Internet of things-enabled smart controller for polymer dispersed liquid crystals films

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Article Info

Article history:

Received Jun 29, 2022
Revised Jan 2, 2023
Accepted Feb 26, 2023

Keywords:

Blynk application
If this then that
Internet of things
Light dependent resistor
Passive infrared sensor
Smart controller
Voice-command control

ABSTRACT

The evolvement of smart glass technology has gained a lot of interest through its energy-saving potential as one of the heating, ventilating, and air-conditioning (HVAC) system. This paper focuses on polymer dispersed liquid crystal (PDLC) film, a smart glazing film that changes its opacity in response to an electrical impulse. The power consumption of the smart film is considerably small. However, improper handling of the smart film such as not turning off the film after usage can lead to energy wastage. Hence, connecting the smart film to an internet of things (IoT) controller would be one of the possible solutions to ensure that the film is maintained properly. The objective of the work here is to develop a smart, low cost and efficient IoT-enabled smart controller for PDLC films with energy-saving features. In pursuance of materializing this concept, this paper delineates the design of a smart controller for the PDLC films. The implementation of the IoT features, NodeMCU, and environmental sensors enabled the smart film to be capable of switching automatically. In addition, voice-command features were also incorporated into the controller. With the successful development of the IoT smart controller, the PDLC films can operate autonomously and wirelessly.

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1. INTRODUCTION

It has been reported that approximately 50% of all electrical energy supplied to buildings is used for heating, cooling, and lighting the building's interior [1]. This is because traditional windows are unable to block the near-infrared (IR) light emitted by the sun from entering indoor spaces [1]. Therefore, to solve this problem, a smart energy-saving solution has been implemented, namely the introduction of smart glass. Smart glass is commonly known as switchable glass because it can dynamically control the transmittance of the glass by reversibly switching between a transparent state and a blocking state [2]. The amount of light that can penetrate through the glass is determined by the transparency of the glass. Smart glass can be categorized into either passive or active technology [3]. Photochromic and Thermochromic are two types of passive smart glasses that respond to non-electrical stimuli [4]. On the other hand, polymer dispersed liquid crystal (PDLC), electrochromic, and suspended particle devices (SPD) are active smart glasses that require electrical voltage stimuli to operate and change their transparency [5].

Out of the different variations of smart glasses, PDLC is one of the most popular smart glasses due to its wide range of applications. PDLC can be used as partitions in meeting rooms [6] and to replace traditional bathroom doors [7]. PDLC can be also used to shield residential and commercial buildings from Sunlight [8], and to allow the flow of natural daylight into the room when incorporating it into hospital wards [9]. When installed onto the windows of automobiles, PDLC films can protect the passengers from the external infrared radiation emitted by the Sun hence providing more comfort [10], [11].

PDLC exists in the form of film that is sandwiched in between glasses to form a smart glass [12]. PDLC film is composed of encapsulated liquid crystal microdroplets dispersed in a polymer matrix [13]. The transparency of the PDLC film depends on the alignment of the liquid crystal [13]. When electricity is applied to the polymer matrix, these liquid crystals will realign themselves in the direction of the electric field [13]. This causes incident light to penetrate through the film hence it appears transparent. On the other hand, in the absence of electrical stimuli, the liquid crystals will be randomly arranged thus scattering the incident light falling onto the film [13]. This phenomenon causes the film to appear opaque.

The internet of things (IoT) is a concept that allows seamless communication between sensors and electronic devices to ease human lives [14]. With IoT, devices that previously worked independently can now be connected to the internet to improve their efficiency. The efficiency can be increased even further by increasing the controllability of the devices remotely [15].

Prior experimental work had been conducted with a similar concept as this paper. Jabbar *et al.* [3] had developed an Android application to remotely control the switching of a PDLC film. The PDLC film was applied to glass in their prototype, and the electronic hardware circuitry was controlled by an Arduino microcontroller [3]. The Arduino microcontroller and the Android application communicated with each other using a Bluetooth connection [3]. Furthermore, a light dependent resistor (LDR) sensor was also integrated into their circuit design to identify the illuminance during the ON and OFF states of the PDLC film [3]. In their prototype, the sensor would continuously monitor the environmental light intensity, i.e., sunlight. The intensity of the sunlight would be measured in terms of lux and the data would be transferred to the smart controller from the LDR sensor via Bluetooth [3]. The user would be able to observe the real-time light intensity of sun illumination in the interface of their controller. Based on the illuminance, the sensor would automatically change the switching of the film to reduce sunlight penetration or, the user could also manually switch the opacity of the PDLC film.

Another work by Alghamdi and Almawgani [16] presented a similar system. In their prototype, the system functions automatically with the assistance of various sensors [16]. The sensors that were implemented in their system are the LDR sensor, passive infrared (PIR) sensor, and a digital temperature and humidity (DHT) sensor [16]. In their proposed system, the LDR and PIR sensors are continuously monitoring and collecting data from the surrounding conditions. The PIR sensor is responsible for detecting the motion of people entering the room of the residence [16]. If a motion is detected, the Arduino would trigger the LDR sensor to determine the environmental light intensity. Based on the intensity of the illuminance detected by the LDR sensor, the Arduino microcontroller would trigger the PDLC film to change its transparency. Researcher Uranus [17] also developed a smart IoT-based PDLC system that can be operated by either voice command or by using the developed mobile application installed in their smartphone. Once a command is entered into the smartphone using a virtual assistant, i.e. google assistant, the request will be sent to an if this then that (IFTTT) server followed by the Blynk IoT server [17]. Next, the command is transferred to the Arduino microcontroller from the IoT server, which in turn triggers the PDLC film to switch its opacity [17]. In their system, the Arduino acts as an IoT node, hence, it would continuously monitor the IoT server for any commands sent by the user [17]. If a command is detected, the microcontroller would generate a pulse width modulation (PWM) signal with an equivalent duty cycle to either activate or deactivate the film [17]. If the user wishes to operate the PDLC film manually, they could perform this action by manually pressing the button inside the developed Blynk application.

Although the concept of these prior works is similar to the idea of this paper, the proposed solutions did not consider the actual implementation of the solutions as a commercial product. The prototype and systems designed by the researchers utilized a small-sized commercial PDLC film that was operated without a step-down transformer. This limitation is shown in Table 1. Whereas in commercial implementation, PDLC films installed for various applications have larger dimensions, and several films are connected in a parallel configuration. Hence, a step-down transformer is needed to reduce the voltage from the mains and supply it equally amongst all the PDLC films. It is the intention of this paper to demonstrate an integration of IoT technology into real-life PDLC film implementation such that the developed solution can be deemed commercially viable with implementation readiness. The actual real-life implementation of the PDLC films was emulated whereby multiple PDLC films were connected to a step-down transformer and a relay module. The relay module is responsible for turning on or off the PDLC films. To allow the user to control the switching of the relay wirelessly, the design of an IoT-enabled smart controller for PDLC films with energy-saving features is also depicted which can be incorporated for commercial applications of PDLC films on building fenestrations.

Table 1. IoT-based smart controller for smart film developed by previous researchers

Researcher	Type of smart film	Number of films implemented	Microcontroller	Sensors	Limitations
Jabbar and Zaki [3]	PDLC	1	Arduino	LDR	- The prototype consisted of a single PDLC film, whereas in the real-life implementation, multiple large-sized films are connected in parallel to each other. - The PDLC film cannot be remotely controlled as Bluetooth is used instead of Wi-Fi to operate the film.
Alghamdi and Almawgani [16]	PDLC	1	Arduino	LDR, PIR, and DHT	- The prototype consisted of a single PDLC film, whereas real-life implementation requires multiple large-sized PDLC films which are connected in parallel - Lack of a smart controller to operate the films wirelessly
Uranus [17]	PDLC	1	Arduino	None	- The researcher did not implement any sensors into their PDLC system, thus, there is no scope for autonomous operation of the films. - The developed system was tested on a single small-sized PDLC film which is not viable for commercial implementation.

2. RESEARCH METHOD

2.1. Proposed block diagram

Most PDLC smart film requires the users to switch the film on and off manually. The proposed smart controller allows the user to control the switching of the PDLC film just at the end of their fingertips no matter the distance between the user and the film. Figure 1 illustrates the proposed block diagram of the energy-saving smart system for switching the opacity of the PDLC films using an IoT-enabled smart controller. The main components of the system are NodeMCU LoLin V3, PIR motion sensor, LDR sensor, 30 W step-down transformer with a 60 VAC output, 5 V-single-channel relay module, 5 V adapter, Blynk android application, IFTTT automation tool, and PDLC films.

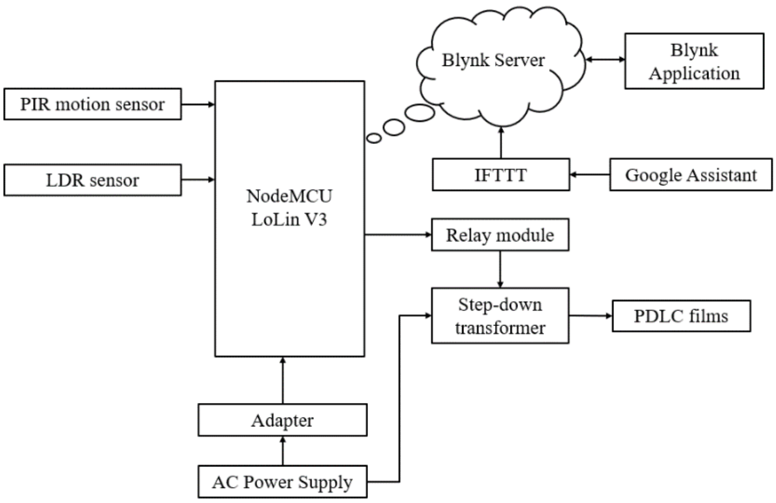


Figure 1. Block diagram of the proposed system

In the proposed intelligent system, alternating current (AC) voltage from the mains is fed into an adapter and a step-down transformer. The adapter reduces the voltage to 5 V and sends it to the NodeMCU LoLin V3 to power up the device while the step-down transformer decreases the input voltage from 220 VAC to 60 VAC to operate the PDLC films. The NodeMCU microcontroller in the system is responsible for enabling wireless communication between the PDLC films and the smart controller. With the integration of sensors such as the PIR motion sensor and the LDR sensor into the smart system, the PDLC films can switch automatically based on environmental conditions. Next, the relay module that is connected to the NodeMCU serves as a switch in the smart system. Based on the signal from the microcontroller, the relay module can either open or close the hardware circuit. Furthermore, the Blynk application allows the user to control the PDLC films remotely through their smartphone. Lastly, IFTTT has also been integrated into the smart system to allow the user to operate the PDLC films using voice commands with the aid of Google Assistant.

2.2. Hardware design

The hardware design consists of a series of components that are interconnected to each other in order to operate the switching of the PDLC films. The components that are incorporated into the hardware design are the NodeMCU LoLin V3 microcontroller, PIR motion sensor, LDR sensor, 5 V-single-channel relay module, 30 W 60 VAC step-down transformer, and a 5 V adapter. Figures 2 and 3 show the circuit and schematic diagram of the hardware connections to operate the PDLC films respectively.

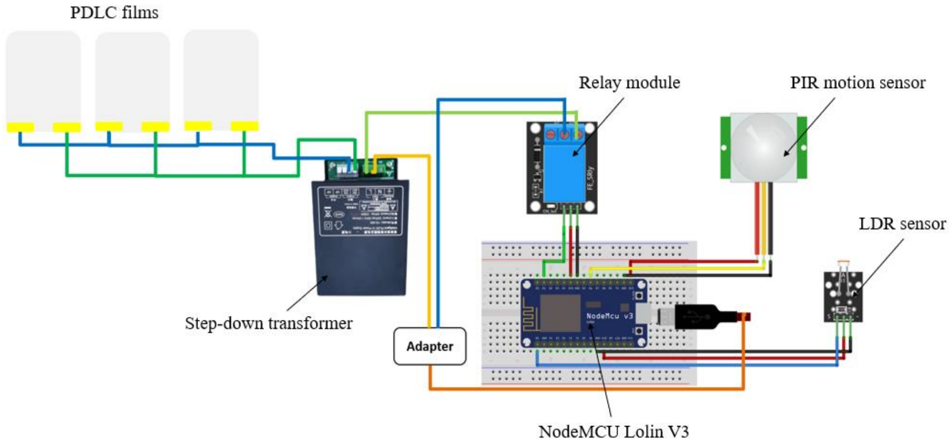


Figure 2. Circuit diagram of the hardware connections to operate PDLC films

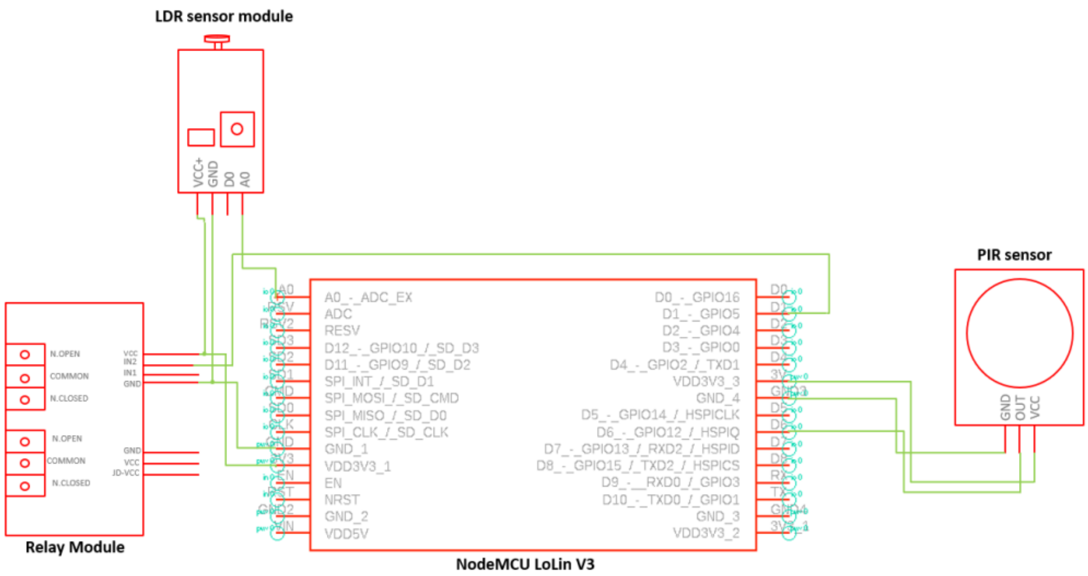


Figure 3. Schematic diagram of the hardware connections to operate PDLC films

The microcontroller used in this project is NodeMCU LoLin V3. NodeMCU is an open-source firmware based on Lua with its development board [18]. In the proposed system, the NodeMCU microcontroller is acting as the brain of the system. It retrieves and exchanges data between the environmental sensors and the smart IoT controller. The relay module acts similar to a regular switch, whereby it can open or close its contacts based on the DC current supplied to it [19]. In the hardware system, the relay module is responsible for controlling the switching of the PDLC films. The sensors that are incorporated into the system are LDR and PIR sensors. LDR sensor detects the surrounding light intensity and changes its resistance value according to the light intensity [20]. Hence, if the LDR sensor detects a high intensity of environmental light, it would trigger the PDLC films to turn opaque. On the other hand, the PIR sensor detects motion within its proximity by detecting the emitted infrared energy by objects [21]. In the developed system, if a motion is detected by the PIR sensor, it would trigger the PDLC films to turn transparent. Whereas if no movement is detected within its proximity, the PDLC films will be triggered to turn opaque. Additionally, a step-down transformer was also included in the system, as the device is capable of lowering drop the input voltage [22]. The transformer reduces the main voltage to 60 VAC as it is the operating voltage of the PDLC films.

2.3. Performance testing of the environmental sensors

The sensors used in the PDLC smart system are the PIR motion sensor and LDR light sensor. These sensors were responsible for monitoring the surrounding conditions and responding to them. A set of experiments was conducted to identify the performance of these individual sensors. The experimental procedure that was carried out to test the PIR sensor is shown in Figure 4 [23].

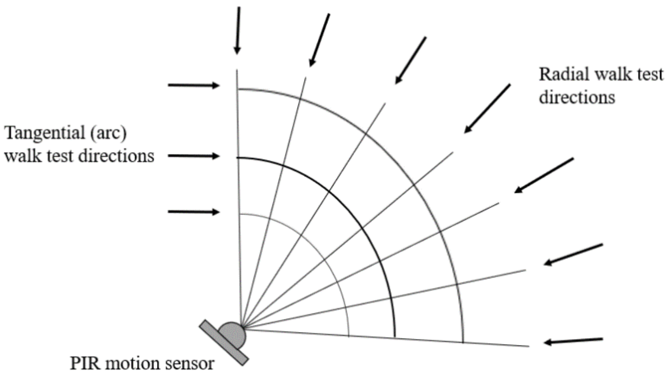


Figure 4. Performance testing of the PIR sensor in the PDLC system [23]

During the tangential walk test, firstly, the test object was outside the detection area of the PIR sensor. The detection area of a commercial PIR motion sensor is approximately 110^{o}, thus the test was conducted within this range. When the user was outside the detection area, the sensor did not detect any motion, hence the PDLC films were in the OFF state. Next, the user would walk 1 foot at a time along the path till the sensor detects the motion [23]. As the motion is detected, the user would stop walking and mark the position [23]. Then, the user would return back outside of the detection area to ensure the PIR sensor is reset. This test was repeated several times for each of the tangential walk test directions. This is to ensure that the PIR sensor was not defective and was in optimal working conditions.

Once the tangential path was tested, the next test involved walking in the radial direction [23]. Similar to the previous test, the user would initially stand in front of the sensor. The sensor would detect the user thus turning on the PDLC film. The user would then keep walking backward till the PIR sensor no longer detects any motion, causing the PDLC to turn off. This position would be marked as the furthest distance the sensor can detect till. Next, the user would walk along the radial paths 1 foot at a time from the maximum distance till the sensor detects the motion [23]. Once motion is detected, the position is marked, and the user would return back to its original position so that the sensor would reset itself. This test was performed multiple times along the different paths to ensure that the sensor is reliable and capable of sensing motion within its radial paths.

To carry out performance testing on the LDR sensor, a table lamp was used as the source of light during the experiment. The lamp was kept closest to the LDR sensor at the beginning of the experiment. These procedures were carried out in a dark room to prevent any external light source from affecting the accuracy of the results. Once the setup was prepared, the LDR sensor was turned on using the smart controller and the light intensity was set using the Blynk application. Initially, the LDR sensor would detect high intensity of light, hence causing the PDLC to turn off. Next, the lamp was moved away from the LDR sensor 1 foot at a time. As the lamp was being moved, the detected illuminance by the sensor was constantly monitored by observing the values displayed on the smart IoT controller. This step was very crucial to ensure that the LDR sensor was functioning in its optimum condition. If the sensor was detecting lower light intensity as the lamp was moved 1 foot backward at a time, it indicates that the sensor is sensitive to changes in incident light intensity. The whole procedure was repeated multiple times whereby, each time the lamp was moved away from the LDR sensor one step at a time till the sensor no longer detects any incident light.

2.4. Software design

The IoT smart controller that was developed to control the opacity of the PDLC films was designed in an application called Blynk. This application allows the user to add widgets based on the requirement of the prototype. Additionally, an automation tool called IFTTT was also incorporated into the software design to enable voice control of the PDLC films. This was possible with the aid of the android virtual assistant, Google Assistant. Figure 5 illustrates the flowchart of the IoT smart controller system.

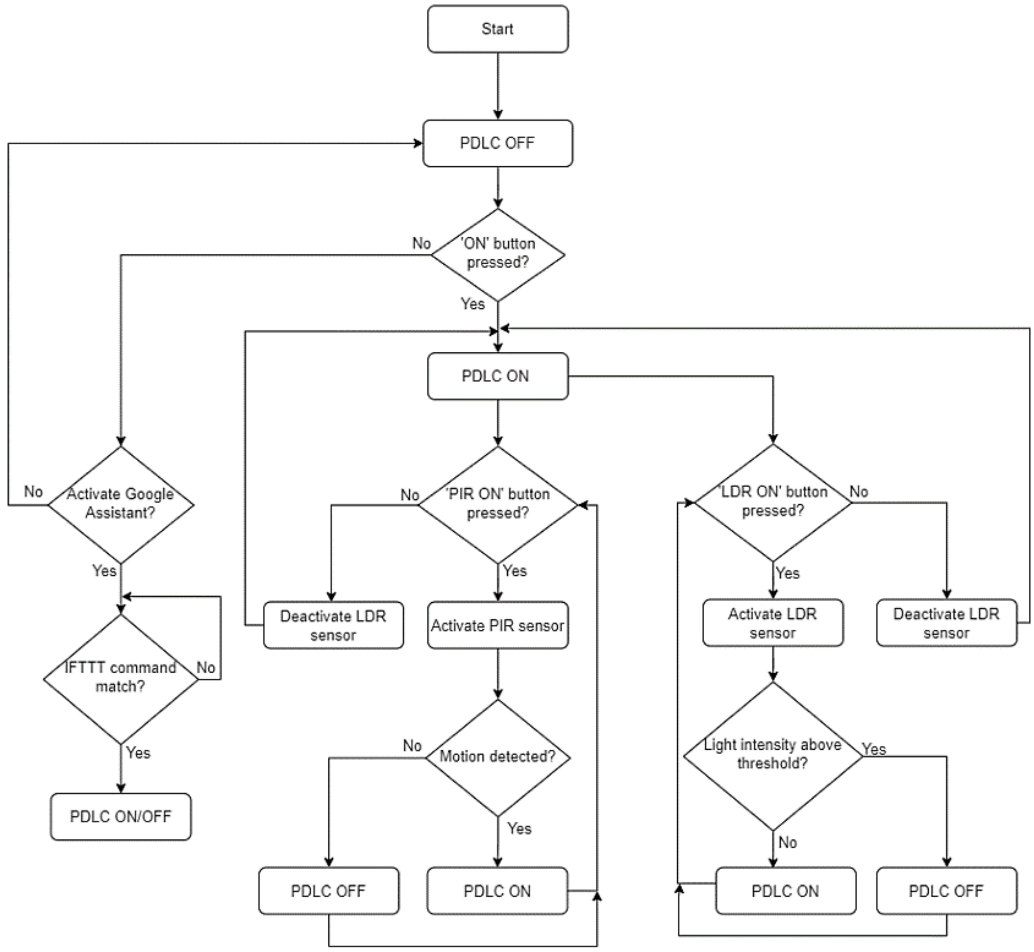


Figure 5. Flowchart of IoT smart controller system

Using the smart controller to operate the PDLC films, the user has the option to either turn on the PIR and LDR sensors or deactivate them. If both sensors are deactivated, the switching of the PDLC films will be controlled based on the ON/OFF button in the Blynk app. On the other hand, if the PIR sensor is activated, the sensor will continuously monitor any movements in its surrounding. If a motion is detected, the sensor will trigger the PDLC films to turn on, while in the absence of motion, the PDLC films will turn off. Similarly, when the LDR sensor is activated, the sensor will constantly monitor the ambient light intensity in the surrounding. If the surrounding light intensity is higher than the limit set by the user, the PDLC will turn off to shield the interior of the building from the incident light. Whereas, if the ambient light intensity is lower than the light intensity limit, the PDLC will turn on. Apart from this, if the user decides to operate the PDLC films without any smart controller, they could use Google Assistant to control it. By voicing out specific commands such as 'turn on smart window' or 'turn off smart window', the user can change the transparency of the films. If the commands entered by the user do not match the pre-set commands in the IFTTT application, the google assistant will not identify the instructions hence the PDLC films will not switch their opacity.

2.4.1. Blynk application

Blynk application is software that can be installed on both android and iOS mobile phones to wirelessly control devices such as NodeMCU, Raspberry Pi, and Arduino via the internet. In addition, the software can display and store the data collected by various sensors [24]. The Blynk application also allows the user to add and customize widgets in the software based on his needs [24]. For the Blynk application to send or retrieve data from the IoT devices, it has to communicate via the Blynk server [24]. Blynk server can be run privately and locally [24]. In our project, the smart controller to operate the PDLC films was designed inside the Blynk application.

2.4.2. If this then that

IFTTT is a web-based platform that allows various digital services to interconnect with each other over the internet [25]. Examples of services are Amazon, Google, smartphones, credit cards, and more [25]. To configure the IFTTT service, the user needs to specify the conditions and the consequence that occur if the conditions are fulfilled [25]. In this project, two conditions were set up in the IFTTT, which are “turn on the smart window” and “turn off the smart window”. If either of these commands is voiced by the user into their smartphone, the relay module will be triggered thus causing the PDLC films to switch their transparency.

2.4.3. Google assistant

Google Assistant is a voice-controlled virtual assistant from Google [26]. This application is available on any smartphone including Android and iOS smartphones. Google Assistant is embedded with a feature that allows the user to issue commands on their device via voice command [27]. This is a great alternative to manually controlling the applications. In addition to this, Google Assistant is also capable of two-way communication with the user [26]. Hence, by giving instructions to the virtual assistant, it will immediately respond to the commands. In our proposed system, we were able to communicate with the IFTTT service with the aid of Google Assistant. Entering voice commands into the Google Assistant application then sends the commands to IFTTT where they are compared to the pre-set commands. If the commands match, the corresponding actions are taken, i.e., turning the PDLC films on or off.

2.5. Network delay test

A test was performed to record the time needed for the PDLC film to switch its transparency after its corresponding button is pressed on the Blynk mobile application. A significant amount of delay was noticed as the experiment was conducted. This is because as the button was pressed in the Blynk application, the data was transmitted to the Blynk server, from where it was transferred to the NodeMCU microcontroller. After that, the NodeMCU sent a signal to the PDLC film to operate it. The average delay that occurred due to these processes was approximately 2.21s. The delay test was repeated several times and the recorded delays are shown in Figure 6.

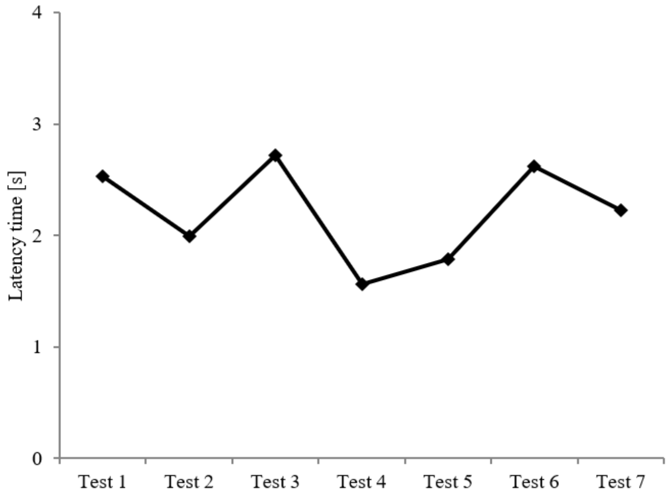


Figure 6. The latency time for the PDLC to operate upon button press in the Blynk app

Although the delay is in terms of seconds, however, it is an acceptable value. This is because there is no negative impact of having a delay in the smart IoT-based PDLC system. Even with the presence of the delay, the overall functionality of the IoT system remained unaffected. As long as the PDLC films can be operated remotely using the developed smart controller, the delay in the system is of less importance.

3. RESULTS AND DISCUSSION

A prototype has been assembled on the hardware circuit. This prototype consists of the circuitry components connected to the PDLC films. Figure 7 shows the hardware connections enclosed within a 3D-printed package. Figure 8 shows the complete packaged prototype connected to three PDLC films. These PDLC films are pasted onto a large acrylic sheet.

The hardware circuit connections were made according to the proposed block diagram, with the relay module, PIR motion sensor, and LDR sensor being connected to the pins of the NodeMCU LoLin V3 microcontroller. The microcontroller was powered by a 5V adapter. The output of the relay module was connected to a 30 W step-down transformer, and the output of the transformer was connected to the busbar of the PDLC films. Three PDLC films were used in this setup and the films were connected in parallel to ensure that equal voltage is being applied to each PDLC film. Additionally, the PDLC films were pasted onto a large acrylic sheet to test the prototype as if it were implemented in a real-life application. Figure 9 shows the PDLC films in their opaque and transparent states. Figure 9(a) demonstrates the prototype of the PDLC system in the "OFF" state, while Figure 9(b) demonstrates the prototype in the "ON" state.

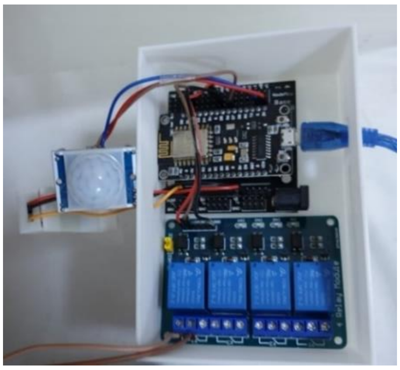


Figure 7. Hardware connections enclosed within a 3D printed package

Figure 8. Complete packaged prototype connected to PDLC films

(a) (b)

Figure 9. Prototype of the PDLC system in the (a) "OFF" state and (b) "ON" state

Figure 10 shows the interface of the smart controller. This smart controller was designed to operate the PDLC film wirelessly through Wi-Fi. The controller was developed using the Blynk application, which is available on Android smartphones.

The smart controller has been customized with several widgets programmed to perform specific functions. Firstly, there are three ON/OFF buttons to turn on/off the PDLC films, the PIR motion sensor, and the LDR sensor. The buttons have each been color-coded with different widget colors to make it easier for users to grasp the application's user interface (UI). When the user presses the ON button for PDLC, the user also has the option to turn on either the PIR or LDR sensor as well, depending on the area of application of the films. In the scenario where the PIR sensor is turned on by the user, the sensor starts working and continuously monitors any movement in its vicinity. On the other hand, if the user wants to use the LDR sensor, they need to turn off the PIR motion sensor and then press the LDR sensor ON button. Next, the user must set the light intensity limit that he desires. This can be done with the slider that can be moved from 0 to 100 light intensity limit. In addition, a gauge widget has been added to the smart controller, which constantly displays the ambient light intensity detected by the LDR sensor when switched on.

In Figure 11, images are taken of the different methods used to operate the PDLC films wirelessly. Figures 11(a) and (b) show the user controlling the PDLC films directly using the ON/OFF button. When the user presses the ON button in the Blynk application, the button widget will be in the ON mode. As long as the button is in this mode, the PDLC films remain transparent. If the user decides to turn off the PDLC films, the widget button has to be pressed again, which turns the button to OFF mode.

In the next figure, Figures 12 (a) and (b), the user is operating the PDLC films transparency using the LDR sensor. To operate the LDR sensor, the corresponding sensor button has to be pressed in the Blynk application. Next, the user must set the desired light intensity limit by utilizing the slider widget. The slider allows the user to choose a limit between 0% to 100%. If the limit selected by the user is greater than the surrounding light intensity, the PDLC films become transparent whereas if the limit is less than the surrounding light intensity, the PDLC films become opaque.

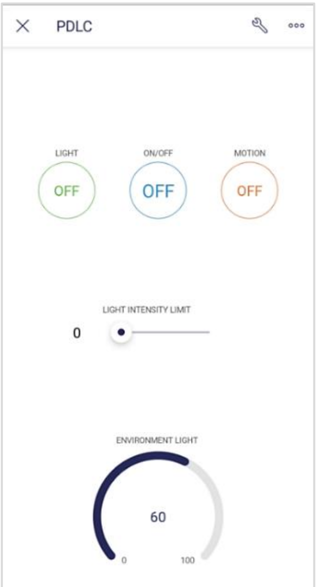
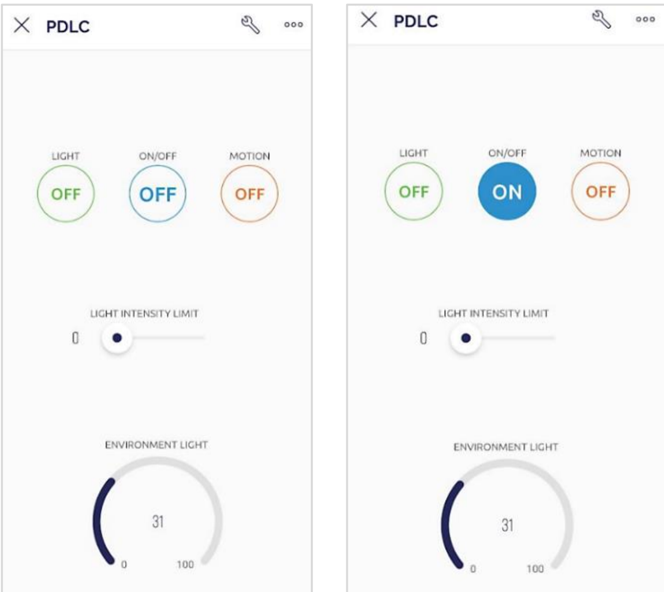
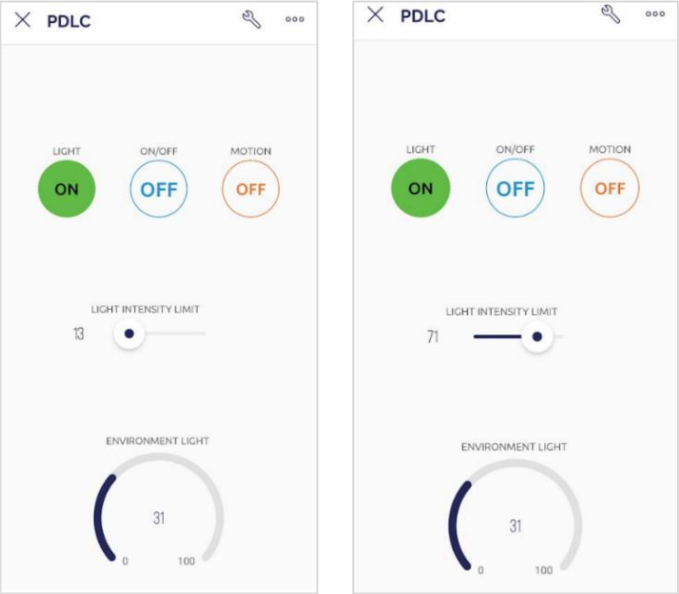


Figure 10. IoT smart controller in Blynk application to control PDLC films wirelessly



(a) (b)

Figure 11. PDLC films controlled using the ON/OFF button. PDLC films in (a) “OFF” state and (b) “ON” state



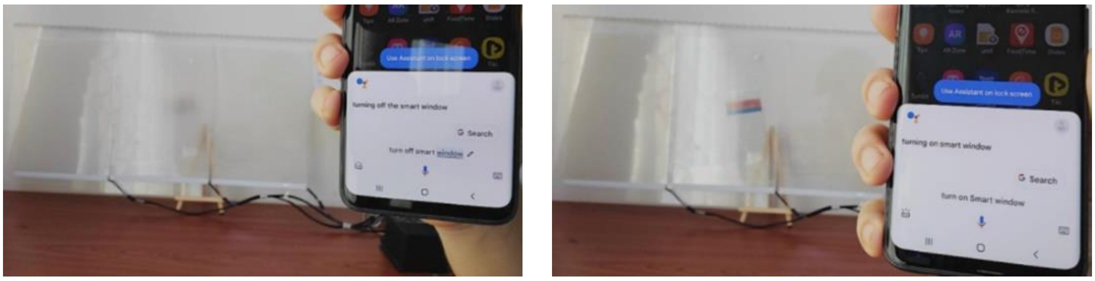
(a) (b)

Figure 12. PDLC films controlled using LDR sensor. PDLC films in (a) "OFF" state and (b) "ON" state

The third method, which is controlling the PDLC film using a PIR sensor based on the motion detected in the surrounding is shown in Figure 13. To activate the PIR motion sensor, the sensor button must be switched on in the Blynk application. Once the ON button has been pressed, the PIR motion sensor will continuously monitor for any motion in its proximity. If a motion is detected by the PIR sensor, the sensor will trigger the PDLC films to turn on. Whereas, if no motion is detected within the range of the PIR sensor, the sensor will trigger the PDLC films to turn off and switch to opaque transparency.

Figure 13. PDLC films operated using PIR sensor

The final method to operate the PDLC film does not involve any smart controller rather it uses voice command to control the switching of the film. This is shown in Figures 14(a) and (b) whereby the user inputs a specific command into the google assistant application. If the command matches the pre-set commands on the IFTTT website, the PDLC films will either turn on or off. To change the opacity of the PDLC films to a transparent state, the user needs to give the command "Turn on Smart Window". On the other hand, to turn off the PDLC films, the user needs to verbally input the "Turn off Smart Window" commands.



(a) (b)

Figure 14. PDLC films controlled using voice command. PDLC films in (a) “OFF” state (b) “ON” state

4. CONCLUSION

In conclusion, despite the low power consumption of the smart PDLC film, improper handling of the film can result in significant energy wastage. To address this issue, an IoT smart controller with energy-saving features was developed to operate the PDLC films. The smart controller was designed with a user-friendly interface that allows wireless control of the films via Wi-Fi. Additionally, by integrating sensors such as the PIR motion sensor and LDR sensor, the PDLC films can also be controlled automatically without any human intervention. Moreover, a voice command feature has also been implemented, allowing the user to verbally change the film's opacity without physical control. This feature is helpful for those who cannot use the controller due to disabilities. With the increasing demand for smart films in recent years, the PDLC film market is expected to bloom. By integrating an IoT smart controller into the operation of the films, the areas of application of the films can be significantly expanded. The developed prototype is compatible with the commercial installation of PDLC film in the market. The developed system is to be used for applications such as buildings, office meeting rooms, transportation, hospital rooms, toilet doors, and more. The IoT smart controller that has been developed is expected to be a stepping-stone towards a society with advanced technology and better energy management.

ACKNOWLEDGEMENT

We are grateful for financial sponsorship by MMU under the MMU IR FUND 2022 (Ref: MMUI/220052) with Research Project entitled, IoT Enabled Polymer Dispersed Liquid Crystal (PDLC) Smart Films for Deployments in Residential and Commercial Applications.

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