Energy efficient and privacy protection window system for smart home using polymer-dispersed liquid crystals glass

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ABSTRACT

Hot climates smart home system is steadily advancing recently. The main concern is energy efficiency particularly in the Arabian Gulf region. Privacy is another prioritized concern culturally. This project presents a solution for both demanded priorities implementing a polymer-dispersed liquid crystals (PDLC) glass system. The proposed design was validated via a developed prototype that was measured experimentally. Its experimental results show about 39% improvement in energy saving compared to conventional systems without depriving the indoor-outdoor connections and the privacy of the smart home inhabitants. Furthermore, it also achieves several other additional goals, for instance, decreasing cost as well as wasted energy by automatically off the lighting and air conditioning systems whenever they are not in used. Moreover, it is also capable to significantly reduce the risk of harmful exposure to ultraviolet A/B (UVA/B) of solar radiations, which conventional curtains are not capable to protect.

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1. INTRODUCTION

Among worldwide crucial problem that direly needs urgent solution is energy waste where the priority is to solve with innovative efficient or saving energy systems by improving energy usage efficiency [1]–[5]. This problem is more critical in the house design of the Arabian regions especially in the scorching and arid weather of Arabian Peninsular area that demands higher priority to indoor privacy and reducing indoor heat gain [6], [7]. Their traditional small windows are installed with a semi-transparent glass, which are covered with thick curtains. Worse, most of the windows are partially covered with opaque glass film. Hence, it disregards the window functions of natural day lighting, ventilation, and outdoor-indoor connection. These reasons motivate this study to look for an alternative window system to achieve triple functions of the windows: i) penetrating natural lighting, ii) reducing heat gain, and iii) preserving indoor privacy where the interior area is not easily visible to the exterior area or outsiders. Thus, choosing glass window system using polymer-dispersed liquid crystals (PDLC) is an ideal alternative to accomplish windows system that offers both energy efficiency and privacy. This is due to the integration of PDLC with the outdoor/indoor daylight luminance level, which automatically controls the transparency of the window glass.

Energy efficiency is a global hunt pursued by many who are continuously discovering better techniques that save more wasted energy consumption from less economical traditional ways. Speaking of the Arabian Gulf region where most of its countries usually experience extremely hot and dry weather at very high temperatures that can reach up to 54 ºC with zero humidity [8]. Accordingly, inhabitants must adapt to these challenging environments like have to adapt living in fully air-conditioned buildings, in spite of their energy and cost inefficiencies on both acquiring and maintaining the cooling equipments. Factually, residential and other type of buildings in Saudi Arabia consume approximately 76% of the national total electrical energy consumption. It seriously causes carbon dioxide (CO_2) emission that inflicts the inhabitants further with green house effects like releasing extreme heat flare in the air emerged from greenhouse gases (GHGs) as the area has the least greenery to consume the GHGs in photosynthesis process [9]. 52.1% of the proportion originated from energy consumption of residential buildings that overcome indoor extra thermal gain transferred into its interior space of buildings with traditional cooling solutions of air conditioning.

Consequently, it becomes a no. 1 priority to intervene the heat and privacy problems via window design and glass type technology. The challenge is more complicated to solve the problems of protection from thermal gain, and outsiders peeking the house interior from outside at different lighting and shade levels throughout the day. Traditionally, the transparent glasses are being covered by costly curtains or blinds or sliders or shutters for privacy and shading purposes especially for the female family members of Arabian houses [10]. Their cost is very high to acquire and maintain, plus, usually easily attract and accumulate dust especially in certain menacious dusty seasons of the year. Thus, the team members try to offer solutions being understanding to these unavoidable common problems experienced in the desert climate**.** Historically, the buildings here are identically constructed in a rectangular or cubic small and simple shapes. Although it is common for humans at any phase of history to desire for more efficiency and privacy but it was not archeologically found they implemented automated smart environmentally friendly, and energy efficient system, which is remotely controllable until after modern inventions like vacuum or washing machines were initiated [11].

The trend shifted into a more innovative era where more possibilities are realizable using automatic control on thermal and light regulation for buildings. The most common method is applying programmable thermostats. Their user-friendly design of options setting allows the users to opt their preferred temperature at its sensor boards and lighting sensor boards from inside a building. These smart windows technologies called switchable glazing are connected with temperature and lighting regulators. They can modify the light transmittance, transparency, or shading through the composed material within the windows that responds to any of these environmental stimuli: time, light, temperature, and motion (e.g., wind) [12].

In the same vein, a recent noteworthy research in [13] investigated the performance of an integrated electrochromic (EC) window lighting system in a testbed consisting of three large offices. The EC window exhibited a maximum of 0 to 3% reductions of lighting demand on a sunny day compared to the other two window types with the same daylighting controls. Lighting demands and illumination energy would be significantly higher if the referenced case had no daylighting controls like old day’s ordinary window designs. The energy saving system would be more efficient if there is occupancy sensor that responds to switch off the lighting system when nobody is in a room/space. However, to reach accurate EC controller system needs extra practical experiments. Another relevant study is as in [14] where a department of energy (DOE)-2 computerized energy simulation of a prototypical commercial office building is studied for potential EC windows and daylighting systems. The improved EC windows were compared to a broad range of static window types usually opted for climate zones in the USA, specifically in California. The experiments confirmed the initial optimized simulated assessments that the adjustable prototypes have potential to be implemented onto buildings located in moderate to hot climates that previously constructed with large areas of non-tinted windows facing different directions of the compass regardless of the construction factors: window material type, orientation, size, or climate of the building.

Other noteworthy reference is a smart controlling system that regulates over-heating, ventilation, and air conditioning (HVAC) altogether [11]. The combination of control is more energy saving for regulating based on inhabitants’ coziness. Unfortunately, the HVAC smart systems comprised of a large number of maintaining sensor points to function in real time relying on a cloud-based system to remotely control, which inevitably increased design complication and cost. Apart from that, another smart glass window project reported in [15] was using a type of smart materials in the building construction and finishings. It differently contributes to the building inhabitants’ coziness at higher energy efficiency at less energy consumption but gained better technical performance from its simpler management of direct sunlight and glare. These developments demonstrated constant utility advancements of the smart glass technology. It is among practical and cost efficient choice of the architectural and engineering companies to suggest to their cost and energy conscious consumers who prefer sustainable livable healthier environments [16] by minimizing energy consumption and waste. This idea is materialized in the proposed smart system utilizing PDLC glass windows.

2. METHOD

The proposed energy-saving smart system is shown in the block diagram as in Figure 1. The system comprises of liquid crystal display (LCD) interface that shows responses from programmed Arduino, which is connected to light dependent resistor (LDR) sensor, passive infrared (PIR) motion sensor, and digital humidity and temperature (DHT) sensor that regulate together the PDLC glass and light emitting diode (LED). An Arduino is an open-source platform [17]–[19] used to simply combine programmable electronics circuits like in [20]–[24]. The Arduino controls the transparency percentage of the PDLC glass adjusting to the amount of sunlight and inhabitants' motions within the room. The proposed system is illustrated in Figure 2 where the entire electrical circuit components are clarified. Table 1 illustrates a test model scenario responding to different sky conditions. Where the recommended lux level for residential spaces 200-500 lux.

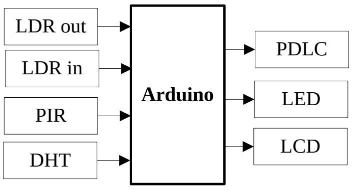


Figure 1. Block diagram of the proposed system

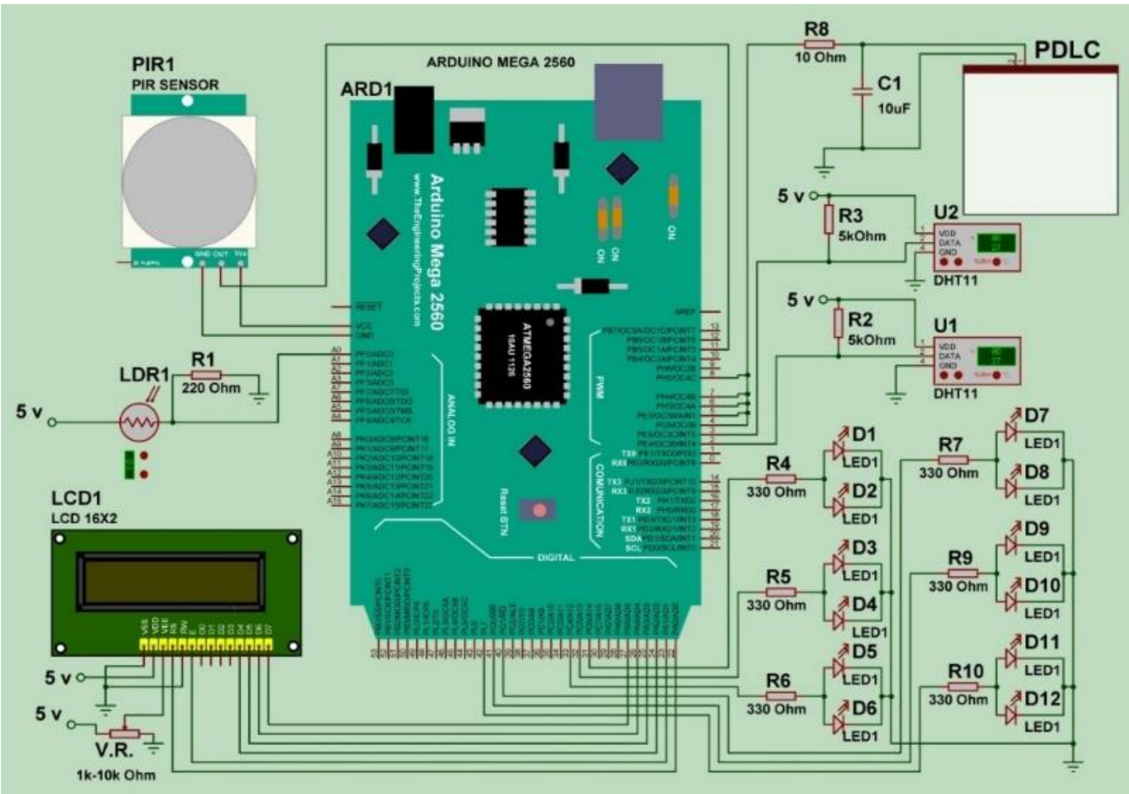


Figure 2. Electrical circuit of the proposed smart PDLC window system

The proposed smart PDLC window system flowchart of the workflow is shown in Figure 3: i) the motion sensor distinguishes whether the room is empty or occupied, ii) whenever sensed it is occupied, the sensor automatically signals so to the Arduino, iii) the Arduino responds to the light sensor to regulate shading-transparency percentage on the PDLC glass adjusting to the amount of sunlight outside the room for privacy purposes, and iv) it has complete isolation function that responds to switch OFF the PDLC glass when no sunlight is detected by the light sensor.

Table 1. Model test scenarios according to different sky conditions

Scenarios	Outdoor range, lux	Prototype range, lux	Transparent %	Privacy	Energy saving	
					Preventing heat	Daylighting
1	300-500 lux sunrise/Sunset	≤ 10	0.0% Off	Yes	----	No
2	500-5000 lux	10-150	25%	Yes	---	Yes
3	5000-15000 Overcast	350-450	50%	Yes	----	Yes
4	15000-40000	150-350	25%	Yes	Yes	Yes
	10000-20000 Partly-cloudy					
5	20000-100,000lux clear sky-Direct sun light	≥ 450	0.0% Off	Yes	Yes	Yes
6	NA	On-Off	100%	Custom for outdoor connection		

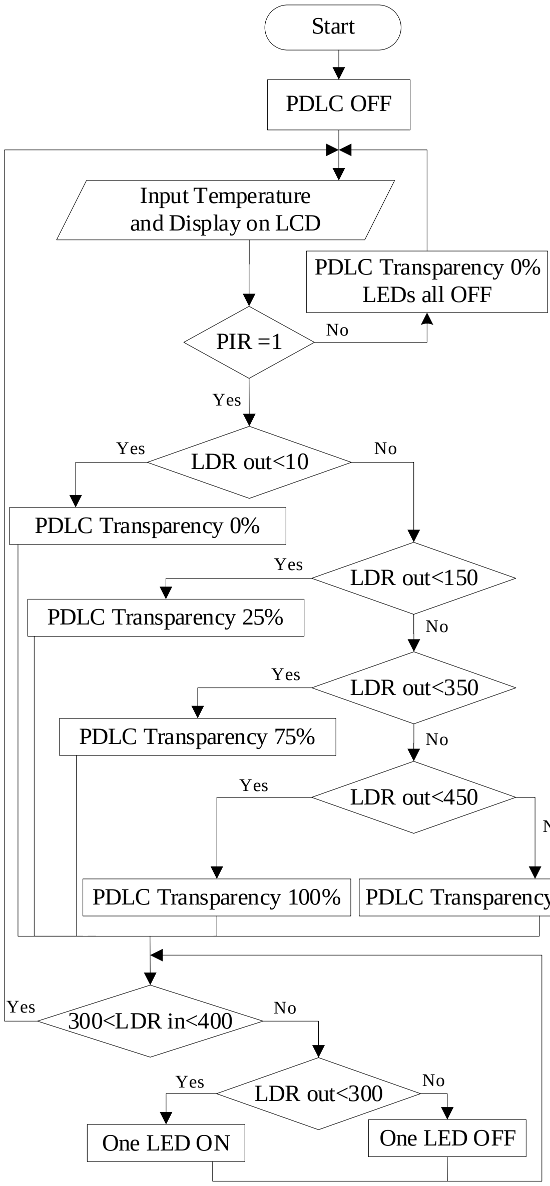
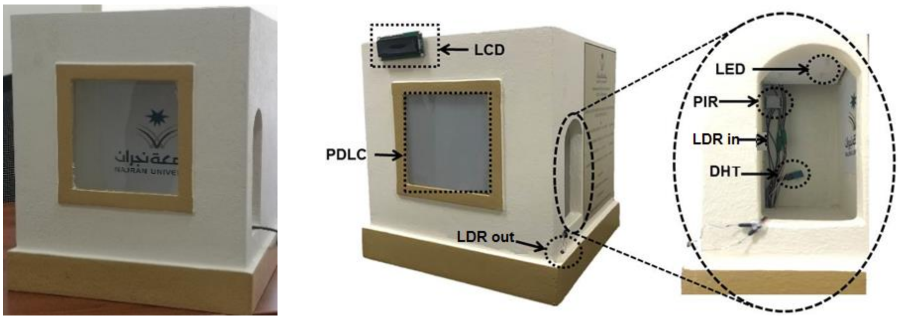


Figure 3. The workflow of the proposed smart PDLC window system

The design method of the proposed smart system was fabricated in a small-scale environmental test-cell (1:10) prototype for validation. The prototype encompassed these components: PDLC, LED, LCD, Arduino, LDR, PIR, and DHT, which is shown in Figure 4 see in Figures 4(a) and 4(b). A photograph of the circuit system design is shown in Figure 5. The PDLC transparency is the relied output that depends on the PIR to signal detected motion to auto-run the system where the LDR sends signaled data of the illumination intensity outside the room to determine the film shading-transparency percentage.



(a) (b)

Figure 4. Photographs of the tested system (a) reference cell and (b) perspective view of the proposed system

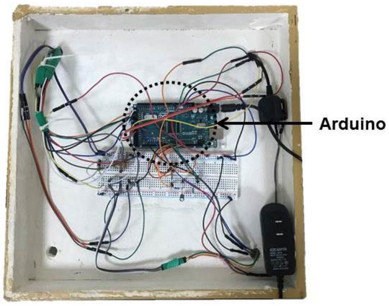


Figure 5. Photograph of the circuit system design

The smart PDLC window system functions: i) the motion sensor distinguishes whether room is occupied or empty; ii) whenever the room is occupied, the sensor will notify the Arduino so (data available); iii) the Arduino corresponds to the light sensor (LDR-out) to regulate according to sunlight exposure; iv) any sunlight illumination, will respond to a certain shading-transparency percentage on the PDLC glass as shown in Table 1; v) the shading-transparency percentage corresponds to the intensity of outdoor illumination that it is adjusted by passing different voltages based on sunlight exposure percentage; vi) if there is no sunlight sensed, thus, the light sensor will not increase voltage. Consequently, the PDLC glass will be switch OFF i.e., in complete isolation; vii) certain number of lamps will be switched ON corresponding to the transparency ratio and the amount of sunlight illumination detected by the LDR-in; viii) if the LDR-in detects light less than 10 lux, so, 6 LED (all) lamps will be switched ON; ix) if it detects light between 10 to 150 lux, so, 4 LED lamps will be switched ON; x) if it detects light between 150 to 350 lux, so, only 2 LED lamps will be switched ON; and xi) if it detects light more than 350 lux, so, all LEDs will be switched OFF.

3. RESULTS AND DISCUSSION

The design method of the experimental PDLC smart window system is shown in Figure 6 to testify its claimed privacy and energy efficiency. Initially the PDLC film is completely transparent as being exemplified in the Figure 6(a) where the palm-like icon in the tintable film (left) is highly visible when the outdoor sunlight illumination level is between 350 lux and 450 lux. Meanwhile, when the LDR sensor detected a small amount of sunlight, it adjusts the PDLC into a slight shaded windows with 2 lights are switched ON as in the Figure 6(b). That means the outdoor sunlight illumination is between 150 lux and 350 lux. However, when the outdoor sunlight illumination is detected more than 450 lux, so, the PDLC will be 50% shaded where 4 lights are switched ON to maintain the lux needed inside the room and prevent harmful sunlight exposure as in the Figure 6(c). Lastly, when the sunlight illumination is less than 10 lux where the PDLC will be 100% shaded, and nothing is visible through the window, so, all the lights are switched ON as in the Figure 6(d).

After the prototype was tested both results of temperature (cooling) and lighting energy savings were favorably achieved. The temperature in the smart room is reducible by close to three degrees within ten minutes' duration, as illustrated in Figure 7. In addition to that, the efficiency of lighting power consumption was significantly improved as shown in Figure 8. When the conventional and the smart room lighting were being compared to verify its design validity, we embarked the comparison at the LED consumption of 75 mw per hour according to the datasheet in [25]. The energy consumption is further studied comparatively in details on the lighting usage between the conventional and the smart lighting that is calculated in watts per day. We discovered that the power consumption of the conventional lighting will be 75 mw×6 LEDs×24 hours=10.8 watts per day. Interestingly, the observed results of the smart lighting are as follows under clear sky condition as shown in Table 1: i) initially, all LEDs are switched OFF from 9:00 a.m. to 3:00 p.m. at the power consumption of zero; ii) when 2 LEDs are switched ON from 7:00 a.m. to 9:00 a.m. and from 3:00 p.m. to 5:00 p.m., the power consumption is calculated at 75 mw×2 LEDs×4 hours=0.6 watts per day; iii) when 4 LEDs are switched ON from 6:00 a.m. to 7:00 a.m. and from 5:00 p.m. to 6:00 p.m., the power consumption is calculated at 75 mw×4 LEDs×2 hours=0.6 watts per day; and iv) when 6 LEDs are switched ON from 6:00 p.m. to 6:00 a.m. the power consumption is 75 mw×6×12=5.4 watts per day; and iv) therefore: the power consumption for the smart room=5.4+0.6+0.6=is equal to 6.6 watts per day.

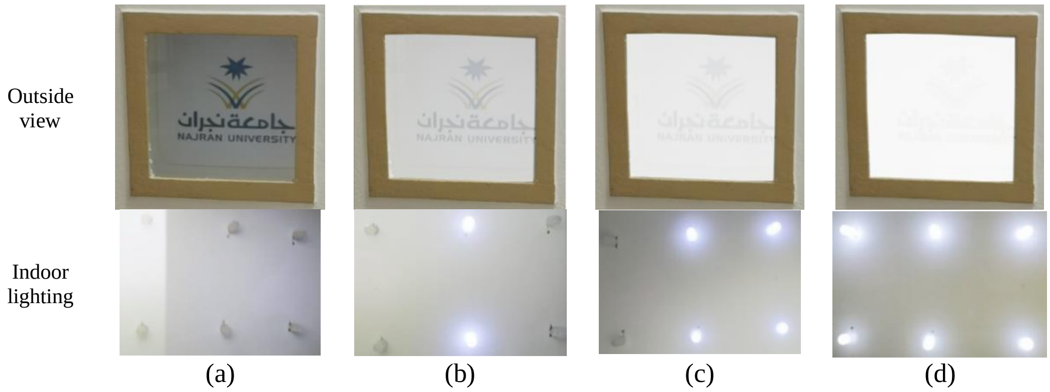


Figure 6. Transparency experimental illustrations of the proposed system

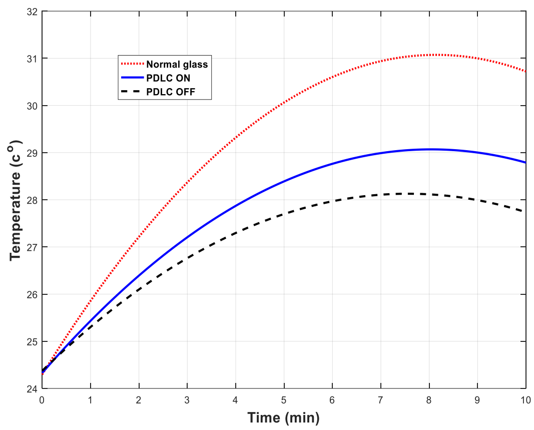


Figure 7. Temperature versus time

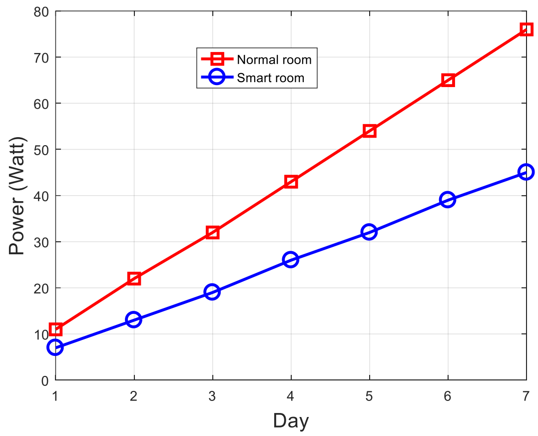


Figure 8. Power consumption with and without PDLC glass

In comparison, the conventional lighting used 10.8 watts per day whereas the smart lighting only used 6.6. watts per day at energy saving about 4.2 watts of energy per day, which saves about 40% more energy. The measured results also showed cost effective benefit. When evaluating these results, the limitations must be considered to supply further research in the future for improvement ahead. However, the use of reduced scale models commonly leads to an over/under-estimation of data with respect to those collected in reality. It is, therefore, preferable for future research to carry out tests in a real case study under real weather condition to verify the results accurately. Moreover, it is advisable to examine the integrated PDLC with a low-e glass as a smart double-glazing system in order to attain more targeted energy efficiency together with home privacy in a real arid climate area and also by sampling different durations for all possible weather changes of its area.

4. CONCLUSION

This paper shared an innovative design method of a smart PDLC glass window for building privacy protection and energy efficiency. It is fully automated adjusting into either a fixed or varied programmable schedules, which can be remotely controlled; apart from being manually determined at the user's shades, timer and lighting of choice. The system depends on the sun movement or sunlight exposure percentage of a building throughout the day from any direction of the building, which is detectable by a programmable Arduino light sensor. This is beneficial for predictable weather patterns areas especially for those who prefer smart windows over traditional curtains or blinds or shades to save on their costly acquisition and maintenance. The system is useful to control daylight illumination, sunlight exposure, and heat gain control according to the weather changes. Conclusively, the simulated and measured results are in a good agreement where the latter productively gains approximately 40% of energy saving compared to the standard systems (reference systems). It proved its claim of reducing energy consumption, waste and overall costs from its automated lighting based on outdoor illumination percentage. It is also suitable for local cultural privacy control, which is highly desirable in the Middle East and the most exclusive feature of the design. Healthily speaking, it also significantly filters the harmful UVA/B solar rays. What a remarkable invention was suitable for the Arabian culture.

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