Advanced Engineering Informatics 29 (2015) 87–100

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Dynamic shading of a building envelope based on rotating polarized film system controlled by one-dimensional cellular automata in regular tessellations (triangular, square and hexagonal)

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ARTICLE INFO

Article history:
Received 15 March 2013
Received in revised form 19 July 2014
Accepted 27 September 2014
Available online 16 October 2014

Keywords:
Adaptive architecture
Organic architecture
Building envelope
CA shading

ABSTRACT

The original prototype of the cellular automaton (CA) shading system (CASS) for building facades was based on rectangular array of cells and used liquid crystal technology. This paper introduces polarized film shading system (PFSS) – an alternative approach based on opto-mechanical modules whose opacity is a function of the rotation of polarized film elements. PFSS in regular tessellations: triangular, square and hexagonal are discussed. Simulations for each type of tessellation are presented and visualized. Visual attractiveness of emergent CA patterns manifested by "particles" and "solitons" is discussed.

1. Introduction: towards intelligent building envelope

In architecture, building envelope (BE) besides the size and shape of a building, is the most apparent statement of designer's creativity. Too often, however, architectural decisions are based on aesthetics only, which has the evident disadvantage of limiting the potential of performance improvement [1]. BE as the interface between the exterior and interior serves several important functions, such as:

- protection from external factors, as it improves security and reduces the levels of noise and pollution,
- protection from climatic changes (temperature, humidity, glare),
- provision of natural light and visual contact with the environment, or the visual isolation from the exterior if required.

Furthermore, today's BEs often play a significant role in energy conservation by reducing the demands for artificial lighting, by either collecting solar energy or shielding from its excess. Rising energy prices and the need for reduction of the greenhouse gas emissions necessitate the development of intelligent buildings (IB) that operate on an energy-efficient and user friendly basis [2]. IB is to provide a productive and a cost-effective environment through optimization of its four basic elements: structure, systems, services & management and the interrelationships between them [3]. The biggest challenge is to optimize the trade-off between energy consumption and occupants' comfort [2]. The climatic requirements for the interior conditions vary among the occupants, however in relatively narrow ranges. Conversely, the exterior conditions vary substantially both in circadian and annual cycles. Therefore, BE of IB should also be somewhat intelligent, that is adapt both to the occupants' requirements and to the variable outdoor conditions.

1.1. Daylighting: visual and thermal comfort indoors and energy conservation

> *"No space, architecturally, is a space unless it has natural light."* – Louis Kahn

The main benefits of daylighting as a design strategy:

- *Economy/ecology:* D. substantially reduces the energy consumption and greenhouse gasses emissions [4,5].
- *Physiology:* D. is an effective stimulant to the human visual and circadian systems.
- *Well-being:* D. provides high illuminance and permits excellent color discrimination and color rendering; enables occupants to see both a task and the space well, and to experience some environmental stimulation [6], working by daylight is believed to result in less stress and discomfort.
- *Society:* those of higher status in organizations are often given spaces closer to/with more windows [6].

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http://dx.doi.org/10.1016/j.aei.2014.09.008
1474-0346/

For the survey of literature on the benefits of daylight through windows see [7].

A study of the shading effects presented in [8] showed that in hot and humid climates such as Hong Kong, daylighting is always an energy saver. In the Nordic climates, the direct solar gains can greatly reduce the heating demand during cold seasons, however, it can also cause glare [5]. It is also worth noting that: glare is much more tolerated from a daylight source than from its artificial equivalent [9], significantly less incidents of eyestrain are reported by people whose workstations received large proportions of natural light [10], and high luminance contrasts were more tolerated when the window occupied a large portion of the visual field [11].

The nature of thermal and visual comfort differ substantially. Post occupancy evaluations showed that occupant satisfaction with the room temperature correlates strongly with the possibility of the occupants to change their working environment (e.g. operable windows or temperature control of heating or cooling system) and their sensation that the environment actually changed (e.g. perceived temperature increases or decreases) [12]. On the other hand, occupants' satisfaction correlates poorly with the actual room temperature and the temperature sensation [13]. In the case of daylight control, when manually operated shading devices are available, people tend to set them and then rarely to change them. However, photocontrolled shading devices also need overriding occupant controls if they are to be accepted [14].

This conforms with the classic observation in modern psychology, that perceived control can moderate stress reactions [15]. For example, when people were given the opportunity to end an aversive noise (although they did not use it), they did not experience the negative aftereffects on task performance that were observed in people who had not had that opportunity [16].

Moreover, personal preference of illuminance levels and the degree of the glare discomfort vary, and desired quantities of additional electric light depend on the type of task and the distance from a window. For a survey of literature on how different factors influence human comfort indoors see [17].

Daylight offers a dynamic, changing pattern to stimulate the eye. It also provides a very wide range of illuminance: from 0 to over 25,000 lx. It is much beyond commonly required values which range from 10 to 1000 lx, that is from the lowest level of color discrimination to the bright appearance [18].

There are a number of systems for controlling these variances to appropriate levels. Light coming through windows can be controlled by (e.g. anidolic) blinds, louvers, sun directing glass, laser-cut and prismatic panels, light (guiding) shelves to name the most common systems. Daylight can be also harvested, usually from a roof, and redistributed inside a building with so called light pipes. For a survey of such systems see [19]. However, no universal solution exists. A daylight control system should be selected according to climatic characteristics, that is the predominant sky type and the latitude at the building site. Ref. [20] recommends that its careful integration with the rest of a building's design should begin <u>early</u> in the design process to produce a high-quality environment.

Daylight control and modeling is particularly difficult in urban areas since the illuminance on the external face of the window is not only a function of the light coming directly from the sun and sky, but also of the component reflected from the ground, and obstructions above the horizon [21].

1.2. The outside view

Traditionally, in many cultures, a window is not only the source of natural light, but as research indicates, there is a psychological need for visual contact with exterior. Views that incorporate horizon and sky are the most satisfactory, particularly after dark. In fact, night scenery of cities and their skylines seem to be equally, or even more appealing to human eye than natural scenes [22].

Importance of visual landscapes is not limited to aesthetics, but also includes a range of influences on emotional states, in other words the individuals' psychological well-being. Therefore it should be given explicit attention in planning and design decisions [23]. Positive effect of natural scenery on restorative process of surgical patients have been demonstrated in [24], and therapeutic advantages of urban scenery over natural views for chronically understimulated patients have been suggested in [25].

It seems that constructing an entirely artificial device which would satisfy all the requirements mentioned above is not economically feasible. Therefore the most realistic approach for intelligent building envelope (IBE) is to control the incoming light through natural apertures of buildings – windows.

1.3. Smart windows

Windows with dynamic optical properties seem a straightforward solution for IBE. The technology of electrochromism, liquid crystal switching and electrophoretic switching was discovered and made publicly in the 1970s and the 1980s, respectively. However, according to [26] the progress has been slow. After several decades, dynamically tintable, or so-called smart windows (SW) became available to the market. The required properties for SW for building energy control applications: solar transmission and reflection, switching voltage, memory, cycling lifetime and operating temperature at bleached and colored states have been documented in [27]. The technologies of electrochromic, gasochromic, liquid crystal and electrophoretic or suspended-particle devices were examined and compared for dynamic daylight and solar energy control in buildings in [26]. Based on surveys among architects, professionals accredited by Leadership in Energy and Environmental Design and window manufacturers, the most desired properties regarding the performance of SW are:

1. integration with other coatings, e.g. low thermal emissivity (low-e),
2. <u>glare reduction,</u>
3. <u>consistent-looking tint changes regardless of window size,</u>
4. <u>light control to any point between the dark and clear transparent state,</u>
5. <u>high blockage of UV light,</u>
6. fast switching speeds.

In the list above the properties particularly relevant to IBE and CASS are underlined. It shows that they share much of technological fields. However, due to low cost effectiveness and durability, the applications of SW in architecture are still rather sparse. According to [28], there is, however, gradually growing interest in SW among the architects due to:

1. the large scale introduction of smart glass,
2. steadily rising demand for windows and doors,
3. <u>consumer interest in quality-of-life enabling technologies,</u>
4. <u>positive impact of daylighting,</u>
5. <u>movement toward increased energy efficiency.</u>

In the list above the issues particularly relevant to IBE and CASS are underlined. It also shows similarities in architects' motivations.

However, although many SW systems are promising, none of them is truly satisfactory. For detailed analysis see [26].

As shown above, the requirements for BE are not only difficult to meet, but often contradictory. Moreover, creating buildings that can alter their appearance is one of perpetual dreams in architecture.