighted space with static blinds positioned horizontally for view on clear sunny days throughout the year (Figure 2). The testbed monitored daily cooling load differences between the two rooms to within 5% and lighting energy use to within 0.2%. Control system performance was found to be reliable throughout the variety of transient daylight conditions that occur with this climate. Mechanical and operational characteristics were further refined to smoothen blind movement and reduce noise.

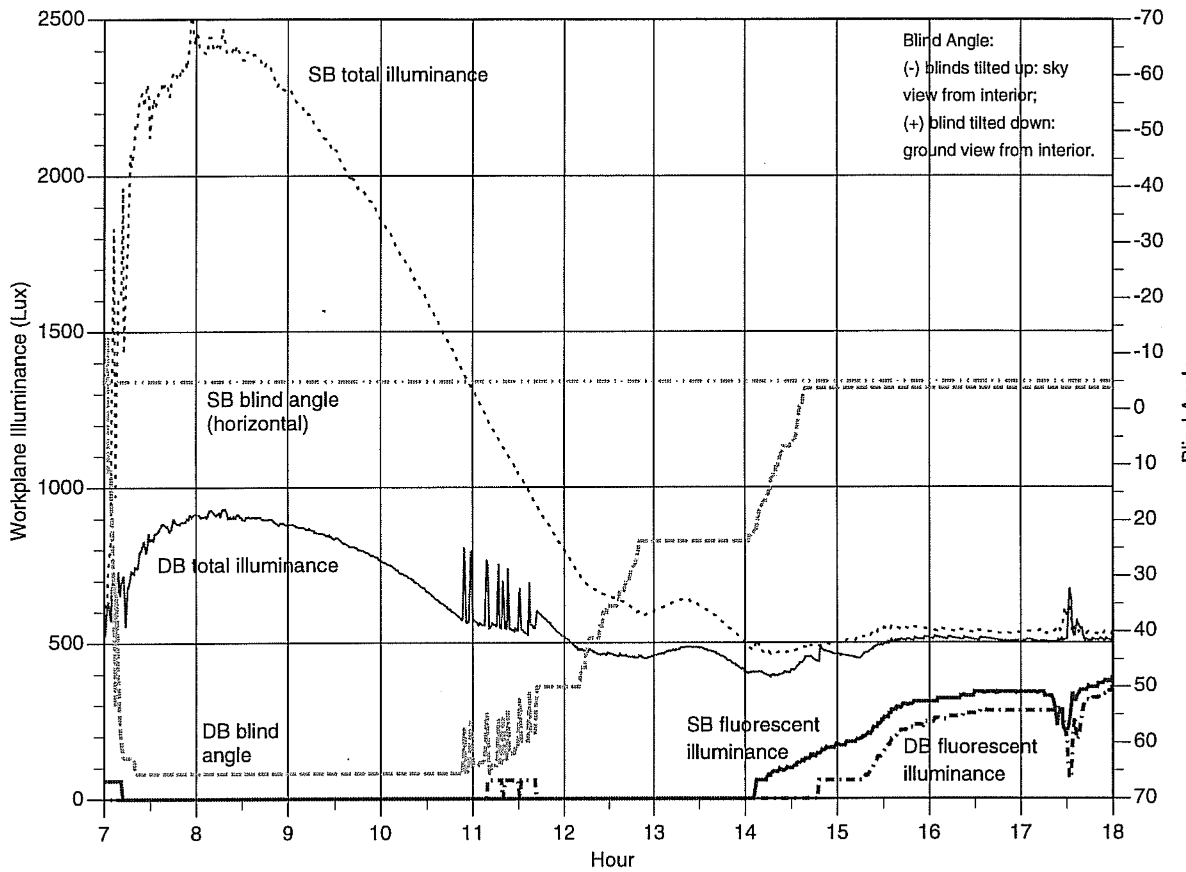


Figure 2. Monitored total workplane illuminance, fluorescent lighting illuminance, and blind angle for the static horizontal blind (SB) and the dynamic venetian blind (DB), both with daylighting controls. Daily cooling load savings were 21%. Peak demand savings were 13%. Daily lighting energy savings were 21%. Data are shown for southeast facing offices in Oakland, California on August 15, 1996.

Because we are interested in the overall impacts of these systems and the total cost-effectiveness as viewed by the building owners, we are interested in better understanding the effects of these dynamic envelope systems on the occupants' general comfort and productivity. A short term human factor survey was conducted on fourteen volunteer subjects at the full scale testbed to determine the level of acceptance of such a system and to ascertain their basic preferences for the environment that resulted. Visual comfort and lighting quality were investigated in parallel. Results from these surveys suggest that the systems performed as designed, most office workers were satisfied with the system, and there were few complaints.

We are also examining how a dynamic system might respond over an even greater range of conditions using other advanced simulation tools. We performed some initial simulations for an electrochromic glazing in a west-facing office space in Phoenix, Arizona over the course of a clear sunny day (Moeck et. al. 1996). The resultant interior luminance levels were compared to the Illuminating Engineering Society RP-1 guidelines for interior office lighting. Using the RADIANCE program, photorealistic renderings were created of the office interior under a variety of daylight conditions with both conventional static glazings and a hypothetical electrochromic glazing. Luminance levels throughout the day with static glazings (clear and tinted) substantially exceeded the threshold of 840 cd/m^2 set by the IES. If the glass was made dark enough to control the luminance, it provided very little light under more typical conditions and a poor view to the outside under overcast skies and at night. The luminance of the various room surfaces surrounding the VDT monitor also exceeded the recommended 1:3 and 1:10 ratios, thus suggesting that task performance might suffer. The electrochromic glazing in the dynamic facade had a daylight transmittance range of Tv=0.08-0.88. It was able to provide a pleasant interior daylight environment with desired illuminance levels while controlling luminance levels to within acceptable values.

CONCLUSIONS

These studies show that a dynamic envelope/lighting system has the potential not only to capture greater energy savings in climates with dynamic extremes but also to provide a more pleasant and comfortable work environment for occupants. In the quest to cost justify the added expense of these facade and daylighting systems, the additional benefit of occupant comfort and the potential improvements in productivity, yet unproven, could provide the additional cost justification needed for more widespread interest in these systems. In addition, there is still potential to extract greater cost and performance benefit from these systems by further refining their design and operation.

Future work should concentrate on 1) linking this local zone solution to the building-wide scale to enable electric load shedding in response to real time pricing from utilities, 2) further HVAC optimization in both design and operation, 3) detailed long-term studies on the effects of dynamic systems on occupant satisfaction and comfort, and 4) continued efforts to design integrated systems and components with reduced manufacturing, installation and calibration costs.

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