The Autonomous Smart Window

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***Abstract* — Various window accessories are available to consumers, each of which aims to fill a different market need. Very few products, however, offer multifunctionality and customization. The Autonomous Smart Window integrates various window accessories into one compact, custom-built window. A variable tinting feature was achieved by using a system of rotatable linear polarizers, a switchable PDLC screen was incorporated into the design to provide privacy on-demand, color-varying LED lighting was installed provide artificial window lighting, and a variety of sensors allow the window to operate autonomously or to be controlled by a user.**

***Index Terms* — Windows, autonomous systems, light emitting diodes, infrared sensors, photodiodes, microcontrollers.**

I. Introduction

The motivation behind the Autonomous Smart Window stems from the shortage of fully customizable window options that are currently available on the market. In addition to the aesthetic beauty of windows, there are economic features and security functions that have yet to be integrated simultaneously within a single window unit. The goal of the Autonomous Smart Window project is to identify and incorporate as many window features as possible within a single window unit, and to make the entire system customizable, fully interactive, controllable, user friendly, and autonomous.

There are many window accessories available to consumers, each of which is designed to accomplish a specific goal. For example, if one wishes to limit the amount of light coming through their windows, this can be accomplished using curtains, blinds, tinting films, stained glass, etc. The same applies if one wishes to have a privacy feature (blackout curtains, blackout tints, blinds, light scattering films, etc.). However, it is extremely difficult, if not impossible, to find a window or accessory that can accomplish more than one or two functionalities at the same time. The Autonomous Smart Window is an attempt to solve this problem and is meant to serve as a proof of concept rather than a finished product.

As previously mentioned, the Smart Window aims to incorporate as many features into one window as possible; however, the project was limited to only integrating a handful of the many features that we brainstormed. With more time and funding, we could have further optimized some of the included features, and we could have added additional features (stretch goals) as well. With that being said, this paper discusses the design and methods behind the primary features that we elected to include.

II. Overview of Window Features

The Smart Window conglomerates various window functions into one compact window unit, each function serving a specific purpose. This section discusses each major aspect of the Smart Window and the desired specifications to be demonstrated. Section III details how each functionality was accomplished and provides specifics on the design and integration processes.

A. Compact Window Unit

Throughout the design process, the intention was always to ensure that the window maintained a visually pleasing appearance. Knowing that there would be numerous components involved in the design, it was imperative that a custom window encasement be built in order to house all of the necessary hardware. So, we built a custom, double-paned window unit by hand to meet all of our needs. It is practical, but simple and elegant in appearance.

B. Variable Tint

The Smart Window has a variable tint feature that allows for the window to vary the amount of light being transmitted through the window. This allows the user to select how many lumens of light to allow through the window. This feature can also be used to limit the amount of heat that enters the home via ultraviolet and infrared rays from the sun.

C. Switchable Privacy Screen and LED Lighting

Another feature that the Smart Window boasts is a light scattering privacy screen, which the user can switch on or off within milliseconds. The privacy screen provides instant privacy, but also allows the window to give off a beautiful, frosty-white appearance. In addition, the privacy screen acts as another heat prevention measure by blocking infrared rays from the sun.

An LED light source is also contained within the window unit and works in tangent with the privacy screen to provide a customizable, colorful light source in a dark room. The color of the LED light source can be selected by the user, and the light is scattered across the window by the privacy screen in order to provide a cool, uniform illumination across the surface of the window.

D. User Controlled vs. Autonomous Operation

The Smart Window has been designed to support user-controlled operation as well as autonomous operation. The user can control the Smart Window via a computer or mobile device. The autonomous operation is made possible by a series of sensors that governs the behavior of the window. Additionally, the user can select which mode the window is operating in and can set up a schedule for the window to abide by.

E. User Feedback

Finally, the user can receive feedback from the window in two ways: an LCD display mounted on the window, or a mobile device connected to the same Wi-Fi network as the window. The LCD display presents text that informs the user about the status of the various Smart Window features. The mobile device does the same but is able to display more detailed information about the window simultaneously. It is worth noting that neither of the user feedback media have not been fully developed. However, the prerequisite hardware has been installed into the window so that the feedback system can be functional with some additional software updates.

III. Compact Window Unit

The window unit is comprised of a birch wood housing and two clear polycarbonate sheets. The unit includes a hinged window face on the interior side. This is incorporated so that it is easy for the technicians to access the electronics. The birch wood housing is coated with outdoor polyurethane, which offers the finest wood-warp and weathering protection out of all common coatings. The window itself is dual-paned, with ample space between the two panes to allow for internal component mounting. The panes of the window are plexiglass, which made our overall window more cost-efficient and reduced its mass.

Fig. 1. Photos of empty window unit (taken immediately after construction was completed).

IV. Variable Tint Mechanism

This section discusses the design behind the variable tinting mechanism, the components utilized, and how the system was assembled. The section is broken up into sub-sections, each of which discusses a major aspect of the tinting mechanism.

A. Polarizing Films

Variable tint is accomplished by having all incident sunlight pass through a pair of linear polarizers before passing through the window. One laminated polarizer is attached to the outer pane of the window, and the other is attached to a rotating bearing centered between the two windowpanes. When the bearing is rotated, the angle of the rotating polarizer with respect to the stationary polarizer will vary, causing a dimming effect. The transmissivity of the window obeys Malus' Law as shown in Equation (1) below,

$$I_{out} = I_{in} \times \cos^2 \theta \quad (1)$$

where I_{out} is the intensity of the light passing through the window, I_{in} is the intensity of the incident light, and θ is the angle difference between the optical axes of the two linear polarizers. Malus' Law dictates that the Smart Window can transmit anywhere between 0% and 50% of all incident sunlight.

Fig. 2. Images showing the tinting effect in action. In the image on the left, the two polarizers are aligned along the same optical axis, maximizing light transmission. In the image on the right, one of the polarizers has been rotated to generate the tinting effect.

B. Rotating Mechanism

A mechanical pulley system was constructed to allow the rotating polarizer to rotate in precise angular increments. The pulley system comprises of a stepper motor, a rubber timing belt, and a wooden gear that is attached to the rotating bearing. The gear was laser cut to ensure that adequate contact is maintained between the gear teeth and the timing belt, allowing for efficient torque transfer.

The motor used is a short body bipolar NEMA 17 stepper motor with a holding torque of 16 N-cm and a step angle of 1.8 degrees per step. These two characteristics ensure that the stepper motor has enough torque to rotate the pulley mechanism, and that precision is guaranteed whenever the user requires a certain tinting level for the window. The size of the motor was also chosen so that it would fit inside of the window enclosure. The motor was placed in the upper left corner of the window so that gravity would aid the motor in turning the pulley, since both the torque of the motor and the force of gravity are acting on the pulley along the same direction.

In conjunction with the motor, an L298N motor driver was used to step up the low input current going into a high current which was used to run the stepper motor. These motors require high currents to operate; for the motor chosen, the rated current per phase was 1.0 A. This motor driver was not only very commonly used, but it was also very economical given the budget. In addition, it could be operated by an Arduino.

The Arduino code used to rotate the stepper motor was implemented using an ESP32 microcontroller, which is able to rotate the motor in both the clockwise and counterclockwise directions using the Stepper.h Arduino library. The revolutions per minute (rpm) of the motor can be changed to obtain any speed desired, and the delay between each rotation can also be changed. After testing, the desired speed was kept at 30 rpm so that the tinting of the window could be achieved in a reasonable amount of time.

V. Privacy Screen and LED Lighting Integration

This section discusses the design behind the privacy screen and LED lighting, the components utilized, and how the system was assembled. The section is broken up into sub-sections similarly to the previous section.

A. PDLC Film

A polymer dispersed liquid crystal (PDLC) film is used as a privacy screen and is attached to the pane of the window that corresponds to the inside of the home. When no voltage is applied to the screen, it scatters all incident light and becomes opaque with a frosty white appearance. This is considered to be the “privacy” mode of the screen. When a voltage is applied to the film, the liquid crystal molecules align themselves in an orderly fashion, causing the window to be transparent again. The film can be dimmed based on the amount of voltage applied; when 30 V are applied the screen becomes fully transparent. Users have the ability to switch the privacy screen on and off in less than one second, and it can also be dimmed to a level of opacity that lies between fully opaque and fully transparent.

Fig. 3. Images showing the privacy screen in action. The image on the left shows the privacy screen with 30 V applied voltage, and the image on the right shows the privacy screen in “privacy” mode (no voltage applied).

The voltage that is applied to the film is allocated and delivered by an Arduino Nano, which uses a XL6009 DC-DC boost converter module that is placed on one of the PCBs; its job is to step up its maximum 5V digital output voltage to obtain the desired 30 V required to make the screen transparent. The boost converter also allows for voltages between 5 V and 30 V, which allows the user to dim the privacy screen rather than just switch it on and off.

B. LED Lighting

SMD 5050 LED strips have been mounted between the two windowpanes in a manner such that the majority of the emitted light is directed towards the inside of the home (towards the windowpane with the privacy screen attached to it). The LEDs are not meant to be turned on when lots of sunlight is present; rather, when it is dark outside the LEDs can be turned on, and the privacy screen can be set to “privacy” mode to diffuse the colorful LED light across the windowpane. This design combines the privacy screen’s light scattering ability with the LED light to provide a unique lighting effect that is aesthetically pleasing and also bright enough to be appreciated; the lights are even capable of illuminating a portion of a room.

The LED strips are powered by the ESP32 microcontroller but require an LED amplifier in order to provide ample power for the entire length of the LED strip. Commands from the ESP32 dictate what mixture of RBG light the LED strips will emit. This provides the user with a large color gamut to choose from.

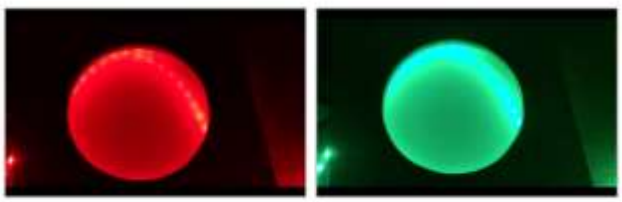

Fig. 4. Images showing the LED lighting effect. In the above images the LEDs are not permanently mounted (these images were taken for our midterm progress report). The privacy screen is in privacy mode, diffusing the LED light across the windowpane.

VI. User Remote-Control Capability

This section discusses how the Smart Window can be operated remotely by a user via mobile device and provides details about the user interface and the communication network that the Smart Window employs.

A. Communication Network Between Mobile Device and Window Features

The communication between the electrical components themselves is achieved via serial communication. This serial communication allows data from the Arduino Nano to be sent directly to the ESP32 and vice versa, which communicates via Wi-Fi with the mobile device; this is made possible by the ESP32’s Wi-Fi compatibility. Serial communication was very easy to achieve, and only two connections between the Arduino Nano and the ESP32 board were required in order to allow two-way communication.

Some of the devices including the photodiode, and motion sensor require this type of communication since they are directly connected to the Arduino Nano and not the ESP32. The rest of the components such as the stepper motor and LED strips are controlled directly via the mobile device since they are connected to the ESP32 board. The privacy screen is also connected to the ESP32 board via a relay that can be controlled via the mobile device, turning the privacy screen on and off using an NPN transistor.

B. User Control via Mobile Device

The user may configure and control the smart window unit through the means of a mobile device. The embedded processor hosts a webserver that controls the device. Mobile devices that connect to the server communicate via HTTP to configure the system as well as pull data from it. Features that the user can control include the schedule, privacy screen, LEDs, and tinting feature. We chose to use Wi-Fi because it allows the unit to connect to the network without needing to route additional wires. Since nearly all homes in the market for IOT devices have Wi-Fi, we can use the user network and avoid having to install our own.

VII. Autonomous Operation

This section discusses how the Smart Window has been designed to operate autonomously via the use of various sensors. It also mentions the different operating modes that are supported as well as a scheduling feature.

A. Passive Infrared (PIR) Motion Sensor

The passive infrared motion sensor, Panasonic’s AMN34111, is used to detect motion outside of the window. The motion sensor scans the area 10 meters in front of the window. It has a 110-degree detection area in the horizontal direction and a 93-degree detection area in the vertical. Upon activation the motion sensor will take an average of 7 seconds to stabilize and detect motion; however, it can take up to 30 seconds. Once activated, the motion sensor will scan the detection area every 1 second. If an object is moving between 2 detection zones within the visible area, then motion has been detected.

After motion has been triggered a 70 micro-amp signal is sent out through a 68,000-ohm resistor, where it activates a transistor and sends roughly 4.2 volts to an Arduino Nano analog pin. The Nano reads that the pin has been set to ‘high’ mode, or that it is receiving more than 2.5 volts, and will trigger the notification that motion has been detected. From there the user will be able to engage the privacy screen and determine how much time will elapse before the motion sensor will be reset and begin to search for motion again.

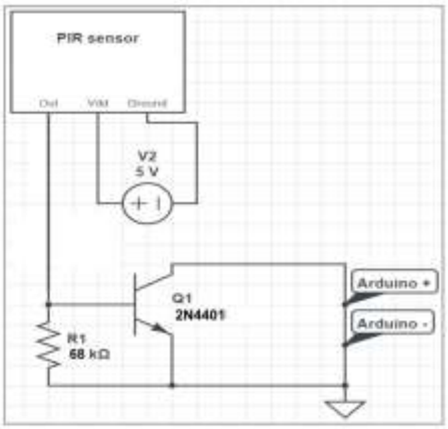

Fig. 5. Circuit diagram for the Panasonic AMN34111 PIR motion sensor. For the Smart Window project, an Arduino Nano supplies the necessary 5 V reverse bias voltage.

B. Photodiode

The photodiode, FDS1010 from Thorlabs, has been mounted to the bottom of the privacy screen with the surface area facing out towards the sun. The photodiode will be used in photoconductive mode by applying a 3.3-volt reverse bias from an Arduino Uno. When sunlight is incident on the window, the wavelengths that penetrate the two polarizers will reach the photodiode. Current is be generated from the photodiode and is be transformed into voltage. The lumen output can then be determined using the following equations: the relationship between photocurrent and power (2), the relationship between photo voltage and power (3), the relationship between photodiode area and window area (4), and the relationship between generated watts and perceived brightness of the window (5).

$$P\left(\frac{Watts}{cm^2}\right) = \frac{I(photocurrent)}{R\lambda(responsivity)} \tag{2}$$

$$P\left(\frac{Watts}{cm^2}\right) = \frac{(V(out))}{R\lambda(responsivity)x\ RL(load\ resistor)} \tag{3}$$

$$P(watts) = P\left(\frac{Watts}{cm^2}\right) * A(window\ area) \tag{4}$$

$$Lumens = P(watts) * 683 * y(\lambda) \tag{5}$$

The photodiode sends the photocurrent in the form of voltage through the Arduino Nano, where the math is processed and the voltage is converted to a lumen output. Lumens are calculated using perceived light intensity and is dependent on wavelength. The sun produces a large bandwidth of wavelength. Therefore, we use the 555 nm wavelength as the chosen wavelength to calculate perceived light intensity emitting from the window, since the human eye perceives this wavelength to be the brightest [3].

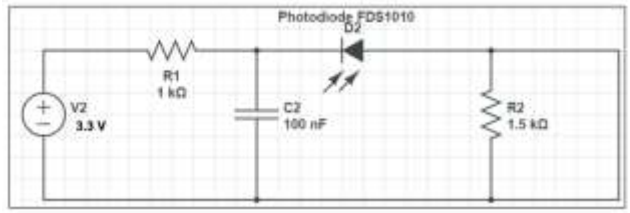

Fig. 6. Circuit diagram for the Thorlabs FDS1010 photodiode. For the Smart Window project, an Arduino Nano supplies the necessary 3.3 V reverse bias voltage.

The photodiode generates photocurrent from light that is between the range of 350 nm and 1100 nm. To calculate the lumens, the responsivity of the photodiode at 555 nm is 25 amps per watt. The user will be able to use the photodiode to choose how bright they want their window to be. The user will also be able to use the photodiode to monitor how much light is incident on the window so that they can choose to block out light and heat being emitted from the window.

Fig. 7. Images showing the PIR motion sensor and photodiode that were used. The image on the left shows the Panasonic AMN 34111 PIR motion sensor. The image on the right shows the Thorlabs FDS1010 photodiode.

C. Operation Modes

There are three primary autonomous modes that the window can operate in. The first is called Security Mode, wherein the PIR motion sensor is set to actively scan the area outside the window. If motion is detected within ten meters of the window, the Smart Window will automatically engage the privacy screen, disallowing anyone from seeing into the home. This feature is meant to protect against loiterers or other suspicious characters. In addition to the privacy screen being engaged, the user can opt to receive a message on their mobile device to alert them if excessive movement is detected. Further, an added feature might allow for the window to black out fully when motion is detected instead of turning on the privacy screen, since either alternative will make the window opaque.

The second mode is called Eco Mode. This mode allows the user to select a certain value of lumens that they would like the window to continually emit. It is mainly meant to be used on very hot and sunny days when the user does not want lots of sunlight to enter the home, but also does not want to block out all of the light. The Smart Window will monitor the incident sunlight and vary the tint percentage in order to maintain the specified amount of light that the user wishes to be transmitted through the window. Additionally, the user can select a lumens threshold that they do not want to be exceeded. This can be used to limit the amount of light coming through, but it can also be used to limit heat radiation through the window. For example, if it is overcast outside the user might not have any issue with allowing all the sunlight to enter the home. But if the sun comes out and begins heating up the room, the Smart Window will engage the tint and prevent heat from entering.

The final operation mode is called Schedule Mode, where the user sets up an hourly schedule for the window to follow. The scheduling feature allows for full customization over the privacy screen, tinting feature, lighting feature, and the aforementioned modes. The user is able to determine what times of the day they would like the window to operate in Eco Mode or Security Mode, or they can create custom instructions for each of the window functionalities. It is worth noting that the window can operate in both Eco Mode and Security Mode simultaneously since they do not interfere with each other. As previously mentioned, we did not have time to fully develop the scheduling feature, but the necessary hardware is present to allow for such an option.

VIII. User Feedback

This section discusses how the smart system provides feedback to the user. This feedback is meant to inform the user about the operating mode of the window, the status of the privacy screen, and the tint level that the window is set to.

A. Feedback via Web Server

The user may access the web server via computer or smart device to view the system configurations. These configurations include the brightness setting, privacy setting, scheduling, and LED functionality. The webserver allows the user to receive feedback through multiple devices such as desktop computers, laptops, mobile devices. It also allows a layer of security because it forces intruders to get through the security from the router before they are granted access to the webserver.

B. Feedback via LCD Display

The LCD display allows users to choose which window information they would like to see. This Adafruit LCD display is able to display 2 rows of text of up to 16 characters. Not only does the LCD have a bright blue LED backlight for viewing text, but is also allows supports varying contrast. The LCD display is powered and coded using an Arduino Uno and the LiquidCrystal.h library, where the output text to the LCD is set. Currently, if motion is detected from the motion sensor, the LCD displays the text "Motion Detected!", and when no motion is detected it displays the text "Motion Stopped!".

IX. Conclusion

The Smart Window project is a success in that it adequately serves as a proof of concept for a device that may one day become a marketable product. It illustrates that it is possible to construct a compact window unit that contains most (if not all) of the typical, popular window accessories while also providing additional functions that are not readily available to consumers today.

The autonomous operation of the window worked as intended, as did the local Wi-Fi server. Developing an Android application with a beautiful and user-friendly UI was one the stretch goals of the project that we were unable to achieve due to time constraints, but we have shown that a mobile application would be easy to integrate into the communication system. With more funding and time to develop, the Autonomous Smart Window can be improved upon and become a fully polished product that many consumers can benefit from.

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THE ENGINEERS

Nomar Barreto is a 21 year-old graduating student at UCF who will be obtaining his Bachelor of Science degree in Electrical Engineering in Spring 2021. He will later move on to work in industry and later pursue either a master's degree or a PhD in Electrical Engineering. His areas of research interest include electromagnetics and optics, robotics, and deep learning.

Bradley Howder, is graduating in 2021 with a Bachelor's degree of science and engineering in Photonics and Optics and a minor in Mathematics. He is currently employed at Control Micro Systems as a laser application engineer and plans to continue growing his career in the field of photonics. He also plans to pursue a Masters degree in Photonics at UCF's CREOL in the future.

Abdullah Husain will be receiving his Bachelor of Science degree in Photonic Science and Engineering in Spring of 2021 from the University of Central Florida. He will graduate with a minor in mathematics as well as honors recognition from UCF's Burnett Honors College. He will be returning to UCF in Fall of 2021 to pursue a PhD degree in Optics and Photonics, as he has been accepted into the Optics and Photonics PhD program and has been granted an ORCGS Doctoral Fellowship to assist in this academic endeavor.

Kenneth Sauers, Will be receiving his Bachelor's for Computer Engineering With a minor in Intelligent Robotic Systems. He currently works full time as a junior software engineer.

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