University of Central Florida

Department of Electrical Engineering and Computer Science
& College of Optics and Photonics

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Senior Design II

Smart Window

Final Document

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1. Executive Summary

Windows have accompanied buildings for as long as humanity has constructed homes. They allow light, sound, and sometimes air to enter into homes and buildings, and serve as a meaningful way to connect with our outside environments. Early windows might have used cloth and wood in place of transparent glass. Then the Romans learned how to manufacture glass well enough to use it as building windows. In modern day, sophisticated optical films, and advancements in glass strength has resulted in windows capable of reflecting heat, and withstanding hurricanes and tornadoes.

While humanity's improvements to the rudimentary windows of Roman times are of great mention, the modern window has much further to go. We rely on windows to give us information. It is easy to look out the window in the morning, and decide if the weather is clear of rain. It's difficult to guess the temperature just by looking out of your window.

The Smart Window has a robust set of onboard sensors alongside WiFi connectivity to give accurate weather and forecast information pertaining to our immediate and regional areas. All the user needs to do is approach the Window, and the built in proximity sensor will trigger an onboard display to show the users local weather information. Weather information such as: temperature, humidity, UV Index, and a local forecast. To ensure that the information will not obstruct the users view of the outside world, the display will be partially transparent.

People have long used curtains and shades to increase the privacy of their home windows. Conventional blinds and curtains are often bulky, and frequently break. They are excellent dust collectors, and also difficult to clean. For these reasons, we've implemented a switchable privacy film to the Smart Window. The Window will have a transparency toggle to allow for the privacy of the user as well as everyone else inside the house. With just a single switch, the entire window will become opaque, allowing all the light entering to scatter through the room like a warm diffused light, while also ensuring the privacy of all indoor inhabitants. Using the PDLC film as a window shade also allows for simple cleaning of the window. Without bulking blinds or curtains, cleaning off interior dust is as simple as wiping the window with a cloth.

Finally, since windows typically receive sunlight for a good portion of the day, it makes sense that our device blocks unwanted ultraviolet and infrared radiation from entering the room. Therefore, the group will ensure that the PDLC film is able to cut down on these types of radiation as much as possible. To keep the Window true to its form, these components will be sure not to degrade the view of the outside environment. All of these features will give its users a seamless experience to help them better decide how to spend their day with as little effort as possible.

2. Project Narrative

The project narrative covers a high level overview which outlines the major aspects of the project's functionality. It also includes diagrams explaining team member responsibility, and the group's intentions for the design and performance of the Smart Window.

2.1 Goals and Objectives

To design a user-friendly smart window that displays real-time weather information collected by onboard sensors and from WiFi connectivity, all while maintaining a low production cost. The Smart Window system will have a privacy mode, enabled by PDLC film, that makes the window opaque. The primary display, a transparent LCD panel, should be integrated seamlessly to the glass pane to create an aesthetically pleasing user-friendly interface. The window should be easy for users to setup and use for home or office use, and therefore will receive its power from a single cord attaching to a standard U.S. 120VAC connection.The Smart Window project development involves numerous features working in tandem, and the group is eager to make the design as feature rich as possible. To help distinguish between the core features which are critical to fulfilling the project requirements, and stretch-goal features which the group hopes to include, two lists have been compiled.

Core Project Features

- Transparent Display
- Temperature Sensor (indoor / outdoor)
- Humidity Sensor (indoor / outdoor)
- UV Sensor (outdoor)
- IR Proximity Sensor (indoor)
- PDLC Privacy Film
- UV Blocking Film (if necessary)
- LED accent lighting
- Smartphone Compatibility

Stretch-Goal Features

- Wireless LED Control
- Solar Panel
- Alexa Integration
- Variable PDLC Opacity
- Solar Tracking

2.2 Motivation

During the course of the year, many people have found themselves spending more time indoors. It isn't uncommon for people spending more time indoors to miss their outside areas. Typically, we only have one way to interact with the outside while still in our homes. Windows offer us a glimpse of the outside world, but don't give many details.

We often consume information like temperature, humidity, UV index, and a daily forecast to decide our outside activities on any given day. Unfortunately, this information often is conflicting, and comes from multiple remote sources. A weather forecast on the TV, and a zip-code forecast from our smartphones tell two different stories. This inspired our group to create this project. Additionally, the capability of the PDLC allows changing the windows opacity to reduce glare from outdoor lighting, and provide privacy. The motivation is to provide an adaptive device that informs people of the current atmospheric conditions indoors and outdoors while providing the optical appearance of a window with shutters or blinds.

2.3 Potential Customers

Several types of customers can be easily identified for this type of device. Because the window has potential to be size adjustable, it could be easily modified for use in different sizes. Therefore, It could be suitable for large formats such as the lobbies of hotels or apartments, which typically use large glass windows, or be adjusted for home use, for the environment-conscious consumer. The use of customizable widgets for the user to determine which aspects of the display are of primary concern to them. This customization also helps to attract a larger audience. With these points in mind, the main customer that that project aims to appeal to is the home consumer. The Smart Window is built using a two foot by three foot glass window, as this is a common size of glass windows which could be found in many U.S. homes. The reasonable price and accommodating size hopes to appeal to a typical U.S. homeowner interested in incorporating modern technology into their homes.

2.4 Preliminary Design Mockup

Design mockups are excellent tools for experimenting with the project's aesthetic and features. By constructing multiple design renditions, the group is able to see how each element of the Window interacts. In the diagram shown below in Figure 1, multiple key elements of the Smart Window are seen. At the very top of the display, the LED light bar rests above the windows frame. This placement is convenient, as any electronics unable to be housed inside of the lightbar could be placed in the frame.

The frame could also house many of the sensors and the electronics of the other features, such as the sensors and display wiring. By organizing cables and electrical components this way, the project can have a clean look that won't distract from the outside view, and the display content.

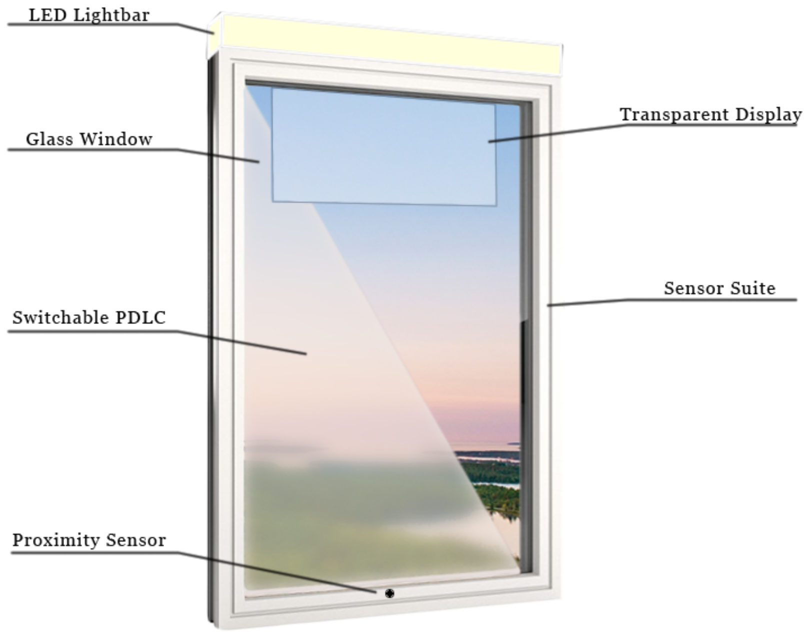


Figure 1: Early Design Mockup of the Smart Window

Visual explanations of the smart film and transparent display can also be seen in Figure 1. The smart film will maintain privacy through the window, without attenuating too much of the outdoor light. This preserves one of the key functions of a window, as a light source to indoor environments. In the mockup, the transparent display is seen hugging the top of the windows frame. This placement is preliminary, as more testing will need to be done as the project develops to ensure proper functionality for the Window to be placed at different heights.

There is a possibility of placing the display at the bottom of the window frame, although side placements are hypothetically possible as well. It is ideal to place the display at an edge alongside the frame, as the display contains some electrical components that are unable to be removed or adjusted, and these will need to be concealed with the window frame to preserve a clean look. The group originally intended the framing of the Window to be hollow, for the purpose of routing the electronics and various connections inside the frame. However, project assembly dictated that to ensure the project prototype was stable, more weight was needed at the bottom of the project, and a compartment box had been added to support electronics and internal connections in place of a hollow frame.

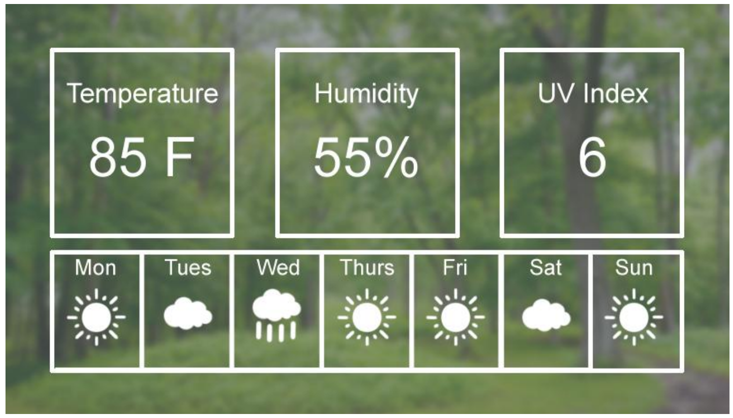


Figure 2: Early Design Mockup of the Smart Window Display Interface

Figure 2 seen above gives a more detailed view of the Smart Window transparent display UI. While this figure is an early rendition of a possible interface for the display, it does highlight some significant features of the project. Seen at the top of the interface, temperature, humidity and UV index are all fed as a live feed to the display. These values are monitored in real time from the onboard sensor, and they are displayed by part of the microcontroller loop. In future renditions, these would likely show both indoor and outdoor values, or could be replaced by a separate widget, if the user desired. The project team wants to encourage the end user of each Smart Window to customize the UI panel to most meet their desired use case. For example, a user who was not interested in the humidity reading could replace it with a panel which shows the sunrise / sunset times for the day. One important aspect of the figure is that it shows a slightly darkened, but clearly visible background, representing the outside view. The darkened view is due to the crossed polarizers of the display.

2.5 Project Function

The smart window is designed to use a connection to the home power grid for cloudy or rainy days. The system will have real-time monitoring of basic weather conditions such as temperature, humidity and UV index as well as indoor temperature and humidity monitoring for maintaining the optimal air comfort level. Forecast information from internet sources will also be available to users. Using the data from these sensors, the Smart Window will be able to allow for planning indoor and outdoor activities as well as monitor the current weather inside and directly outside the home. There are also plans to add a calendar planner which can be displayed on the window and edited through a mobile app. The system will have multiple privacy features such as the PDLC film that allows an opaque and transparent mode for the window. The proximity sensor will detect when the user is in front of the window and automatically switch from a low power mode to display the weather information in order to be energy efficient.

2.6 Requirements and Specifications

The system requirements for the Smart Window Project are listed in Table 1.

Market Req.	Engineering Requirement	Justification
1,2	1600x900px Resolution. Allows >50% light transmission in visible spectrum.	A large conventional LCD could be made translucent by backlight disassembly, yet offers a high quality image.
2,4,6	<60V | 2 ft x 3 ft	PDLC FIlm Offers privacy, and reduces glare
2,5	Custom built window pane, wood	Be aesthetically pleasing and able to house sensors
2,4,5	Multiple lighting modes (12W Max power draw per color) 2700K / 6700K Light Temperatures	Using two lighting modes offers color mixing,, and 1200 lumens should provide adequate lighting in any environment
2,5	LED Power control between 0-1 amp	Two knobs control current to offer variable lighting between 2700-6000K and between 0-2400Lumen
2	Matches length of window frame, completely covers LEDs	A scattering film and bulb housing gives the LED lighting a professional appearance.
3, 4, 5, 6	60V Max to PLDC film 3.3V to MCU 120VAC Input / Solar Panel Input	Photovoltaic cells charge batteries and connect to the home grid, given there is no sunlight. Power Supply to distribute electricity to components
1	Raspberry Pi	Gets weather forecasting data to screen using wifi
1	Graphical display of temperature, date, and weather forecast in main screen	Display shows temperature, humidity and weather and serves to retrieve information from a website
1	MySQL database to contain user's first and last name, static face image file path in system, and main screen preferences	To offload memory from microcontroller, to retrieve database information from face recognition software when input face image is matched, and to save settings for different users
1	3ft Range, in all lighting conditions	Proximity Sensor for the window to only display information when a user is nearby
1	+- 2% Relative Humidity / +- 0.5 C	Outdoor sensors to reliably determine the weather
1,3	+- 5% Relative Humidity / +- 2.0 C	Indoor Sensors determine the house conditions

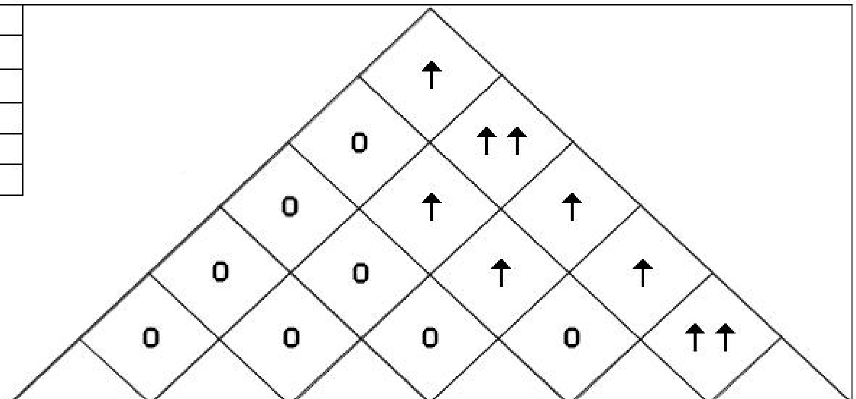
Table 1: Requirements & Specifications

Market Requirements
1. The window must have components capable of delivering accurate information
2. The window must be aesthetically pleasing, without interfering with functionality.
3. The window should be affordable to the average consumer
4. The window should be accessible to a user of little technical ability
5. The window should use renewable energy/ have low power consumption
6. The window should be able to be transparent or opaque

2.7 House of Quality Diagram

The house of quality diagram is used to investigate the relationships between the technical requirements of the project, and the expected market requirements of the consumer. Shown below in Figure 3, the HoQ diagram will aid in informing the groups decisions in prioritizing features and components of the design. The legend in the House of Quality diagram below represents correlations between different requirements of the project. These correlations help the group to recognize how seemingly separate parts of the design bear relation to each other.

Legend	
Strong Positive	↑↑
Positive	↑
No Correllation	o
Positive Polarity	(+)
Negative Polarity	(-)



			Technical Requirements					
			Data Accuracy	Display Quality	Built In Lighting	Proximity Sensor	Dimensions	Device Cost
			(+)	(+)	(+)	(+)	(+)	(-)
Market Requirements	Functionality	(+)	↑↑	↑↑	↑	↑↑	↑	↑
	Ease of Use	(+)	o	↑	↑	↑↑	↑	↑
	Quality	(+)	↑↑	↑↑	↑↑	↑↑	↑	↑
	Dimensions	(+)	o	↑	o	o	↑↑	↑↑
	Operating Cost	(-)	o	↑	↑	↑	↑	↑↑
	Engineering Requirements		± 2% Rel. H ± 0.5 °C Temp.	50% Trans. 1600x900 Res.	0 - 2400 Lumen 2700K / 6700K	<3 ft Detection Length	2ft x 3ft	$400

Figure 3: House of Quality Diagram

Primary observations of the House of Quality diagram shown above are as follows. In increasing the display quality, the device cost increases strongly. The same can be said about the project dimensions. Observations towards the marketing requirements show that increasing the data accuracy, display quality, and proximity sensor efficacy all relate to a strong increase in project functionality. These factors all offer valuable considerations into how to proceed with the project's development. The HoQ Diagram will be an important reference to decide how to allocate the projects budget, as well as development time of specific features of the Smart Window.

2.8 Block Diagrams

2.8.1 Overall Project Block Diagram

The Project Block diagram in figure 4 shows a rough flow of component interaction for our Smart Window project.

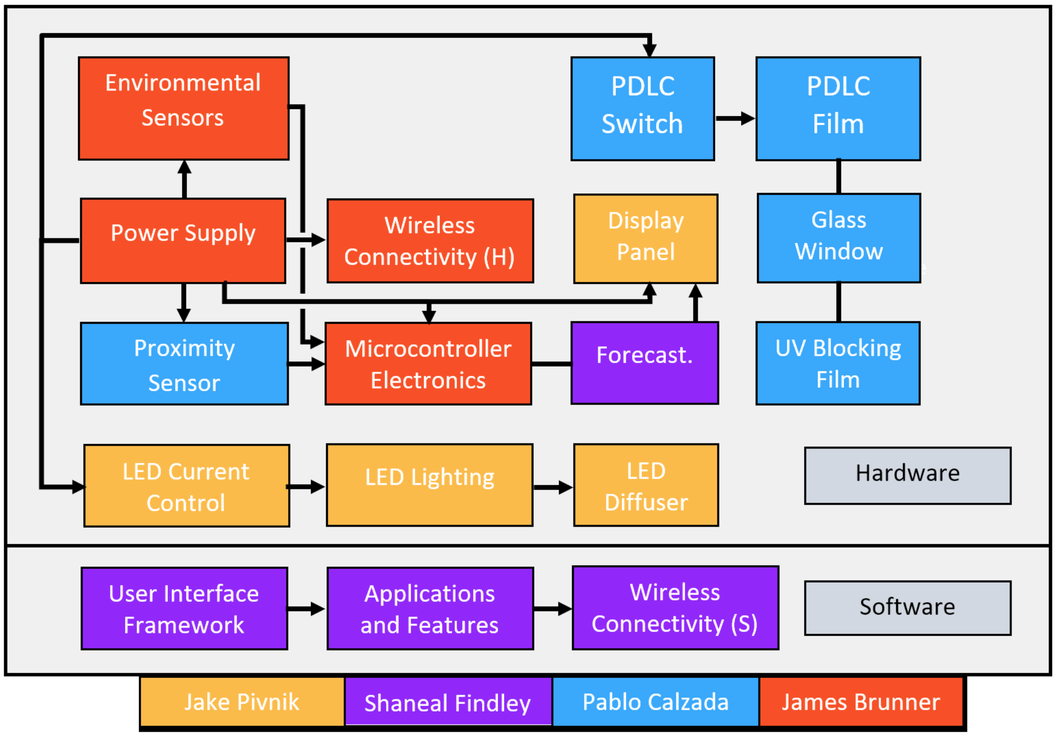


Figure 4: Overall Project Block Diagram

The colored blocks are labelled with the single or group of parts which can be categorized into specific areas of importance. For example, the PDLC Switch seen in blue at the top of Figure 4 represents the On/Off switch controlling the PDLCs privacy screen. This is a representation of a block which serves a single function. Another example is a more complicated block, such as Environmental Sensors seen in red at the top-left corner of figure 4. The Environmental Sensors block constitutes the temperature sensor, humidity sensor, and the UV Index sensor. Arrows can be seen indicating part interaction, such as the power supply acting as an input to the sensors of the block which require power to function, and an output to the Microcontroller electronics block, which represents a flow of data from the sensors to the primary microcontrollers of the project. These blocks have been color coordinated to the group member who is the primary lead of that aspect of the project. While this diagram lacks subtle information, it primarily serves as a visual aid to show which group member is responsible for those essential parts of the project's design.

2.8.2 Block Diagram Specific Details

Graphical Display:

The display will be used to interact with the users to display the option for the user to register themselves or to display the settings options for the user. The display will be operated through a graphics library API developed and hosted on GitHub. The display in low power ‘sleep’ mode will not display information. In the event that the proximity sensor reports motion it will trigger an interrupt to initialize the display software. The window will display its default screen with the temperature, date, and weather icon indicating the daily forecast which is retrieved online from the website https://openweathermap.org/api. If no motion is reported in the default time or the time set by the user, then the window enters low power mode and has the display cleared. When the window initializes the display menu will display options to select and create users, it will also communicate to the microcontroller to initialize screen and sensor readings.

The goal of this project is to develop a window that is used to display relevant information requested by the user through the cloud, transforming an ordinary window into a personalized interactive device to display weather, time, notifications from the internet as well as through the microcontroller in one centralized location, therefore the user interface will consider the mentioned requirements.

The main display and user interface for the Smart Window would be developed as an ElectronJS project, that will display a static webpage that returns and renders HTML (HyperText Markup Language), CSS (Cascading Styling Sheets), and JS (Javascript) on the backside of the Acer LCD display used for the window screen.

ElectronJS is an open-source framework that is used for building cross-platform native desktop applications that combines the Chromium engine and the Node JS runtime environment. The Chromium engine saves the webpage as an HTML file on the Raspberry Pi and uses the Render process that has access to DOM and Node.js APIs. Chromium browsers support saving webpages as HTML files onto the native system that hosts the browser, Like that of Figure 5, on the following page. As Electron is a JavaScript technology, the final app will be deployed to common desktop operating systems such as Linux in 32-bit and 64-bit versions.

For this project, the app will be running constantly. Communication from the main process to the renderer process is achieved using IPC communication. The main process bootstraps the app and coordinates other processes in the background while the render process is used to drive the user interaction. You could also use IPC directly, but messages must be serializable, and any state changes would have to be synchronized between all processes in the NodeJS application.

Database:

To be able to post a sensor profile to the real-time database for an application to perform a real-time collection of the data. Firebase is a backend as a service platform developed by Google for creating mobile and web applications. The Firebase Realtime Database synchronizes application data across the Android and Desktop Node application.To support user data and calculate measurements based on sensor readings, we will be using firebase's Realtime Database. The real-time database is a NoSQL database that provides timing restrictions to data. We will connect to firebase through the desktop application and mobile app to store the user profile information and sensor data.

The data will be published to firebase as a JSON through the Node application and can be queried by users through the mobile app and the display-window console. The real-time database provides permission-based access. The sensor data will not be persistent. The sensor data will be captured and stored in a text file on the Raspberry Pi from the microcontroller at daily intervals. The Desktop application will read the text file and publish it to the website daily. The Node JS application running on the Raspberry will store daily results polled each hour alongside median, high, and low measurements. This will be used to perform calculations to return information for the user through the mobile app and publish on the Electron JS Rendered Display. An example of this process is seen above in Figure 6.

Open Source Weather Software:

The OpenWeatherMap is an online service, owned by OpenWeather Ltd, that provides current weather data and forecasts. It provides more than twenty weather APIs to return current weather data for a location by city name, city id, geographic coordinates, zip code, or multiple locations by geographic coordinate bound by a rectangle or a definite circle. The APIs allow the calling user to download the current weather data and forecast data in JSON format. This will be applied to the mobile app to return the current weather data from the user's latitude and longitude reported on their Android device if the mobile app is granted permission to read the user's location. For the browser desktop application used for the display.

The API will be used to return the latitude and longitude for a given IP address, cell tower, and wifi access point to return the latitude and longitude which is then used to return the current weather data through calling the OpenWeatherMap's suite of APIs. On both the browser application and mobile app the JSON response will be parsed to return a message to the user indicating the current weather conditions alongside a scalable vector graphic icon that represents the weather description returned from using an HTTP GET request from api.openweathermap.org.

We expect to use the free plan from OpenWeatherMap to access their forecast, which contains the following features:

- Calls per minute: 60 calls
- 3 hour forecast: 5 day
- Secure API Key used to make calls to api.openweathermap.org
- Current Weather Forecast
- Government WeatherAlerts
- Minute Forecast 1 hour
- Hourly Forecast 2 days
- Daily Forecast 7 days
- Historical weather 5 days

OpenWeatherMap can be called from the Raspberry Pi, and it will also return information that the group is unable to get from the onboard sensors alone, such as air pressure, cloud coverage, and wind speed. It will also be able to provide a set forecast, helping users to plan for incoming weather phenomena, like thunderstorms, hurricanes or tornadoes thanks to its ability to provide government issued severe weather alerts.

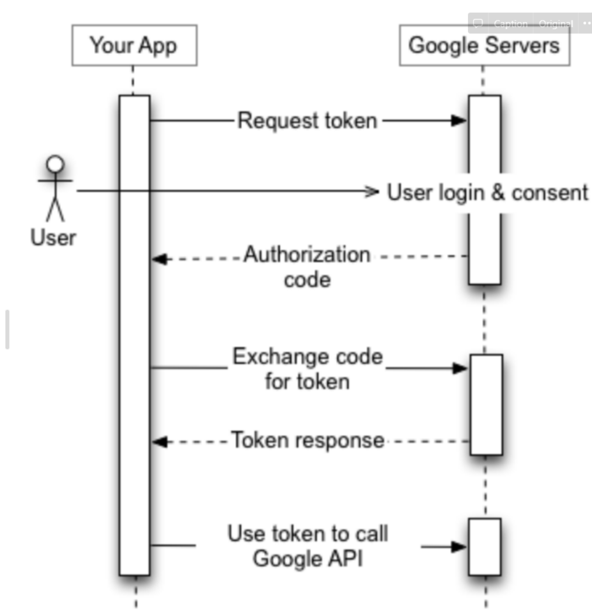


Figure 5: Use case of client app using Google API

Google Authentication

OAuth 2.0, developed by the IETF OAuth Working Group, is the industry-standard protocol for authorization. It specifies the required authorization flows for web applications, desktop applications, mobile phones, and smart home devices. To integrate Google APIs into the application for the Smart Window, a third-party application, Google APIs use the OAuth 2.0 protocol for authentication and authorization to develop a client-side application required to use their APIs including Google Calendar, Google Geolocation, and Google Text to Speech. A developer account will be provided an access token to the API in the HTTP authorization request header to send the token to the Google API. This complex process is better visualized above in Figure 7. The access token provided to the client application is limited to the set of operations in the scope of the request, therefore, the node js application will require individual access tokens to have access to the Google Calendar, Google Sign In, Google Geolocation, and Google Text to speech APIs. We will embed the client ID within the source code of the mobile app and the node js application to connect to the Google API.

Enable Google Sign In

The application uses the OAuth 2.0 protocol to access Google APIs and has authorization credentials to identify the application on Google's OAuth 2.0 server.

Google Calendar

The Google Calendar API lets users perform most of the operations on a normal Google Calendar a user can on the Google Calendar website and mobile app. To provide calendar functionality to the Smart Window we will integrate the Google Calendar API to display, create and modify calendar events and calendar-related objects. The Node JS application will implement Google Calendar RESTful calls to connect to Google Calendar API v3 API endpoints.

To integrate the Google Calendar into the Smart Window, the module is designed to be displayed as a static HTML code embedded into the app. This will be returned from the user's Google Calendar Settings, given a user is signed on into the app with the user credentials. The Google Calendar Module will render a fixed size, seen below in Figure 8, with the option to display the weekly, monthly, and agenda for each Calendar a user has set to visible. Similar to the Google Calendar App, the user will have access to a subset of the Calendar Options to set the 'Default view,' 'Week starts on,' 'Background,' and 'Timezone' as shown in the following screenshot. Through the App, the user will also have the option to toggle the sub-calendars to maintain a similar user experience to the Google Calendar web and mobile application.

In order to display the Calendar on a desktop application to display on the Smart Window LCD. The display will need to make it available to the public and integrated into the ElectronJS application using a user's calendar unique calendar key. The integration will be applied to the webpage as the iframe code that will return HTML code as a function of the Options the user chooses after a Publish Event call. Changes to the settings of the display will generate a new iframe embedded code and the render process will restart to reflect the new HTML code.

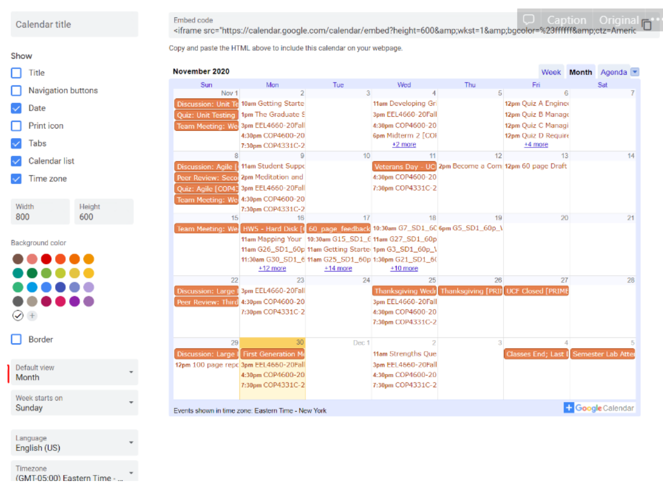


Figure 6: Generated code and HTML for Embedded Google Calendar

Google Geolocation API

To get the latitude and longitude of the operating device, we will use Google's Geolocation API to return a location and accuracy radius based. This feature is limited to HTTPS and requires permission from the user in the mobile app to report location information.

The Geolocation API is used by sending a POST command using a JSON formatted request. On a successful request, the JSON-formatted response returns a user's estimated latitude and longitude, in degrees, and the radii of the circle around the given location to represent the accuracy of the estimate. This information will be used to send a request to the OpenWeatherMap API, to return the weather information for the given latitude and longitude coordinates returned from the API call.

Raspberry Pi:

A microcomputer is a small computer with a microprocessor as its central processing unit (CPU) with limited I/O, circuitry, and memory. The board that we will be discussing that fits into this category is the Raspberry Pi 3.

The Raspberry Pi 3 is a stand alone computer that can be used to connect to WiFi, connect to an OLED display. The Raspberry Pi is a Linux based microcomputer capable of running multiple distributions of embedded Linux Releases. The Raspberry Pi 3 has built in 4.2 Bluetooth and dual band Wi-Fi. This allows the sensor readings reported from the microcontroller selected to be reported to the internet without implementing the WiFi feature ourselves. This allows our device to be operated remotely, and with W-Fi, access a remote database that can store the users settings for the device.

The Raspberry Pi's 1.2 GHz clock speed and 1 GB RAM allows the Raspberry Pi to perform intensive processing actions such as facial recognition and voice in addition to processing sensor readings. It becomes inefficient for simple tasks due to its high power consumption. As it is a microcomputer the Raspberry Pi has a filesystem that can host the required software to display on OLED and process sensor data. It can connect to an OLED display using 7 jumper wires and SPI (Serial Peripheral Interface) communication pins in the Raspberry Pi. If the microcontroller is present Implementing the connection between the Raspberry Pi and microcontroller will make the PCB design a challenge as the Raspberry Pi communicates through an SPI interface.

Glass Window:

The glass window will be a 2ft by 3ft single-pane window on which the PDLC Film and display are mounted. Careful considerations to the structural stability of the glass window will be made as the project continues. While some windows in-home use are typically larger because of the testing and transportation involved in making the first model of the Smart Window, this deems making the glass pane too large a hazard to the overall design. In future iterations of the Smart Window, or with a significantly higher budget, considerations to a multilayer glass panel with a larger size could have been made. Other options which were considered are transparent plastic screens which are significantly lighter than real glass but conversely might be flexible and less sturdy. Part of the glass window considerations is also its eventual integration into the custom window frame.

Solar Panels:

Photovoltaic panels were a feature that the group hoped to include into The Smart Window project. However, the group's limited budget and time restrictions led to the feature instead being left for future iterations of the project. Solar power would have provided a cleaner energy source compared to a connection to the existing electrical grid. As more research was done, it became clear to the group that many additional components would be necessary to develop all for the purpose of supporting the solar power system. A custom transformer would be needed to convert power from the battery bank which holds the solar power to a AC standard for the PDLC film.

Several voltage regulators, battery IC circuits, and other electronic components would be necessary to develop, and risk other core functionality of the project not working. Therefore, the group opted to not develop the solar panels for this iteration of the Smart Window.

Smart Window Applications

The project team wants users to be able to customize their experience with the Smart Window. We understand that users have different needs, and may not be interested in receiving information about things like dew point, or wind speed. Therefore, users will be able to customize which weather modules appear on the display, by using the mobile app. Our currently planned modules include: Indoor Temperature, Outside Temperature, Indoor Humidity, Outside Humidity, UV Index, Forecasting, Wind Speed, Dew Point, Sunrise/Sunset, Moonrise/Moonset, and Moon Phase. Users will select which of these modules they choose to show on the transparent LCD window display through an interaction with the included mobile app. If no preferences are set, or wifi is disabled, a preset of modules with readings from the onboard sensors will be shown.

3. Research and Part Selection

Qualitative analysis and comparisons between different technologies allow the group to best decide how to proceed with fulfilling the market and engineering requirements of the project. Cursory research and exploration of parts and features was done by the group members. This helped to identify the parts and features with the most relevance to the project, and those which could be appropriately integrated. After identifying the relevant parts and features, the group conducted research to note how they could fulfill the market and engineering requirements of the project.

3.1 Similar Products / Projects

Investigating similar products and technology already on the market and is a beneficial aid to the development of our own device. While no product exactly matches that of the groups Smart Window, features that have been incorporated into other products and projects worth mentioning are detailed below.

3.1.1 Smart Mirror

Some potential customers of the project may have had exposure to the “smart mirror” projects that have been popular in a niche sect of DIY builders. Utilizing two way mirrors and LCD displays, smart mirrors are cheap but effective ways to incorporate a display into a mirror, and commonly use a microcomputer to pull relevant information from the web.

Smart mirrors are reflective, and if a mirror would be used in place of a glass panel, it would block out outside light from the window. While the microcomputer is able to pull weather conditions from online sources, the information it provides is only as accurate as the data it receives. Local weather forecasts are typically no more accurate than the zip code or city they are set to. This means that the information received may not be accurate for the device's exact location.

3.1.2 Smart Windows

Existing smart windows do not typically have sensors or displays. Transparent displays are currently prohibitive in both accessibility and price to the consumer market. Other displays that are available to the consumer market are in no way normally transparent. PDLC film, a cornerstone feature of our project, is incorporated in some smart window designs. PDLC film can be colored depending on the polymer mixture used to disperse the liquid crystals. Commonly, smart windows will distinguish themselves from typical glass windows because of some proprietary film. The film could be UV blocking, IR blocking, or self-cleaning film in some cases. The group has been unable to determine a competing product to the one we are producing.

3.2 Technologies

The technology section of this report aims to explain relevant aspects of the different types of technologies relevant to the project. These different technologies were investigated to most properly choose which of them could be incorporated into the Smart Window project in the most adequate and effective manner. In this section of the documentation, we aim to familiarize the reader with all important parts and technologies for the project. Not all technologies outlined in this section will be included in the final iteration of the design, but each technology listed and discussed showed enough merit to be considered for use with the project.

3.2.1 Displays

Displays are devices which are able to display information is a pictorial form. Since the invention of the cathode-ray tube, monitors used alongside computers have developed in stunning fashion. Modern displays typically use thin film transistors, alongside backlighting which is now typically done by LEDs. They utilize proprietary cables to handle signal transmission between computers and the panel, like VGA, DVI, HDMI, and DisplayPort. Modern display panels have been typically back or edge lit. This means that the layout of a display involves an attached light source which is filtered through color filters, and several polarizing layers to form an image.

These display panels require power connections, as well as a standard display cable, either VGA, DVI, HDMI, Displayport or USB to communicate with a computer to handle what should be shown on the display. The display the group chooses will need to exhibit some sort of transparency as to not obscure the outside environment beyond the window. It also needs to have enough contrast to distinguish the information shown on the screen from the ambient light around it.

Display quality is evaluated across a few key metrics. The one most commonly known among consumers is the display resolution. The modern standard for widespread resolution is still 1920x1080p. This is the resolution of most US television stations, and is the standard high-resolution video format of websites which host videos such as YouTube. Computer displays have more variance than television displays, and resolutions of 2560x1440p called 2K resolution and 3840x2160p called 4K resolution are both now commonly found in higher end displays. Equally important to resolution is the display size. The size of the display is of extreme importance because it defines the pixel density. When pixels of the display are spaced closer together, the details of an image are significantly more clear. As an example, an Iphone 11 has a display resolution of approximately 1800x800 pixels. This is less than the standard television high definition 1920x1080 pixel resolution. But why does the display look so much more clear on the phone than the television? It is because the phone is able to capture this resolution in a display no larger than 6x3 inches.

As screens become larger, it is necessary to increase the resolution to maintain a high fidelity image. If a television had a 1080p resolution across a 60 inch display, you would need to sit very far away from it to prevent yourself from noticing the large and spaced out pixels. Another important metric of displays is the display's color capabilities. In display terms, color is typically expressed with two terms. What the color bit depth is, and how much of the chromaticity diagram it covers. An example of bit depth is given by Figure 7.

Figure 7: Color bit depth, As the number of color bits increases, the total possible colors mixable increases exponentially.

The human eye is able to distinguish about 100 shades of each color. Because our eyes can see in three channels, red, green and blue, this offers 100^3 total colors combinations, or around one million distinguishable colors. In an 8 bit color system, there are 2^8 color combinations, or 256 colors per channel.

While the figure above is in a CMYK color scheme, computer displays, like the cones in our eyes, utilize three channels. This corresponds to red green and blue colors. In this three channel system, using red green and blue colors in an 8-bit display would give 256^3 total color combinations, for around 16.7 million colors. This is more than adequate to accommodate the range of human vision.

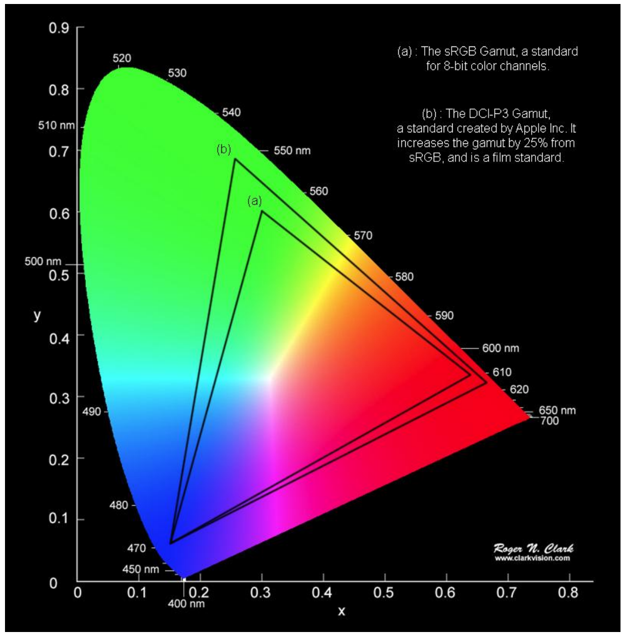


Figure 8: The Chromaticity diagram, showing all human perceivable colors, as well as two display gamuts, sRGB, and DCI-P3 [ClarkVision]

The other important characteristic of color is the gamut coverage. Most 8-bit displays cover >90% of the sRGB gamut. However, for consumers that work on color-sensitive material, They typically prefer to use a display which covers more of the chromaticity diagram seen above in Figure 8 [ClarkVision]. Gamut coverage in LCD displays has historically relied heavily on using a backlight which is very broadband. If the light being filtered through the TFT pixels does not contain each of the three color channels in robust amounts, less of the gamut will be accessible from the display.

3.2.1.1 OLED

Only recently have OLED displays begun to reach the market. OLEDs distinguish themselves from other panels because they use self-emissive LEDS to form the image. This allows the screens to be made without any additional backlight. OLEDs are lighter, typically brighter, and offer higher contrast than typical backlit panels. OLED displays are able to achieve much higher contrast ratios because they do not need a backlight to filter out colors from, like a typical LCD display. When an OLED display is supposed to display a black pixel, the self-emissive LED pixels switch to the off state.

This results in the contrast of the display much better than that of an LCD, as an LCD may have problems filtering out the backlight completely through its crossed polarizers. Another advantage of using OLEDs over a typical display is that some OLEDs are specifically made to be transparent. By increasing the separation between the self-emissive LEDs, ambient light can filter through the panel, allowing the user to distinguish both the image of the display, as well as any object behind it. These factors result in OLED displays being much more expensive than other panels. Unfortunately, transparent OLEDs that fit in the group's budget are not large enough to display all sensor information, and features offered by the Window’s technology.

3.2.1.2 LCD

LCD or Liquid Crystal Display is a display technology that has been developing since the 1960’s. It employs a polarizing filter, and liquid crystals to attenuate a backlight into forming images. Modern LCDs are typically robust, and offer high resolutions, contrast ratios, and color fidelity. They also typically use LED backlighting which is broadband, and then filtered through colored pixels to attain the desired color. Because of the polarization filters in place, the amount of light which could pass through the display is limited, but their accessible nature makes them the ideal candidate for a large display within the budget of the project. While most LCDs do not compete with the contrast, color gamut, or brightness of an OLED display, the main criteria of the display which is desired by the group is transparency. LCDs seem to present a reasonable path to a transparent display, without exceeding the total project budget.

3.2.1.3 See-through Display

Our group has identified several possible candidates for transparent displays. OLED is typically out of the potential customer price range. It offers the truest sense of a transparent display, using self emissive pixels that are spaced far enough apart to allow ambient light to pass through the gaps between LEDS. LCD Panels have potential to be partially transparent without applied voltage.

Twisted nematic “TN” Panels are fitted with cross polarizers that modulate incoming light. Unfortunately they have relatively low transmission coefficients compared to OLED panels because of the polarizers in use. Hypothetically, a TN LCD display should not be able to be more than 50% transparent, as the light passing through the display would be at least half way absorbed by the linear polarizers.

Another potential avenue to See-through display would involve a short throw projection system. Specialized films are being manufactured at accessible prices which would act as a see through projection screen. A combination of display film and projector offers some advantages and disadvantages over a transparent display.

The transparent film offers nearly complete visibility to the area outside the window. This is considerably better than the 50% transparency offered by an ideal LCD display. A projection system also makes its own light, rather than modulating outside light. This would allow the use of the display at night, when no sunlight is available. However, there is an issue of the user blocking the projection when in front of the display. If the projection was limited to the top of the display, It's possible that a roof mounted projector would allow the image to pass over the users head. But because of these issues, a projection system is not currently being investigated at this time.

3.2.2 LED Lighting

Because the display used in the Smart Window project is not self-emissive, it will not be possible to form an image on the display at night. Therefore to add functionality and additional use for the Window, an LED lighting system will be included in the display. LED Lighting is both energy efficient, and economical. It offers distinct advantages over incandescent lighting, and fluorescent lighting, in terms of safety, energy efficiency, and light output. While high power single LED junctions are commonplace, to form a soft diffused light, the group determined that multiple LEDs used in a strip would better suit our design. They offer the same brightness with significantly less heat per LED, improving device safety.

LEDs also come in a variety of colors, which is mainly due to the combination of phosphors in the bulb. By modulating the power of LEDs which use different phosphors, different color tunings could be made. Consumers have shown preference to a variety of different color temperatures, described by Kelvins. A higher Kelvin describes a bluer light, while a lower Kelvin describes a warmer light. By using two LED strips with a high and low Kelvin number, many color combinations between those colors will be achievable by modulating the power of those individual strips.

Figure 9 : An example of possible light color temperatures available by modulating the power of the two LED strips.

3.2.3 LED Lighting Control

LEDs are Current controlled devices, which require proper heat dissipation to maintain their electrical characteristics. In certain current regions, LED light output varies mostly linearly with current put into the junction. This allows the possibility of color mixing shown above in Figure 9. The group decided that using two knobs to control the output optical power of the LED lights would be the most accessible way to control the LED lights. Most consumers are already familiar with operating basic knobs, and having the visual feedback of watching the lights increase in illuminance will allow the consumer to control the LEDs with enough precision.

There are two established methods for changing the brightness of an LED. The first method is analog. By modulating the input power to the LED, The optical power can be adjusted within a certain range. LEDs have a limited region where they operate linearly, and therefore the levels of light output which can be controlled is limited. LEDs have a very small transition region where they go from the off state, to a state of high brightness. During this transition period, the color of the LED also changes. When LEDs are operated with low power, the color tends to be warmer, and as power increases, the tone of the light becomes gradually more blue. Analog controls, while limited in the regions of operations, are rudimentary to implement in this electronic system.

The second method involves a technique known as Pulse Width Modulation (PWM.) In PWM control, a square wave signal switches the LED from the off state to the on state. By switching the state of the LED at a high enough frequency, the LED appears to have a steady state brightness, determined by the frequency, and duty cycle of the square wave signal. PWM offers superior control over output power at low operating regions, and would allow more user flexibility to mix colors at a greater range. Figure 10 [SparkFun] below shows various examples of PWM square waves with different duty cycles.

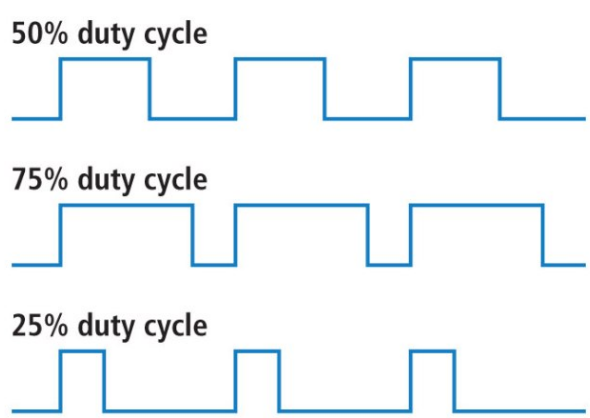


Figure 10: Differences in PWM duty cycle signals for modulating LED Brightness [SparkFun]

3.2.4 LED Lighting Diffusion

LEDs typically operate with either a Gaussian or Lambertian illumination pattern. This means that the optical power provided by the diode is not uniform with respect to its angles. More light is directed at 0 degrees than it is at higher angles. This works well for flashlights, and the beam forms a spot of tightly focused light. However, this is not always ideal for consumer lighting. Our Window features a bright, color adjustable lighting fixture, and consumers frequently prefer soft, diffused and uniform lighting for indoor applications.

Light can be diffused by rough surfaces, such as frosted glass or a thin adhesive sheet. This offers an easy solution to turn harsh, focused light into diffused light for a fixture. By constructing a box to house the LED strips, a thin sheet of diffusing material can be adhered to the acrylic surface panel, and the light passing through it will be diffused on the other side. Another advantage of using a diffusing panel is that it will allow the color mixing of the two LED strips to be improved. By passing both colors of light through the diffusing panel, the warmer and cooler colors will be thoroughly mixed. The ability to mix the colors of the two LEDs is important, as the strips intended to be used for the project operate with different color temperatures. Having a diffusing film after the light exits the strips increases the gradient color temperatures able to be recreated by the two PWM controlled LED strips

3.2.5 Microcontrollers

Microcontrollers are self contained computers on an integrated circuit chip. They are most commonly used as parts of automatic control systems. Because of their reduced size and cost compared to microprocessors, they have allowed for digital control of many kinds of devices and processes. Use of a microcontroller will be essential for this project since there is no other option for the same price to communicate with sensors, digitally enable or disable current flow to devices, and store information. Each of these processes, though not limited to them, will be done by the microcontroller (MCU) to provide a seamless integration of the Smart Window.

3.2.6 Smart Film

Smart film is the name given to a type of film that can be applied to glass, acrylic or polycarbonate surfaces with the main purpose of giving otherwise clear glass two modes: transparent and opaque. This technology is also known as smart glass, as some vendors tend to sell the film already applied onto a glass pane. Smart film has hit the mainstream recently with consumer demand increasing in the last few years.

Typical customers of this technology are homeowners, hospitals and corporations who wish for additional privacy to add to their windows and office buildings. This technology can also eliminate the need for blinds or window shades which can make it a good financial choice. This type of film can come in various configurations, some use tempered glass to make it more rugged, and other vendors specialize in having the thinnest possible film. There is also a wide selection of different tints that can be applied to the smart film in order to give the window some sort of hue or to vary the transmissivity of visible light and in the process, make it darker. Besides all these opportunities for customization, smart films are divided into two major categories based on the type of technology they used to achieve the opaque mode.

3.2.6.1 Passive Smart Films

Passive smart films use non-electric, non-user provided stimuli such as light and heat as a means to transition between the transparent and opaque modes. There are multiple subtypes of passive smart glasses and films in the market with a variety of enabling technologies which will be explored in this subsection. Thermochromic film uses thermal energy to change from transparent to opaque states. This type of film was designed with energy efficiency in mind, as it is most widely used on windows which develop an opaque white tint when exposed to thermal energy from direct sunlight.

The working principle behind this film is a property that some materials have known as thermochromism. Certain substances and materials such as certain liquid crystals and leuco dyes are able to have reversible changes in color when heat is applied, and these dyes and crystals are embedded in thin films. The operation cycle of a typical thermochromic film can be observed in Figure 11 [Science Direct].

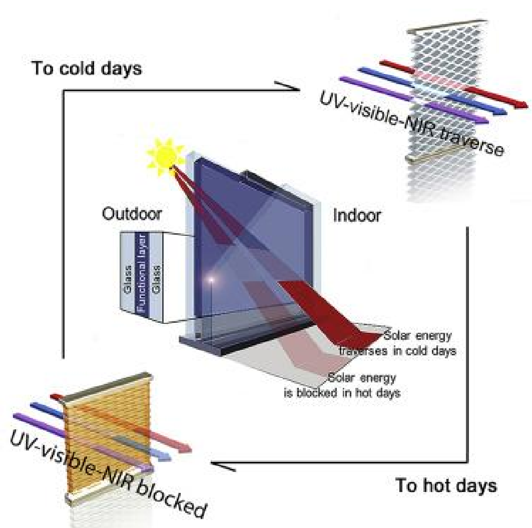


Figure 11: Thermochromic Film Operation [Science Direct]

One of the most interesting facts about this type of film is the thermal management properties which they exhibit. In warmer days, the film becomes opaque, scattering a wide spectrum of electromagnetic radiation and therefore avoiding extra heat from getting into the building. Likewise, on cold days, the film becomes transparent which allows heat to enter.

The main advantages of thermochromic film are its thermal management and that it uses fully renewable energy (solar), which makes it efficient and inexpensive. On the other hand, its disadvantages are that it cannot be controlled by the user, not being as useful in cities with moderate weather, and the lack of control over opacity can lead to poor visibility.

Photochromic film, similar to thermochromic film, operates using one of the types of chromism known as photochromism. As the name suggests, photochromic film will change between transparent and opaque states depending on the intensity of the incident light on the film. This type of material is mostly used in color changing sunglasses, as photochromic molecules which darken upon encountering UV radiation can be embedded into glass.

Some advantages of this technology are the fully renewable energy usage and the capability of production with organic molecules. The limitations of this technology at this time are very similar to the ones in thermochromic film: the switching between states and level of opacity cannot be controlled by the user, and in the case of photochromic glass and film, this transition may take multiple minutes of exposure to sunlight, making it potentially fairly inconvenient for the user.

3.2.6.2 Active Smart Films

Active smart films are activated at will by the user using electric signals in order to transition between the transparent and opaque modes. Active smart films have a larger share of the market, as customers seek for an energy efficient technology which allows them to make windows opaque on command. There are multiple subtypes of active smart glasses and films in the market with a variety of enabling technologies which will be explored in this subsection. Electrochromic film is a type of reversible, opacity changing film made up of a material that exhibits electrochromism. This type of material becomes opaque when a voltage is applied across it, as the voltage applied starts an oxidation reaction in the system. Unlike passive films, the fact that electrochromic film is activated by voltage means adding switches to the system and enabling the user to change from transparent to opaque modes at will.

The setup and operation of a typical electrochromic film can be seen below in Figure 14 [HowStuffWorks (1)]. In between two glass panes, two layers of a transparent conductive material are located and these are connected to an electrical source.

When an external DC voltage is applied to the conductive layers, lithium ions cross the electrochromic material and through the ion conductive material to get to the ion storage on the outside glass pane (left side on Figure 12.) This process causes the electrochromic material to become opaque.

Some of the advantages to using electrochromic film are the fact that once a voltage is applied and the ions move across the electrochromic layer, the film remains opaque until the user shuts off the voltage and the glass regains its transparency. This, along with the fact that electrochromic film can scatter a high percentage of incoming UV radiation makes it a very energy efficient technology. Despite these benefits, electrochromic film still uses a chemical reaction and thus it takes a fairly long amount of time to reach full opacity. Our group mainly wants a technology which can provide relatively instantaneous changes from transparent to opaque and vice versa.

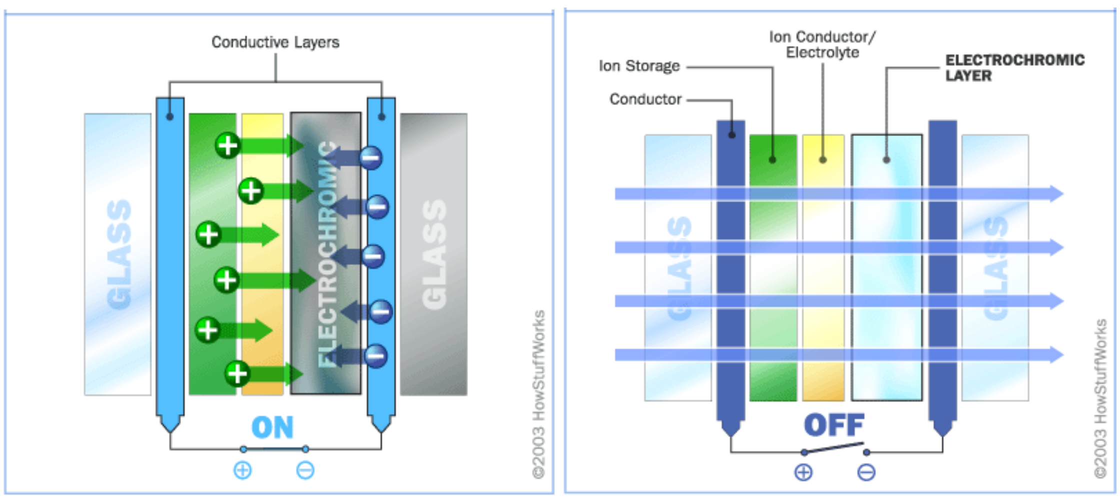


Figure 12: Electrochromic Film Operation Modes [HowStuffWorks (1)]

Suspended particle devices, also known as SPDs or light valves, are a type of glass with an inside conductive coating which contains a transparent liquid in which millions of small particles are suspended. When a voltage is applied across the suspension liquid, the particles line up in straight lines allowing light to pass through the glass. Likewise, when the electricity is turned off, the particles scatter randomly, which gives the system an opaque appearance which reflects incoming light. The operational method of SPDs is depicted on Figure 13 [HowStuffWorks (2)].

The major improvement that this technology offers over competitors is the high speed when switching between the “off” and “on” states. The transmittance modulation can be done in a matter of seconds.

One of the pros of using this technology is that the nanotechnology company that patented it, Research Frontiers, developed a method for retrofitting windows with switchable enhancements. This makes it so that a new window does not have to be bought and two regular glass panes can be retrofitted into becoming an SPD. In addition to this, the company holds a patent on a control method to vary the transmissivity of the system (US Patent 6,804,040 B2) which claims an efficient and low cost method to vary the percentage of light the system allows to get through.

Some of the cons to suspended particle devices include the fact that the retrofitting method is not as simple as applying a film to the glass pane since there is a suspension liquid involved. Another issue with SPDs is that since a single company holds the patent (and despite them licensing it) their product is not as widely available as other competing technologies.

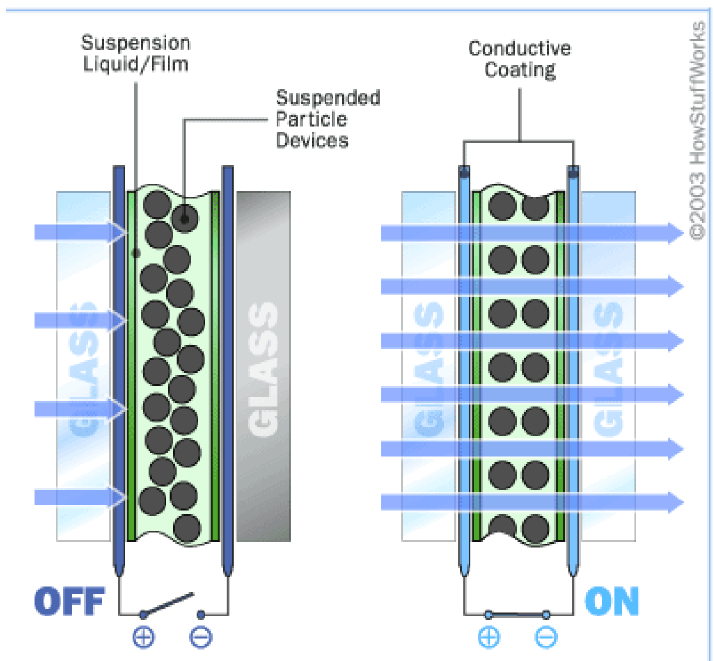


Figure 13: Suspended Particle Device Operation Modes [HowStuffWorks (2)]

Micro-blinds, also known as micro-shutters, are microscopic, rolled thin metal blinds of different shapes which are applied to glass and can be controlled by introducing a voltage in order to vary the amount of light transmitted through the glass. Figure 14 [SPIE] shows a scanning electron microscope (SEM) image of an array of micro-blinds with a trapezoidal shape. As it can be seen, the micro-blinds are about a hundred microns which makes them invisible to the naked eye.

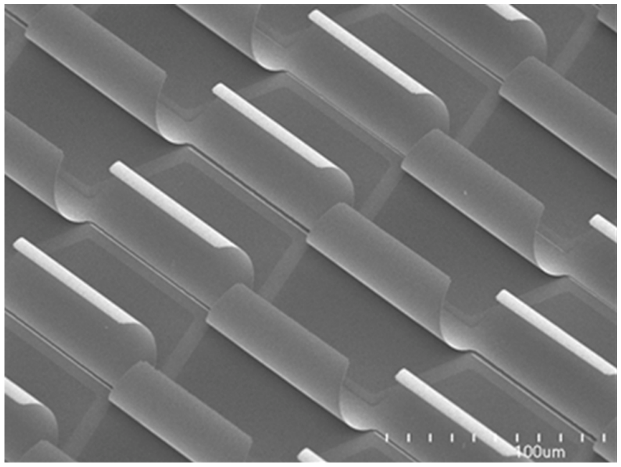


Figure 14: SEM image of micro-blind array produced by the NRC [SPIE]

The application process involves magnetron sputtering, a vacuum coating technique which allows the deposition of materials such as metals onto surfaces. The metal is applied to a glass substrate which includes a transparent conductive oxide layer as well as a thin, transparent insulator layer.
Then, the thin film of metal is patterned using laser lithography into small rolled “blinds” which allow for transmission of light when there is no applied voltage. When a voltage is applied, an electric field is formed between the electrodes of the transparent conductive and metal layers. This electric field stretches out the micro-blinds, rolling them out and blocking all incoming light.

This technology was developed by the Canadian National Research Council (NRC) and to our knowledge, there is no indication that it is being sold to private customers. There have been a few research papers from various universities published on this technology, but it appears that there is still work needed to show that they are a feasible product with production that could potentially be scaled up.

PDLC Films

Out of all of the smart film technologies which have entered the market in the past couple decades, perhaps the most successful and widely used is polymer dispersed liquid crystal film (PDLC). PDLC is found as either an adhesive film, or as PDLC glass which is already retrofitted in order to have switchable modes. As the name of this technology suggests, it consists of a liquid polymer layer in which liquid crystals are dispersed. After this, the polymer is cured, solidifying it. The curing process creates droplets of liquid crystals embedded within the solid polymer, with the size of these droplets determining the properties of the final film. Then, this liquid crystal/polymer mix layer is enclosed by two transparent conductive material layers.

A fairly basic diagram of this kind of structure can be seen in Figure 15 [HowStuffWorks (3)], along with the two different modes of operation. The operation of PDLC films resembles that of suspended particle devices. A power supply is attached to the transparent conductive layers. The liquid crystals are arranged in microdroplets which range in size from 0.5-1 microns within the polymer layer. Within the droplets, the liquid crystals are aligned, but the orientation is random between droplets when there is no voltage applied. This results in very rapid scattering of the incident light resulting in an opaque appearance. Otherwise, when the recommended voltage is applied, an electric field is created between the two transparent conductive layers which aligns the liquid crystal droplets in order to use the birefringence of the liquid crystals such that the LC refractive index matches to the refractive index of polymer. This allows most of the incident light to be transmitted through the system which results in the display having a translucent appearance.

PDLC technology is currently the gold standard when it comes to smart films and smart glass. The reason for this is initially, the cost: despite it not being particularly inexpensive, the price per square foot of PDLC beats its competitors handily. Secondly, the transition between the opaque and transparent states is done in a fraction of a second, making it extremely user friendly. Another benefit to the use of PDLC films is the fact that at lower voltages, it is possible to control the degree of transmittance in the system.

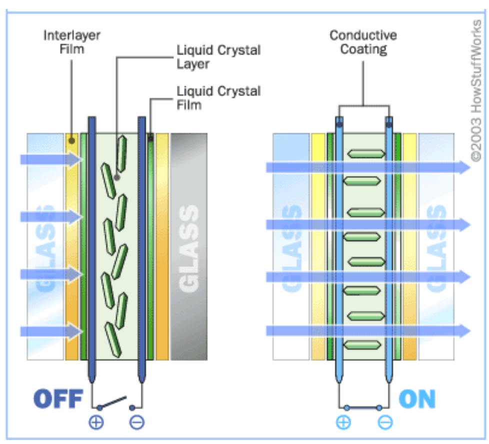


Figure 15: PDLC Film Operation Modes [HowStuffWorks (3)]

PDLC films come in a variety of tints, thicknesses, and structure types which can be used in a plethora of different applications. As mentioned previously, some vendors sell smart glass with PDLC film already applied or built into the window. Of the companies that sell PDLC film separately, some sell a “tempered glass” version which comes in a thick, impact resistant packaging, as opposed to the regular thin and flexible film ready for application.

Basic PDLC film is known for its opaque, milky white color when a voltage is applied, but through the use of tints or extra tinted layers, manufacturers offer multiple different colors, each with a different haze and transmittance percentage.

Another benefit to the use of PDLC technology is the fact that it performs extremely well when it comes to filtering UV light. Some vendors specify that their PDLC films can filter up to 99% of incoming ultraviolet light. This means that PDLC films can not only protect users from the dangers of long-term ultraviolet radiation exposure but also reduce the need for indoor air conditioning to run as often, helping home and business owners save energy and money in the long run.

3.2.7 Sensors

The Smart Window would not be that smart if no sensors were included to give information about the current surroundings. With no data to rely on there could be no day planning or energy saving. The day planning of the window relies on various weather data in the immediate surroundings which primarily comes from the onboard sensors and a microcontroller to process the given data. The Smart Window would not be able to save energy autonomously if it could not detect when someone approaches it so there must be a sensor related to that as well. In short, to make this window smart, it needs to have sensors.

A variety of sensors are included with the smart window to give data about temperature, humidity, proximity, and UV index. There will be two temperature and humidity sensors, one for indoor measurements and the other for outdoor, one proximity sensor to detect when the user approaches the window, and a UV sensor to provide data to the MCU to calculate the UV index. The temperature and humidity values can also be used to find the dew point which is useful for determining the comfortability of the surrounding air.

3.2.7.1 Temperature Sensor

Temperature sensors are used almost everywhere as temperature is a very useful quantity to know. The measurement can dictate whether or not a chemical reaction occurs, give insight to the condition of machinery, and even warn a user before they plan on touching something hot. There is a lot of value placed in knowing the temperature of something so choosing the right sensor for the intended application is worth spending some time on.

A thermistor can be used to calculate the temperature by measuring its resistance. The relationship between temperature variance and resistance of a thermistor is very predictable making this sensor an effective and cheap solution to measuring temperatures. Since these types of sensors are so cheap, accuracy must be sacrificed.

The resistance can change on the order of tens of ohms fluctuating much more wildly than other types of resistance based sensors such as RTDs. The resistance vs temperature curve for these sensors are also not linear which makes reading the sensor more complex. These sensors also have a low maximum temperature threshold. Thermistors are not meant to be used to measure temperatures above 130 ℃ or below -100 ℃, which is fine for this application since the indoor temperature would most likely not exceed 35 ℃. This limited range of sensing is something to consider when selecting a sensor for a hot environment.

Another temperature sensor which is based on the resistivity of the component is called the Resistance Temperature Detector (RTD). One main difference between an RTD and a thermistor is that thermistors are typically made of metallic oxides while RTDs are made out of a pure metal, typically platinum, wrapped in ceramic. This difference in sensor design gives the RTD curves much more linear performance than thermistors. Another advantage is that these curves are established through rigorous standards to make sensor readings easy to configure.

An RTD can come in one of two packages, Positive Temperature Coefficient (PTC) and Negative Temperature Coefficient (NTC). With a PTC sensor, the resistance rises with a rise in temperature while an NTC's resistance decreases with a rise in temperature. The typical range an RTD can measure is between -200℃ to 650℃, which is much broader than a thermistor. However, for the application of measuring someone's indoor temperature this range is not needed. RTD's offer a far less sensitive resistance curve which can lead to more accurate readings, but as accuracy rises so does the cost of the device.

Thermocouples are made using two different types of metals joined at one end, the hot end, and disconnected at the other, the cold end. When the hot end is heated, a potential difference arises due to the difference in metals that can be measured and read using an amplifier and microcontroller. There are different types of thermocouples to consider such as beaded wire, surface probe, or thermocouple probe. Typically, beaded wire thermocouples are used for gas measurement since liquids could corrode the beaded tip and metal surfaces indirectly acting as a ground for electrical systems could interfere with the accuracy but these considerations do not matter when measuring the temperature of a room.

Surface probe thermocouples are generally used to measure surfaces which can be difficult for other types of sensors. Thermocouple probes are just the basic thermocouple design housed inside a metallic tube. The tip of this tube can be grounded, ungrounded, or exposed. Choosing a grounded thermocouple would make sense when rapid readings are needed since the response time is the fastest of the three. This however makes it susceptible to ground loops.

An ungrounded thermocouple tip would be used in the case where more accurate readings are needed but not as often. The exposed tip thermocouple probe is best suited for air measurements since all of its surface area is in contact with the air around it making it the best suited of the three thermocouple probes for room temperature sensing applications. Thermocouples also offer the widest range of temperatures they can measure from -250℃ to 1250℃ depending on which calibration is selected.

The last type of temperature in consideration is the semiconductor-based IC temperature sensor. These sensors work on the principle of measuring the variation in forward voltage across a diode. The readings get less accurate the further away from the calibration point which is typically 25℃. Semiconductor sensors are also very accurate, second only behind RTDs while maintaining a low cost and can be used without an external ADC. This makes semiconductor temperature sensors a major consideration for any room temperature sensing application. The resistance versus temperature curve is very linear as well and a room’s temperature is well within the limited range of temperatures these sensors offer. These qualities make this class of sensor type the optimal selection for the Smart Window readings.

Type	Operating Range	Linearity	Price	Accuracy Ranking
Thermistor	-55 - 120℃	exponential	$-$$$	4
RTD	-200 - 850℃	Fairly linear	$$$	1
Thermocouple	0 - 1800℃	Fairly exponential	$$-$$$	3
Semiconductor IC	-55 - 125℃	linear	$-$$	2

Table 2: Characteristics of Temperature Sensors

Table 2 summarizes the deciding characteristics of each of the sensor types mentioned above. Using the results from this table, one can see that the semiconductor IC is the cheapest, most linear, and very accurate temperature sensor that falls within the operating range of a typical room's temperature. There is no reason to choose any other sensor type for this type of application. Figure 16 [Omega 3] shows the resistance versus temperature graphs of each type of sensor.

Linear operation is a crucial characteristic for the sensor chosen by the group. By selecting a sensor with a wide range of linear responses, we ensure that the data gathered by the sensors is accurate over a large number of values. As shown by Figure 16 below, the I.C. Sensors offer the most linear response, while thermocouples can offer a somewhat comparable response, their purpose is really in measuring temperatures too extreme for our purpose.

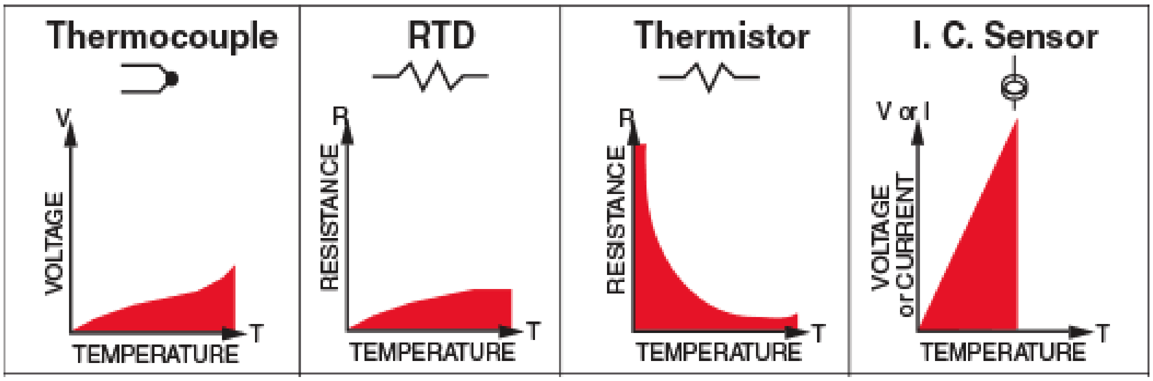


Figure 16: RV / Temperature curves for four classes of temperature sensors in consideration for the Smart Window [Omega 3]

Many manufacturers also make dual purpose sensors that include both temperature and humidity readings. Figure 17 [Mouser] shows a picture of such a sensor which could be a very strong candidate for selection. A sensor able to take both temperature and relative humidity conditions makes it very appealing for the Smart Window project. These sensors' primary advantage over separate sensors is that they are able to fit these electronics in a very small package, like that seen above in Figure 19. As outlined in the sections above, the project requires sensors which meet high levels of accuracy in their measurements. This is primarily to highlight the Windows advantages over online weather sources. For these reasons, a combination humidity and temperature sensors must meet the required engineering standards of the projects to be used in the design.

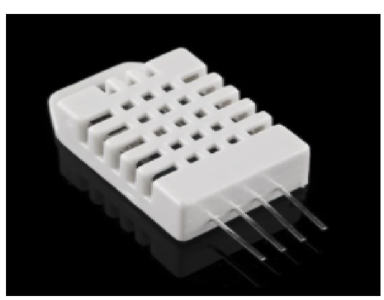


Figure 17: Combination Relative Humidity and Temperature sensor [Mouser]

3.2.7.2 Humidity Sensor

Humidity plays a large part in how comfortable a certain temperature feels. The more humidity in the air the stickier the air feels. This is an important measurement to consider for the Smart Window since the user would want to know how comfortable the air inside feels for themselves and/or guests. The same humidity at different temperatures can make the air feel comfortable or not depending on a new variable known as dew point. Dew point is the temperature at which water droplets begin to condense resulting in dew forming. Dew point can be calculated from both temperature and humidity in a complicated formula, shown in Equation 1 below and only valid for temperatures between -45 and 60℃, and is a much more accurate predictor of whether or not the air feels comfortable to be in. Generally, a dew point of less than 16 ℃ is considered comfortable. Calculating the dew point is easy enough once the proper measurements are taken so it is important to select an accurate sensor for this application. Humidity sensors generally fit into three categories: capacitive, resistive, and thermal.

$$\text{Dew Point} = \frac{243.12 \times [ln(RH/100) + (17.62T)/(243.12 + T)]}{17.62 - [ln(RH/100) + (17.62T)/(243.12 + T)]}$$

Equation 1: Dew point calculation, relative humidity (RH), and temperature (T) [CalcuNation]

Capacitive humidity sensors are constructed by placing a thin metal oxide between two electrodes. As the humidity in the atmosphere changes, the oxide's electrical capacitance changes linearly. This type of sensor can measure from 5% to 95% relative humidity with an accuracy of ±1%. One problem with these types of humidity sensors is the need to calibrate regularly which is not ideal for a consumer product. Therefore this type of sensor will be considered as a last resort. Figure 18 [Fierce Electronics] below shows how manufacturing specificifications can affect the shape and size of a capacitive humidity sensor.

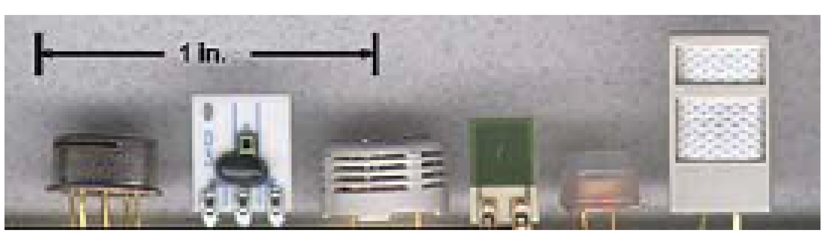


Figure 18: Size and shape differences of humidity sensors [Fierce Electronics]

Resistive humidity sensors have an exponential resistance versus humidity curve making them less optimal than capacitive humidity sensors, but the lifetime of these devices is much longer, averaging greater than five years as opposed to the regular calibration needed to keep a capacitive sensor working. Once the resistive humidity sensor is calibrated, it does not need to be touched again until the lifetime of the device comes to an end. The linearity of the relative humidity versus output voltage is relatively exponential but can easily be linearized via digital or analog methods. Resistive humidity sensors can measure from 15% to 95% relative humidity with an accuracy of ±2%. This is not much worse than capacitive humidity sensors and with the lifetime of these sensors being so long while being easily replaceable, resistive humidity sensors would make a very good choice for the Smart Window. Figure 19 [Fierce Electronics] shows different variations of resistive humidity sensors

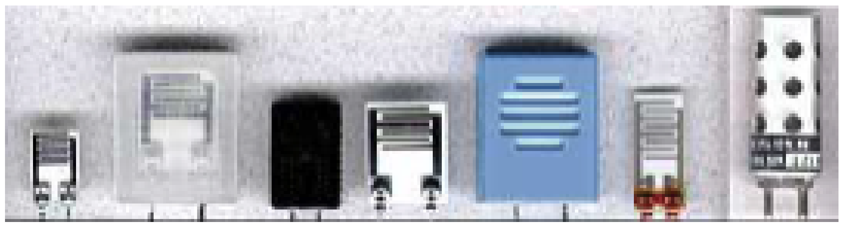


Figure 19: Variations of resistive humidity sensors [Fierce Electronics]

Thermal conductivity humidity sensors work by measuring the thermal conductivity difference between dry air and humid air. These sensors consist of two thermistor elements, one exposed to the air and one sealed. They are then bridged together and the output resistance can be measured to calculate the humidity. These types of sensors can operate at very high temperatures and are very durable making them optimal for situations where the other types of sensors would not survive. Figure 20, [Fierce Electronics] shows different variations in thermal conductivity humidity sensors.

Figure 20: Variations of thermal conductivity humidity sensors [Fierce Electronics]

Overall, it makes sense to select the semiconductor IC humidity sensor. Though it is less accurate than a capacitive sensor, it does not need to be regularly calibrated which would be a hassle for the user. Thermal conductivity sensors are the least accurate of the three despite having the largest operating temperature range so they are also out of the equation. While resistive humidity sensors are a good option for economic constraints, the resistance versus relative humidity curve is more exponential than the semiconductor IC sensor for the same price.

Thus, the semiconductor IC humidity sensor will be chosen. To help note the differences between each of these sensor classes, Table 3 summarizes the key characteristics of each of the sensor types mentioned above.

Type	Operating Range	Linearity	Cost
Capacitive	5%-95% RH	Very linear	$$-$$$
Resistive	15%-95% RH	Relatively exponential	$-$$
Thermal Conductivity	5%-95% RH	Very exponential	$$-$$$
Semiconductor IC	5%-95% RH	Very linear	$-$$

Table 3: Characteristics of different humidity sensor types

Choosing the semiconductor IC class for this experiment reduces the number of options to choose from significantly, but there are still thousands of sensors to choose from. The main criteria that this humidity sensor should meet would be I2C communication, ±2% relative humidity, and to be as cheap as possible.

3.2.7.3 UV Sensor

The UV sensor should be located on the outside plane of the window to collect accurate data since glass filters UV light. This data can be used to calculate the UV index for the day which is used for classifying the power of ultraviolet radiation. This information can be used to determine whether or not to wear sunscreen for the day. There are several classifications to UV light which need to be taken into consideration before selecting the appropriate sensor including UVA, UVB, and UVC. Each of these refers to a different range of wavelengths of UV light which have different effects on plants and animals.

UVA refers to the spectrum of UV light that falls within 315 to 400 nm. Almost 90% of UVA light makes its way through the ozone layer and reaches Earth’s surface meaning that it also comes into contact with everyone who is outside. This is the least harmful of the categories with the main association being skin aging. Measuring the UVA light intensity could be useful for certain applications but the intention for the UV sensor is to warn the user of the Smart Window to put on sunscreen.

UVB refers to the spectrum of UV light that falls within 280 to 315 nm. This spectrum of light can be harmful to humans in that it can cause sunburns, though not penetrating deeper than the top layers of skin. UVB is the main concern when selecting the sensor since this type of light is what causes the sunburns which is what we want the Smart Window to warn the user of before going outside.

Only about 10% of UVB light from the Sun makes its way to the surface of the Earth but that little amount sure can do some damage as everyone who has had a sunburn would know. Long term exposure of UVB can also lead to cancer so it is of the utmost importance to be able to reliably determine the concentration of UVB light outside.

UVC refers to the spectrum of UV light that falls within 100 to 280 nm. This type of UV light is the most dangerous and can penetrate the human skin causing severe burns as well as eye damage. Luckily the Earth's atmosphere filters this light out so that none reaches the surface of the Earth. The only way to come into contact with UVC is via a man made source.

UV sensors measure the intensity of UV light using a variety of techniques including photodiodes and Charge Coupled Devices (CCD). A photodiode works by absorbing incident photons into the diode, which creates electron-hole pairs. This generation of pairs causes a current to flow, which can be measured and then quantized to read the data.
Since each photon corresponds to one electron-hole pair the light intensity can be very accurately measured, after considerations to the dark-current of the device are made. A CCD is an IC etched into a silicon wafer to form pixels which are sensitive to light. When incident light hits the surface of the silicon, a charge is generated and can be decoded by a microprocessor to read the wavelength. CCD's are much more expensive than photodiodes and since the UV sensor is just to get a general idea of what the UV index is outside, precise measurements need not be taken. Thus, the sensor type for the Smart Window will be a photodiode though the exact part has not been selected yet.

3.2.7.4 Proximity Sensor

Proximity sensors are a type of sensor with the main purpose of determining the distance between the sensor and a target. The theory behind proximity sensors uses the physical nature and properties of waves, as they can be reflected from nearby objects and return to their source. Knowing the speed of the wave in the medium as well as the time it took the wave to reach its target object and back to the source allows it to determine the distance between the source and the target.
If an object is not present near the sensor, the wave simply dissipates in the environment. The use of sensors for object proximity detection and ranging has been reliably used for over a century, with the main types of waves used being radio waves (radar), acoustic waves (sonar) and light waves (infrared and LIDAR). Other types of proximity sensors include Doppler effect sensors, capacitive sensors, and hall effect sensors. Most of these were not considered due to their impracticality as it relates to our project and some types, such as inductive sensors, require the target to be made of metal which would not work to detect a human user as we intend.

Proximity and distance sensors are ubiquitous nowadays, finding their applications in consumer electronics such as smartphones and tablets, security systems with motion detection, military and defense with missile tracking, and self-driving automobiles which use LIDAR for collision avoidance. In nature, animals such as bats, whales and dolphins are known to use echolocation to identify locations of objects in dark spaces. Echolocation is essentially a type of biological sonar which uses the same principles of wave behavior mentioned in this section, with the “source” being the animal itself and the wave used, ultrasonic. The team concluded that the relatively lower range of infrared sensors was not a significant issue as the design only calls for 3 ft between the window and the user. This along with the speed and accuracy of infrared sensors makes them best suited for our application. Therefore, after weighing in the pros and cons of each type of proximity sensor, the team decided to use an infrared sensor for the Smart Window design.

IR Proximity Sensors

Before delving into infrared proximity sensors, it is important to note the physical characteristics of infrared waves and what makes them perfect for use in this type of project. It can be seen in Figure 23 [Wikimedia] that infrared waves occupy a spot in the electromagnetic spectrum in between visible light and microwave radiation. “Infra” means below in Latin, so the name of this frequency range translates to “below red”, having lower frequencies than the visible color with the longest wavelength, red. This also means that infrared waves are completely invisible to humans, making them a perfect candidate for our desired proximity sensor, as it would integrate seamlessly into our design and not be noticeable to the end user.

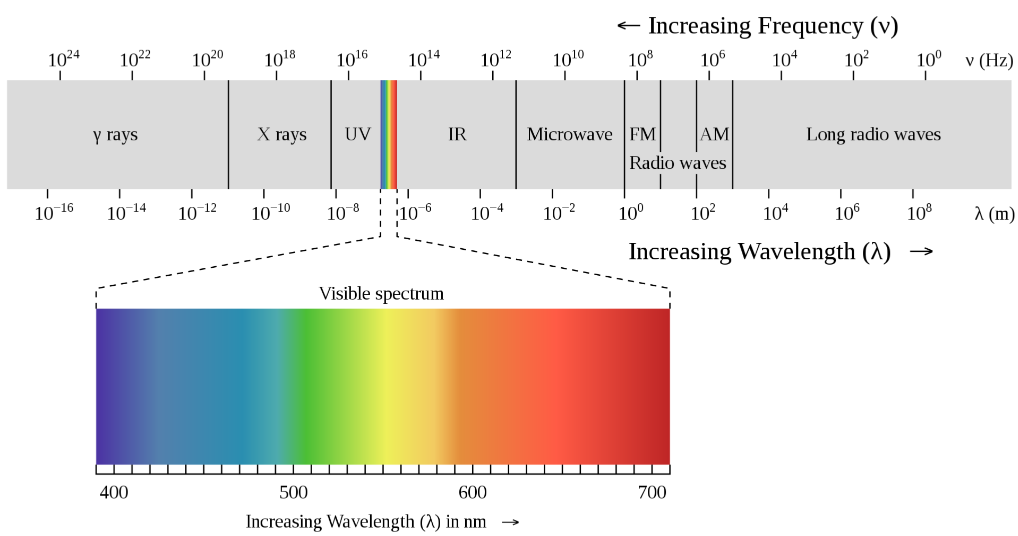


Figure 21: Electromagnetic Spectrum [Wikimedia]

Another important safety consideration is that since infrared waves have lower frequencies than visible light, they are completely safe for long-term use and do not pose any sort of risk from ionizing radiation to the user. There are two types of IR proximity sensors: active and passive. We will explore the working principles of both types in order to qualify which type of sensor would work better with our design.

Active IR Proximity Sensors (AIR)

Active infrared proximity sensors are optical sensors that use infrared waves along with the principle of time of flight to determine the distance between the sensor itself and the target. These sensors are typically comprised of two main components: the light source and the photodetector.

The light source is usually a small IR laser diode or IR LED which are energy efficient, inexpensive and can fit into a small design. Laser diodes usually have light which is not as collimated due to their smaller cavity, therefore along with the light source there is also usually a collimating lens which allows the laser light to be able to travel with minimal beam divergence in air, making the light much more likely to reach the target optimally.

There are multiple types of photodetectors which can be used, the main requirement needed is the capability to detect the wavelength that the light source emits. Some of the most common photodetectors used in proximity sensors include PIN photodiodes and avalanche photodiodes. Another fairly important requirement for photodetectors used in optical proximity sensors is their working speed. Since we are working with speed of light measurements, the detectors need to be able to recognize and process the light within tens of nanoseconds. The last element needed to have a fully working proximity sensor system is a timer circuit. The accuracy of this component is essential as a sub-microsecond margin of error might not allow us to correctly calculate the distances of objects at different but close ranges such as the ones in the application of our project.

After knowing the distance between the sensor and the target, a simple threshold can be set using software so that the Smart Window only displays its interface when the user is within a certain arbitrary distance such as 3 ft. This is as long as the output voltage is high enough to trigger the interface. In the following Figure 22 [Hamamatsu Photonics], the working principles of optical time of flight are depicted in order to visualize how distance measurements are initially obtained using the components previously described.

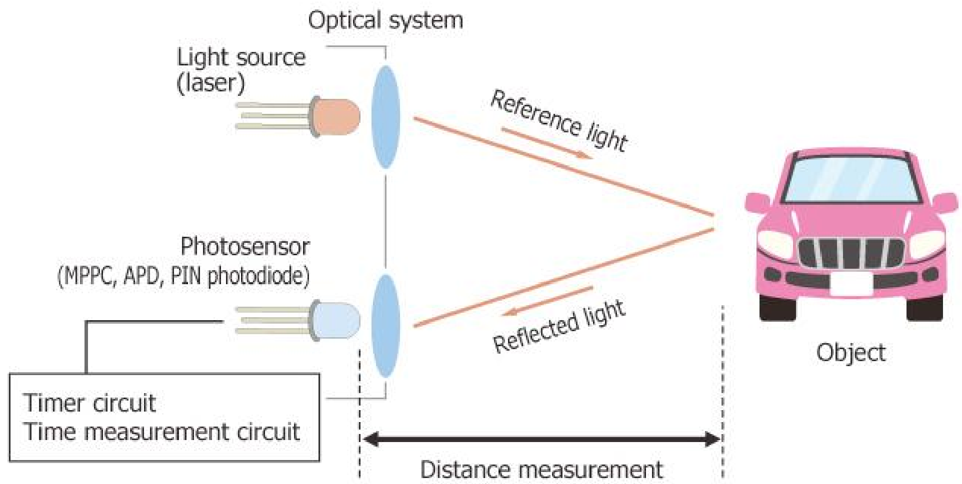


Figure 22: Optical time-of-flight diagram [Hamamatsu Photonics]

Time of flight is an echo-based technology which measures the distance between two objects by producing EM pulses or signals using a laser and detecting the time it takes for the reflected portion of the pulse to return to the source. Since the medium that the laser light will travel in is air, Equation 2 can be used:

$$d = \frac{c * \Delta t}{2}$$

Equation 2: Time of flight for EM Signals

This equation can calculate "d", the distance between the laser source and the target as long as the other variables in the equation are known. In the equation, the speed of light in air is represented by the constant "c", which is widely known through experimentation to be around $3x10^8$ m/s. This leaves the last variable needed "Δt" which is time delay measured as the light makes its round trip from the source to the target and back. An important thing that can be noted is that this simple equation can also apply to acoustic waves by changing the speed of the wave to the speed of sound, as the same theoretical principles are used in sonar techniques.

Up to this point we have described a version of time of flight technology known as direct time of flight. Another type of time of flight that has become increasingly popular is indirect time of flight (also known as Frequency Modulated Continuous Wave, or FMCW). This method uses a very similar formula as direct time of flight except instead of measuring a time delay between the reference and reflected pulses it measures phase differences of continuous modulated light. This light can be, for example, sinusoidally modulated. After the reference light has hit the target and reflected back to the photodetector, the phase difference between the reference and reflected beam is measured.

The phase of the reflected light is proportional to the time of flight and from there, the distance between the sensor and the target can be easily calculated.

Passive IR Proximity Sensors (PIR)

Passive, or Pyroelectric, IR proximity sensors use only an IR photodetector and no light source such as a laser or LED. This means that unlike active infrared sensors, PIR sensors don't use the principle of time of flight in order to calculate the distance between a target and the sensor. This type of sensor takes advantage of the fact that bodies produce heat and therefore radiate light in the infrared range, effectively making the human body the light source from which infrared light is detected.

The unique operation of PIR sensors opens opportunities to nice applications such as only detecting the bodies of humans and animals as they walk into view and change the temperature within its detection area. If a body is detected, the output voltage of the sensor will be high, and if there are no bodies present, the output voltage will be low. In the context of some other uses, this might be a disadvantage to this type of sensor. Fortunately, for our Smart Window design the team cares only about detection of users, and not objects made of different materials, therefore this type of sensor will also be taken into consideration in the part selection process.

3.2.8 Photovoltaic Cells

The way photovoltaic (PV) cells work is by having photons bombard the surface of the cell to generate electricity. This happens because the silicon is doped with elements of different charge on opposite sides creating an electric field. Much like how a pn junction diode works, though in reverse, a current is generated when a photon knocks an electron loose due to the electric field. This current can then be used as it is generated or directed into a battery for energy storage. Figure 23 [NASA] shows a basic application of this process.

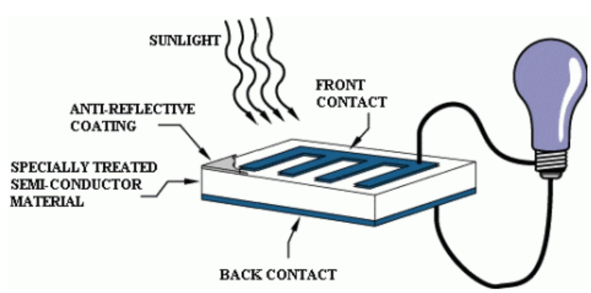


Figure 23: Electricity generation using photovoltaic cells [NASA]

Photovoltaic cells are typically manufactured for commercial and residential purposes in two types: monocrystalline and polycrystalline. Monocrystalline cells as the name suggests are made from a single silicon crystal while polycrystalline use many melted together. Monocrystalline cells have to be manufactured in a very specific way resulting in a high efficiency with the downside of being more expensive than polycrystalline. The alignments of the melted crystals makes it harder for the electrons to flow in a current but this is the price to pay for easier manufacturing. Later in this section, the team will research further into the different types of solar cells in order to determine which technology, if any, will be the best fit for the Smart Window.

Photovoltaic Cell Efficiency

There are three major components that determine the output of a given photovoltaic cell. Two of them are external and can't be controlled by the team: the latitude and the climate of the location where the solar cell will be used. These two factors directly correlate with the amount of sunlight that will be incident upon the cell, therefore ultimately having an impact on how much energy a solar cell generates on a given day.

However, arguably the single most important electro-optical parameter that is used to measure the performance of any given photovoltaic cell is their efficiency. The efficiency is determined by the type of solar cell as well as the material used to create it, as properties such as reflectance and charge carrier separation efficiency have a direct impact on overall efficiency. A solar cell's efficiency is calculated by taking the output power of the solar cell divided by the total input solar power. A ratio of 1 (or 100%) would mean maximum theoretical efficiency, such that a photovoltaic cell converts all incident light into electricity with no wasted energy. As of 2019, the record for highest efficiency in a solar cell is 47.1%, generated by the National Renewable Energy Laboratory in Golden, Colorado, USA.

As the team researches further into the different types of photovoltaic cells in both the technology research and part selection sections, we will explore the approximated efficiency percentages for each type of solar cell in the market and how this information relates to our project. The team will seek partly for the most efficient solar cell that our budget allows, since typically efficiency has a direct correlation with the price of a given PV cell.

Photovoltaic Cell Types

As mentioned at the beginning of the photovoltaic cell section, there are two main types of photovoltaic cells: monocrystalline and polycrystalline. In this subsection, the team will explore further into the technology behind these two types of solar cells in order to determine which one will be best for our project.

In addition to the two major types of cells, the team will also look into the newer technology of thin-film solar panels.

Monocrystalline Silicon Photovoltaic Cells

Monocrystalline silicon cells (also known as mono c-Si cells) are a type of solar cell that is designed with a base material of only silicon. This pure silicon is prepared as either an intrinsic semiconductor or it may be doped.

This type of PV cell is easily recognizable due to its uniform dark color, as it can be seen on Figure 26 [EnergySage]. Monocrystalline silicon cells are known for their higher overall efficiency due to the use of pure silicon in their manufacturing as well as its dark blue color which allows for a better absorption of photons.

Currently, the record efficiency for mono c-Si solar cells is 26.7% efficiency, making them the highest efficiency cells widely available for purchase, but also as mentioned earlier, leading to overall higher costs. The fact that this type of cell has higher energy, however, allows for more energy generation even in potentially lower sunlight conditions, which can be very important as a Smart Window does not receive direct sunlight throughout the day, only in the few hours when the sun is facing the window.

Polycrystalline Silicon Photovoltaic Cells

Polycrystalline silicon solar cells (also known as poly-Si cells) are, as the name suggests, a variant of photovoltaic cells where multiple small silicon crystals (crystallites) are melted together using the Siemens process, which is a chemical purification technique. The result of this type of production is a very recognizable metal flake appearance which can be seen in Figure 24 [EnergySage] and is much different than the dark blue or black coloration of monocrystalline silicon solar cells.

The lighter coloration of the cells means there is less absorption of photons and this, along with the fact that the cells are composed of multiple small crystals, leads to less overall efficiency. However, despite their slightly worse efficiency, poly-Si solar cells are the most common form of PV technology, holding about 50% of the global market share. This means that a plethora of companies are developing polycrystalline cells in large quantities, which leads to an overall less expensive product than the other solar cell technologies.

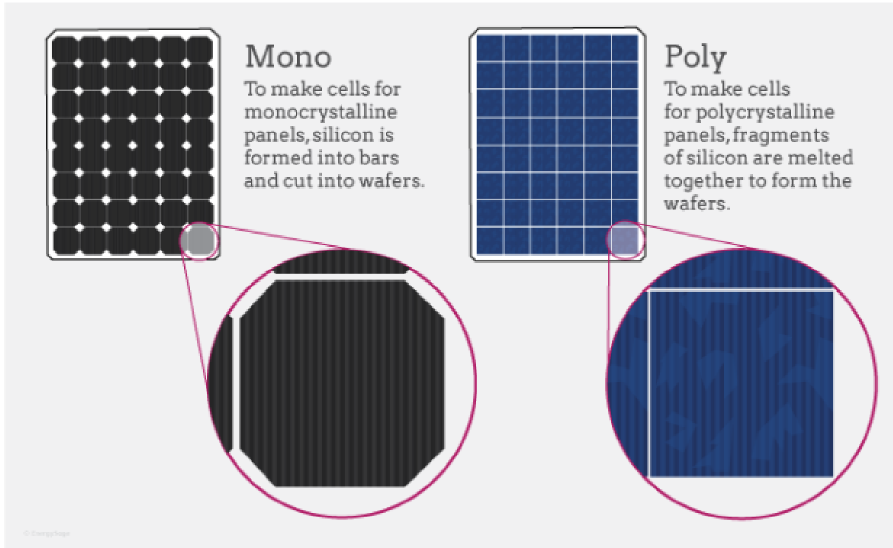


Figure 24: Mono and Polycrystalline Si Solar Panels [EnergySage]

Thin-film Photovoltaic Cells

Thin-film solar cells are made by depositing one or more layers of any photovoltaic material on a substrate. The thicknesses of these thin films may vary from nanometers to micrometers, making them not only thinner but lighter than conventional photovoltaic panels. Another advantage to using this type of solar cell is that depending on the material used to create the cell they can be flexible which opens this technology for multiple applications as well as giving it more durability.

Some of the most notable materials used for thin film PV cells are cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and a form of non-crystalline silicon known as amorphous silicon (a-Si). The efficiency of these types of solar cells is approximately the same as polycrystalline silicon cells, and despite this, they remain costly and account for approximately 9% of the worldwide PV cell market.

Photovoltaic Systems

Another important consideration that must be made by the team when looking into solar panels is the type of system we want to design for use in this project. As renewable energies become increasingly popular and consumer demand skyrockets for solar panels, two main types of solar systems are usually seen in both commercial and residential applications of photovoltaic cells: grid-connected and off-grid systems.

Grid-connected PV systems, as the name suggests, are connected to the electric grid of a city. This means that the energy generated by the solar cell is used to power the appliance or house that it is connected to, and any excess energy generated is supplied to the rest of the local community. This provides a great solution to residential customers who want to use renewable energy but also want to have a backup in case of a cloudy day. Alternatively, the solar energy generated can serve as a backup anytime there is a power outage in the community.

On grid-connected solar systems, there is no need for a battery pack, which helps save a considerable amount in upfront setup costs. In addition to this, another economic benefit to this type of system is the fact that electric utility companies tend to reimburse users for any amount of energy that they provide back into the grid. On the other hand, grid-connected systems can be more difficult to set up since there is the need to contact the local electric utility company and get their written permission, which makes this type of system beyond the scope of the autonomous Smart Window we want to achieve in this project.

The alternative to grid connected systems is off-grid systems. This type of solar energy system is entirely self-sufficient, and instead of providing the excess energy generated into the grid, it is stored for later use using a battery pack. This type of photovoltaic system is very common on stand-alone solar powered items such as backpacks, calculators and watches, and it can be scaled up for powering boats and cabins in a remote place. The upfront cost in this type of system is much higher since there are no energy refunds and a battery pack must be purchased.

Despite the economic disadvantages, the team decided that using an off-grid photovoltaic system is definitely the way to go for this project since we want to be able to relocate the Smart Window and obtaining approval from the Orlando Utility Company seems beyond the scope of what we want to accomplish. Due to this, in the following section the team will be conducting technology research into batteries for the battery pack which would be powered by a solar panel and will have a backup plug in case the user wants to power the system using their home electrical outlet.

In order to choose the right photovoltaic panel for the application of powering the Smart Window, the team will take into consideration both economics and efficiency. To ensure that the window does not have to connect to mains power from a standard wall outlet, monocrystalline cells should be the first choice for their photon to electron conversion efficiency. This feature may have to be put on hold if the economics of this project start to spiral out of control. There is a limited budget to produce this window and there might have to be a sacrifice in efficiency to stay within the budget.

When the costs become more finalized, a selection between thin film photovoltaic cells, polycrystalline silicon cells, and monocrystalline silicon cells will be made. This final selection, along with a review of solar panels from the major vendors will be found in section 3.3 of this document.

3.2.9 Batteries

The basic function of a battery is to store energy. This energy is to be used when the user wants to use energy and stored when the user does not want to use any. One of the marketing points for the Smart Window is the ability to rely on solar energy rather than fossil fuels which generate most of the electricity for people's homes. Two main factors to consider when selecting the right battery for a certain application are energy density power density. Energy density is measured in watt hours per kilogram (Wh/kg) which relates to the capacity of the battery while power density is measured in watts per kilogram (W/kg) which relates to how quickly that energy can be used. It is important to factor in both of these variables so that optimal power can be provided with the minimal number of batteries used.

The highest energy density battery available to consumers today is the lithium ion battery ranging from 100 to 250 Wh/kg. This allows for high capacity batteries to come in small casings such as the popular 18650 (18mm x 65mm). These batteries also have a high power density ranging from 300 to 1500 W/kg allowing for high continuous discharge currents. A typical 18650 cell has a nominal voltage of 3.7V with capacities ranging from 2000 to 3200 mAh. For the Smart Window, it would be wise to select batteries on the upper end of the spectrum so that a lesser quantity will be needed in the final product.

3.3 Major Part Selection

After taking the research of relevant technologies into consideration, the project team was able to narrow down specific vendors which supply parts which meet the criteria of the project. To be sure of the purchasing choices, numerous vendors were considered. The selections outlined in this section offered the best result of both price, lead time, and engineering requirements for their purpose in fulfilling the project brief. Parts that have been selected in this section are either already being purchased by the team for testing, or are awaiting the results of prerequisite tests being done before the item is ordered.

3.3.1 Display Selection

The team has decided to use an Acer S201HL 20” LCD Display. The primary reason for this decision is that the group is already in possession of this display from previous work, and it meets all of the criteria outlined in the relevant engineering and marketing requirements.

The S201HL display is a TN display, the panel type which has been identified as having the best potential to be modified for use as a see-through display. It also meets the size requirements of the project. Because the display resolution is 1600x900, but the monitor size is only 20 inches, the smaller than HD resolution will still maintain a clear picture, for reasons outlined in section 3.2.1. The monitor supports a fast response time of 5ms, and a large color bit-depth capable of producing 16.7 million distinct colors.

At the project's current state, the group is optimistic about the potential of this display to be used as the concrete choice for the project. Testing the monitor in different environmental lighting scenarios is being conducted, as well as further modifications to make the display as transparent as possible. More documentation on the current testing results for the selected monitor can be found in section 5.4.1

3.3.2 Smart Film Selection

The switchable Smart Film is one of the major features of this project and potentially the most expensive one. Therefore, a great deal of market research has to go into selecting the final component. As mentioned in section 3.2.6, smart films and glass are typically divided into two major categories. Those two categories are active smart film and passive smart film. In this section, the team will explore the pros and cons of the two main categories and all the variations of smart film that fall within them to determine which is the best fit for our project. Besides from this, the team will also explain the reasoning behind the final part selection and the vendor that it will be ordered from. Many specifications will be kept in mind when deciding the final smart film but some of the major concerns are power consumption, haze coefficient in the transparent and opaque modes, and cost.

In the technology research section we introduced the concepts of active smart film and passive smart film. The main difference between the two is that active smart films are controlled by the user by using either voltage or current, while passive smart films (thermochromic and photochromic) use external stimuli such as sunlight or temperature to change between opaque and transparent modes. Given the nature of our project and the fact that the team wants to provide a very user-friendly experience with our Smart Window, the team decided to go with an active smart film. By using this type of film in our final project, the user can decide when they want to activate and deactivate the privacy mode without having to depend on external stimuli from nature.

After having decided to move forward with an active smart film, the next step is to make the decision on which specific type of active smart film we will use on our Smart Window. The first consideration which must be taken into account is the possibility of buying a smart glass or buying a regular glass and retrofitting it by applying a smart film.

For example, one of the types of active film, Micro-blinds can only be applied to glass through magnetron sputtering, which is an expensive technique which is why this type of smart glass technology is not widely available in the consumer market. This completely disqualifies Micro-blinds from our consideration, leaving the other types of smart film (electrochromic, suspended particle devices, and polymer dispersed liquid crystals) as possible parts for our project.

Another important consideration that came up when doing the technology research for smart films is that multiple PDLC film vendors claim in their specification sheets that liquid crystals can block up to 99% of incoming UV radiation. Despite the advantages of this fact as outlined in section 3.2.6, this would also help the team since there would no longer be a need to use a UV filter in the project for thermal management.

Even though this claim needs to be researched further and possibly tested, should PDLC films be selected, the team will take this claim at face value preliminarily and it will be considered an advantage to using a PDLC. In the following Table 4 the team will examine the advantages and disadvantages of all the different types of active smart film.

Type of Active Smart Film	Pros	Cons
Electrochromic	Partial UV Filtering Switching can be enabled by DC or AC voltages	Uses oxidation reaction for switching between opaque and transparent states, leading to longer switch times
Suspended Particle Devices (SPD)	High switching speed	SPD film not available to consumers High cost for SPD glass
Polymer Dispersed Liquid Crystals (PDLC)	Low cost Market availability High switching speed UV and IR Filtering capabilities	Switching between modes requires AC supply voltage

Table 4: Pros and cons of different types of active smart film

From the information we have gathered in Table 4 the team decided to use a PDLC switchable film as the privacy technology in the Smart Window. In the following paragraphs we will conduct a market analysis of some of major PDLC film manufacturers that the team contacted for a quote and their respective products in order to decide on a final supplier to acquire the PDLC film from.
Each vendor’s film must meet the requirements of the project as well as provide a good balance between high performance and a low price point that fits within the project’s budget.

Smart Film by Impelwell, Inc.

The Smart Film made by Impelwell, Inc is a PDLC film manufactured in China and exported worldwide. This PDLC film can switch from opaque to transparent upon applying a voltage of 35-60V AC. Impelwell offers an adhesive film with maximum dimensions of 71" Wide (1.8 m) by 164 ft long (50m) which is well above the desired dimensions for our project. It has a thickness of 0.4mm making it not noticeable when applied to glass.

Impelwell's Smart Film has both an opaque and transparent mode. In the transparent mode, Impelwell claims the PDLC film blocks or reflects up to 99% of UV radiation as well as 90% of infrared radiation, and it has a haze coefficient of under 3%. In the opaque mode, the film blocks 99% of UV light, 95% of infrared light, and has a haze coefficient of over 92.5%. The switching between modes occurs in under 45 ms, and the film is able to operate in temperatures of -30 to +90°C which is well within reasonable outdoor weather.

Despite its impressive technical specifications, when the team looked into the pricing for a 3 ft by 2 ft section of adhesive Smart Film by Impelwell plus shipping it's clear that it is outside of the group's budget for this project, despite being rated for over 80,000 hours of transparent use and coming with a two-year warranty period.

Smart PDLC Film by Magic-Film

The Smart PDLC Film from Magic-Film is a PDLC film produced in China and shipped worldwide. This film switches from opaque to transparent in under 60 ms when a voltage of 48 - 65 V AC at 50Hz is applied to the film. The vendor offers an adhesive and non-adhesive version of the film, with the adhesive type offering a thickness of 0.36mm and maximum dimensions of 1.52 m wide by 30 m long (5 ft x 98 ft) which is above the desired dimensions of the project.

Magic-film offers data on their film's solar gain coefficient, which is 0.79 on the transparent mode and 0.06 on the opaque mode. Along with this, their smart PDLC film offers over 99% of UV radiation blocking in both opaque and transparent modes, as well as >20% and >80% infrared blocking on transparent and opaque modes, respectively. This model also offers a haze coefficient of under 6% on transparent mode and over 90% on opaque mode.

This manufacturer claims the film is rated for >100,000 hours of use at temperatures from -20 to +60°C. The team contacted Magic-Film for a quote on a 3 ft by 2 ft adhesive Smart PDLC film but as of the writing of this document we have not received a reply from this vendor.

Switchable Smart Film by EB Glass

The Switchable Smart Film from EB Glass is a PDLC Film manufactured in China and able to be shipped worldwide. The vendor offers an adhesive film which comes in three different versions that change from opaque to transparent mode at three different AC voltages (36 V, 48 V, 60 V) and using a current draw of 150 mA per square meter of film, leading to a power consumption of under 5 W per square meter. The maximum width for EB Glass' adhesive smart film is 1.5 m (5 ft), and the maximum roll length can reach up to 30 m (100 ft). It is a very thin film with a listed width of 0.38mm, therefore this can be a possible candidate for our final PDLC film.
EB Glass' Switchable Film is sold with impressive optical characteristics such as over 99% UV blocking in both opaque and transparent modes, over 80% and over 20% IR radiation blocking in opaque mode and transparent mode respectively. The film also has the exact same solar coefficient values as the Magic-Film PDLC film, with 0.79 on the transparent mode and 0.06 on the opaque mode. This PDLC Film is rated for over 100,000 hours of opaque mode use in temperatures from -20 to +60°C as well as offering switching times under 200 ms. As of the writing of this document, EB Glass was contacted via email but no quote has been received for a film of our required dimensions.

Smart Tint® by Smart Tint, Inc.

The Smart Tint PDLC Film is made by Smart Tint, Inc, a company based in the United States. This film changes states from opaque to transparent in under 40 ms. This process occurs upon applying a voltage of 35-65V AC or 12-24V DC when used with a separately sold dimming attachment. Smart Tint offers an adhesive film and a non-adhesive film with maximum dimensions of 71" Wide (1.8 m) by 163 ft long (50m) which is above the desired dimensions for our project. The film also has a thickness of 0.35 mm which makes it virtually invisible to the end user. The film is composed of two protective layers of film with Liquid Crystal Polymer and an ITO Layer, as well as Smart Cling® Adhesive for the adhesive films.

Smart Tint has both an opaque and transparent mode as well as the possibility to dim the system using their Mobile dimming system. In the transparent mode, Smart Tint's PDLC film blocks or reflects up to 99% of UV radiation as well as more than 80% of infrared radiation, and it has a haze coefficient of 5%. In the opaque mode, the film blocks 99% of UV light, 95% of infrared light, and has a haze coefficient of 93%.
The film also has solar gain coefficients of 0.71 when transparent, 0.1 when opaque and is able to operate in temperatures of -10 to +60°C which is well within the typical outdoor weather in Florida. As the team is interested in an adhesive film instead of a non-adhesive rigid material, we looked further into Smart-Tint's adhesive product, which features their proprietary Smart Cling® technology.

This technology creates a seal between the film and the glass such that moisture and heat are not trapped in between during the film's application. This use of a specialized adhesive keeps virtually the same clarity of the glass once the film is applied and avoids any sort of damage to the glass.

The information provided up to this point is from the DIY Mobile Kit from Smart Tint, as opposed to their alternative traditional film, since the Mobile Kit features their Low-Voltage film which uses 3 W per meter squared per hour. The team researched into this since our application requires us to try to keep energy usage to a minimum in order to make this system energy efficient, and this kit features a 36 by 24 inch adhesive film which is exactly the size the team required for the Smart Window's glass.

PDLC Film Component Selection

In the following Table 5 the team will summarize the technical specifications from the different Smart Film products in order to make a final selection.

Parameters	**Impelwell**	**Magic-Film**	**EB Glass**	**Smart Tint**
Haze Coefficient *(transparent, opaque)*	<3%, >92.5%	<6%, >90%	<6%, >90%	5%, 93%
Visible Light Transmittance *(transparent, opaque)*	>83%, <70%	≥80%, <4%	≥80%, <4%	90%, 4%
IR Light Transmittance *(transparent, opaque)*	10%, 5%	>80%, >20%	>80%, >20%	>20%, 5%
UV Light Transmittance *(transparent, opaque)*	1%, 1%	1%, 1%	1%, 1%	1%, 1%
Viewing Angle	160°	145°	150°	150°
Maximum Switching Speed	45 ms	60 ms	200 ms	<40ms
Solar Gain Coefficient *(transparent, opaque)*	0.8, 0.2	0.79, 0.06	0.79, 0.06	0.71, 0.1
Power Consumption	<3 W/m^2	3.6 W/m^2	<5 W/m^2	3 W/m^2

Table 5: PDLC film technical comparison

Based on the specifications compiled in Table 5, as well as the pricing information provided by the PDLC vendors when contacted for quotes, the team made the final decision to go ahead with the Smart Tint® film. The optical and electrical parameters of this film are outstanding and a great fit for our project.

It has a low power consumption, high optical gain coefficient and high haze coefficient when in the opaque mode. The fact that the vendor offers a “Mobile Kit” with the exact dimensions we need for the project which includes pre-installed wires along the bottom such that it can be directly connected to the power source is extremely convenient. From the product research the team conducted, this vendor has the best pricing we were able to find as well as being made and shipped within the United States, being the main PDLC supplier for reputable companies such as BMW, SpaceX, Apple and the Walt Disney Company.

3.3.3 LED Selection

In the selection of LEDs numerous considerations were made. Early into LED research, the question of using single or multiple LEDs was considered. While a single high power LED can offer substantial lighting, it also requires adequate heat dissipation systems to prevent LED damage. This, alongside it showing all of the light from a single source gives a single high-power bulb disadvantages to a strip based LED system.

LED strips typically differ from single bulbs by running multiple diodes in parallel connections. This makes LED strips ideal choices for diffused lighting scenarios, such as area and sign lighting. Two primary criteria for deciding the groups LED strip choice were the lumens output, which describes how much optical power the LED strip generates, and the color temperature, which offers information of the color profile of the light (see Figure 7 in section 3.2.2.)

The LED strips chosen were the IP20 HD 3ft Strips from LEDSupply, which offered a high density of bulbs. At 60 LEDs per meter, the strips in total offer close to 1100 Lumens. Combined between 2 strips, this gives the light a total of near 2200 Lumens for the entire lighting panel, which is about the same as what would be offered from a 34” Fluorescent bulb. Another benefit of the strips is that at only 14.4W/m, each LED in the lighting panel only consumes around 0.25W running at nominal power. This means that heat generation per bulb is extremely low, and considerations for cooling each strip is fairly simple.

To be sure that the LED strips chosen were supervised with proper quality control, the strips were purchased from LEDSupply, a business with 50 years of experience handling orders for everyone from DIY hobbyists to major tech companies. The group has used LEDSupply in the past for other high-power LED projects, so previous positive experiences with their products and customer support influenced the decision to choose them over other common suppliers.

The price per lumen of the strips selected was only 0.925 cents per lumen, which was considerably better than the next well known option of Phillips Hue strips, which was 2.63 cents per lumen, a difference of almost 3 times.

To be sure of the consistency and quality of the strips, the group only considered products with available technical documentation, which excluded cheaper alternatives from popular online retailers.

3.3.4 Microcontroller Selection

Selecting the microcontroller (MCU) for this project was done by considering price, ease of use, power consumption, and peripheral capabilities. To make the overall cost of the window as cheap as possible to assemble, it is important to choose a MCU that does not overperform to keep the price down. Some popular considerations include the MSP430 series, ATmega328p, and STM32 series.

The MSP430G2553 was used in previous classes at UCF so this makes it a promising option when the price is also considered. Using an Arduino board to test would make the development using an ATmega328p MCU easy due to the Integrated Development Environment (IDE) as well as the many libraries Arduino provides. The STM32L432KC MCU provides a 12 bit Analog to Digital Converter (ADC) and ST provides a very well written and in depth Application Programming Interface (API) to make development for embedded systems easier.

Arduino is an open-source hardware and software company that designs and manufactures single-board microcontroller and microcontroller kits for building digital devices. Arduino boards contain microcontrollers that are pre-programmed with a boot loader that simplifies loading of programs to the on-chip flash memory.

The Arduino Uno is an open-source development board based on the Microchip ATmega328P microcontroller. The board contains 14 digital analog I/Os pins where six are capable of Pulse-Width Modulation (PWM) and six analog I/O pins. It is programmable with the Arduino IDE through a type B USB cable. It can be powered by a USB cable or by an external battery. It accepts voltages between 7 and 20 volts. The microcontroller in the Arduino is the Microchip ATmega328P, preprogrammed with a bootloader. It's operating voltage is 5 Volts. The board has pins to support UART, I2C, and SPI communication. The DC current for each I/O pin is 20 mA, and the DC current for 3.3V pin is 50 mA. Its clock speed is 16MHz.

Ti MSP430 is a mixed-signal microcontroller that is built around a 16-bit CPU RISC Architecture. The MSP430G2xx are flash-based, low power MCUs that support MIPS (Million of Instructions Per Second) with an 1.8 - 3.6 operating voltage range. It includes a low pin count option and internal pull-up/pull-down resistor. The device supports UART, I2C and SPI communication.

The main purpose of a microcontroller is to read data from various sensors (temperature/humidity/proximity/UV) and send that data to the window’s display. Since the readings will not fluctuate rapidly, we can take advantage of using the low power modes of the microcontroller.

After consideration, the MCU that was selected was the STM32L432KC. (STM 32) The STM32 is a family of 32-bit microcontroller integrated circuits by STM32microelectronics. Each family is grouped into a related series around the same 32-bit ARM processor core, such as the Cortex-M33F, Cortex-M7F, Cortex-M4F, Cortex-M3, Cortex-M0+, or Cortex-M, each microcontroller in the STM32 series contains the processor core, static RAM flash memory, debugging interface and various peripherals.

The STM32 is based on the Cortex-m4F, a 32-bit RSC ARM processor core. Applicable features of the project are that it contains a floating point unit. Additional relevant features of the M4 architecture are listed below:

- Optional floating-point unit (FPU): single-precision only IEEE-754 compliant. Instruction set
- 32-bit hardware integer multiply with 32-bit or 64-bit result, signed or unsigned, add or subtract after the multiply. 32-bit Multiply and MAC are 1 cycle
- 1 to 240 interrupts, plus NMI
- 12 cycle interrupt latency
- Integrated sleep modes
- 120 MHz
- 3-stage pipeline with branch speculation

The STM32L432KC is an ultra-low power microcontroller that operates at a frequency up to 80 MHz. The MCU features a floating point unit single precision which supports all arm single precision data-processing instructions and types. The notable features of the device is listed below:

- Flash memory up to 256 Kbyte, 64 Kbyte of SRAM
- 12-bit ADC (5 Msps)
- 1 general-purpose 32-bit timer
- 16-bit PWM timer dedicated to motor control
- 4 general-purpose 16-bit timers
- 4 general-purpose 16-bit timers

The STM32L432KC is able to operate in the -40 to +85 °C (+105 °C junction), -40 to +105 °C (+125 °C junction) and -40 to +125 °C (+130 °C junction) temperatures from a 1.71 to 3.6 V power supply. This MCU was chosen for its ultra low power consumption (28 mA in standby mode), quantity and quality of peripherals, as well as a large API and native USB for easy development.

The peripherals offered include a 12 bit ADC for analog sensor readings and conversions, 14 communication interfaces including but not limited to I2C, SPI, and UART/USART, two comparators, and an op-amp. The MCU has an ARM M4 architecture, runs on 3.3V, and a 32 kHz internal clock with 11 timers.

3.3.5 Battery Selection

The parameters for selecting the batteries include: 18650 packaging, greater than or equal to 3000 mAh, and as cheap to order as possible. With these parameters being considered, the final battery chosen was the LG MH1 INR 18650 cell. The plan is to put two packs in parallel containing three or four cells in series each resulting in a nominal voltage between 11.1V and 14.8V. The batteries are rated at 10A continuous discharge so two packs in parallel could yield up to 20A resulting in a maximum power of 296W. This should be more than enough power to run the display, Raspberry Pi, LEDs, microcontrollers, and sensors for quite some time.

3.3.6 Battery Charger IC Selection

Lithium ion/polymer batteries are wonderful in that they can be charged and discharged many times for reuse. However, they can be very dangerous as well. Overcharging and/or overheating one of these batteries can lead to smoking, fire, and in the worst case an explosion. Therefore, it is essential to charge these batteries in a way that is safe for the user. There are many types of battery charger ICs being offered by different manufacturers so choosing the right one can cause some headaches. For this application, the IC needs to be able to charge multiple lithium polymer batteries in series, have a high efficiency, voltage and current regulation, and thermal regulation.

After much research, it seems as though there will have to be two different battery charger ICs which both fit the aforementioned criteria differing in the power input, one for a wall adapter and the other for solar power. The wall adapter will be considered first since there is not much experience working with photovoltaic cells and if the charging circuit does not work then the entire window could still be powered through the wall adapter.

One chip that meets these specifications is the BQ24765 by Texas Instruments. This IC offers integrated power MOSFETS, >95% efficiency, thermal regulation (T_j = 120℃), ability to charge up to four battery cells with many different chemistries, and <1mA current draw when chip is disabled. This will be the main battery charger IC to begin designing around and if the charging is successful then the next solar power battery charger IC will be considered.

3.3.7 Sensor Selections

When selecting the temperature and humidity sensors, it's important to note that many come as a dual package. It would be optimal for these sensors to communicate via I2C or SPI since there will be multiple other sensors to consider with limited input pins on the MCU.

The outdoor temperature and humidity sensor must be able to reach the outside plane of the window while the indoor sensor can be mounted on the PCB so long as there is ventilation to the inside plane to gather accurate data. The accuracy of each of each of these sensors should not exceed ± 0.5℃ and ±2% relative humidity. This information can then be used to plan outdoor activities, clothing choices, and indoor thermostat tuning. Many manufacturers are selling temperature and humidity sensors so picking the right one for the job is a matter of balancing performance and price.

3.3.7.1 Indoor Temperature Sensor Selection

When selecting a temperature sensor it is useful to know what types there are and how they work so that when it comes time to choose a component, the best selection can be made. Common types of temperature sensors include thermistors, Resistance Temperature Detectors (RTD), thermocouples, and semiconductor-based integrated circuits (ICs). While each of these sensors are used to measure temperature, they use different means to do so, and are made of different materials. Therefore, it is beneficial to divide these devices into smaller classifications.

Based on the research done in section 3.2.7.1, the semiconductor IC based temperature sensor category was selected for the Smart Window's indoor temperature measurement. A strong contender for this sensor is the STS-31-DIS from Sensirion AG. This sensor features a fully calibrated and linearized digital output, accuracy of ±0.1℃, very tiny package, and I2C communication while maintaining a very low price.

The testing for this sensor will have to be done on a PCB due to its small size (2.5mm x 2.5mm) not allowing for jumper wires or clips to be attached. Substituting a small decrease in accuracy would be viable if the semiconductor also features a humidity sensor. The HDC2010YPAR by Texas Instruments is such an IC that fits the description. This sensor is a dual purpose temperature/humidity sensor that features a low supply current (550nA), I2C communication interface, 11 bit precision, programmable samping rates, ±0.2°C temperature accuracy, and ±2% relative humidity accuracy.

3.3.7.2 Indoor Humidity Sensor Selection

Based on the research done in section 3.2.7.2, the semiconductor IC based humidity sensor category was selected for the Smart Window's indoor humidity temperature measurement. The IC that was chosen is the model HDC 2010 PAR sensor, from Texas Instruments.

3.3.7.3 UV Sensor Selection

Based on the research done in section 3.2.7.3, the photodiode UV light sensor category was selected for the Smart Window's UV light measurement. Choosing a sensor for this application was no easy feat as most UV light sensors are very expensive or their datasheets are stamped with "Not for use in new design" discouraging the buying of that component. In the end, the SI1132-A10-GMR from Digikey was selected as it was advertised to provide UV index sensing which would allow for less complications in calculating the index and for its low price compared to many other options. This sensor will be able to communicate with the MCU via I2C and has a factory calibration which can be used to account for variations in manufacturing the specific component used.

3.3.7.4 Proximity Sensor Selection

In this section, we will explore some of the major considerations that came up while researching infrared proximity sensors. These constraints are important to keep into account as the team moves forward with incorporating the proximity sensor into the hardware design and prevent any errors.

Minimum distance: This is a constraint specific to active infrared proximity sensors. There exists a "dead zone" or "blind zone" which is a small area right in between the front of the source and photodetector lenses where an object might be located and will not be detected by the proximity sensor.

The team considers that in practice this minimum distance will not be much of a concern, as it is very unlikely that the user will get that close to the Smart Window without walking from a farther away, detectable distance.

Maximum distance: The maximum sensing distance of an IR proximity sensor is caused by the divergence and attenuation of light in air. This parameter is determined by the optical output of the source as well as the sensitivity of the photodetectors. For cases which are beyond the maximum distance, detection can be partly determined by the material of the object being sampled and its ability to absorb infrared radiation. This is a consideration that should be tested once the final part has been received in order to confirm the specifications provided by the vendor and reach our target maximum distance of 3 ft.

Accuracy loss: This consideration is highly correlated to the sensor's maximum distance. As we approach and surpass the maximum distance, light will diverge and this will cause loss of accuracy determining the distance from the sensor to the target. This is also determined to be a minor consideration, since the Smart Window should be able to detect the presence of a user only within a practical short distance.

Beam angle: The maximum angle at which the sensor can detect the presence of a user is a major consideration to keep in mind as we move forward with the part selection and design. The user should be able to approach the window from a reasonably wide variety of angles and not necessarily perpendicular to the window in order for the process to appear seamless and user friendly.

Spacing: The spacing between the photodetector and the infrared source must be kept in mind when positioning them in the frame. If these two components are too close, noise from the IR source will be picked up by the photodetector, causing false positives. This is a minor consideration since most manufacturers of active IR proximity sensors include an enclosure to make it easier to incorporate into a design.

IR Proximity Sensor Component Selection

Multiple aspects were taken into account by the group when selecting the type of proximity sensor to be used. The performance, user-friendliness and energy efficiency of the Smart Window are dependent on both the accuracy and range of the sensor. The team set a goal range of around 3 ft for the sensor to have the capability to detect a user standing in front of it, but not too far of a range so that the Smart Window displays information when someone is just walking by on the other end of the room. Other constraints considered were the type of targets it can detect, and the cost, response time and reliability of each type of sensor. The following Table 6 describes the advantages and disadvantages of each type of sensor in the context of our project.

Type of Sensor	Pros	Cons
Radar	Reliability Ruggedness	Large equipment size Less accurate measurements
Sonar	Low cost Longer range	Sound gets partially absorbed by targets with soft surfaces
Infrared	High speed measurements Low power consumption	Low range

Table 6: Pros and cons of different types of proximity sensors

The team concluded that the lower range of infrared sensors was not a significant issue as the design only calls for 3 ft between the window and the user. This along with the speed and accuracy of infrared sensors makes them best suited for our application. Therefore, after weighing in the pros and cons of each type of proximity sensor, the team decided to use an infrared sensor for the Smart Window design.

The group also researched the specifications of multiple IR proximity sensors in order to determine which one makes the most sense not only within the context of our design and the engineering aspects and specifications, but also such that the sensor stays within our budget, is able to be integrated nicely into the frame and microcontroller and keeps power consumption to a minimum. Both active and passive infrared sensors were taken into consideration. Some of the strongest candidates for our design as well as the final choice will be listed in the following paragraphs.

The first component that was taken into consideration to be the final IR proximity sensor on the Smart Window is the Sharp GP2Y0A02YK0F Long Range Infrared Proximity Sensor. This sensor is composed of a position sensitive detector (PSD) and well as an infrared emitting diode which serves as the light source. It uses a triangulation method to determine distances which are output as an analog voltage between 0-3 V, making it suitable with a majority of 5V microcontrollers.

The sensor operates with a supply DC voltage of 4.5-5.5 V and 33 mA of current consumption, making it extremely energy efficient. Some vendors sell the sensor with a three-pin Japanese Solderless Terminal (JST) connector included, which allows for easy connections and avoiding having to solder wires to the sensor. It has a measuring distance of 20 to 150cm, which equates to approximately 8 inches to 5 ft, making it well within the desired range of 3 ft and measurements are taken each 38±10 ms, with an average sampling rate of 26 Hz.

Another IR proximity sensor which was taken into consideration by the group is the Sharp GP2Y0A60SZLF Infrared Proximity sensor. This sensor offers very similar specifications to the previous sensor as well as a similar price point. There are a couple of slight updates on this model such as better minimum range (initial measurements start at 10cm, or around 4 inches) and a higher sampling rate of 60 Hz. The main drawback is the absence of the JST connector on this model, which requires soldering.

The final proximity sensor taken into consideration was the only passive infrared sensor: the HC-SR501 PIR Pyroelectric Module. With a working voltage between 5-20 V and a current consumption of 65 mA this is the least energy efficient option out of all the components we considered for the project. On the other hand, it has a detection cone angle of 120 degrees as well as a range of 7 meters.
Another benefit to this component is that being a passive infrared sensor, it only detects sources of infrared light (human bodies or animals) which makes it useful for our type of application.

After taking into account the pros and cons of all of these different infrared proximity sensors, the team decided to select the Sharp GP2Y0A02YK0F Long Range Sensor. This decision was based on its optimal range distance, low energy consumption and ease of integration into our system.

Other considerations which helped make our final choice was the reputation of the manufacturer, Sharp Corporation which would indicate that the specs on the datasheet are reliable, as well as the low cost of the sensor.

3.3.7.5 Outdoor Sensor Selection

Choosing the ideal outdoor temperature and humidity sensors is very similar to choosing the indoor sensors with the main difference being the temperature and humidity outside will vary much more compared to inside so the operating ranges need to be considered before designing a circuit around them. Another difference to consider when selecting these sensors is how they can be placed outdoors while remaining attached to the main PCB.

This problem can be solved by creating a small PCB with headers or terminals that connect to each pin so that wires can carry the power and data that the sensors need and send. Given these parameters to design around, it looks as if the same sensor for the indoor temperature and humidity sensing HDC 2010 YAPAR will do the job. This sensor’s datasheet says that it can operate from 0%-100% relative humidity and -40℃ to 85℃ which is more than a wide enough range for ambient temperature and humidity measurements.

Using the same sensor for indoor and outdoor temperature/humidity measurements will simplify design and testing making this selection even better. There will not be as many datasheets to comb through, footprints to download, tests to conduct, nor will there be any issues with data variance from chip to chip since they are the same product line. All said and done, using the HDC 2010 PAR for the outdoor environmental sensing makes the most sense.

3.3.8 Glass Window Selection

The glass for the project was fairly straightforward to choose. The requirements for the glass are not incredibly rigorous, as the project is not intended to withstand severe weather, or significant loading or forces. The glass must be 24” by 36” and be thick enough to support the mounting of the PDLC film, and display panel. It is important that the glass is uncolored, and optically clear, to insure a clear picture of the outdoor environment can be observed through it. The group has allocated around $15 of the project budget to it. Using thicker glass is ideal, as it is less prone to cracking and more structurally stable.
Home Depot offers a wide selection of glasses at low prices, and their 24” x 36” x 0.125” Clear Glass panel was selected for the project. At only $13.98 it fits nicely into the project budget, and is the groups first choice for the project's glass window.

3.3.9 Solar Panel Selection

Several considerations need to be taken into account when deciding which photovoltaic module or modules will be used for the Smart Window projects power management. The panels selected should be able to supplement a large portion of the Windows electricity requirements. However, the budget for the project is important, and allocating too much of it to the solar panels for energy generation might cost functionality in other areas of the project.

To get an idea of how much power the panels should generate, it helps to consider which components of the Smart Window will draw significant amounts of electricity from the battery bank. The group had determined that the features with the most significant power draw are the Display subsystem, the PDLC subsystem, the LED lighting, and the device sensors. The display is known to use a 30W Adapter, and the LED strips both generated ample amounts of light while using 12W per strip. The group estimates the PDLC to use a maximum of 10W when it's held in the on-state allows it to transmit light. The sensors and other device's electronic systems like the microcontroller and charge controller are expected to also draw no more than 20W in total.

Adding these expected power draw requirements together gives the group a rough estimation of the Smart Windows total power draw. This total comes out to approximately 85W of power draw when all features of the Smart Window are being used. With the battery bank expected to be able to output 296W, The group is able to consider which solar panel would be able to support the majority of the power requirements. The solar panels that the group decides to use should be able to generate at least 50W of electrical power. This will allow the battery bank to charge up while the window is not in use, and still offer enough reserved power to use features like the LED lighting during the night when the solar panels are not receiving any additional power until the sunrise. Using a monocrystalline panel will allow higher efficiency solar to electrical conversions.

Although the group opted to forgo the use of photovoltaics for the project, the 50W Monocrystalline Solar Panel from “NewPowa” would have been our intended choice. NewPowa's panel has a relatively small footprint of around 2 square feet, and advertises a maximum power generation of 50W. The group expects this would have been enough to supply the expected 85W max power draw of the other electrical components used for the Smart Window.

3.3.10 Component Selection Summary

The team summarized all major components selected for each category of the Smart Window project. Table 7 below will recap and include all of the final selections made in section 3.3, and will be updated as necessary in case any new decisions are made by the group with regards to component selections.

Part	Model Selected
Display	Acer S201HL 20" LCD Display
Glass Window	Home Depot Model #92436 Clear Glass
Smart Film	Smart Tint ® PDLC Film
LED Strips	LEDSupply IP20 HD 3ft Strips
LED PWM Control	Hiletgo B073R7H52B
Microcontroller	STMicroelectronics STM32L432KC
Batteries	LG MH1 INR 18650 Cell
Battery Charger IC	Texas Instruments BQ24765
Temperature Sensors	Texas Instruments HDC2010YPAR
Humidity Sensors	Texas Instruments HDC2010YPAR
UV Sensor	DigiKey SI1132-A10-GMR
Proximity Sensor	Sharp GP2Y0A02YK0F Long Range Sensor

Table 7: Component Selection Summary

4. Project Standards and Design Constraints

Standards are the key to allowing compatibility between similar devices. Standards are especially important when it comes to connecting computerized devices. Very few devices are used in an isolated fashion, and therefore require stands to ensure interoperability. Standards can also be described as a specific way of doing something. Just like countries have standard languages, driving rules, and other ways of doing things ensuring all parts can work together. Standards are also present in engineering, technology and scientific disciplines in order to facilitate collaboration between people.

Constraints are important factors describing limitations on designs. They can be budgetary constraints, size constraints, power constraints, and many others. Having all group members aware of the project constraints helps to minimize issues of incompatibility, and helps the group define what is possible in the scope of the project. Constraints also help the group minimize potential problems for the end user. In this section, the team will explore both standards and constraints which are helpful to keep in mind as they apply to our Smart Window project.

4.1 Standards

Engineering standards are multifaceted pieces of documentation that are essential for modern projects. They typically are outlined in the scope of how much details they describe, and will offer definitions of commonly used technical jargon for its relevant industry. An engineering standard will also likely have both general considerations, and specific use cases. Not all standards necessarily follow the same format, as standards are widespread across multiple engineering, technological and scientific disciplines. With this fact in mind, the group will try to be as accurate and compatible with each relevant standard for all technologies used in the Smart Window.

Standards may also be given from competing organizations. Therefore, it’s important to try and stick with the most commonly used and popular standards. By following standards which are given by groups like the IEEE standards association, the project is less likely to run into compatibility errors when more parts are added.

For parts of the project relevant to PCB and Hardware design, it may be better to follow standards issued by the Association Connecting Electronics Industries (IPC.) IPC is ANSI accredited, and is commonly referred to for being the leading authority in several electronics and assembly standards. Although PCB designs for the project have not been initialized as this point of project development, the group will follow IPC Standards during that design period.

4.1.1 Display Standards

The relevant standards for the display used in the Smart Window relate to the screen’s display resolution, aspect ratio, color depth, and refresh rate. The display used in our project follows the HD+ standard. The HD+ Standard defines a 1600x900 pixel resolution with a 24bpp color depth. The aspect ratio of the display is 16x9, and supports refresh rates up to 60Hz.

Most modern displays implement thin-film transistor technology. TFT offers RGB control in each pixel where each subpixel has its own transistor. Manufacturing errors, or damaging events can occur which causes an individual transistor to short or remain open causing a defective or “dead” pixel.
There is no industry standard on the acceptable level of dead pixels on an LCD screen, however, panel manufacturers typically have a dead pixel policy, denoting manufacturers standards for replacing defective panels meeting a certain quantity of defective pixels per native resolution on any LCD panel. The display itself is a modified Acer S201HL 20 inch Panel. It supports VGA and DVI video output connections directly, and is HDMI compatible with the use of a converter. It is a TN Display, which makes it a good choice for attempting to convert it into a Transparent LCD Display.

4.1.1.1 Display Communication Standards

Two relevant display communication standards have been identified by the group pertaining to the Smart Window project. The first is Digital Visual Interface (DVI.) DVI is compatible with both analog and digital signals. DVI is an important interface because of it's compatibility between older standards such as VGA, a serial connection, and newer digital interfaces like HDMI and DisplayPort.
There are three relevant subclassifications of DVI, which help specify which signals can be implemented. DVI-I is the most robust, supporting digital and analog signals in the same connection. DVI-D is a digital only signal, and DVI-A is an analog only signal.

When the DVI interface connects both the signal source and the display, the display characteristics are read by the EDID block over an I2C Link. In high resolution displays, DVI dual link doubles the number of TMDS links which transmit data from the input source to the display, allowing resolutions up to 2560x1600 pixels at a refresh rate of 60Hz. The standard single link cable by contrast, only supports 1920x1200 resolution at the same 60Hz refresh rate. The bit rates for single and dual link DVI are 3.96Gbit/s and 7.92Gbits/s respectively.

Like all cables, the signals transmitted through the DVI link are subject to losing fidelity over long transmission distances. Therefore, the maximum recommended cable length for a single link DVI cable is 15 ft. If the DVI cable is required to be longer by some project constraint, a DVI signal repeater (which might use an external power supply) is recommended to aid in mitigating signal degradation.

4.1.2 LED Standards

For implementing PWM control to the LED system, IEEE PAR1789 is an important standard to observe. It provides guidelines on handling visible flickering artifacts from PWM control, which if enacted poorly, could cause extreme neurological problems like epileptic seizures. While this is an extreme example, a light source which flickers at a perceptible rate can cause common symptoms like eye strain, fatigue, or headaches.

IEEE PAR1789 outlines the recommended practice for minimizing flicker as follows: The frequency of the modulation is multiplied by either 0.025 for frequencies under 90Hz, or by 0.08 for frequencies above 90Hz. The human visual system is less sensitive to flicker at higher frequencies, and therefore more flicker is deemed safe in high frequency systems.

As an example, If the LED system operated with a square wave signal of 30Hz, the maximum percentage of allowable flicker would be

60Hz *0.025 = 1.5 => 2% Flicker.

If the system operated at 120Hz, the maximum percentage would then be:

120Hz * 0.08 = 9.6 => 10% Flicker.

To further adhere to the guidelines offered by IEEE, the group will take caution to use pulse-width modulators with components which shape the square wave accurately, and offer high signal accuracy. Electronic components will also be bench tested to assure adherence to the guidelines.

IEC, the International Electrotechnical Commission is the international standards and conformity assessment body for all fields of technology. The testing methodologies for LED photometric and colorimetric are defined in the standards developed by IESNA. IEC 62031:2018 specifies the safety requirements of non-integrated LED modules and semi integrated LED modules for operation under constant voltage, constant current or constant power. Integrated LED modules for use on DC supplies up to 250 V or AC supplies up to 1000 V at 50 Hz or 60 Hz.

4.1.3 Communication Standards

This section will cover all of the major transmission standards that are going to be implemented in the Smart Window project, including Serial, SPI, I2C, Wifi, and Bluetooth. Observing and implementing these standards correctly is crucial to the functionality of the project, and implementing bluetooth and wifi standards correctly will ensure that the Smart Window is easy and simple to interface into the consumer’s desired environment.

4.1.3.1 Serial Communication Standards

Serial Data transmission standards are widely used for the data link layer, providing connectivity. Serial data transmission links use cable to send data reliably between two devices. Recommended Standards RS232, RS422, and RS485 describe common serial data transmission standards. The communication mode can be full duplex and half duplex.

RS232 defines the signals connecting between a DTE (data terminal equipment) and a data circuit terminating equipment. The standard defines the electrical characteristics such as the timing of the signals, the meaning of the signals and the physical size and pinout of connectors. The current version of the standard is TIA-232-F, titled Interface Between Data Terminal Equipment and Circuit-Terminating Equipment Employing Serial Binary Data Interchange. It is used in computer serial ports. Voltage Levels: Valid signals are in +3 to +15 V or -3 to -15 V , this means that the range between -3 to +3 V is not a valid RS-232 level. The main problem with RS232 is the sensitivity for noise on the signal lines. RS422 is the common short form title of ANSI standard: Electrical Characteristics of Balanced Voltage Differential Interface Circuits.

These characteristics specify the electrical characteristics of the balanced voltage digital interface circuit. RS422 intended to replace RS232 with a standard that provides better immunity to noise. RS22 systems can transmit data at rates as high as 10 Mbps.

RS485 now maintained as TIA-485, specifies the electrical characteristics of the generator and the receiver. It defines the required voltage ranges, open circuit voltages, thresholds and transient tolerance. The transmitter and receiver compare the voltages of the data and handshake lines with one common zero instead of the absolute voltage level signal line. Additionally, multipoint systems are supported.The Simplex communication channel that sends information in one direction only. In simplex method, either of the medium i.e. sender or receiver can be active at a time. It is a one way communication technique. Well known implementations of the simplex method are television and radio broadcasting, where information flows from the transmitter site to multiple receivers at different locations.

A duplex communication system is a point-to-point system composed of two or more connected parties and devices that communicate to opposing points in both directions. In the half duplex method or semi duplex communication system, both the sender and receiver can be active, however the sender and receiver cannot be active at the same time. Common implementation of the half duplex is internet communication where the user sends a request for data and gets from the server. Half Duplex systems are used to conserve bandwidth as opposed to full duplex as a single communication channel is needed to communicate in both directions.

In the full duplex method, both receiver and transmitter can send data to each other at the same time. A cell phone, a full duplex device, requires two frequencies to carry two simultaneous voice channels for each direction. A benefit to using full duplex as there are no collisions, therefore, a device is not forced to retransmit frames.In Asynchronous Serial Communication, also referred to as (Transistor-Transistor Logic) serial, and is defined where the high voltage equates to the bit value 1 where the low voltage equates to the bit value 0.

The majority of microcontrollers available today contain a Universal Communication Receiver Transmitter for serial communication. Microcontroller development kits often use serial communication through a serial port to program the microcontroller using a computer as a host. This is often done through USB-to-RS232, where RS232 is a well known serial protocol that is widely used on PCs today.

To implement asynchronous communication. Both devices are required to be set up in order for both devices to interpret the voltage level of the serial pulses in the same way. This way, both devices are able to agree whether a low voltage is interpreted as a zero bit or a one bit. Additionally, each device will require a ground to serve as a common reference point to measure voltage levels, the transmit line Tx, and the receiving Rx line.

The rate at which a serial communication takes place is defined as the baud rate, measured in bits per second. For complex communication such as communicating with a microcontroller to program from a host computer a baud rate can be 9600 bps. Microcontrollers typically sense a high voltage level at +3.3 or +5 volts for serial communication. When using a baud rate of 9600 bps, the receiver will poll the line and determine the pulse as a high or low level voltage and translate it to a bit 0 or 1.

To implement serial communication between two devices, both devices would benefit from using the same baud rate and protocol. UART, or Universal Asynchronous Receiver Transmitter is a physical circuit in a microcontroller or a stand alone integrated circuit. UART is used to transmit and receive serial data. As UART is asynchronous there is no clock signal used to synchronize the output of bits to the data frame being transferred. These are the stop and end bits, used to define the beginning and the end of the data packet so that the receiving UART knows when to start reading the bits.

To configure UART to communicate through two devices, it requires two wires and a ground. Synchronous serial communication relies on synchronized clocks between the devices on the serial bus, allowing each to sample and transmit data at known intervals. Compared to asynchronous serial communication, this eliminates the need for start and stop bits, thereby increasing throughput. One of the most common synchronous serial communication protocols is the Serial Peripheral Interface (SPI), a board-level communication standard that uses a shared clock line for synchronization.

Serial Peripheral Interface

One of the most popular interfaces to connect to sensors is SPI. SPI is a synchronous serial communication interface specification used for short distance communication. Applications include LCDs. SPI devices communicate in full-duplex mode using a master slave architecture with a single master and multiple slave communication. It requires four jumper wires. The graphical portion of the display can only be interfaced through SPI. However, SPI also demands more signal lines or wires than other types of communication. There is also no standard message protocol for communicating over SPI, meaning that every device could have its own convention for data message formatting. Figure 25 [Wikipedia(2)] below shows possible connections between master and slave devices.

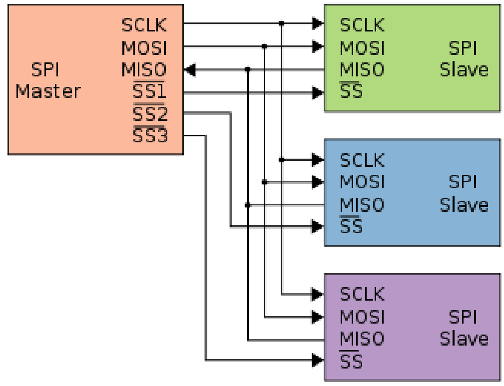


Figure 25: Interconnections in a SPI interface [Wikipedia(2)]

I2C: Inter-Integrated Circuit

Another communication protocol which is important to consider for this project, as it will be widely used by the team is I2C. I2C is commonly used to attach lower-speed peripherals to processors and microcontrollers. The I2C protocol can be used to connect a microcontroller with different sensors or peripherals simultaneously. It is a serial, half-duplex protocol that uses 2 bi-directional wires to communicate with other devices. Figure 26 [Analog Devices] below illustrates the basic configuration for a master device connected with slave devices.

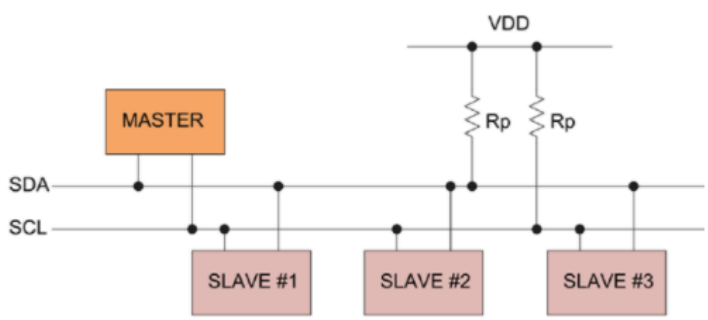


Figure 26: Configuration of master device with multiple outputs [Analog Devices]

4.1.3.2 IEEE 802.15.1 (Bluetooth)

The standardized Bluetooth as IEEE 802.15.1, but no longer meets that standard. Bluetooth is a wireless technology standard used for exchanging fixed and mobile devices using UHF radio waves and mobile devices. Bluetooth can be applied to wireless control and communication between devices including a mobile phone and a handsfree headset, Bluetooth compatible stereo system, smart lock, portable wireless speakers, PC input and output devices, and between PCs where little bandwidth is required, making it a widely used technology in modern user electronics.

Wi-Fi and Bluetooth are complementary. Bluetooth is symmetrical and serves between two devices. Wi-Fi is complementary and contains an asymmetrical client server connection where all traffic is routed to an access point. Table 8 below shows technical specifics of Bluetooth 5 specifications on the Raspberry Pi 3B+ which will be used in the Smart Window project.

Specification	Value	Notes
Range	400m	More than enough for project in use case scenarios
Data Rate	2.1 Mbps	Very high, more than enough for product
Latency	100 - 300 ms	Low, sufficient to achieve real-time accuracy
Power Consumption	30 mA (15mA min)	Low
Implementation Complexity	High	High, If implemented from scratch

Table 8: Analysis of Bluetooth 5 specifications on Raspberry Pi 3B+

4.1.3.3 IEEE 802.11 (WiFi)

WiFi represents IEEE 802.11 and is part of the IEEE 802 set of local area network LAN protocol, and specifies the set of MAC and physical layer protocols for implementing wireless network communication. Our team is deciding to use WiFi as it is required to retrieve the RSS feed information from the internet to display in the user interface of the window, therefore knowledge of the 802.11 protocol is extremely important. The following Table 9 shows technical specifics such as range, data rate and latency of implementing WiFi for use within the Smart Window.

Specification	Value	Notes
Range	150 m indoors, 300m outdoors	More than enough for project in use case scenarios
Data Rate	6.93 Gbps	Very high, more than enough for product
Latency	2ms-3ms per RTT	Low, sufficient to achieve real-time accuracy
Power Consumption	400 mA (2.0 W)	Very high, will draw power unless disabled
Implementation Complexity	High	Very complex communication protocol

Table 9: Analysis of WiFi specifications applicable to project

While WiFi is used for wireless communication, there will be drawbacks to using WiFi as its power consumption in comparison to its benefits which include fast data transfer speeds, more range than other communication technologies such as Bluetooth (IEEE 802.15) in addition to more range and lower latency.

4.1.4 Power Standards

In the United States, power outlets in homes run on a standard 120V (AC) at 60 Hz and use two (Type A) or three (Type B) pronged connectors for the users to access the power. Most common power adapters can convert this power into 5V (DC) output through a USB connection. This USB connection can then be fed to a micro USB female connector attached to the PCB as a power supply. In the event that power must be transmitted through wires, it is important to use the appropriate colors for easy troubleshooting. Though there is no set standard, it is recommended in the United States to use white as the grounding wire and red or black as the positive terminal wire for DC power and green for the grounding wire, white for the neutral wire, and red, black, or blue for the line wire for single or three phase AC power.

4.1.5 PCB Standards

When manufacturing a PCB there is certain information a designer must list when submitting a design to the manufacturer. IPC-2581 is the generic standard to adhere to when sending design data between manufacturer and designer. The information to be included in this XML file are the copper image information for etching, board layer stack information, netlist, bill of materials, and assembly notes and parameters.

4.1.6 Programming Language Standards

Much like how everyone agrees to speak a certain language by using the correct syntax and pronunciations, programming languages need a set of standards so that developments can be made with less complications. In the following subsections, three specific standards which pertain to the project will be discussed in detail.

4.1.6.1 C Programming Language

ANSI C, ISO C, and Standard C is a term commonly used to refer to the original group of C standards, also known as C89 and C90, published by the American National Standards Institute and the International Organization for Standardization. Software developers are required to confirm to these standards for portability between compilers. They are not used as they are outdated.

C99 is the most widely used standard for the C language. The C99 standard was adopted in March 200 by ANSI and is the most portable version of the C standard. The portability of this standard means that the code has the largest portability between compilers and is supported by the largest set of devices. This is important for firmware and embedded programming as the target device processor must be able to support the compiled language. This standard of C adds new data types and additional compatibility with C++.

The C11 standard was published in 2012 and replaced the C99 standard. C11 mainly standardizes features already supported by common contemporary compilers with a detailed memory model to support multiple threads of execution. The C11 standard modernizes the C language by improving Unicode support for the language. Although these new additions modernize the language by standardizing features supported by complimentary compilers , it is not as portable as the C99 standard based on the hardware manufacturing that is available. Not all embedded hardware has caught up to the C99 standard.

The C17 standard was published in 2018 which replaced the C11 standard and is the most recent C programming language standard. It introduces defects in C11 without introducing new language features.

4.1.6.2 React JavaScript Native

React Native is a framework that is used to build native apps using React JS. The apps built on react native work on both Android and iOS with performance better than a hybrid app.

4.1.6.3 Python Programming Language Standards

Python is a programming language that is optimized for exploratory code; that is, Python is useful for benchmarking code and analyzing the state of the GPU, CPU, etc. Although most operating systems have Python pre-installed, this version of Python is insufficient for development. Installation of Python and its third-party extensions (such as Pip and PyTorch) are all implemented through Command Prompt. Python, like other programming languages such as C and Java, has its own libraries and syntax. Code written in Python is saved with the ".py" extension and is executed through Command Prompt with its respective argument.

4.2 Design Constraints

Design constraints help outline criteria that needs to be met for a project to be successful. Constraints identified for the Smart Window project can be directly related to the project itself, or related to how its used and constructed.

Constraints that relate to the project directly are those of size, power, health and safety, and economic constraints. Other constraints include ethical, social, political, and time constraints. All_constraints work together to help the project group to outline the scope of the design, and also keep it within the bounds of what the Smart Window hopes to become. In these following sections, the group will explore all of these constraints in more detail and will follow the constraints in order to be able to complete the project without any major issues.

4.2.1 Size

The smart window should be big enough to classify as a traditional window while staying within the price range of the group. The price of PDLC film grows very rapidly as the area increases so making a balance between size and price is necessary, which is why the team initially decided on a 3 ft by 2 ft window area. If the group was to consider glass panes much larger than this size, they would also need to be heavier and thicker to facilitate the additional structural integrity of the glass. Taking power generation into consideration also impacts the overall size of the window. Considering the base size of the window, it might also be worth the effort to make a scalable design in order to reach beyond the typical consumer into industrial applications. LCD displays used for project scale fairly well, however because the group is already in possession of 20" LCDs to use for the transparent display, having a glass size able to accommodate this is crucial for the project. Therefore, the size of the glass subsystem needs to be wide enough to accommodate the chosen display.

4.2.2 Power

One of the main concerns and constraints for this project, as is the same for almost any application, is power. There is an ever rising number of people who are switching to renewable energy devices such as roof mounted solar panels and electric cars, so it is essential to design a proper power supply for this window that does not rely on non-renewable energy sources. To do this, two main areas of focus need to be considered: power consumption and generation. The team will explore both of these areas individually in the following sections.

4.2.2.1 Power Consumption

Three main areas of concern for power consumption of the Smart Window would be the Raspberry Pi, LED strips, and the PDLC film. The Raspberry Pi is a power hungry device that constantly consumes 400mA at 5V resulting in a constant 2W. This means that the power supply should be designed to easily supply 2W to the Raspberry Pi at all times. The LED strips can also draw large amounts of power, able to use a maximum of 14.4 W/m. There must be careful consideration and testing of the length of the LED strip to ensure that the rest of the components will receive adequate power.

Some power can be conserved from the LED strip using Pulse Width Modulation (PWM) which allows for the LEDs to be turned on and off at a frequency that has a dimming effect. The last area of concern is the high voltage required to power the PDLC film which is around 60 V. The display however does not use that much current, but power will be lost in the form of heat when generating this high voltage. It is important to design proper safety circuitry to isolate the PDLC's high input voltage requirements from the low input voltage requirements of the other components.

4.2.2.2 Power Generation

The smart window will be using solar energy to power itself but to do so, the power consumption of the components will need to be considered for the selection of the proper panels. Some main concerns about each photovoltaic cell would be the output voltage and constant current draw as well as the dimensions and cost. We need enough power to reach the window and all the components supporting it but there must be a balance with how much surface area is required. It would be unsightly to power the Smart Window with a solar array much larger than the window itself, and therefore using monocrystalline photovoltaic cells offer the group the ability to generate the same amount of power with solar panels taking up a smaller footprint.

Another concern when it comes to selecting the right solar cell is its efficiency, as a solar cell of larger area might not produce as much output power as a smaller solar cell with higher efficiency. The cells themselves might not be enough to power the window constantly given that the dimensions of the window will limit how many can be applied to the base and/or perimeter. Therefore, it would be logical to use a battery bank to store any excess power the window might not be drawing, and save its use for later.

4.2.3 Health and Safety

When working with mains electricity it is important to protect from electrocution and possible fires. The primary power source will be a combination of photovoltaic cells and lithium ion batteries so cooling will have to be considered when designing the housing of the batteries. Charging circuitry will also need to be included to protect from overvoltage failures of the batteries. To combat this, standard power adapters will be used to provide a secondary source to the window with an input fuse to protect from any shorts that would destroy the electronics and/or cause injury. Another safety risk posed during the project construction is the need to use power tools like drills, saws, and dremels during the construction of the window frame. To minimize tool related injury and potential hazards like dust inhalation, or eye injury, proper safety equipment and workplace standards will be adhered to.

This includes working in well ventilated and well lit areas, as well as wearing proper protective equipment like safety glasses.

4.2.4 Ethical, Social & Political

As technology advances, the dependence on fossil fuels should decrease to help combat climate change. To help make this process quicker it is important to use renewable energy sources such as solar energy to power electronics. The window will be an ethical solution for consumer technology since the power generation will be minimally dependent on fossil fuels. A social constraint presented is that implementing a device that is connected to the internet in their home might pose a cyber threat.

This argument has become more common as smart devices grow more widespread in home uses. The group aims to resolve this problem by allowing users the option for their device to function offline, and in that case only the onboard sensor suite will be used to offer information to the display. Another social constraint is ensuring the privacy expected when using the opacity mode of the smart film. Political constraints might occur if the smart window were mass produced. A deal between fossil fuel companies and manufacturers, or subsidies from government programs might discourage the production of devices using renewable energy.

4.2.5 Economics and Time

This smart window is not funded by any outside corporation or group other than the four students working on the project. Since college students are notoriously stretched for money this project has a tentative budget of approximately $500 split equally amongst the four. When choosing parts for the smart window it may be necessary to take not only quality but also price into consideration so that a physical realization can be built from the designs. The group also understands that unexpected costs like shipping and handling may occur for some products, and that our approximate budget may be a hopeful estimate. As far as time constraints go, there is a strict time constraint of two full academic semesters. The project must be completed and presented by the end of the second semester (May 2021) or the group will fail.

5. Subsystem Design and Testing

This section will describe the developments, current designs, and testing of major components, and their integration into their relevant subsystems. Developing and testing project components and subsystems during the Fall 2020 semester poses unique challenges because of COVID-19 and the move towards online learning, with somewhat restricted access to the Engineering College and CREOL facilities at the University of Central Florida main campus.

Therefore, current tests have been performed outside of standard laboratory conditions due to public health concerns. The team hopes that in the spring semester availability for on campus labs will increase but for the time being, in an effort to provide as robust and reproducible results as possible, whenever testing environment conditions are relevant to the results of the tests (such as ambient lighting conditions for display transparency testing,) the group has tried to document these important conditions as thoroughly as possible.

5.1 Battery Bank

As mentioned in section 3.2.9, the batteries chosen were the LG MH1 INR 18650. These batteries have a nominal voltage of 3.6V with a maximum charge of 4.2V, 10A continuous discharge current, and 3200maH capacity all inside of a cylindrical casing with diameter of 18mm and height of 65mm. Since it is dangerous to directly solder on wires to the terminals of these batteries, contacts or battery holders will be used to connect the batteries. To minimize costs, battery contacts make more sense to design around. Since there will be no holders, a housing must also be designed for the batteries to prevent any unwanted movement between cells. This will be done using a 3D printer which the group is already in possession of.

Numerous free and open source designs were available to the group, especially because the battery model, 18650, is a fairly common choice for lithium ion batteries. In looking for a proper battery holder model, a few criteria were set. The holder must be able to accommodate the contacts as well as 4 cells in series. By alternating the direction that each successive battery is facing, connecting them in series will use less wire which will be soldered to the contacts. There must be two of these battery holders made since there will be two groups of four cells in series powering the Smart Window. There should also be room to solder leads to the outer contacts for easy power distribution to any of the test boards, most specifically the battery charge controller.

The final choice used an innovative plastic spring system to keep the battery cells from moving inside of the battery holder. To reduce the amount of wire needed for placing the batteries in series, and to simplify the wiring in general, the group decided to modify the existing design which used the plastic spring. Figure 27, seen below shows the pre-print design for the battery holders. Room for 4 cells can be seen on the model, but because of the limitations of the build plate, two separate models will need to be printed.

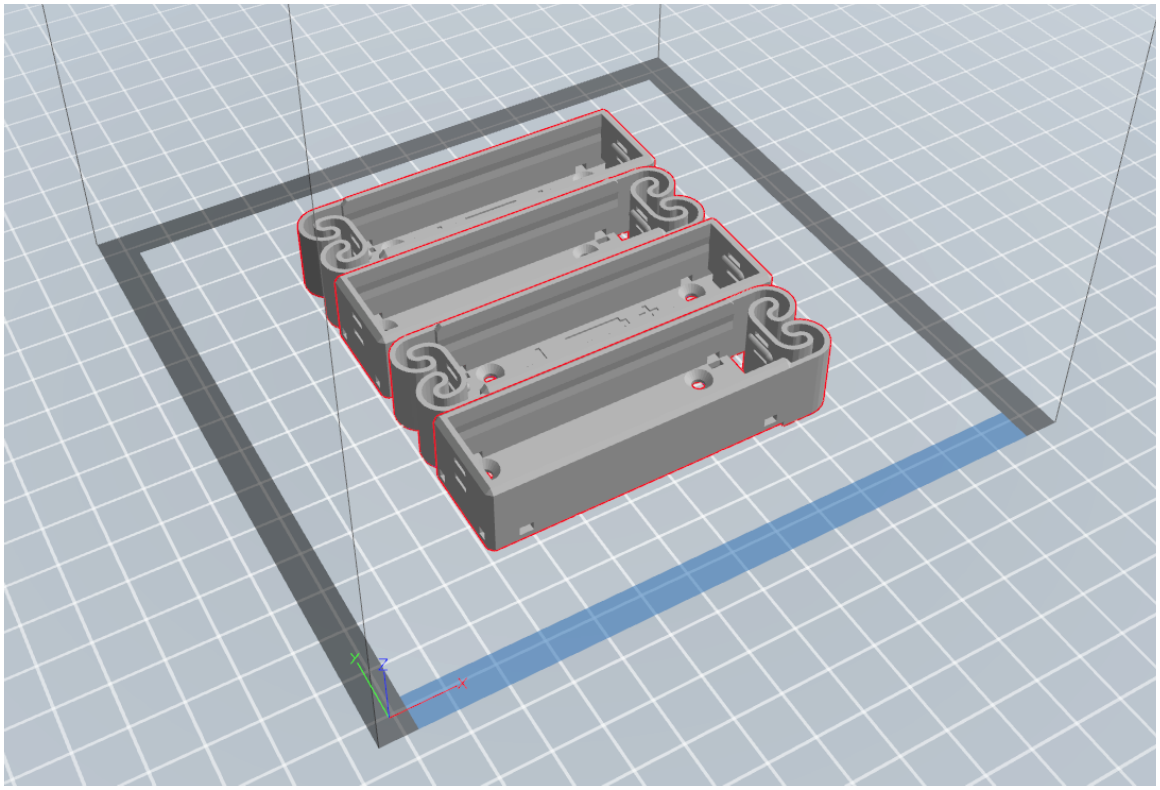


Figure 27: Battery Holder Design for the 18650 Cells.

5.2 Power Flow Design

Originally, the power being provided to all the components of the Smart Window was to be supplied by these batteries, so understanding how the power will flow through the system is essential. The original power flow diagram seen in Figure 28 describes this. The batteries will need to be charged and discharged, so their placement in the final circuit will be somewhere in the middle such that they can deliver and store energy to and from the system.

Charging the batteries can occur one of two ways, either from solar panels mounted on the frame of the window or from a wall adapter plugged into a standard American outlet. It would be unwise to connect both of the output lines to the same wire as the short-circuit created may damage one or both of the inputs.

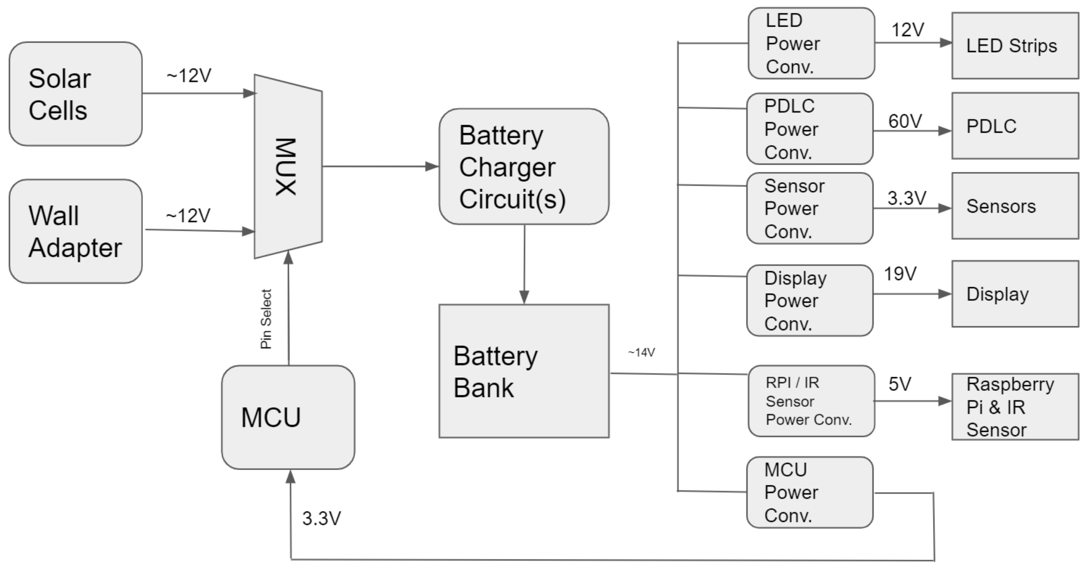


Figure 28 - Power Flow Diagram

This plan fell through as the battery charging IC could not be programmed. To compensate for this failure, power is needed to reach each component by a different means. The final power distribution format is summarized in the block diagram below. All power originates at the mains supply from the home, making its way into various adapters specifically manufactured for each component. The sensors get their power from pins on the MCU development board or Raspberry Pi. This is reflected in the revised power flow diagram in Figure 29

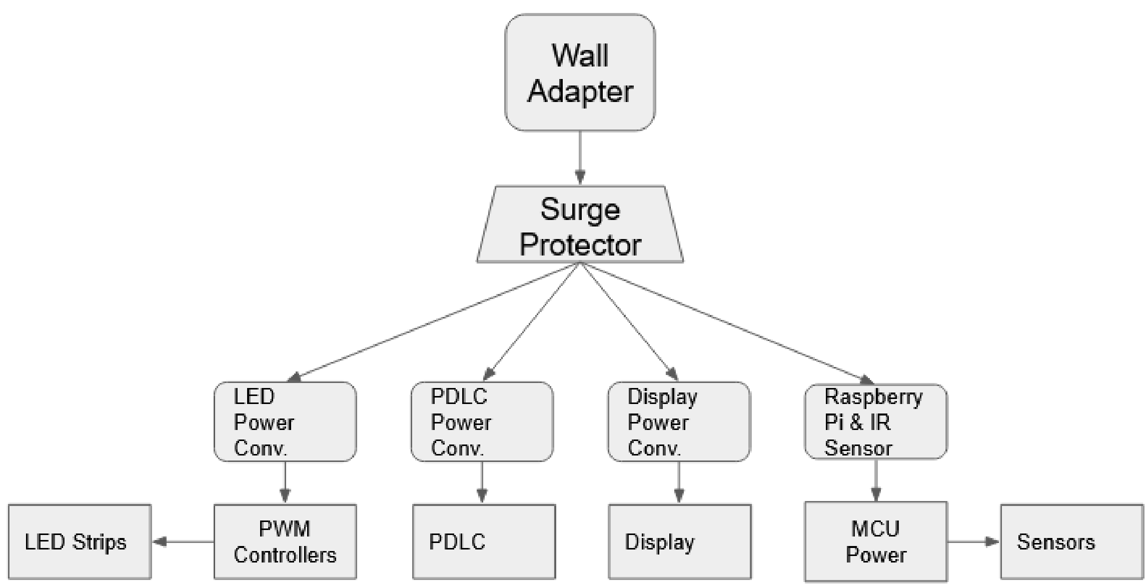


Figure 29 - Revised Power Flow Diagram

5.3 LED Subsystem Design

The function of the LED subsystem is to provide adjustable, user controlled indoor lighting to the ambient area around the Smart Window. This feature is very appealing for consumers who have limited space, as the bright, integrated lighting system is designed with both form and function in mind. Current design considerations for the LED subsystem involve only manual controls which are integrated into the frame of the window.

As project development continues, more advanced methods for controlling the LED lighting levels, and color control will be examined. However, these features are currently a stretch goal for the project. As outlined in section 3.3.3. The LEDs chosen for the lighting subsystem were IP20 rated 3ft long Strips from LEDsupply.com. These strips offered 1100 lumens per strip, and had a very low power usage of only 14.4W/m. Each strip requires 12V (DC), and is currently designed to manually function off PWM dimmers. The PWM Dimmers being tested can vary between 0 and 100 percent duty cycles, and meet the power requirements of the two LED strips.

Because high density LED strips are being used for the Window's lighting, the overall design for the LED subsystem can be simplified. This is because each LED module on the strip draws only a fraction of the total power. The LEDs on the strip are also wired internally, requiring only connections to the DC source of the PWM Dimmer. To better understand the overall connections of the LED subsystem, a diagram is shown below in Figure 30. Figure 30 shows the main power supply supporting 12V DC connections to the PWM Dimmer, which converts the static DC signal into a PWM signal which can dim the LED strip.
To support color mixing, and offer complete control over each LED strip individually, two PWM dimmers will be used in the design. Also shown is the user control knob which allows the user to manually adjust the duty cycle of the PWM dimmer.

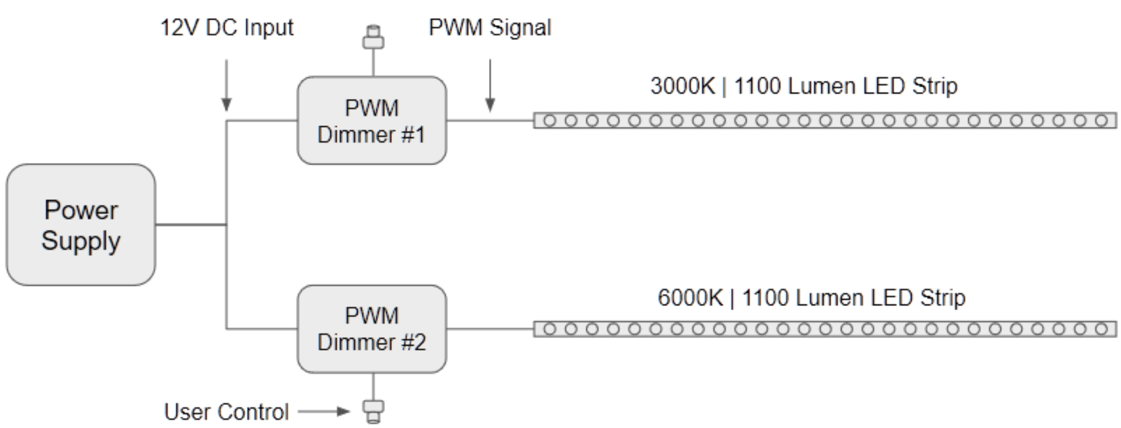


Figure 30. LED Subsystem connections

5.3.1 LED Subsystem Testing

Despite high confidence in the operation of the LED subsystem, the group decided it would be advantageous to test the LED subsystem early on in the project's development. Having sufficient equipment on hand, the LED strips were able to be tested among several criteria; Light output, PWM dimming, Temperature, and Color Mixing. Testing protocols and results for each criteria are given below in the following paragraphs.

Light Output

The LED strips were advertised as outputting a maximum of 1100 Lumens per strip. Because the LED subsystem is marketed as being a supplementary room lighting source, and two LED strips can be used together for a proposed maximum of 2200 Lumens, achieving just 75% of this advertised output would be considered a passed test. To conduct these tests, an LX1330B Light meter was used to measure the output of individual LEDs on the strip under the maximum rated power of 12V DC.

Because the LX1330B Light meter measures Lux and the group would like to measure the output in lumens, the meter was held a distance of 0.5m away from the bulbs, orthogonally and in the direct 0 degree optical path of the bulb. More details on the specific testing setup used to evaluate the light output of individual bulbs on the two LED strips is shown below in Figure 31.

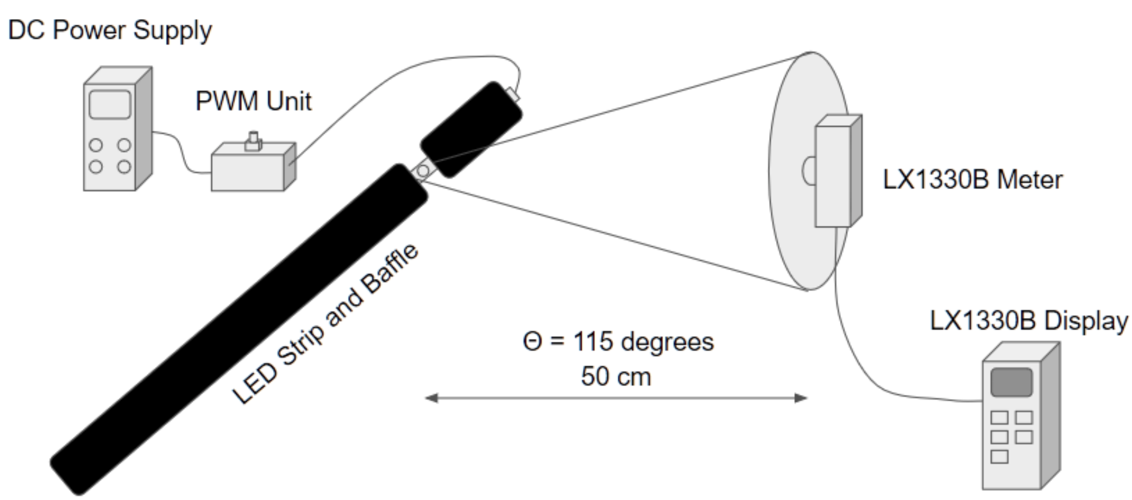


Figure 31. LED output power testing setup

In Figure 31, The DC Power supply was held as a constant 12V and 1A output to both the LED strips. The PWM unit was operated at 100% Duty cycle allowing the DC output of the power supply to pass to the LED Strip unimpeded.

Black electrical tape was used to baffle light from LEDs not being currently measured by the LX1330B light meter, which was placed 0.5 meters away from the LED. Five trials were run for each color strip, each trial testing a different LED along the 1m long strip. To help ensure the accuracy of the experiment, the testing environment was modified to be as dark as possible, limiting the amount of light that could have been detected on the light meter from bulbs or windows.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	**Average**
3000K Strip	20.8 Lux	21.3 Lux	21.4 Lux	19.7 Lux	20.4 Lux	**20.7 Lux**
6000K Strip	27.4 Lux	26.9 Lux	28.1 Lux	27.6 Lux	27.1 Lux	**27.4 Lux**

Table 10: LED Strip Light Output Test Results

All of the parameters are known, the Lux values measured by the LX1330B Light meter can be converted to Lumens. Converting from Lux to Lumens is extremely straightforward, all that needs to be known is either the Lux or Lumen value, and the area of the illumination. Because the beam angle and distance is known, the calculation for the area is simple. The LEDs can be approximated as having a circular spot pattern,and the area of the emission can be calculated from the beam angle and distance.

As the LEDs are listed as having a beam angle of 115 degrees, and the distance to the meter was set to be 0.5 meters, this gives a total area of illumination as 0.7268 square meters. Multiplying the area to the lux value gives a lumen value for the 3000K strip equal to 15.05 Lumen per LED, and the 6000K LED strip measuring 19.92 Lumen per LED.

Because each strip has 60 LEDs on it, this gives a total measured Lumen count for the 3000K and 6000K LED strip being 903 Lumens, and 1195 Lumens respectively. Both LED strips pass the testing requirements of meeting 75% of the advertised light output. Although both LED strips passed the testing criteria, the results showed that the 6000K strip was significantly brighter. One reason why this might have been is because of the more energetic spectral content of the lighting.

Color Mixing

Testing the ability to mix the colors of the LEDs presents a unique challenge. The testing criteria, and necessary equipment are not as straightforward to determine as that of the lighting output test. Therefore, some expectations should be set. To adequately show the ability to mix the colors of the two LED strips, one would expect to vary the output power of each strip by 0 to 100%.

This would allow a full gradient of mixing between the two tones. This would also mean that the PWM control of the two LED strips needs to be independent. There should also be no resultant strobing or flickering of the LED strips, when different duty cycles are mixed together. For the experimental setup of the color mixing test, The two LED strips were both connected to PWM controllers with a duty cycle knob. These PWM controllers were both attached to the same 12V DC Input of a variable DC power supply. Because the light output testing showed the LED strips using 12V and 1amp at their maximum operating load, the DC power supply was adjusted to support up to 1amp of current for each LED strip, so the peak brightness would match that of the previous light output test.

Also included in the tests was an anti-glare film that had been removed during the modification of the transparent display panel. The anti-glare film showed diffusing properties that closely resembled that of frosted glass. This addition was helpful, as the LED subsystem housing is designed to have frosted glass panels to adequately mix the colors of the two LED strips together. To better visualize the testing setup of the color mixing experiment, the connections are shown below in the following Figure 32.

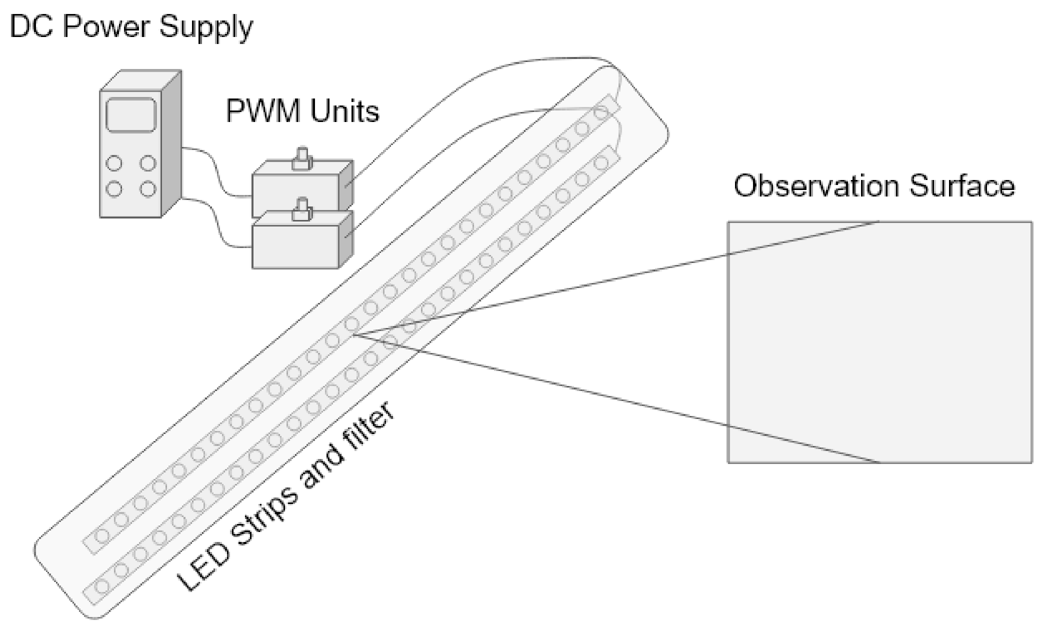


Figure 32: Color mixing test for the LED Subsystem

During the test, The two PWM control knobs were adjusted between values between 0 and 100% duty cycles for each strip. A scattering and neutral colored observing surface, in this case, a white sheet of standard letter size printer paper, was taped to the wall which was being illuminated directly by the two LED strips. At the start of the test box PWM control units were set to a zero percent duty cycle. Varying each PWM unit independently showed no signs of detectable flickering, and a complete range of 0 to 100 percent of the maximum light output of the previous tests.

When both PWM units were varied together, it was observed that the scattering surface could diffuse the full range of color from 3000K to 6000K color temperature. To better simulate possible user experiences, both knobs were turned at a variety of speeds both separately, and together, and in no scenario was any detectable flicker observed. These observations constituted passing criteria for the color mixing test.

Temperature

The temperature of the LED strips is an important characteristic to consider for the LED subsystem. Not only does temperature have an effect on the spectral output of the LEDs, but operating the strips at a higher temperature than what they are rated for could reduce LED lifespan, or potentially, it could even create a fire hazard. To best avoid these unwanted outcomes, some investigation into the operating temperature of the LEDs was done by the group. Each high density LED strip was supplied with 12 Watts of power during the light output test, meaning that each individual LED was drawing only 0.2W of power.

This factor highlights an important benefit of strip lighting. By distributing the lighting output across many LED modules, the individual heat generation of a single module is drastically lower than what it would be from a single module outputting the same amount of light. Therefore, the expectation is that the LED strips temperature should not be much of a concern, even during continuous use. Because the home testing environment in which the temperature tests were done was lacking formal equipment, the testing criteria put forth was that after an hour of continuous use, the LEDs would be cool enough to touch without causing any severe discomfort.

To test the LEDs, the two strips were placed side by side as was done during the color mixing test, and allowed to run for two hours continuously at 100% duty cycle, at the same 12V 1A per strip characteristics for the light output test. The LEDs were also covered with the anti-glare sheet from the color mixing test, as this would help to simulate the effect of shrouding the LEDs in the frosted glass cage per the expected design. This aids in simulating the effect of reducing the airflow for the LED modules.

At the end of the two hour testing period, the DC power supply was turned off, and the LEDs were only just noticeable warm to the touch. During the testing period, the LED strips were mounted on a wooden computer desk, which is not as good of a thermal conductor as the aluminum backplate which will be used for the final design. Therefore, the results of the test were considered passable by the group.

LED Subsystem Testing Conclusion

The Preliminary testing of the LED subsystem provided positive and optimistic results for further development of that block. All three testing criteria, the light output, color mixing, and temperature tests returned positive, passable results. As the LED subsystem is further developed, more testing with formal laboratory equipment will be done. At the time of testing though, the group is confident about the choice for the IP20 LED strips.

The testing done on the LED strips will help inform the group about making decisions to the future of the subsystem development, such as the proper way to adequately mix and diffuse the light output for the two LED strips, and how to position the PWM dimming controls on the windows frame. The testing also helped give insight to the temperature characteristics of the LED strips, and to what degree they require adequate heat dissipation. The group expects to mount the LEDs using the adhesive backing of the strips, onto an aluminium backplate to aid in heat dissipation.

5.4 Display Subsystem Design

The Display subsystem is one of the most critical features of the project, as it handles displaying the information acquired from the sensors and microcontrollers to the end user of the Smart Window. The display chosen for the project was the Acer S201HL 20” twisted nematic panel. This display was selected because TN panels have the benefit of being highly transmissive, which makes them ideal candidates for modifying the panels to make them transparent. When the display panel is off, the orientation of the twisted nematic cells allows the light to only pass through one polarizer. When the display is in the on state, choosing a white background for the display will also allow the highest amount of light to be transmitted by the display.

With the selected monitor in place, some investigation into the cable connections helps to organize the subsystem into smaller blocks. The LCD display is connected to a display module which handles power distribution and the display signal. The main power supply will supply the same electrical characteristics of the AC to DC adapter which was supplied by the panel manufacturer, and the display signal will be supplied from HDMI output from the Raspberry Pi, to DVI input to the display. These connections are better visualized by Figure 34, shown below.

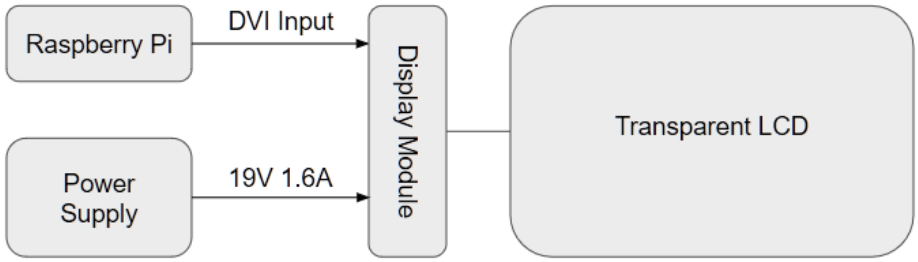


Figure 33: Interconnections of the display subsystem.

In disassembling the LCD panel, it was discovered that the panel backlight consisted of a heavily diffused edge light to illuminate the entire area of the panel. This is ideal for our project purposes, as the backlighting supplied for the project will be the direct and indirect lighting from the window to which the display is attached. This means that natural lighting provided by the window will closely mimic the backlight which was designed for the panel. This has several advantages and unfortunately a few disadvantages. Using the outdoor light as the display backlighting offers a bright, renewable form of lighting for the project. It also simplifies the design considerably, as using the natural lighting from outside requires no parts or electricity.

Using the natural exterior lighting of the window as the backlight for the display does pose some unfortunate problems. Primarily, that without the exterior lighting present, the display will have significant problems in displaying a high contrast image.
This effect is especially severe at night, where moonlight lacks much of the intensity provided by the sun. However, the display is not meant as an entertainment screen, its primary use is to display the information captured by the onboard sensor system. Because the information provided by the sensors is marketed as helping the users to plan their day, the relative inability to use the display at night isn't considered critical to the intended use of the Smart Window. Despite this, it is necessary that the display chosen is able to transmit a large portion of the incident light through the LCD.

Understanding the panel type is crucial for designing the criteria for what constitutes as a passable test. In an ideal case, when the display is set to display only white pixels, the incident light is passing through only a single polarizer. For incident light which is randomly polarized, such as sunlight, only 50% of the incident light is expected to transmit through the screen. There are also possible reflections from the glass layers which house the TFTs and polariers. Therefore, it is unlikely that the panel will be exactly 50% transparent. To consider the selected panel as passing the brightness test, The display should transmit at least 45% of incident light. Such a strict criteria ensures that the display is useful in as many lighting conditions as possible, and should account for the small amount of light lost to surface reflections.

5.4.1 Display Subsystem Testing

To design the LCD lighting test, considerations needed to be made to the possibility of rapidly changing lighting scenarios outside. On a day with unstable weather, a cloud passing overhead could significantly change the backlight levels causing disruptions to the testing data. Therefore, to ensure a stable testing environment, the manufacturer provided backlight of the LCD was used as the reference lighting for the display. Measurements of the backlight intensity were made using the same LX1330B light meter that was previously employed for the testing of the LED brightness. To ensure the measurements made were thorough and robust, the light meter was placed in each corner of the backlight and in the center as well. After collecting the reference lighting points of the backlight, the transparent panel was placed directly on top of the backlight, and the measurements were repeated in the same location. The testing data is compiled below in Table 11.

	Position 1	Position 2	Position 3	Position 4	Position 5	Average
Backlight	5770	5780	5950	6210	6960	6134
Display	2810	2790	2890	2960	3270	2944

Table 11: Testing results of the display transmittance using the LX1330B. Units are in Lux.

The results of the lighting test for the display are consistent with the expectations for the panel type, and what was observed during the preliminary display testing. In examining the two averages for both the backlight reference and the display, the average light transmitted through the display was almost exactly 48%. This is greater than the minimum 45% of the testing criteria, and surprisingly close to the hypothetical maximum of 50% expected in an ideal case. The 2% of light which was not transmitted is likely being mostly reflected by the panel surfaces. These results are highly encouraging for the ongoing development of the display subsystem.

One subject of small concern is the placement of display PCBs. Because the display is a proprietary piece of technology used in the design, the group has not been able to custom fabricate the PCBs to allow the displays function. Therefore, considerations are being made to best accommodate the arrangement of display PCBs on the window frame. While attempts are being made to cover the exposed PCBs, it is a possibility that they may need to attach to other subsystems, such as placing PCBs inside of the LED lighting box at the top of the window frame.

5.4.2 Display Voltage Regulator Design

The display for the Smart Window is a critical element since this is what will be used to display all of the data to the user. This display draws 1.6A at 19V resulting in a power consumption of 30.4W. This element of the final product will use roughly 10.3% of the battery packs total power (296W) mentioned in section 3.2.9. The adapter that comes with the display has a standard barrel connector so the design of this subsystem will need to have an output through such a connector. Using the online software webench power designer and selecting the design parameter for efficiency with output specifications mentioned above and input parameter being 10V - 20V from the battery pack, many circuits are generated that will do the job. Filtering by lowest bill of material cost, the circuit that was chosen is shown in Figure 34. This circuit is based around the TPS55340RTE IC. This chip offers a 3V - 30V input range with up to 38V at the output. Designing a PCB test board for this circuit should only require copying the circuit shown in the figure below as well as adding the output for the barrel connection to the display and input terminals for the batteries.

Testing this circuit should be a very simple process. First, the battery pack must be connected. To do this, four cells will be connected in series and the total voltage will be measured and noted as Vin. Connecting these cells in series will be done through the process mentioned in section 5.0 describing how to make the battery bank. Once the pack is connected, the output voltage will be measured and noted as V_display. This value should be 19V and the test will be considered a pass if V_display is within 0.5V of the expected value.

The next step is to attach another four series cells in parallel with the original four cells. It is important to note that these two packs in parallel should be at the same potential difference to prevent any safety hazards and current losses. To ensure that this is the case, each individual cell will be measured with a voltmeter and tabulated. Once all of the voltages have been recorded, and all the batteries labeled as V1,V2,V3...etc, it is just a matter of choosing the correct cells for each pack to make the total series voltages equal. Table 12 shown below summarizes the data collected as well as the result of the testing.

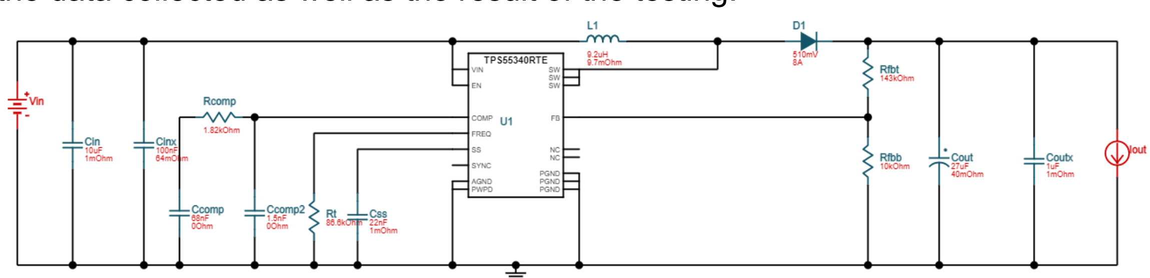


Figure 34 - Battery to Display Power Distribution Circuit

Name	Nom. V/Max V	Measured Voltage	Unit
V1	3.7/4.2	3.62	V
V2	3.7/4.2	3.65	V
V3	3.7/4.2	3.60	V
V4	3.7/4.2	3.62	V
V5	3.7/4.2	3.7	V
V6	3.7/4.2	3.61	V
V7	3.7/4.2	3.60	V
V8	3.7/4.2	3.62	V
V_a (V1+V2+V3+V4)	14.8/16.8	14.49	V
V_b (V5+V6+V7+V8)	14.8/16.8	14.50	V
V_a // V_b = V_in	14.8/16.8	14.49	V
V_display	19	16	V

Table 12 - Battery to Display Power Conversion Measurements

The power conversion circuit for the battery bank to the display did not meet the requirements, but the batteries would not be able to be charged anyway so the adapter that the display came with was used in place of the circuit regardless.

5.5 Charge Controller Design and Testing

Designing the Smart Window to run primarily on solar energy with a connection to the main house grid as the backup is the end goal. Since most charge controller ICs cannot support different inputs, such as photovoltaic cells and a wall adapter, there will be two different charge controlling circuits which will be enabled or disabled by the MCU on the board based on what energy is available at the time. As mentioned in section 3.3.6 the BQ24765 charge controller was one of the ICs selected. This IC can support an input voltage between 7V and 24V which allows for many wall adapter design choices. Since 12V wall adapters are very common for electronics, this would allow the consumer to not rely on the adapter that comes with the final product. Most of these wall adapters have a barrel plug with an inner diameter of 2.5mm so selecting the correct female header for the PCB is essential for providing good contacts and thus power to the rest of the board.

With the main power coming from a 12V adapter, the MCU needs a voltage regulator that handles this input and provides a 3.3V output. For this specification, the L7980 IC was chosen to perform the job. In the original schematics and PCB shown in section 6.1, a linear voltage regulator was chosen and designed around but upon inspection of the datasheet, this component cannot tolerate an input voltage greater than 10V.

The only modifications that need to be done concerning the component swap to the L7980 are connecting the ADAP+ node to the input of the application circuit shown in the its datasheet as well as the GND2 node to the ground of the same application circuit. Some schematic and PCB modifications are needed as well before the final product should be produced. These modifications include, but are not limited to:

- Spacing footprints such that names and values are legible while keeping them as close together as possible
- Add power and ground planes
- Reducing via count
- Change barrel connector from 2.0mm to 2.5mm inner diameter
- Add L7980 regulator application circuit
- Properly label nets in schematic
- Organize grouping of components in schematic
- Add Temp/Humidity/UV/Infrared sensors to schematic and PCB
- Add terminals to connect to connect to battery pack
- Add headers for probing/testing
- Add serial wire debug header/usb connection to program MCU

As more research and testing is done, the solar charger IC, which has not been determined at this time, will be added to the schematic and PCB. A test to determine when to move onto designing the solar charger is having the display run on battery power and successfully monitoring the charging process by measuring the input and output current of the BQ24765 as well as the input and output voltages.

These measurements will be useful for calculating the power the photovoltaic cells should be able to supply and whether or not it is a reasonable decision to add them to the window. Using these measurements will also allow for calculation of the efficiency of this controller by dividing the output power by the input power (Pout/Pin). There were no measurements since communication could not be established to the IC.

Parameter	Measurement	Unit
V_in	N/A	V
V_out	N/A	V
I_in	N/A	A
I_out	N/A	A
P_in	N/A	W
P_out	N/A	W
Efficiency (η)	N/A	

Table 13 - Charge Controller Test Measurements

5.6 MCU Testing

To test the reliability of the MCU (STM32L432) chosen, a NUCLEO-32 development board, based around the aforementioned MCU, from ST microelectronics was ordered so that communication and GPIO peripherals can be tested so that working code will be compiled to the MCU on the PCB. Before this can happen, some software packages are needed to upload the code to the MCU. The packages being used are STMCUBEMX and Arm Keil MDK.

The first test to be conducted is enabling the PA1, PA2, and PA6 pins on the board since these control some power mosfets which will act as switches for controlling the current to the battery charger ICs and the battery pack itself. This will be done by connecting an LED with a current limiting resistor between one of the GPIO pins and ground. When the specified GPIO pin is set high through software, there should be a voltage drop across the LED which can be measured with a multimeter, confirming that the test is a success.
This will be repeated for all of the GPIO pins needed. The LEDs used to check whether or not the pins are enabled or disabled are already on hand from previous projects. Once it is determined that these pins can be enabled or disabled through software, the next test will be to ensure that the communication protocols work.

This can be checked by establishing a UART connection to a computer and an I2C connection with another device. Since there was another development board (MSP430G2553) used in previous courses, this will do just fine. The test will then be to communicate between the two boards and send the data from the NUCLEO-32 board to the computer via UART. Testing the Analog to Digital Converter (ADC) will need to be done using the sensor testing PCB created.

To conduct this test, the ADC will be configured to read an input voltage range specified from the GP2Y0A02YK0F's datasheet. There should be an output voltage relative to the distance an object appears ranging from 20cm to 150cm in length. To check whether or not values can be read from this sensor, all that needs to be done is to check the register associated with the ADC for any values when an object is held within the aforementioned range.

The last test that needs to be done is SMBus communication since the charge controller uses this protocol to send data. Since this protocol is very similar to I2C, the same test used for I2C will be done with differences only lying in software and pins used. The results of these tests will be recorded and tabulated for quick viewing. Table 14 below will show the results of the final test.

Test	Description	Pass/Fail
PA1	Switch Current On/Off	Pass
PA2	Switch Current On/Off	Pass
PA6	Switch Current On/Off	Pass
UART	Confirm Data Link	Pass
I2C	Establish communication between I2C devices	Pass
SMBus	Establish communication between SMBus devices	Fail
ADC	Senses GP2Y0A02YK0F's output to determine distance	Pass

Table 14: SMBus Test Results

5.7 Indoor Sensor Testing

Ensuring that the on board sensors work as intended is critical since their values play a major part in the UI of the Smart Window. If they give false information then the user may experience some conflicts between the weather data sourced from the internet and their local sensor values. This would lead to trust issues with the Smart Window which would then no longer deserve the “Smart” part of its name. To test each of the sensors, a PCB had to be made with components including the HDC2010YPAR (humidity and temperature), SI1132-A10-GMR (UV index), GP2Y0A02YK0F (IR proximity sensor) and the STM32L432KC (MCU). Using the software developed from testing in section 5.4 for I2C and UART communication, each of these sensors had their values read and validated according to varying specifications.

Testing the ADC of the MCU occurred simultaneously with the GP2Y0A02YK0F since the output of this sensor is an analog voltage ranging from 0.5V to 2.75V. This range should give a clear indication on whether or not the ADC works as well as provide design considerations for the activation range of the Smart Window. Testing began with the GP2Y0A02YK0F (proximity sensor) since it is the easiest to verify. All that needs to be done is to place an object in front of the sensor and move away slowly until the sensor is no longer triggered. The output voltage of this sensor will be sent to the ADC of the MCU. The test concludes when the ADC register gathers values greater than 0 for the specified range of this sensor. The actual ADC conversion does not matter for this test since it is only to gather information on whether the sensor works or not. Software can be added to limit the activation range resulting in less frequent activations and power loss.

The next sensor to test is the temperature sensor since its value should match the thermostat’s value when conducted in the same room. The value read via I2C and sent to the computer terminal via UART should match the thermostat’s temperature reading within 1℃ for the HDC 2010 PAR to pass the temperature accuracy test. The humidity sensor is a little bit trickier. To check if this component does not work, the values that need to compare with the value that the HDC 2010 PAR displays will be taken from the weather channel app. Since the app cannot be accurate to an exact location, a hygrometer could be used to verify the accuracy of the sensor. This option would add to the bill of materials in a significant way since its only purpose would be to verify one sensor while costing much more than the component itself. The UV index will be tested in the same way as the humidity sensor, comparing the value that the component gives to that from the weather channel app. Table 15 summarizes the test procedure and results. The schematic and PCB design for these sensors are shown in sections 6.1 and 6.2.

Part	Test	Result
HDC2010YPAR (Temperature)	Compare to thermostat	Pass
HDC2010YPAR (Humidity)	Compare to weather channel app/hygrometer	Pass
SI1132-A10-GMR (UV Index)	Compare to weather channel app	Pass
GP2Y0A02YK0F (Proximity)	Validate ADC works	Pass

Table 15: Indoor Environmental Sensor Test Results

5.8 Outdoor Sensor Testing

Since all of the sensors for this project were tested in the previous section, the validity of them is not the main concern. Testing the outdoor sensors will be making sure that the connections will ensure that the MCU will be able to communicate with them over I2C. To do this a simple schematic and PCB will be created, shown in sections 6.1 and 6.2 as figures 31 and 39 respectively, with input connections to the indoor sensor testing PCBs power and output connections to the MCU's I2C clock and data lines. The test will conclude when the data can be read from these sensors with the results shown in Table 16.

Part	Test	Result
HDC2010YPAR (Humidity)	Read data over I2C	Pass
HDC2010YPAR (Humidity)	Read data over I2C	Pass
SI1132-A10-GMR (UV Index)	Read data over I2C	Pass

Table 16: Outdoor Environmental Sensor Test Results

5.9 LED Power Conversion Design and Testing

The main power for the Smart Window will be coming from the battery pack mentioned in section 5.0. The nominal voltage of this battery pack is higher than what the LED strips need to operate so a conversion must take place to ensure that the strips will light up when needed.

Using webench as mentioned in section 5.2.1, a circuit was generated, shown in Figure 35 below, that fits the following criteria: input voltage between 14V and 17V, output voltage = 12V, and a max output current of 2.5A. Each LED strip runs on 12V at 1A but since there are two strips being powered, there should be a minimum capability of supplying 2A.

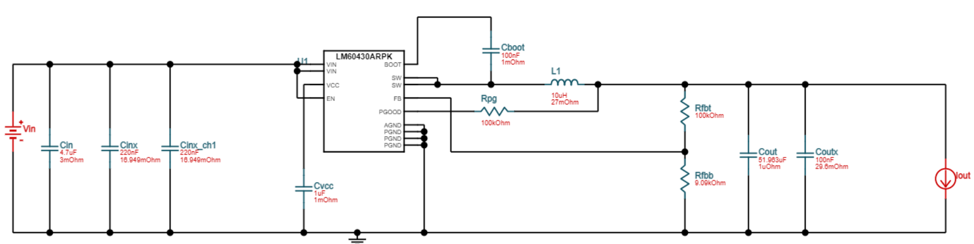


Figure 35: Battery to LED Power Conversion Circuit

This circuit shown above is based on the LM60430ARPK IC. This chip features low Electromagnetic Interference (EMI), output voltage range from 1V - 24V, peak efficiency greater than 95%, and low quiescent current (25 μA). Testing this circuit starts with creating a schematic and PCB shown in Figures 37 and 41 respectively. V_in will be the battery pack's input voltage (V_a // V_b) as mentioned in section 5.2.1 in Table 12The LED strips will be connected in parallel in place of the label I_out shown in the circuit above.

Once everything is attached some measurements are ready to be made. The first measurements will be the input voltage, V_in, and input current, I_in. Next the outputs, V_out and I_out, will be measured. The input and output power as well as the efficiency of this circuit can then be calculated from those measurements. Parts for the battery bank and LED Power conversion circuit are currently ordered and waiting to be assembled. Of course, it's still useful to set out testing plans and designs to maintain a proper schedule for the rest of the project. Once these parts arrive and are assembled by the team, testing data can be taken. All of this data will be summarized in Table 17 below.

Parameter	Measurement	Unit
V_in	N/A	V
V_out	N/A	V
I_in	N/A	A
I_out	N/A	A
P_in	N/A	W
P_out	N/A	W
Efficiency (η)	N/A	

Table 17: Battery to LED Power Conversion Test Measurements

5.10 Raspberry Pi Configuration Testing

The Raspberry Pi is the computer that drives the display of the Smart Window. There needs to be a way to communicate with the MCU to gather the data collected from the various sensors mentioned in the sections above. A simple solution to this would be to configure the I2C port on the Raspberry Pi and attach those pins to the corresponding data and clock lines on the main PCB. The Raspberry Pi will then be subject to the same test outlined in section 5.4 concerning I2C communication. This test did not yield favorable results so UART communication between the development board and the Pi was used instead.

5.11 Glass Subsystem Design and Testing

The main goals of the glass subsystem are to be able to apply the PDLC film to the glass pane, integrate it to the power source and into the overall design in order to be able to effectively switch from opaque to transparent privacy modes and vice versa depending on the user's needs. The PDLC film that was chosen by the group to be part of the final design is the Smart Tint adhesive PDLC film. This film was chosen partly for the benefits it provides in terms of its impressive optical performance and highly efficient electrical specifications, as outlined on section 3.3.2 of this paper where the major PDLC competitors are compared to one another.

Once the PDLC film is delivered and the glass pane is acquired, the very first step was to apply the film to the glass. The group convened in order to apply the film to the glass pane, following the instructions of the manufacturer to guarantee a correct application. This consisted of applying isopropyl alcohol to the glass pane using a microfiber cloth in order to remove any debris, dirt or oil, followed by letting the glass air dry.

After this, the team slowly attached the adhesive layer to the glass pane, starting at one vertical end and using a horizontal motion with the squeegee provided by the manufacturer in order to ensure that there are no air bubbles forming in between the film and the glass pane. This process of cleaning and applying the film is crucial as air bubbles and debris in between the glass and the film are not aesthetically pleasing to the end user and they reduce the efficiency of the window.

The next step after the film was applied to the glass pane, was to test at which voltage we can get the maximum transmittance out of the film. As mentioned previously in the PDLC film research and selection sections, this type of film, similar to the operation of a liquid crystal display, needs to be driven by an AC voltage.

Even though the Smart Tint vendor provides an estimated voltage for the transparent state between 35 and 65 V AC, testing could have been done in order to quantify the minimum voltage at which we can get acceptable results and this way the team can ensure an appropriate balance between performance and energy efficiency.

This initial testing could have been fairly simple as long as the team can get access to a UCF lab with a signal generator. The PDLC film already comes pre-wired from the manufacturer so we can simply connect the film to the signal generator, produce a sine or square wave at the recommended frequency of 60 Hz (according to the datasheet provided by Smart Tint) and vary the voltage at 5 V steps until full transparency is achieved.

This testing was not done, however, since the team decided to use the 60 V AC power supply provided by the manufacturer of the PDLC film with the purchase. Since the solar-powered battery bank that would have been used in the project outputs DC voltage, the data from this experiment could have been used to make an informed decision on which type of power inverter will be needed to power the PDLC film. This is partly why this testing can be important to the final project design. This potential basic setup can be visualized in Figure 36, shown on the following page.

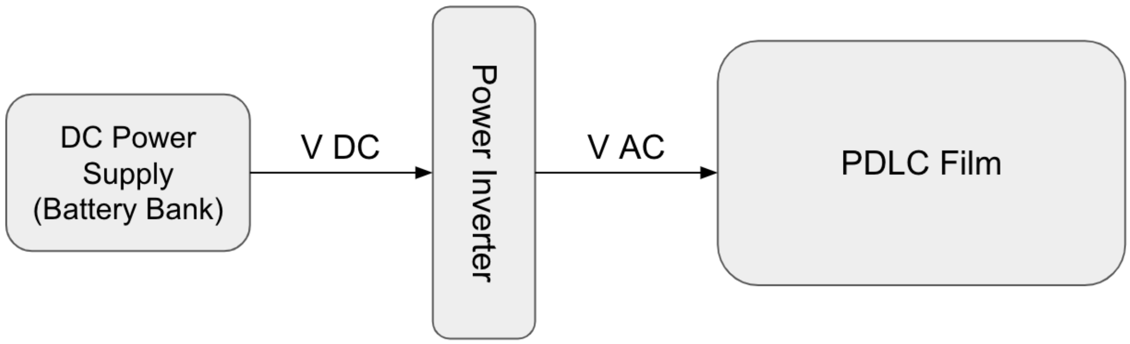
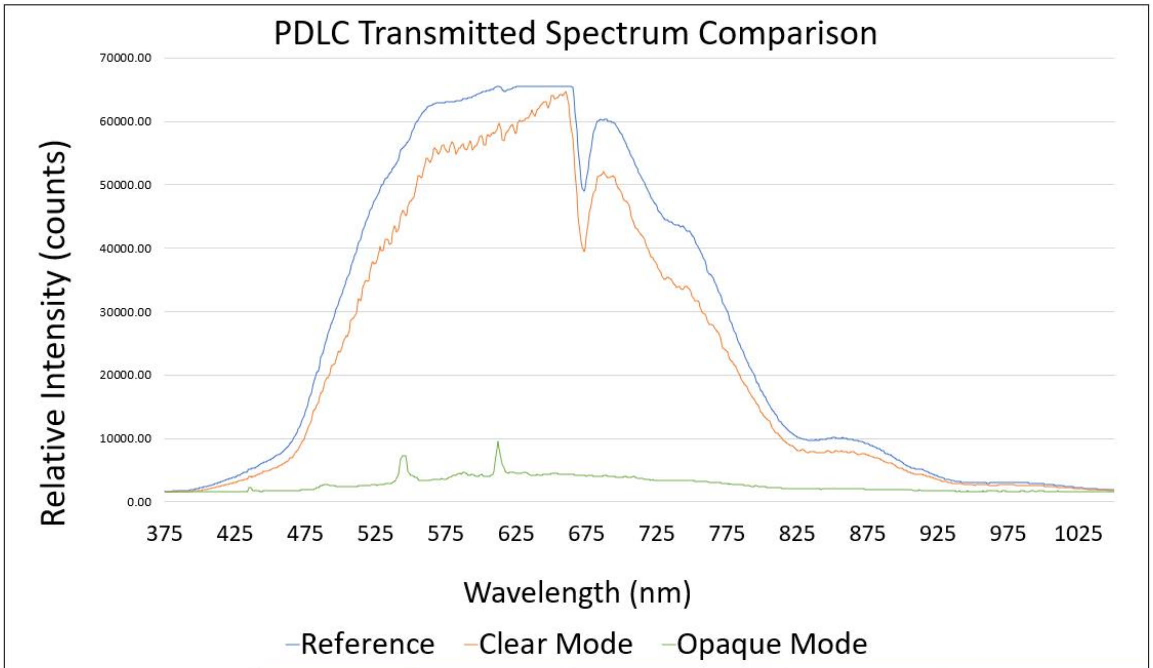


Figure 36: Potential setup of the PDLC subsystem

The setup shown in Figure 36 was not used, however, since the team decided to forgo the solar-powered battery bank for a more straightforward surge protector setup connected to a wall plug.

Once the basic functionality and electrical testing was completed, a goal for the team was to conduct optical tests in order to verify the transmittance values provided by the manufacturer. This required access to the CREOL senior design lab such that the team could have certain equipment at our disposal such as a broadband fiber light source and a spectrometer.

An example of this type of testing which was conducted consisted of measuring the output spectrum from a broadband fiber light source using a spectrometer, and then measuring the spectrum transmitted through the film in both the fully opaque and fully translucent modes. This allows the team to measure the relative intensity at different wavelengths and from that the team can extrapolate the percentage of light scattered at both modes of the PDLC film, which allows the team to verify the specifications provided by the manufacturer. The results of this testing can be seen below in Figure 37.



Wavelength	Reference	Opaque	% Red. of Ref.	Clear	% Red. of Ref.
Long UV-A (400 nm)	2196.20	1544.60	29.7	1780.60	18.9
F Line (486.1 nm)	22846.00	2556.80	88.8	17194.00	24.7
D Line (589.3 nm)	63508.00	4585.00	92.8	55462.00	12.7
C Line (656.3 nm)	65535.00	4399.50	93.3	64179.00	2.1
Near IR-A (890 nm)	7418.30	1918.90	74.1	6160.60	17

Figure 37: PDLC Subsystem Spectrometer Testing Results

As it can be observed in Figure 37, the results show an average of 75% of incident light scattered in the opaque mode of the PDLC film, as well as an average of 15% of incident light scattered in the translucent mode. Unfortunately, the broadband light source used for this testing did not output a significant amount of ultraviolet light therefore the results are inconclusive for that particular wavelength.

The team also conducted a photometric test using an LX1330B light meter to measure the illuminance transmitted through the PDLC with sunlight as the reference. This test was repeated for both clear and opaque modes of the PDLC film and at three different locations of the window to reduce error from changes in sunlight conditions. The results of this test, which are all in units of Lux, are shown in Table 18.

	Reference	Clear	Opaque
Top	1475	1225	965
Middle	1450	1250	1025
Bottom	1425	1202	957
Average	**1450**	**1226**	**982**

Table 18: PDLC Subsystem Photometric Test Results (Units of Lux)

Analyzing the data from Table 18 shows an average of 84.5% of incident light being transmitted through the PDLC in its clear state, and 67.7% of incident light being transmitted in the opaque state. Also, as the project continued and the team applied the PDLC film to the glass pane and finished up testing, the team looked into the possibility of varying the input voltage to the film in order to achieve a “dimming” effect (vary the opaqueness of the system). The vendor for the PDLC film offered a dimming control but this would’ve added to the project cost so the team decided to just acquire the PDLC film with a button.

A power supply adapter converts the main 120 Volts electrical connection to the 60 Volts AC needed to operate the PDLC film, this power supply is attached to a button used for changing the PDLC film’s state from opaque to clear mode. The glass subsystem was one of the main considerations when designing the frame, which was built to provide a durable and aesthetic support structure, helping to prevent user error of damaging the PDLC film wiring connections with a built in notch for the glass. It also covers the sharp corners of the glass pane to prevent injury to the end user. The team also drilled holes into the compartment box to wire the PDLC film and its button neatly.

5.12 Power Inverter Design and Testing

One of the main features of the Smart Window is its ability to provide privacy or shade by enabling the PDLC film on the glass pane. This component is unique in that it requires an AC voltage to operate whereas all of the other components use DC. This presents a new design challenge of converting the battery bank’s DC voltage into AC. As mentioned in the previous section, the manufacturer recommends a sine or square wave input between 35V and 65V at 60 Hz. Producing a pure sine wave from DC would require much more time and effort than needed to operate the PDLC as specified.

A square wave can be produced by swapping the polarity of the input voltage, in this case the battery bank terminals, at a constant rate. Doing this 60 times every second would be quite difficult for a physical system, so creating a circuit to generate the waveform would be the best solution. Designing this circuit can be done through the use of a 555 timer. For the IC selection, the LCM555CMX IC was selected for its wide input range.

The timer can be used in multiple modes of operation, monostable and astable, but the mode most fitting for this application is astable mode. The astable operational mode of the 555 timer allows for DC input to charge and discharge a capacitor at a certain duty cycle determined by the circuit's resistor and capacitor values.

Formulas to calculate these values are typically found in the component's datasheet under the detailed description section of the document. For this application, a duty cycle of 50% will be considered. The output of the timing circuit will need to be amplified and shifted, both of which can be done through the use of a differential operational amplifier circuit and transformer.

The operational amplifier selected to perform this function is the TLV9151SIDBVR for its specified input and supply ranges which include the battery bank's nominal voltage. Once a schematic and PCB are created and assembled, testing the inverter should be very simple. The first measurements will of course be at the input of the 555 timer circuit or the terminals of the battery bank. The input voltage and current will be recorded as V_in and I_in respectively. Next is to measure the output voltage, V_tim, and frequency, f, of the timer which should be producing a square wave at 60 Hz.

Lastly, the output voltage and current of the transformer and level shifter will be recorded as V_out and I_out respectively. P_in, P_out, and the efficiency of this subsystem, η, can then be calculated from these values to help determine the total power consumption of the Smart Window.

Rather than buy an oscilloscope for much more than the entire window will be worth, the test can be conducted in the Senior Design laboratory which has all of the necessary testing equipment. All that needs to be done is to schedule a time frame for the testing and then show up to perform the tests. Table 19 on the following page will provide the results of these tests.

Parameter	Measurement	Unit
V_in	N/A	V
I_in	N/A	A
V_tim	N/A	V
f	N/A	Hz
V_out	N/A	V
I_out	N/A	A
P_in	N/A	W
P_out	N/A	W
η	N/A	%

Table 19: Power Inverter Test Results

Because the group decided to omit the use of solar panels as the primary power source, battery banks were not used, and a power inverter was no longer needed. The PDLC was supplied power through the manufacturer's supplied AC adapter. This adapter was made specifically for the film, and worked immediately without requiring any additional testing.

5.13 Transformer Design and Testing

The output of the 555 timer circuit will be a square wave from 0 to 12V at 60 Hz. Shifting this output to ±6V will be done through a differential amplifier circuit. This is not a suitable AC waveform to power the PDLC film which requires a minimum of 35 VAC. When looking to purchase a suitable transformer, none of the products seemed to match the input and output specifications needed.

Therefore it was decided to build a transformer as they are relatively simple in concept. All that needs to be done is to wrap two windings around opposite sides of a ferrite core. The turns ratio needed is proportional to the necessary gain required for the PDLC film which will be between 6 and 10. Choosing a large enough core is necessary to ensure that the windings will fit properly. Similarly, the diameter of the wire used in this build will also come into play.

The wire should be thin enough to make at least a few hundred turns while thick enough to handle the current going through it. Research is being conducted to make sure that each of these concerns will be addressed appropriately. Testing the transformer will be very easy and similar to previous tests conducted in other subsystems.

Testing will begin with measuring the input voltage, V_in, and input current, I_in, and end with measuring the output voltage and current, V_out and I_out. If the output values are not suitable for powering the PDLC film, then windings on the secondary coil will be removed or added depending on the need to step up or step down the voltage.

During the PDLC testing and assembly, the group decided that the original PDLC power adapter which converts to 120VAC wall input to a 60VAC output for the film could be used instead of a custom transformer. This allowed extra time for the group to improve functionality of other areas of the project.

5.14 Blueprints and CAD Designs

This section will be used to showcase the CAD designs for the electronics housing, battery pack casing, and solar panel mounting/interconnect units. The creation of these CAD designs will be done in Fusion 360 as it is a free-to-use software by Autodesk. The CAD designs for the Window frame and Lighting Unit were done using Solidworks Student Edition. By utilizing CAD software before constructing the physical devices, the group is able to be much more sure about the dimensions of components, and all parts abilities to interact correctly.

5.14.1 Window Frame CAD Designs

The window frame constitutes an important design consideration. Because the frame will have the dual purpose of providing both structural support to the display subsystem, as well as house much of the device electronics, it's important that it's design is well thought out. Two designs were considered for the window frame placing emphasis on the frame performance of two functions; to keep the glass window supported and sturdy, and to house the electronics that support the project's features. The initial design idea for the window frame was to house the majority of the design electronics inside the frame of the window, as can be seen on the following page in Figure 38.

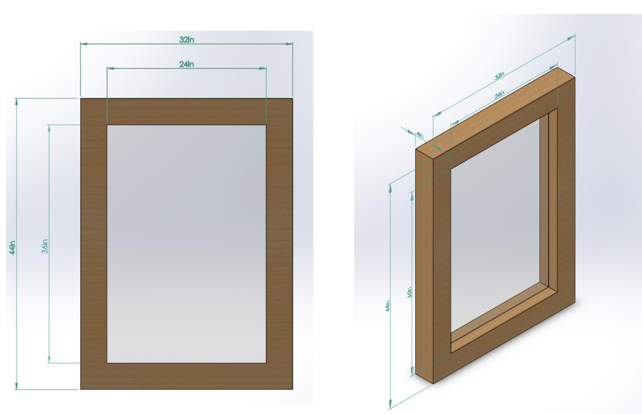


Figure 38: Initial Window Frame Design

The window frame supports the glass subsystem with a 4” cubed border surrounding the glass edges.The frame design shown above in Figure 38 is one that naturally comes to mind when considering a single pane window. The frame wraps completely and evenly around the glass, which covers all exposed edges and corners of the window. The frame is also considerably wide, with a border that's 4 inches in length on all size, the intention would be to take the relevant electronic systems, like the PCBs, temperature, humidity, proximity and UV sensor, and place them inside of the frame which wraps all around the glass.

However, this leads to two problems. The first is that it is difficult to account for all of the various component sizes. Another problem that the group may encounter if the design in Figure 38 is used, could be difficulties in managing the wires and connections between different sized components in a frame that has such aggressive design tolerances. 4” borders should be able to contain most of the small sensors and would be able to contain the microcontrollers, but it could make PCB design difficult and stressful.

There is also the problem of weight distribution. Because the project is not going to be supported by a wall which would typically mount a window, the benefit of building the electronics into the frame could actually be a design flaw, as it does not contain a sturdy base to support it during presentation. These two considerations lead to the design of a new frame, seen in Figure 39.

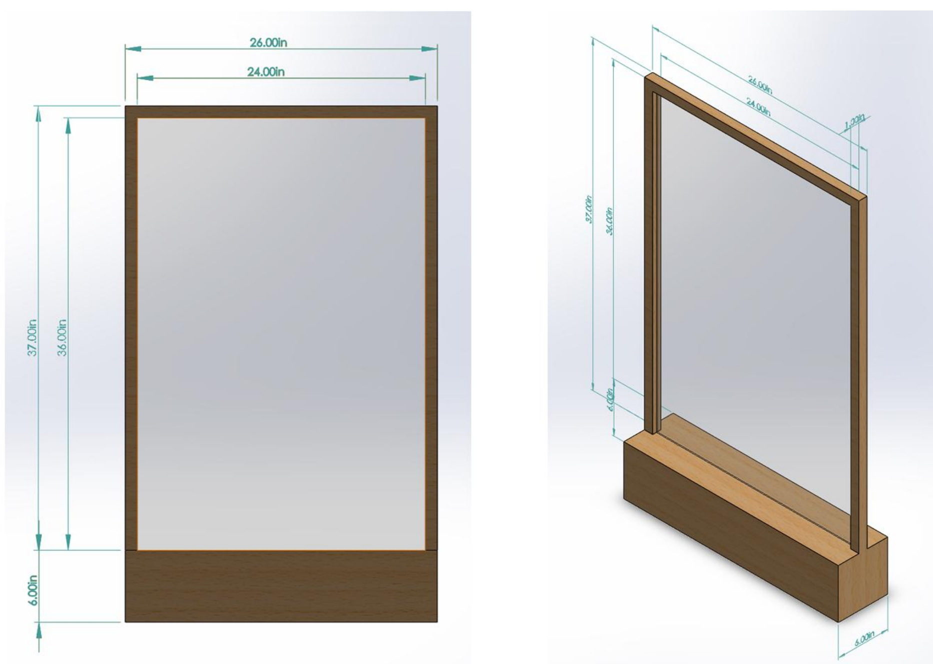


Figure 39: Secondary Window Frame Design

The frame supports the glass with 1” cubed borders, and contains a base for hosing the design electronics, and supporting the weight of the glass subsystem. Figure 39 has advantages and disadvantages compared to the previous design. By housing the electronics below the window, a sturdy base is constructed which helps to maintain the window’s upright position. The tolerances for different sized components are also larger, making the design and fabrication process less stressful. If a PCB turns out to be slightly larger than 4”, it would still be compatible with the bottom design. Another advantage to the bottom design is that using 1” cubed wood supports for the glass subsystem would simplify the frames fabrication. It would be possible to obtain solid wood 1” square boards which could be solid, and would be assembled considerably easier than the first hollow design.

5.14.2 Lighting Unit Design

The Lighting unit consists of a backing which can attach to the frame of the window, and is able to support the two LED strips. To help diffuse the light generated by the LED strips, the LEDs will be obscured by a diffusing plastic base sheet, resembling the appearance of frosted glass. This model is visualized by Figure 40. below. Also seen on the model are two semicircles that will also be constructed from a diffusing plastic sheet, ensuring that no light leakage occurs from the sides of the LED covers. A wooden backing plate is shown which mounts the two LED strips. While the LED testing revealed that the strips did not generate significant heat during extended use, a heat dissipation pad may be installed between the LED strips and the backing to ensure a long device lifetime.

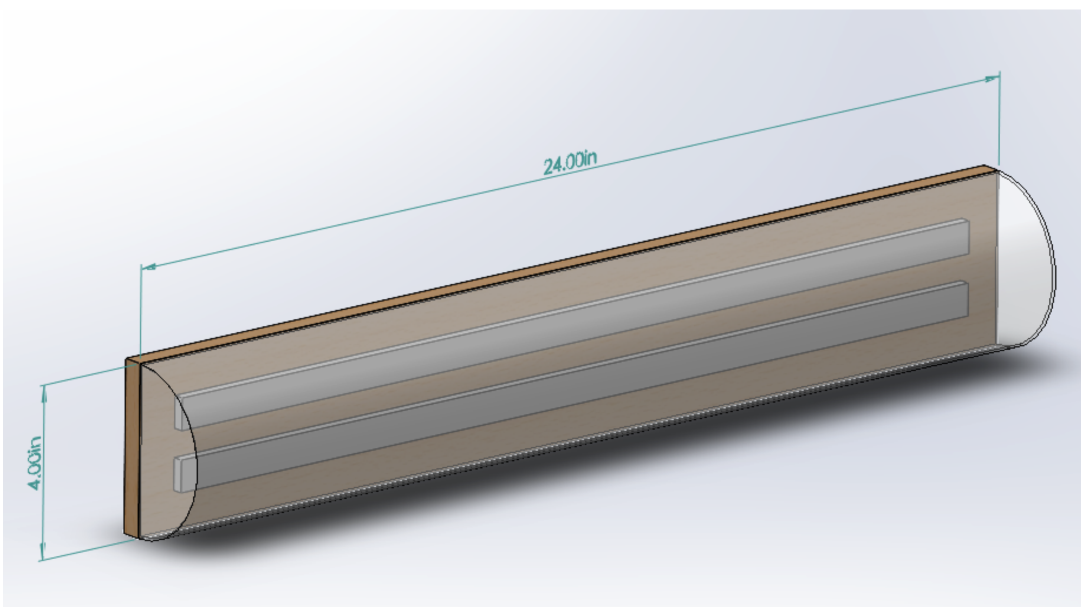


Figure 40: Lighting Unit

The lighting unit design is fairly simple, intending to match the aesthetic of the rest of the designs without compromising functionality. The acrylic sheet, which will act like frosted glass, is left partially transparent in the design to show the two LED strips underneath it. The width of the lighting unit shown above is 24 inches, to match that of the width of the window frame. However, the LED strips both have a length of 36”. Therefore the LED strips will likely be modified to fit inside of this shortened form factor. One solution would be to cut the strips at 24”, leaving a partial strip of 12”. These two additional 12” strips from both the warm and cool colored LED could be attached in series to their longer original piece, and therefore the original output power could still be maintained. The LED strips are both High density strips, containing 60 bulbs per 36” though, so it’s possible that in additional testing of this system during its construction process, this modification may be shown to be unnecessary, and the strips could be left at 24”.

6. System Architecture

The system architecture section of the documentation helps to define a conceptual model which describes the Smart Window in various perspectives. It can describe large and small subsystems, and is generally used to help define an individual systems structure and behavior to better help in its development. Some of the types of architecture used for the development of the Smart Window project consists of electronic schematics, PCB layouts, and software flow diagrams. As development continues, physical and mechanical parts will need to be added to the project, and these will likely consist of project blueprints and CAD designs. Section 6 of the documentation will describe and showcase the current system architecture plans for the Smart Window project.

6.1 Schematics

Schematic diagrams are useful representations of system elements that help to visualize how blocks of the electronics will work. The Smart Window project is feature-rich, and has numerous electronic systems that need to interconnect. The use of schematic diagrams is essential to ensuring proper design and development of the overall electronic systems.

One of the big challenges of the Smart Windows electronic design is ensuring compatibility between all the onboard electronics. Not all of the onboard electronics require the same power characteristics, so the voltage supplied by will need to be adjusted for powering specific components. This can be done through IC’s on PCBs, as well as through the use of boost voltage converters, and more traditional components like OP amps.

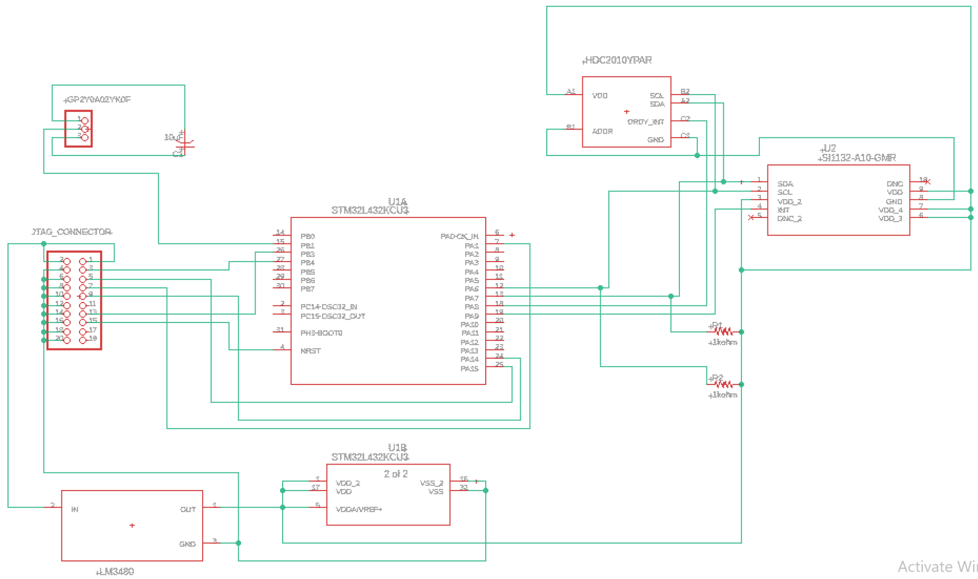


Figure 41 - Sensor Test Schematic

Figure 41 shows the schematic for the sensor test board mentioned in section 5.5. The input power will come from the JTAG connector (ST-Link/V2) and is then fed through a 3.3V linear regulator for simplicity. This board also contains a header to connect to the proximity sensor since there is no footprint available. The above sensor schematic connects the indoor and outdoor sensors, including the temperature sensors, the humidity sensors, and the single UV sensor that measures the outside UV index. All of these connections are to the MCU's I2C Clock and data lines, as visualized in the above diagram.

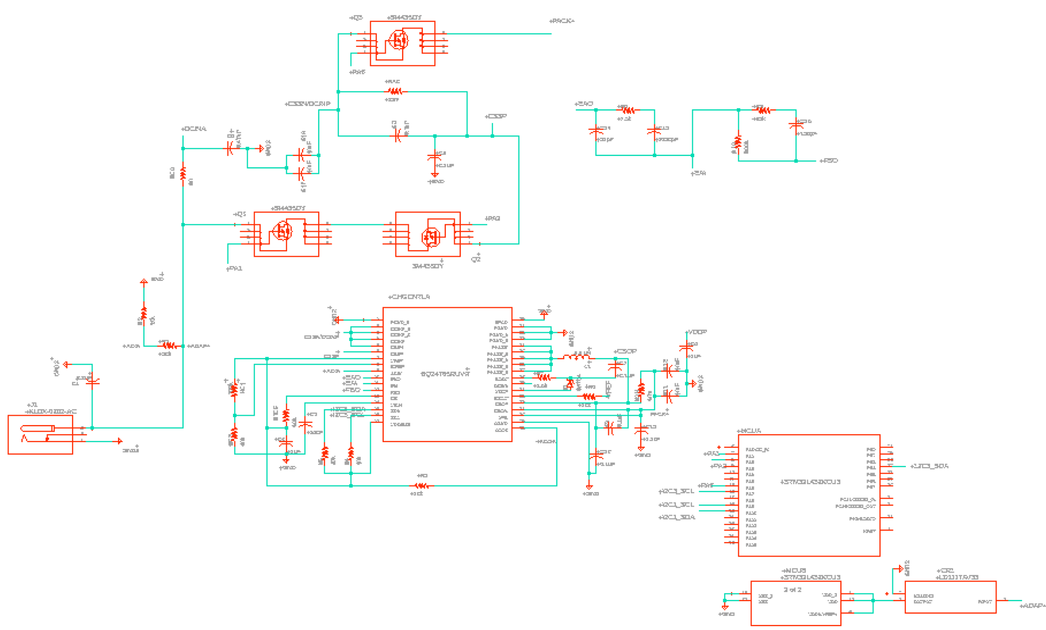


Figure 42: Full Battery Charger Schematic

Figure 42 shows the entire schematic for the battery charger electronics. This schematic is crucial for the project, as it explains how the battery bank will remain charged and operational. The battery bank serves as the primary power source for all electronics on the Smart Window. At its current iteration, the battery charger schematic does not account for the additional input from the solar panels.

To ensure proper operation of the sensors, the schematic is first designed for a single power input, the home electrical connection. Because the schematic is so large, it has been broken down into three smaller sections for the purpose of explanation. The figures on the following pages show three zoomed in views of the full battery schematic. The first is the adapter input shown in the bottom left of the schematic, as a barrel connector which allows for the adapter to give power to the rest of the circuit.

The charge controller IC, which is shown in the center, monitors the battery packs voltage and provides a charge current based on the internal logic of the IC. The last diagram is the MCU & Pin Nets, shown in the bottom right of the schematic, which allow for communication between the MCU and charge controller IC. More details on these three sections of the charger schematic will be given in the subsequent figures.

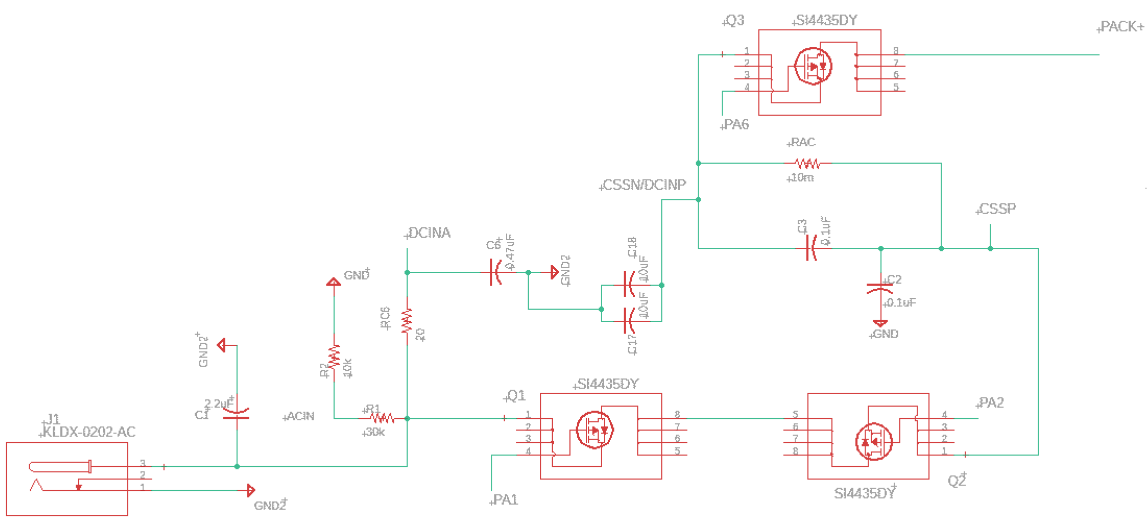


Figure 43: Adapter input

The adapter input section of the battery charger schematic shows a female barrel connector on the left as the main input, seen above in Figure 43. The current from the adapter will travel through various passive components as well as provide a gate to source voltage to the MOSFETs if the MCU allows it to do so by enabling any of the following pins: PA1, PA2, and PA6. The software will dictate whether none, one, two, or all of the MOSFETs will allow the current to pass based on information communicated to the MCU by the charge controller IC.

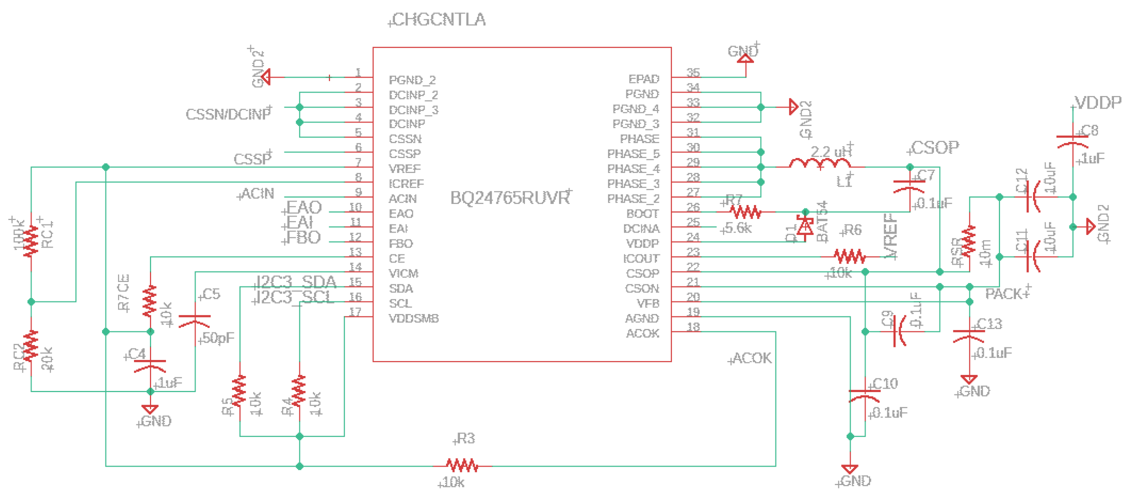


Figure 44: Charge Controller IC

The charge controller IC is shown by Figure 44. It has 34 pin connections plus 1 grounding pad on the bottom of the chip. Each of the connections in the schematic above was based on the typical application section in the ICs datasheet. Some straight forward connections are the power and ground pins which connect to, as one would probably guess, power (12V wall adapter input) and ground.

However, there are two grounds in this circuit, GND (PGND) and GND2(AGND). GND is the ground connection for the digital logic of the chip while GND2 is the analog ground connection which will connect to the battery pack's negative terminal. These pins are only to be connected to each other through the grounding plane on the bottom of the IC. Vref and Icref are used as a reference for the chip.

CE is the enable pin which is connected to Vref through a resistor to limit the current so that the chip will actually function. SDA and SCL are the SMBus pins for this chip which will allow it to communicate to the MCU through SMBus. This must be connected to the MCU on a different I2C line than the rest of the sensors to maintain the differentiation in operating characteristics. ACOK checks whether the input is connected serving a function similar to the CE pin. CSON, CSOP, and VFB are connected to the positive terminal of the battery pack for sensing charge and voltage though CSOP is attached through a resistor.

All of the phase pins are phase switching nodes which connect to CSOP through the output inductor. CSSN and CSSP are used to sense the current coming from the adapter. DCINP pins are the main charging source pins which are connected to the adapter input through some power MOSFETs controlled by the MCU.

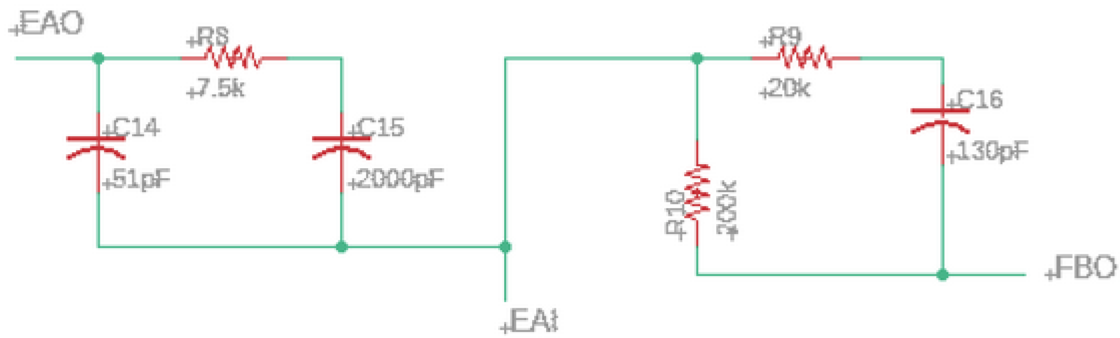


Figure 45: EAO, EAI, FBO Pin Nets

Lastly EAI, EAO, and FBO are the error input amplification, error output amplification, and feedback output compensation pins. EAO, EAI, and FBO connections and their purpose is to form a compensation network that adjusts for variable gains and phases that could affect the reliability of the power supply. These pins form the compensation network input and the entire network can be classified as type III which means there are two zeros and two poles in its transfer function. They are seen above in Figure 45. EAO is located at the top left of the diagram. EAI is seen at the bottom positive connection, and FBO at the bottom right, positive connection.

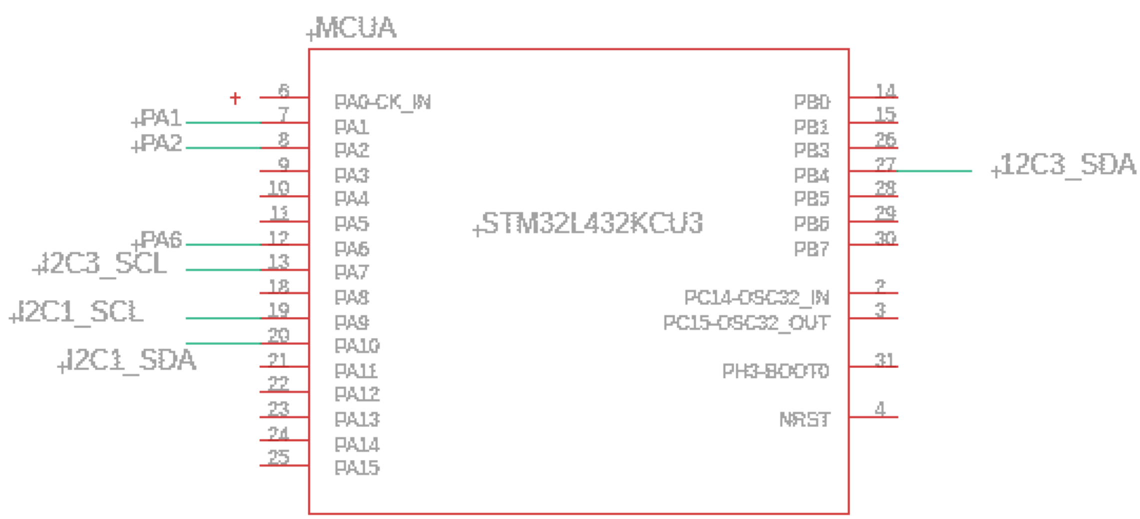


Figure 46: MCU & (EAO, EAI, FBO) Pin Nets

The MCU seen in this Figure, Figure 46, only has seven connections but many more will be added on the final edition of the main PCB. PA1, PA2, and PA6 are all connected to the gates of the power MOSFETs mentioned earlier. PA7 and PB4 are the SMBus clock and data pins respectively and will be used to communicate with the charging controller IC.

The last two pins (PA9 and PA10) are I2C clock and data pins which will be used to communicate with various sensors and the Raspberry Pi when the final schematic is designed. The small block in the bottom right of the main schematic of the battery charger test board contains the power and ground pins for the MCU which for some reason are not included in the main MCU block.

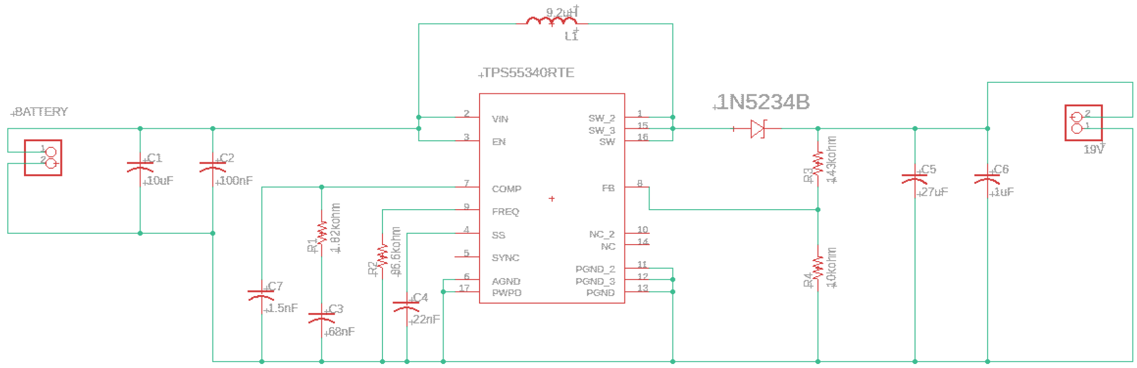


Figure 47: Battery to Display Power Conversion Test Schematic

The LCD Display was supplied with an AC to DC power adapter which rectified the wall supplied AC to an appropriate voltage for the display. However, the electrical connections of the Window can be greatly simplified by attaching as many components as possible to the solar powered battery bank. The battery bank already supplies DC power, so connecting the display to the solar panel battery bank is fairly straightforward. The battery voltage is boosted using a TPS55340 DC/DC Regulator, seen in the center of Figure 47 above, which increases the low voltage of the battery bank to a higher voltage connected to the LCD module for controlling the transparent display.

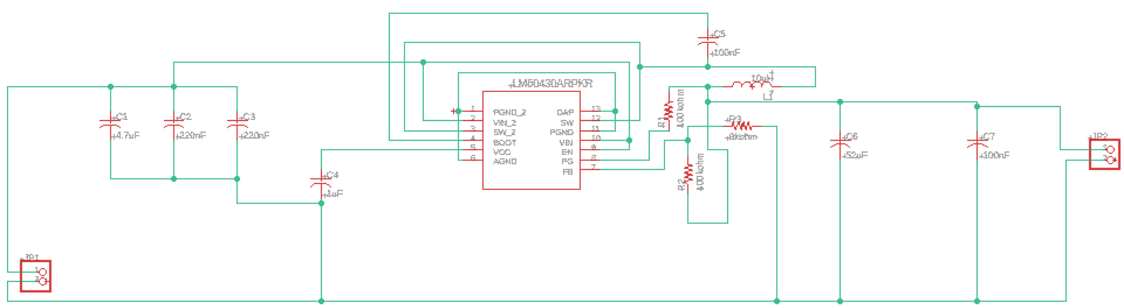


Figure 48: Battery to LED Strip Power Conversion Test Schematic

Since each LED strip runs on 12V, there must be a power conversion from the battery pack to ensure that they can operate without fail. The battery pack outputs roughly 15V and will be attached to the pin headers shown in the bottom left of the diagram below. The current then makes its way through various passive components and the LM60430ARPK IC to provide 12V at the output header shown on the right side of Figure 48, which can then be connected to the PWM controller of the LED strips.

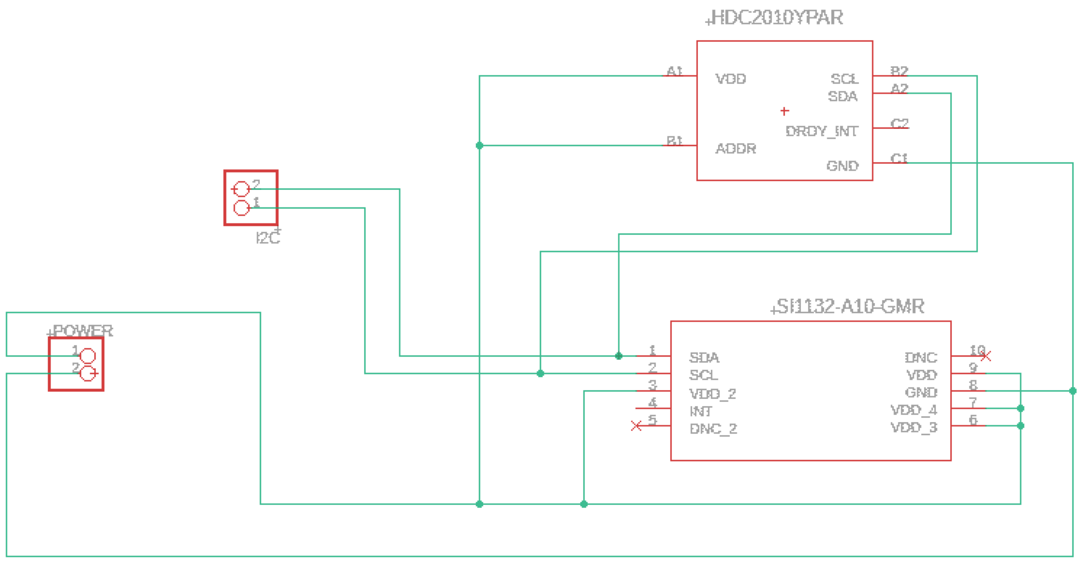


Figure 49: Outdoor Sensor Test Schematic

The outdoor sensor testing PCB is visualized in Figure 49. The input will be powered from the indoor sensor testing board and the output will be to the I2C clock and data lines of the same board. Each of the sensors I2C clock and data lines are connected to each other and to the output. The interrupt pins are left floating since there will be no need for them during testing but they may be connected to the MCU in the final PCB if needed.

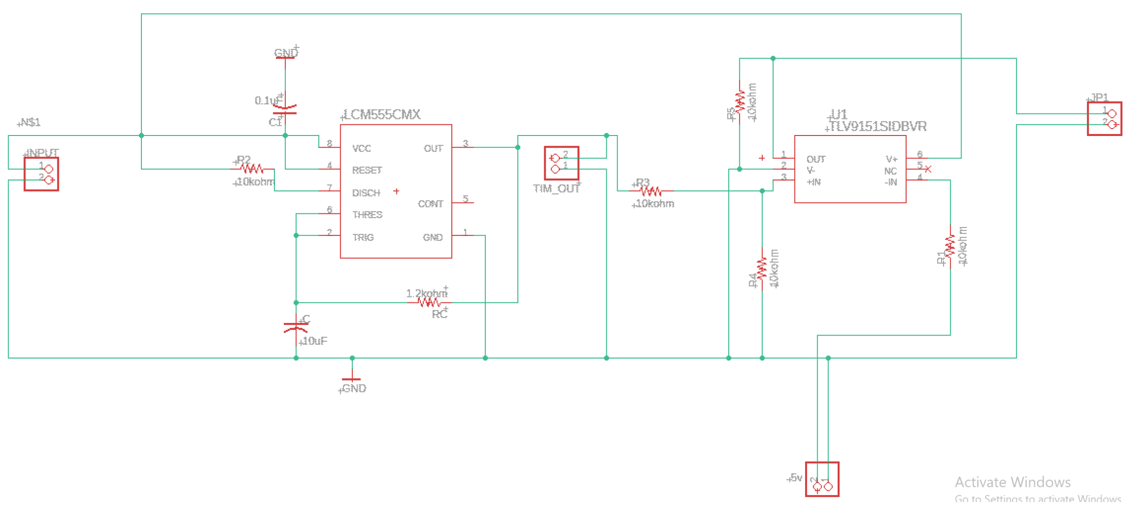


Figure 50: Inverter PCB

The inverter schematic begins on the left of Figure 50, with some jumper pins that will connect to the battery back's inputs. This supply will go through the LCM555CMX timing chip in the 50% duty cycle configuration found in the datasheet for this IC. The values chosen for the passive components were decided through the formulas provided in the datasheet to output a square wave at 60Hz.

At the pin header TIM_OUT is the square wave input to a differential amplifier which will shift the waveform down 5V specified by the 5V pin header at the bottom of the schematic. The resistors connected to the operational amplifier are all the same value to make this amplifier have unity gain. Finally the jumper on the right will be the input to the transformer to be constructed which will then lead to the PDLC film.

The schematics outlined here in section 6.1 were developed, but unused due to difficulties in programming the microcontroller PCB. This impacted the battery charging IC, and removed the necessity for these power conversion schematics. Rather than remove these schematics from the document, they are included as a reference for future iterations of the Smart Window project.

6.2 PCB Layouts

The following PCB layouts were designed in the EAGLE software. EAGLE software is a free to use tool for designing PCBs, and was the preferred software for the group because they had previous experience using it before. The PCBs will be manufactured and assembled by JLCPCB since they provide free smd component assembly with an order of a 4 layer board. Ordering the boards before December 25 will result in paying for the discounted price from $2.

Designing a PCB presents a new challenge in the design process since copying its schematic at face value is not always possible. In a schematic, wires that connect at nodes are shown with dots at their intersection and if there is no dot but the wires overlap then they are not connected. The PCB traces cannot overlap like they seem to do frequently in schematics so organization of components and use of vias, holes connecting different sides of the board, must be considered. Vias cost the manufacturer time and resources to create so adding them will cost the PCB designer some extra money to compensate for this process. It is therefore wise to try and design a PCB with as few vias as possible to keep the production cost at a minimum.

This becomes much more important in mass production of boards since adding just two more vias on a design can result in hundreds or thousands of vias on the boards being manufactured. The preliminary PCB designs shown below will not be mass produced as they will be used for testing purposes so adding vias here and there will not cost that much in the long run, but for the final PCB design, via count will be a parameter to try and minimize. The final PCB design for the entire project has not yet been made as there still needs to be testing before committing fully to the preliminary designs. The layout shown below in Figure 51 is the preliminary PCB for the charge controller featuring only necessary components for the charging of the lithium polymer batteries. As mentioned in section 5.3, there still needs an addition of screw terminals to connect the PACK+ net to the positive battery rail for easy connection.

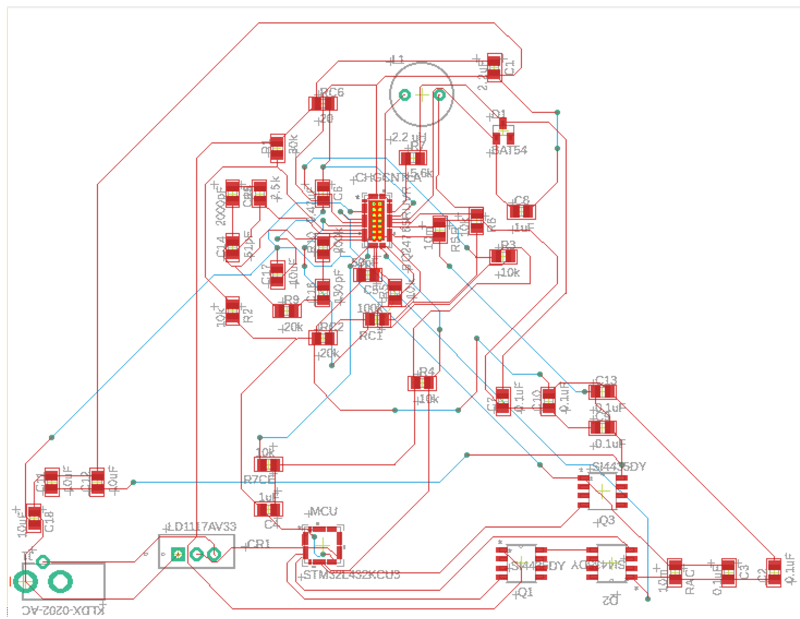


Figure 51: PCB Layout for Charge Controller

The PCB for testing the battery to display power conversion circuit is shown in Figure 52 seen below.

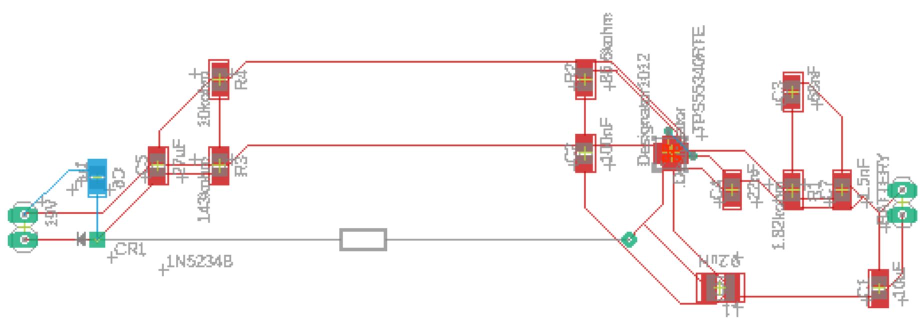


Figure 52: Battery to Display Power Conversion Test PCB

The PCB shown above in Figure 52 is the only testing PCB with components on both sides of the board. This was done as a test for possible future implementations of the final board which will be populated with far more components. If the board turns out successful then the layout for the final PCB will be simplified significantly. There is a minor issue with some of the footprints downloaded from Ultra Librarian. There is a silkscreen layer with various versions of “DESIGNATOR” that cannot be moved or deleted in EAGLE.

This is only a minor inconvenience since it does not hinder the placement of components, as it is only the silkscreen, but reading the neighboring components names becomes difficult as text becomes overlaid if they are placed too close together. The sensor test PCB is shown in Figure 53, below. The footprint for the proximity sensor is not available so it will be connected to the pin headers labeled as its part number. The output voltage (Pin 1) will connect to the ADC of the STM32L432KC.

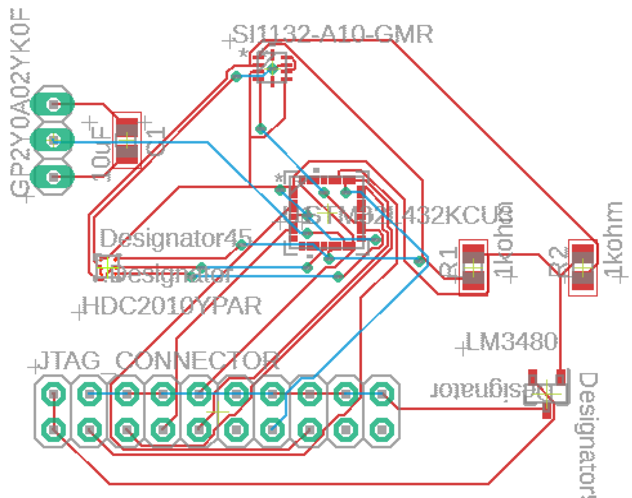


Figure 53: Indoor Sensor Test PCB

The footprint for the proximity sensor shown in Figure 53 is not available so it will be connected to the pin headers labeled as its part number. The output voltage (Pin 1) will connect to the ADC of the STM32L432KC. As the proximity sensor does not have a PCB footprint due to its casing. The solution to this is to add pin headers which will then be connected to the sensor via jumper wires. This also allows for greater mobility and design room for this sensor's placement in the Smart Window's frame.

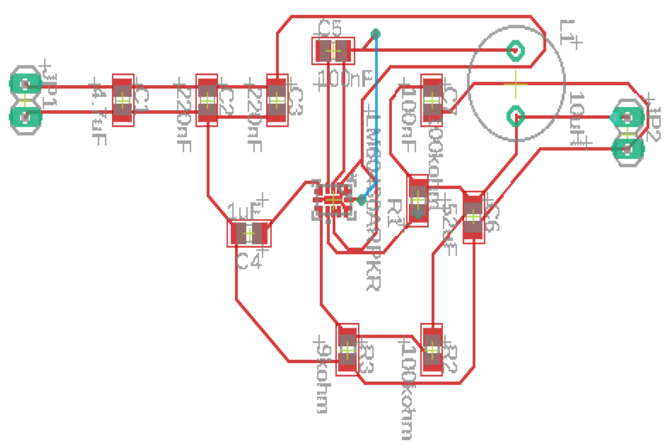


Figure 54: Battery to LED Strip Power Conversion PCB

The PCB layout shown above in Figure 54, was one of the easier to design due to the necessity of only two vias. Different organization of these components or even different pin locations on the main IC may have resulted in no need for vias, but as mentioned earlier, this test board is not going to break the budget because of two vias so no further design was necessary.

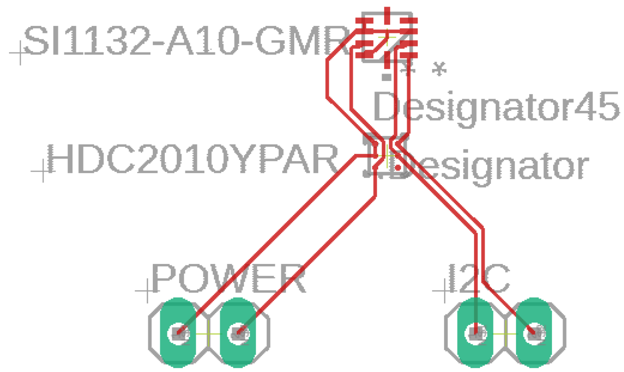


Figure 55: Outdoor Sensor Test PCB

The PCB shown for the outdoor sensor test setup is shown above in Figure 55. The only connections were for power and I2C lines. As mentioned earlier the “Designator” silkscreen names were unable to be deleted which will not impact the performance, only the readability of the neighboring components names, though on this design, the only names that needed to be read are far enough away that the “designators” do not matter.

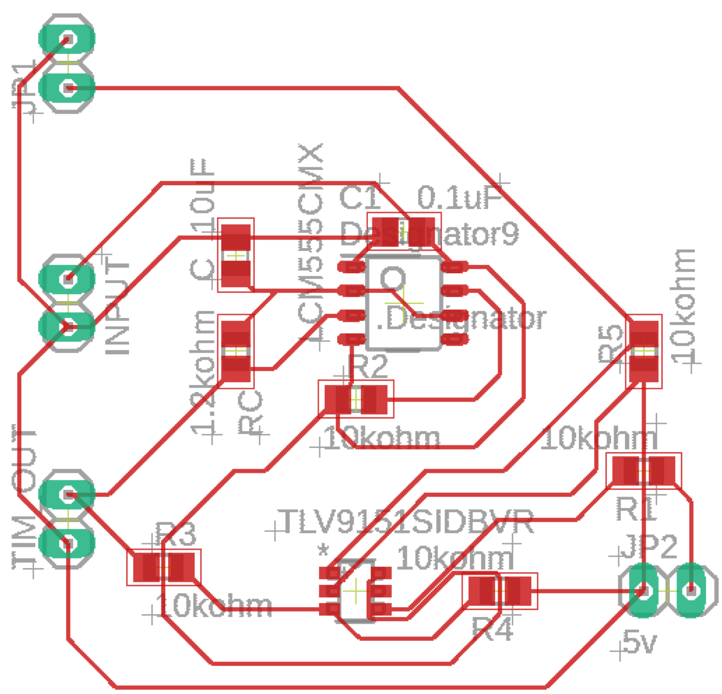


Figure 56: Inverter Test Board

Layout guidelines for the LCM555CMX specify placing the bypass capacitor, C1, as close to the ground and supply pins of the IC. After placing this component it was rather straightforward to layout the remaining components in a way that requires no bias. This led to the creation of the finalized layout for the inverter test board as seen above in Figure 56. The headers are all either inputs or outputs that will be measured so placing them near the edge of the board is for convenience.

In the end, the MCU could not be programmed, causing issues for the battery bank as well as the need for a small breadboard to be used in the final design. With more time and money, an effort to eliminate this issue would have been made. The power conversion circuits failed to live up to the expectations as well most likely due to obscure values for the inductors used in each circuit. Having more time, redesigns could have been made to adjust the inductance values by adding more in series to match the equivalent value needed.

6.3 Software Logic and Control

This section will be used to to detail the control logic, the software program that controls the operations of the program, the application programming interfaces (APIs) which define interactions between multiple software intermediaries, and the software environments used to develop them. In control logic, each implemented command responds to the commands of the user to perform an action. The control logic of the sensors and displayed is often modeled using a flow chart. Showing the control logic as a flow chart helps the process of programming the software logic, and reduces the possibilities of introducing errors to the code. Currently, two separate flow charts have been visualized, but it’s likely that more will be added when development of the software logic and control is furthered during senior design II.

6.3.1 Software Flow Diagrams

Software flow diagrams are useful tools for visualizing the internal processes that enable our project to function. In the following figures, two separate internal software processes are illustrated. The first process, illustrated by the flowchart in Figure 57, is the boot and startup sequence for the Smart Window. It reads from top down, showing a chronological view of how individual processes relate. In the center of the diagram, an important loop shows the user wake protocol from the proximity sensor.

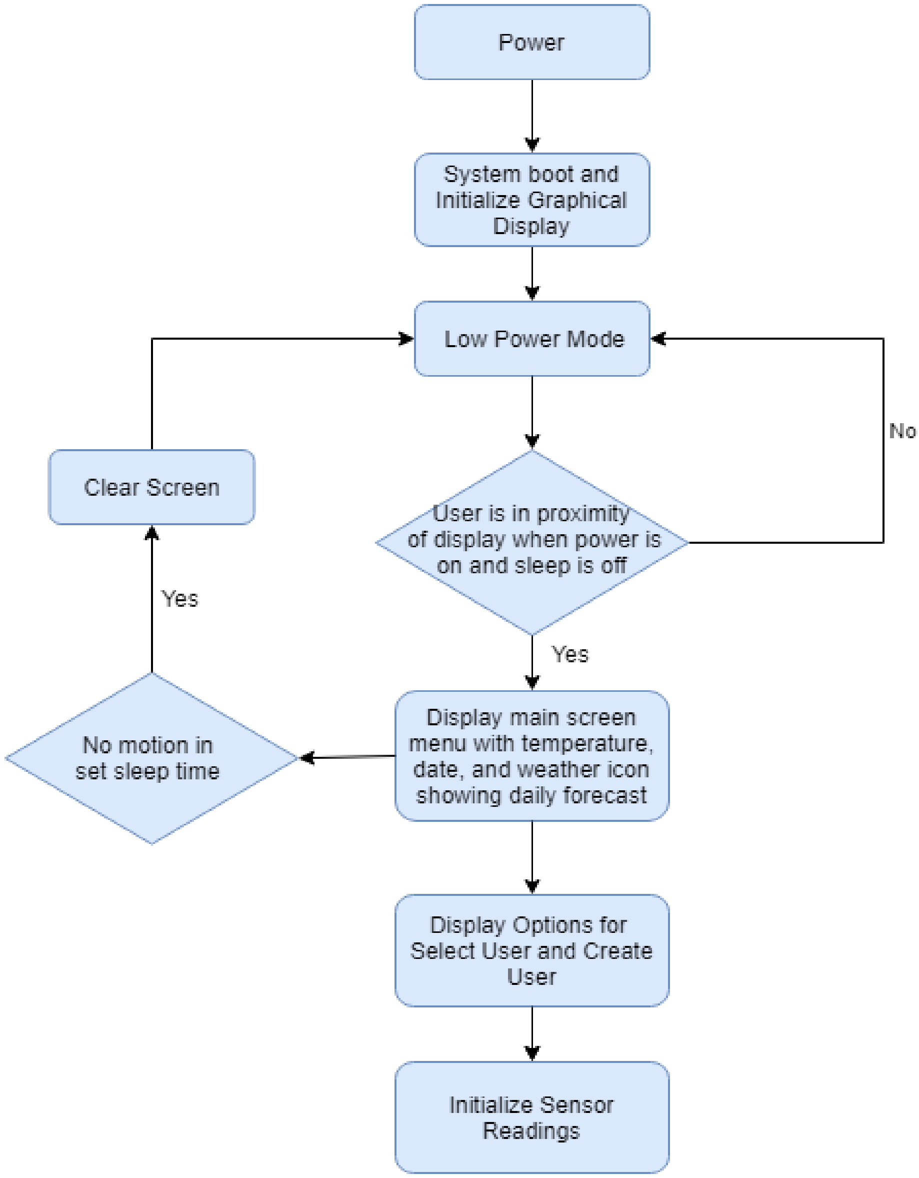


Figure 57: Software Block Diagram of Boot and Startup

One of the important features of the window is that the display will activate when a user approaches it. This feature is described by that loop in the block diagram. On the bottom diagram, Figure 57, the loop for reading the onboard sensors is illustrated. This loop is preliminary, and helps the group members to make considerations for later software development. It shows how each sensor is checked for stability in the reading before sending the current value to the microcontroller. This helps ensure an accurate and smooth user experience.

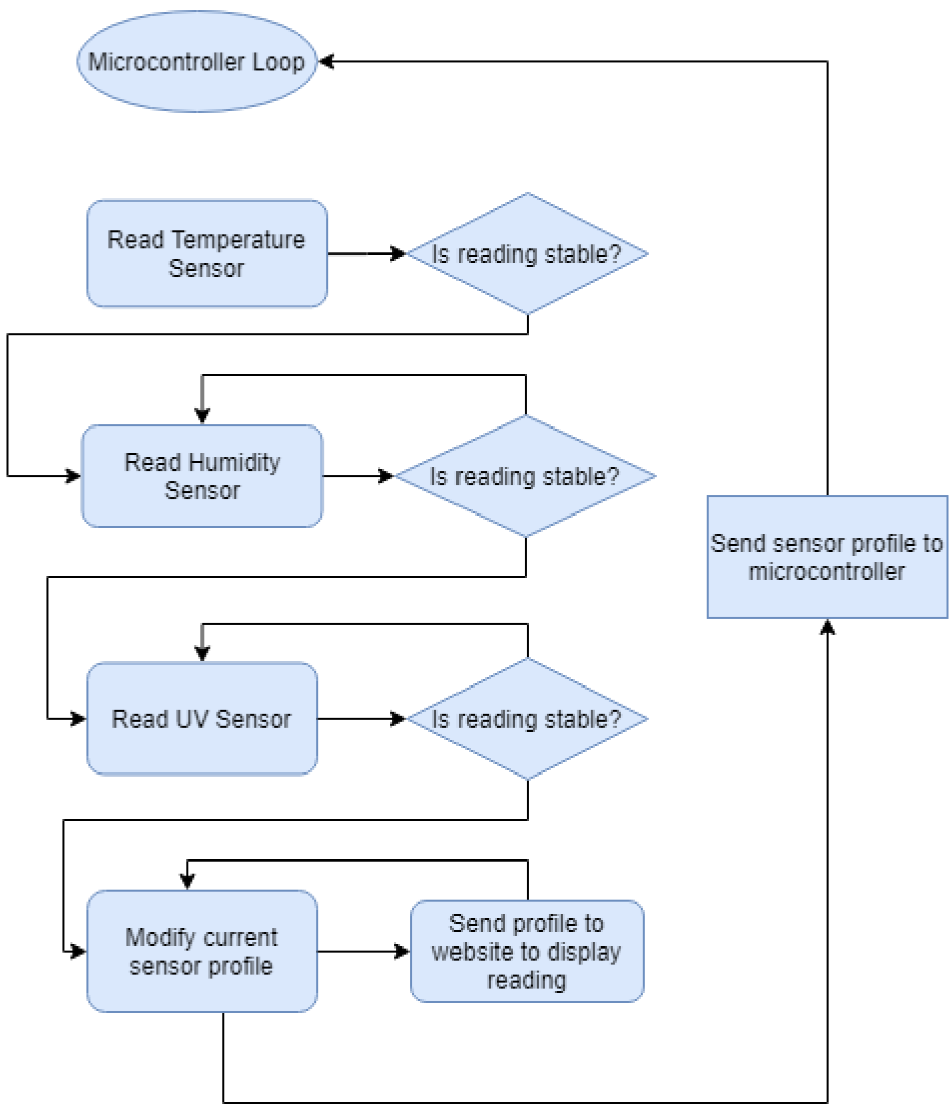


Figure 58: Software block diagram of sensor readings

6.3.2 User Interface:

A robust User Interface (UI) is required to support the sensors and display of the Smart Window. Figure 59, seen on the following page, aids in showing how the user interface connects the sensor information to the rest of the project's software functionality. Because the display aims to be one of the most eye-catching aspects of the project, it follows that the UI matches the design requirements of the project. Mainly, that the UI is clean, easy to navigate, and feature-rich enough to show all relevant sensor information, and information acquired from online sources.

Some applications incorporated into the working design include real time sensor information, such as temperature, humidity and UV Index. Other applications which are not monitored from the onboard sensor suite can be obtained online. These applications include a forecasting module, which should provide a weekly weather forecast. This forecast information will be optional to the user, and will prompt the user to input their location data to ensure that the information acquired is accurate to their specific window.

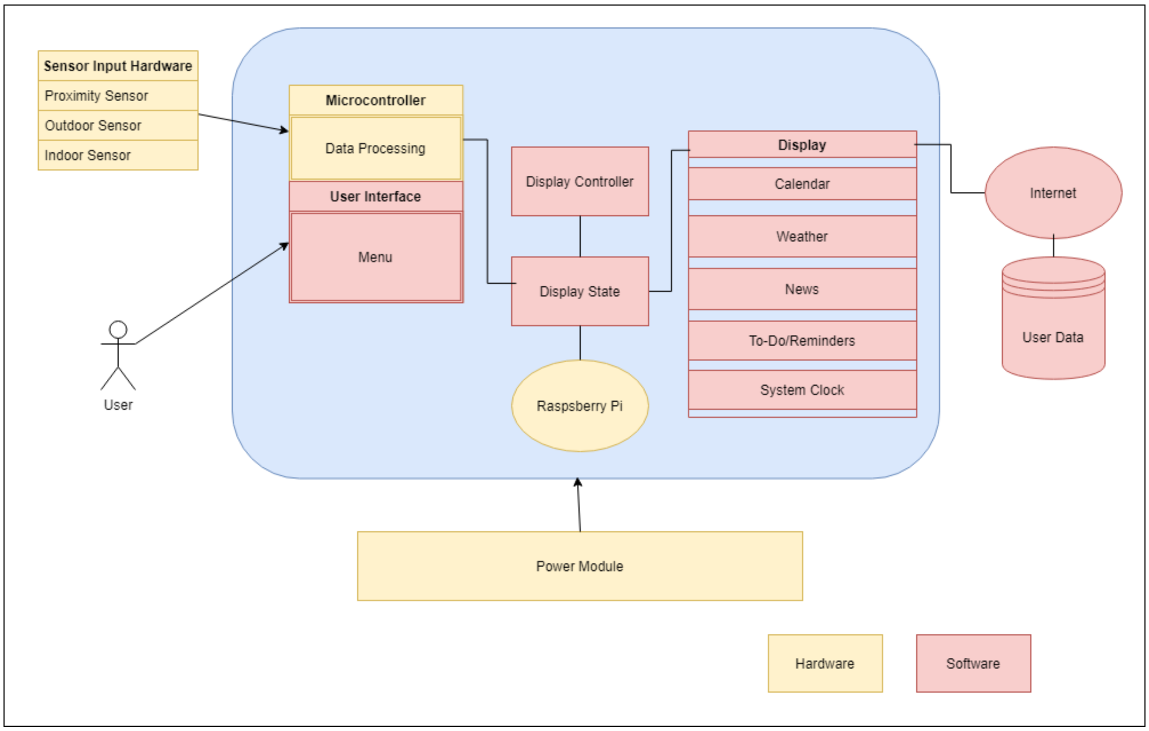


Figure 59: Data Flow in Smart Window Diagram

The key goal of the UI is to provide each user with a Rich Site Summary (RSS) that allows the user to view updates to each module directly and easily, while also giving the user as much customization as possible to pick and choose which modules are relevant to them, based on their preferences.

To adequately display all of these modules, the User Interface must be large enough to display the temperature, data, and weather information in legible font and sparse enough for the user to be able to navigate the system. Using a 1600x900 display resolution helps to ensure that basic implementation of the project can be achieved. Once the basic implementation has been achieved, we can include a more expanded interface to allow additional widgets and functionality to the user.

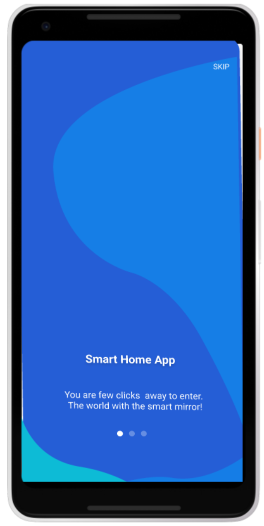


Figure 60: Figma Prototype of Smart Window App on Google Pixel 2XL

The Display will be an ElectronJS powered app that displays an HTML webpage of the components. The user will interact with the mobile app - Smart Window Plus to interact with the device. The Raspberry Pi will always require a power source, when the device has been idle, the modules within the app will turn off. Figure 60 shows the prototype of the companion app on an Android device.

ElectronJS is an open source framework used for building cross-platform native desktop applications that combines the Chromium engine and NodeJS runtime environment. An electron JS app will be developed to support the features of the app. The Chromium engine saves the webpage as an HTML file onto the RaspberryPi and will open a Browser window, Instance as HTML Files on the native system. Then the files are rendered to save the HTML, CSS, and Javascript files, the markup language, styling, and interactive components.

Each electron has one main process running that manages the lifecycle of an app. The main app will open the windows that the end user will see, each window is its own render process running. You can start a new render process by instantiating a browser window until the window loads a regular HTML file . It will render the HTML CSS and Javascript but will do so in a native window, granting the user access to lower level APIs and APIs.

This will allow the Smart Window to integrate lower level APIs to access the RaspberryPi's peripherals, GPIO pins, and interfacing between sensors to display on the screen. While the NodeJs environment has access to Raspberry Pi’s peripherals, it however will run in the user space. Although running user applications as memory-protected processes protects a monolithic kernel from errant user code, a single programming error in a file system, protocol stack or driver can crash the system. In addition, any change to a driver or system file requires OS modification and recompiling, which will be inefficient for a HTML webpage application.

6.3.3 Google Identity Platform

The Google Identity platform contains a suite of tools for developers to build an authentication system for their apps. Their protocols include Google Sign-In is a secure authentication system that enables users to login into an application using their Google Account, the same Google Account that is to access Gmail, Play, Calendar, and other Google services.

The Google Sign In tools will be used for users to sign in to the Android Application using their Google Account. Credentials to access the Google Calendar App to perform create, update, read, and delete events in addition to displaying the view of the calendar

6.3.4 Arduino IDE

The Arduino Software IDE (Integrated Development Environment) is a development environment for Windows. It is primarily used to write and upload programs to Arduino compatible boards, however, third party support enables custom open source compilers to upload sketches to microcontrollers that are not within the Arduino official line of development boards. We will be using the Arduino IDE to develop the microcontroller software as it is a supported STM32Cube IDE and there is an existing repository containing the libraries to support the hardware abstraction layer and low layer drivers running on the STM32L4 series of boards.

6.3.5 STMCube

STM32CubeMX is a graphical tool that allows a very easy configuration of STM32 microcontrollers and the corresponding initialization C code for the Arm Cortex M core. We will use this software to initialize the peripheral to ease the development process in configuring the GPIOs and clock set up for the system. The configuration of the MCU peripherals down through a pinout conflict solver, and launches the code generation that matches the selected configuration choices.

6.3.6 Android Studio IDE

Android Studio is the official integrated development environment IDE for the Android Operating system, It is built on IntelliJ IDEA software and is used for Android development. Android IDE will be used to develop the Android Application Package (apk) for the supporting Android mobile app for the Smart Window. Android studio is very flexible in supporting multiple programming languages for development, including Kotlin Java, as well as C++. This makes the IDE an excellent choice for developing the mobile app.

6.3.7 Energia IDE

Energia IDE is an Arduino IDE designed by Texas Instruments (TI). It allows for high level code compatibility with TI Boards. Using this IDE would allow for faster prototyping, and more efficient testing alongside a compatible MCU. Energia also includes a framework for many APIs and libraries which will help to program the microcontroller

7. Administrative

The administrative section of the report covers topics related to the logistics of system design and testing. These logistics are important for maintaining proper development of the project, and include items such as scheduling of important deadlines, project budgets for both development of a prototype, and the budget for creating a single unit. The section also covers any challenges or concerns of the project development. These relevant concerns or challenges are addressed in the final comment section at the end of the documentation.

7.1 Project Budget And Financing

Our group estimated our total project material cost to be around $500 dollars. This budget is acceptable to the team. Our final bill of materials has been tabulated below in Table 8. The group understood that factors like tax, shipping, and unforeseen costs may occur during the development process, and we were comfortable amending the budget and being flexible as the project design process continued. Some expenses could occur during the development and testing period of the project development which do not directly contribute to the Smart Window's bill of materials. Unforeseen development costs are not directly part of the project budget, and financing is done on a case by case basis by the group member who wishes to retain the equipment used for the development of the window after the project's completion. Those costs are included below in Table 20.

Development Costs	Cost (USD)
LX1330B Light Meter	$35
60V 5A DC Power Supply	$80
STM32 Nucleo Development Board	$10
Total Development Cost	$125

Table 20: Project Development Costs

Expected Bill of Materials	Expected Cost (USD)	Actual Cost
Window frame	<$30	$18
Glass Pane	<$15	$15
18650 Lithium ion batteries (x8)	<$40	$40
Temperature/Humidity sensor (outdoor)	<$5	$4.81
Temperature/Humidity sensor (indoor)	<$5	$4.81
UV sensor	<$7	$5.04
LED strips	<$25	$22
LED Peripherals	<$15	$9.99
PDLC Film	$225	$214.99
Testing Products	<$50	$37.99
Other Electrical Components	$30	$43.50
Shipping	<$50	$115
Total	$497	$531.13
Group Member Contributions	$500 (Flexible)	$531.13

Table 21: Project Budget

7.2 Milestones

Major project milestones have been divided into two tables: Table 20 summarizes the important tasks for Senior Design I, which occurred over the Fall 2020 semester and Table 21 lists the tasks completed for Senior Design II, over Spring 2021. The Senior Design II chart seen on the next page in Table 21 is an important resource for the project team. The table served to remind each member of the expectations for prototype development, and aids in keeping a final design in mind. These tables have been updated with more accurate dates and duration as the Smart Window team progressed through the spring semester and towards completion of the project.

Senior Design I

Description	Duration	Dates
Senior Design 1 Project Idea	5 days	August 24th - August 28th
Project Discussion	5 days	August 31st - September 4th
D&C Document 1.0	12 days	September 7th - September 18th
Initial Project Documentation	5 days	September 21st - September 25th
D&C Document 2.0	3 days	September 30th - October 2nd
Initialize Part Selection Process	67 days	October 2nd - December 8th
60 Page Draft Report	36 days	October 8th - November 13th
Create Schematics	7 days	November 13th - November 20th
Create PCBs	7 days	November 21st - November 28th
Test Low Level Software	2 days	November 29th - November 30th
Test High Level Software	5 days	December 1st - December 6th
100 Page Report	50 days	November 13th - November 27th
Review Documentation	7 days	November 30th - December 7th
Final Document Due	1 day	December 8th

Table 22: SD1 Project Milestones

Senior Design II

Description	Duration	Dates
Build Window Prototype	7 Days	March 1st - March 7th
Testing and Redesign	2 Weeks	March 7th - March 21st
Finalize Prototype	14 Days	March 21st - April 4th
Demonstration Recording	3 Days	April 4th - April 7th
Final Report	15 Days	April 7th - April 22nd
Final Presentation	7 Days	April 15th - April 22nd

Table 23: SD2 Project Milestones

7.3 Final Comments

During the ongoing documentation process, all relevant decisions to project design, features, and implemented technologies have been updated. The Smart Window project team is proud to feature many different technologies and features into its design. To ensure that the project developed smoothly and without issue, care was especially given to the fundamental aspects of the design as well as the core goals and objectives that the team agreed on at the beginning of the project, while keeping stretch goals in mind as potential future applications. In this documentation the group has attempted to provide more breadth and detail into the nuanced aspects of the Smart Window's development and the testing and work that has gone into it during this spring semester.

This project documentation details two semesters of work from a team of four interdisciplinary students. Two students from CREOL for photonic science and engineering, and two from the college of electrical engineering and computer science at UCF. The Smart Window project was successful in reaching nearly all aspects of its core functionality, because of thorough testing and redesigning of components and the physical aspects of the project frame. To ensure that the project was able to be completed within the set time constraints, non-essential components such as the battery bank and solar power were unfortunately omitted, but in doing so, core features were completed to the best of the group's ability.

Sections of this documentation which detail research and choices of components which were not used in the final prototype have been left in this paper. Therefore, the technology and market research as well as the administrative choices made can serve as a guide for future iterations of the Smart Window and similar technologies if they were to become investigated again in the future.

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