High-Level Design

Smart Windows

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1 Introduction

Exciting energy-saving technologies such as the “smart” grid have captured the cultural imagination. Meanwhile, simple household practices are increasingly being used to reduce energy demand. Products like the compact fluorescent lamp (CFL) have shown the commercial viability of these everyday energy-savers.

As identified by the Department of Energy, one simple energy-saving solution is the proper operation of window treatments like blinds and shades. These window treatments are capable of reducing the load on household air conditioning units, thereby reducing energy consumption. In addition, properly operated window treatments offer other benefits, such as security, to the homeowner. However, to maximize the return on these window treatments, an automated system is needed to ensure the timely opening and closing of the window treatments. Through the utilization of current technology paired with innovative engineering design, Smart Windows solves this problem of window treatment automation.

While the Smart Windows system will be adaptable to many types of window treatments, the Smart Window is designed for Solar Shades polarizing window treatments. Solar Shades, a start-up company operated out of Innovation Park at the University of Notre Dame, seeks to revolutionize the design of window treatments. The Smart Windows system will be the brains behind these windows, giving the homeowner central control and powerful automation of the Solar Shades.

2 Problem Statement and Proposed Solution

In collaboration with Solar Shades, Smart Windows will create a bridge between Notre Dame EE Senior Design and Notre Dame’s Innovation Park. For the first time, undergraduate electrical engineers will be faced with real world business challenges.

In addition, Smart Windows seeks to solve a very important technical problem. In a world faced with rising energy demand and depleting energy supply, the next generation of technology must take into account energy usage at every level. According to the United States Energy Information Administration’s (EIA) Residential Energy Consumption Survey (RECS), air conditioning consumes a significant and growing portion of US electric power. From 1997 to 2005, the RECS shows that the percent of US residential electric power used for air conditioning rose from 14% to 20.2%.[1]

To fight rising energy usage, the US Department of Energy’s Energy Savers program recommends reducing the stress on air conditioners. One important Department of Energy guideline is to use window treatments like blinds and shades to reduce the thermal gain through the windows due to radiant solar energy: “Install window shades or other window treatments and close the shades. Shades will help block out not only direct sunlight, but also radiated heat from the outdoors, and insulated shades will reduce the conduction of heat into your home through your windows.” In fact, the Department of Energy says that reflective shades can reduce heat gain up to 45%.[2]

In addition to reducing air conditioning energy consumption, window treatments have other functions. For example, the September 23, 2009 edition of the University of Notre Dame and Saint Mary’s College newspaper *The Observer* recommends window treatments as a crime prevention tool. In an article entitled “Burglars Target Off-Campus Housing,” South Bend Police Captain Phil Trent notices, “There's people with their front windows right open and I can see a 50-inch plasma screen from the street. You can see someone with the lights on in their house and they're working on a laptop computer…A burglar can do an assessment of what they can steal just by walking down the street looking in the windows." The article states, “To prevent burglaries, students should keep their windows and curtains closed.”[3]

These benefits of window treatments are only effective, however, if the homeowner is diligent in opening and closing them. To access the energy benefits of window treatments, the homeowner must constantly monitor sunlight exposure. To access the security benefits, the homeowner must close every treatment prior to leaving the house. Since few homeowners can afford to give this level of attention to their window treatments, the benefits of properly operated window treatments are rarely utilized. For these benefits to be tapped into, the windows must operate automatically in the homeowner’s stead. It is this problem of maximizing window treatment utility through automation and electronic intelligence that the Smart Windows design addresses.

The Smart Windows system is centered on a PC Control Unit (PCCU). The user will be able to issue commands to On-Window Units (OWUs) from this PCCU and from a wireless remote control. Both the PCCU and the remote control will communicate with the OWUs through a wireless interface. The PCCU will consist of a custom-designed PC application with graphical user interface (GUI) which allows users the choice to manually control individual windows, to implement sensor control, or operate all windows in unison. These choices are defined as modes.

The OWU, operating in one of these three modes, will drive the window treatment with an appropriate motor. In sensor-controlled mode, or Green Mode, the OWU will use a light sensor to decide if the Solar Shade should be opened or closed to maximize the efficiency of the household HVAC. In Safe Mode, all the window treatments in the house are closed in unison, typically at night or during working hours. In manual mode, the user operates the windows individually from the PC application, remote control, or on-window buttons. Users will choose from opened, closed, or half opened Solar Shades. The OWU will derive its intelligence from an embedded microprocessor.

[1] EIA online RECS 2005 Status Report. <http://www.eia.doe.gov/emeu/recs/contents.html>.
[2] DOE Energy Savers.
<www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12353>.
[3] Mervosh, Sarah. “Burglars Target Off-Campus Housing.” *The Observer*. 23 Sept 2009.
<http://media.www.ndsmcobserver.com/media/storage/paper660/news/2009/09/23/News/Burglars.Target.OffCampus.Housing-3780142.shtml>.

3 System Description and Block Diagram

The Smart Windows system will consist of three main units, the PCCU, the OWU, and the remote control unit. Each unit will be broken down into several subsystems and the interfaces between them. These units will communicate through two-way RF communication using ZigBee protocol.

The PCCU will consist of the PC application, the microcontroller, and the ZigBee subsystem. The PC will connect to the microcontroller through a USB interface. The ZigBee circuitry will connect to the microcontroller through a serial parallel interface (SPI) synchronous serial interface. This ZigBee circuitry will allow the PCCU to interface with the OWU through ZigBee wireless communication.

The ONU will consist of a central microcontroller with several peripheral subsystems. The ZigBee circuitry that allows the OWU to interface with the PCCU and the remote control unit will connect to the microcontroller through a SPI interface. A light sensor will interface with the microcontroller through an inter-integrated circuit (I^2C) synchronous serial interface. Buttons and an H-bridge motor driver circuit will connect to the microcontroller directly through I/O pins. This H-bridge circuit will directly drive the motor controlling the window treatments. This unit will be powered by rechargeable batteries.

The front-end of the remote control will consist of ZigBee wireless circuitry. This circuitry will connect through an SPI interface to a microcontroller. The user will interface with this remote control through two pushbuttons and a thumb wheel. The pushbuttons will be used to instruct a given window treatment to either open or close. They will connect directly to the I/O port of the microcontroller. The thumb wheel will be used to select which window to control. This switch will connect to the microcontroller using a binary code encompassing 4 I/O pins.

A graphical illustration of the system is shown in **Figure 1**.

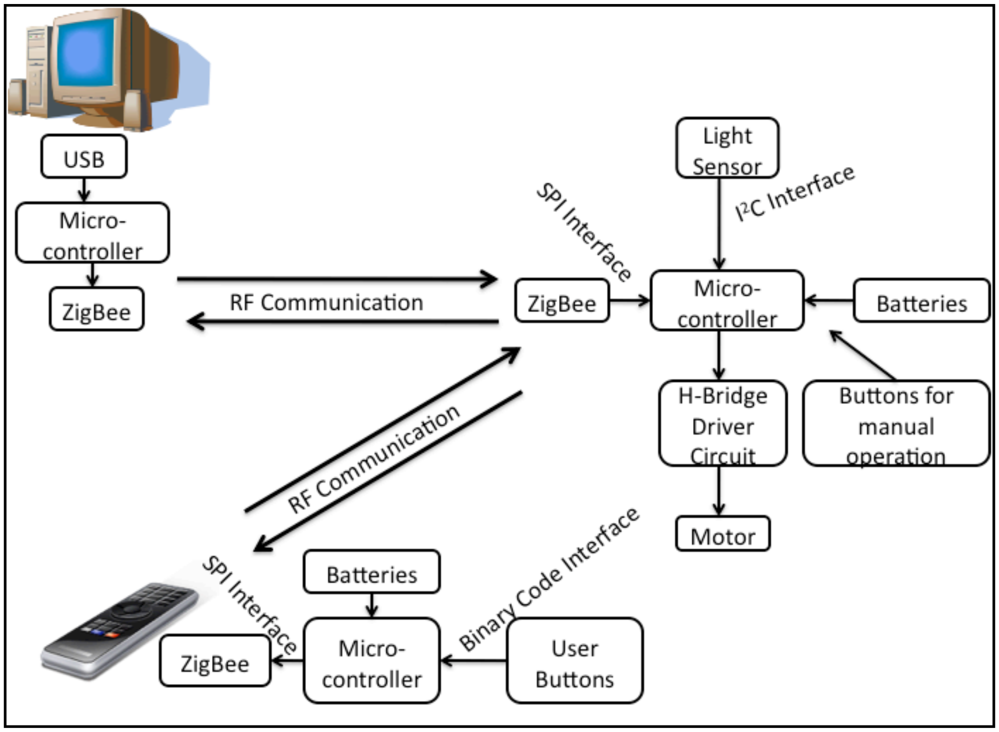

Figure 1. Block Diagram of the Smart Windows system.

4 System Requirements

4.1 Overall System Requirements

Overall Requirements	
General Purpose	Must be capable of remotely operating window blinds from a PC and a remote control
User Implementation	Must be able to be assembled and run without specialized knowledge or atypical household tools Must operate whether or not the software application is running
Wireless Requirements	Must be able to work with window modules within 100 feet Must support up to 20 window treatments at once
Safety	Must be safe in homes Must not carry risk of electrical fires
Power	PC-based portion must draw power through USB Other portions must draw from rechargeable batteries lasting at least 2 weeks between charges
FCC Compliance	Must not cause harmful interference with other household wireless devices
Expected Life of Product	Batteries will not hold charge after 2 years of normal use. Other products guaranteed for 4 years.
Cost	System prototype must cost less than $500 to design and produce

4.2 Subsystem and Interface Requirements

Subsystem and Interface Requirements	
On Window Unit (OWU)	
General	Must be able to control window treatments intelligently Must continue to operate when wireless communication is broken
Size	Must have total dimensions less than or equal to 8" x 5" x 4"
Weight	Must be less than 5 pounds Must be able to be hung from a standard window treatment
Power	Must use 4-8 rechargeable AA batteries lasting a minimum of 14 days
Microcontroller Software	Must use a reasonable amount of program memory Must operate the drive the motor appropriately when necessary Must periodically monitor the light sensor and manual buttons Must decode received wireless messages Must enter power-saving mode when possible
Motor	Must be a DC motor capable of at least 20 oz-in of torque Must be geared to turn less than 100 rotations per minute Must have a safety clutch to protect the window treatment Must make minimal noise when operating Must meet power requirements (see "Power") above
Light Sensor	Must be capable of differentiating a sunny day from a cloudy day Must ignore light coming from inside the house Must be report light levels to microcontroller using minimal I/O pins Must meet power requirements (see "Power") above
Wireless Transceiver	Must send and receive messages at an indoor distance of 100 feet Must be able to address messages to a particular target Must not create interference with other household items Must be able to interface with a microcontroller quickly and reliably Must meet power requirements (see "Power") above
Manual Buttons	Must reliably control the system when used Must be easily accessible Must let the user open or close the treatment one increment
PC Control Unit (PCCU)	
General	Must give the user the highest amount of control over the system Must have control over every connected window treatment in the house
Power	Must be able to draw power from the PC USB connection
PC Software	Must be able to interface to a microcontroller through USB Must have an intuitive graphical user interface Must be capable of placing each window into one of the three modes Must be capable of controlling individual windows when in manual mode Must store at least Wake-up/Work/Return-from-work/Sleep times locally
Microcontroller Software	Must decode messages received through the USB connection Must pass these messages to the wireless transceiver
Wireless Transceiver	Must send and receive messages at an indoor distance of 100 feet Must be able to address messages to a particular target Must not create interference with other household items Must be able to interface with a microcontroller quickly and reliably

	Must meet power requirements (see “Power”) above
Remote Control Unit	
General	Must give the user remote control over a particular window treatment Must be capable of converting a particular window to manual mode Must be able to select an active window treatment to control
Power	Must use 2-4 rechargeable AA batteries lasting a minimum of 14 days
Microcontroller Software	Must monitor the user input buttons Must pass user commands to the wireless transceiver Must conserve power when possible
Manual Buttons	Must reliably control the system when used Must be easily accessible Must let the user open or close the treatment one increment Must let the user select the active window to communicate with Must interface with the microcontroller directly through 8 or less I/O pins
Wireless Transceiver	Must send and receive messages at an indoor distance of 100 feet Must be able to address messages to a particular target Must not create interference with other household items Must be able to interface with a microcontroller quickly and reliably Must meet power requirements (see “Power”) above
Wireless Interface	
Distance	Must connect the various units at a distance of 100 feet
Power	Must not consume more power than the various units can provide
Interfacing	Must be able to address specific units while ignoring others Must operate on several channels to avoid inter-house interference
Speed	Must be fast enough to send and receive a message in about 3 seconds

4.3 Future Enhancement Requirements

Future Enhancement Requirements	
Software OS	Must be able to update software to support Mac OS X Leopard, Mac OS X Snow Leopard, and simple command-line Unix and Linux
Additional PC Software Features	Must be able to update to include the ability to automatically recognize major holidays and treat them as weekends Must be able to update to include the ability to download RSS feeds including weather predictions and use them Must be able to update to include the ability to control windows remotely over the internet Must be able to update to include the ability to control product through a Desktop Widget
Wireless Range	Must be able to increase to the full size of large homes
Smart Window	Must be able to include confirmation when a window changes state
Power	Must be able to include solar recharging ability
Interfacing	Must be able to add an iPhone application which can control window treatments
Security	Must be able to add strong encryption to stop window treatment opening by malicious hackers.

5 High-Level Design Decisions

A high-level design of each unit, subsystem, and interface is given below:

5.1 PC Control Unit (PCCU)

5.1.1 PC application

A program with a graphical user interface (GUI) will be written to interface to the user. Because the PC application will interface to the rest of the system through a universal serial bus (USB) interface (Section 5.1.2), this program must have the ability to send and receive data from one of the PC's COM ports. Several programming languages are capable of these functions. A specific language has yet to be chosen (see Section 6.2).

5.1.2 USB Interface

The interface between the PC application and the wireless transceiver module must be reliable, of reasonable speed, and capable of powering the wireless transceiver directly. A wireless interface is not necessary here. Therefore, a universal serial bus (USB) interface has been chosen. The PC COM port will interface by USB to the embedded intelligence on the transceiver unit through a USB-to-serial converter.

This converter, capable of converting the USB signal into an asynchronous serial signal, will be the FTDI FT232RL. This part is available through Digi-Key with the part number 768-1007-1-ND ($4.50). A DC voltage between 3.3V and 5.25V must be used to power this part.

5.1.3 Wireless Transceiver Board

Because the PCCU will interface to the OWUs through a ZigBee RF Interface (Section 5.2), the wireless transceiver subsystem must have a ZigBee transceiver. For this, we have chosen the Atmel AT86RF231-ZU. This part is available through Digi-Key with the part number AT86RF231-ZU-ND ($4.73). A DC voltage between 1.6 and 3.6 volts is used to power this device. We will choose to power the device with 3.3 volts. This device is controlled through a Serial-Parallel synchronous serial interface (SPI).

To send instructions to this transceiver part through SPI, the transceiver board will need to have embedded intelligence with SPI hardware. Since this microcontroller will accept information from the output of the FTDI USB-to-serial converter, it must also have universal asynchronous receiver/transmitter (UART) hardware built-in as well. This microcontroller will also be powered with the 3.3 volts that powers the Atmel ZigBee chip. The microcontroller and clock sourse choosen for this task will be the same as the one in Section 5.3.1.

To obtain this power signal, a voltage regulator will be used to regulate down the 5 volts from the USB line to the needed 3.3 volts. Such a regulator is sold by STMicroelectronics as the LD1117DT33CTR. The part is available through Digi-key as the 497-1235-1-ND ($0.78).

A USB-powered printed circuit board (PCB) connecting the FTDI converter to the microprocessor and the microprocessor to the ZigBee transceiver chip will be designed. A ZigBee-capable antenna will be attached to the output of the ZigBee transceiver chip. This PCB will serve as the USB- and ZigBee-ready wireless transceiver board for the PCCU.

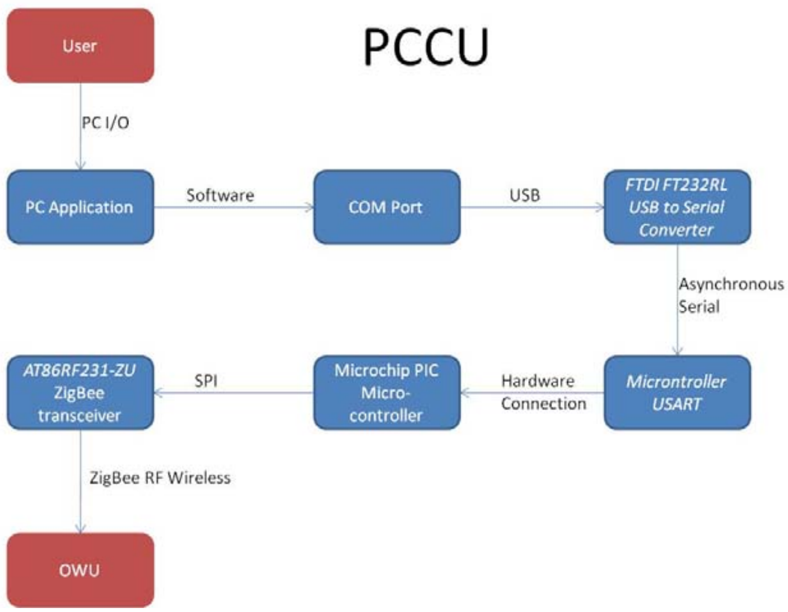

Figure 5.1: Block design of the PCCU unit

5.2 ZigBee RF Interface

The interface between the PCCU and the OWUs must be on reasonable speed, low power, and reliable. It must not interfere with other household devices. Smart Window systems in neighboring houses must not interfere. Also, messages sent from the PCCU must be able to be addressed to a specific OWU.

To meet these needs the IEEE 804.15.4 standard, more commonly known as ZigBee, has been chosen. This is a radio frequency (RF) wireless communication standard which aptly meets our needs. ZigBee messages can be sent over multiple channels, preventing systems in neighboring houses from interfering. ZigBee is tailor-made for mesh networking applications such as the Smart Windows system.

To successfully interface through ZigBee RF wireless communication the PCCU and each OWU will need to have a ZigBee antenna controlled by an appropriate ZigBee transceiver integrated circuit. For this, we have chosen the Atmel AT86RF231-ZU. This part is available through Digi-Key with the part number AT86RF231-ZU-ND ($4.73). A DC voltage between 1.6 and 3.6 volts is used to power this device. We will choose to power the device with 3.3 volts. This device is controlled through a Serial-Parallel synchronous serial interface (SPI).

5.3 On-Window Unit (OWU)

5.3.1 Embedded Intelligence

Based on the needs of the subsystems described in Section 5.3.2-5.3.10, the microcontroller of the OWU must have an asynchronous serial USART, two synchronous serial MSSPs, at least a small amount of non-volatile data memory, reasonable program memory, reasonable amount of RAM, at least 30 I/O pins, and reasonable computing speed. It must be able to be powered on the 3.3V used to power our on-window units.

Many, many microcontrollers meet these requirements. Based on product familiarity, we have chosen the Microchip PIC series microcontrollers. While several PIC microcontrollers meet the project requirements, one possibility is the PIC18LF6722 available through Digi-key with the part number PIC18LF6722-I/PT-ND ($13.18). Specific microcontroller decisions will be made once more is known about the amount of program memory required in this design.

This embedded intelligence will require a clock source. We have chosen to use a 20 MHz clock cycle. Using a ceramic resonator will require a less complicated impedance matching circuit than a crystal resonator. For this, we have chosen the Muratra CSTCE-series ceramic resonator available from Digi-key with the part number 490-4717-6-ND ($0.61).

5.3.2 Battery Power

Based on the system requirements, each OWU will be powered by rechargeable batteries. We will use four rechargeable nickel metal hydride AA cells with a 1.2 volt nominal voltage to produce a 4.8 volt supply. Using two sets of these cells in parallel will allow use to double the energy capacity of the system. Such a battery is available from Energizer as the NH15. The battery can be ordered through Digi-key with the part number N703-ND ($4.40). These batteries have a nominal capacity of 2450 mAh.

To charge these batteries, a commercial battery charger will be used external to the system. These chargers can be obtained almost anywhere batteries are sold for a reasonable price. Most units are able to charge 4 batteries in about an hour.

Because the OWU PCB will be powered with a 3.3-volt supply voltage, this battery voltage will have to be regulated down. To do this, the STMicroelectronics LD1117DT33CTR regulator will again be used. The part is available through Digi-key as the 497-1235-1-ND ($0.78). Since this 3.3-volt regulator has a maximum 1.2V dropout voltage, the 4.8-volt battery stack will be capable of powering it.

To power the window treatment actuator (Section 5.3.9 and 5.3.10) a 3.3-volt supply will also be used.

5.3.3 Wireless Transceiver

As described in Section 5.1.3 and 5.2, the ZigBee communication will be done using a ZigBee-ready antenna and an Atmel ZigBee transceiver integrated circuit. This part is available through Digi-Key with the part number AT86RF231-ZU-ND ($4.73). A DC voltage between 1.6 and 3.6 volts is used to power this device. We will choose to power the device with 3.3 volts. This device is controlled through a Serial-Parallel synchronous serial interface (SPI).

5.3.4 SPI Interface

As mentioned in Section 5.3.3, an SPI interface will be used to connect the microcontroller to the Atmel ZigBee transceiver IC. In this interface, the microcontroller will act as the master and the Atmel IC will act as the slave. Therefore, the microcontroller will provide a clock to the ZigBee transceiver.

5.3.5 Manual Controls

The user will be able to interface to the microcontroller through manual controls. This control will be realized as two simple push buttons, available at very little cost from any electronics supplier. An example push button is available from Panasonic with the Digi-key part number P12222SCT-ND ($0.33).

The push buttons will interface to the microcontroller through a wired connection to one of the microcontroller I/O pins. This interface is described in Section 5.3.6.

5.3.6 Manual Controls Wired Interface

The wired interface between the microcontroller and the manual controls will be very simple. The push button will be configured so that when pushed, the voltage on an I/O pin of the microcontroller will be pulled up from ground to V_{DD}. The microcontroller can easily handle this form of Boolean digital input.

5.3.7 Light Sensor

In order for the system to respond intelligently to changes in light level, an ambient light sensor will be needed. This is a light sensor whose spectral sensitivity is tuned to that of the human eye. This light sensor will be mounted on the window. An appropriate light sensor is available from Intersil through a Digi-key part number ISL29001IROZ-T7CT-ND ($3.04). This part uses an I^2C synchronous serial interface as described in Section 5.3.8.

5.3.8 Light Sensor I^2C Interface

As mentioned in Section 5.3.7, there will be an I^2C synchronous serial interface between the ambient light sensor and the embedded intelligence of the OWU. The microcontroller will provide the clock as the master and the light sensor serve as the slave. The microcontroller will need a separate master synchronous serial port for this application.

5.3.9 Window Treatment Actuator

For the actuator driving the window treatment, a DC motor will be geared down for low rotations per minute (RPM). This motor must have a torque-limiting safety clutch on its output drive shaft. When the system is installed for a particular set of window treatments, a motor configuration will be performed. The motor will be allowed to run in one direction until the window treatment is opened or closed fully and the safety clutch is engaged. The time needed to perform this rotation will be recorded. Future turns of the motor will use this time for a full open or close operation and half of this time for a partial open or close operation. The safety clutch will ensure that damage isn't done to the window treatment.

An acceptable motor is available from Solarbotics.com under the SKU GM7 ($7.00). This motor is internally geared for 7 RPM at 0.5 VDC operation and 146 RPM at 6 VDC. Since we will run the motor at 3.3 VDC, we can expect about 50-75 RPM no-load. This motor has an internal safety clutch that engages at 25 oz-in of torque. If a lower torque clutch becomes necessary, clutches are available at any level from http://www.accuclutch.com/accutorq_specifications.asp.

5.3.10 Window Treatment Actuator Driver

The microcontroller I/O pins cannot directly drive the DC motor. Since the microcontroller must be driven in both the clockwise and counter clockwise directions, an H-bridge drive circuit is desired. Such an IC is available from Intersil through Digi-key with the part number HIP4020IBZ-ND ($5.29). This device can be powered with a supply voltage of 3.3 VDC and uses several microcontroller I/O pins as control signals. The motor can be connected directly to the output of this driver IC.

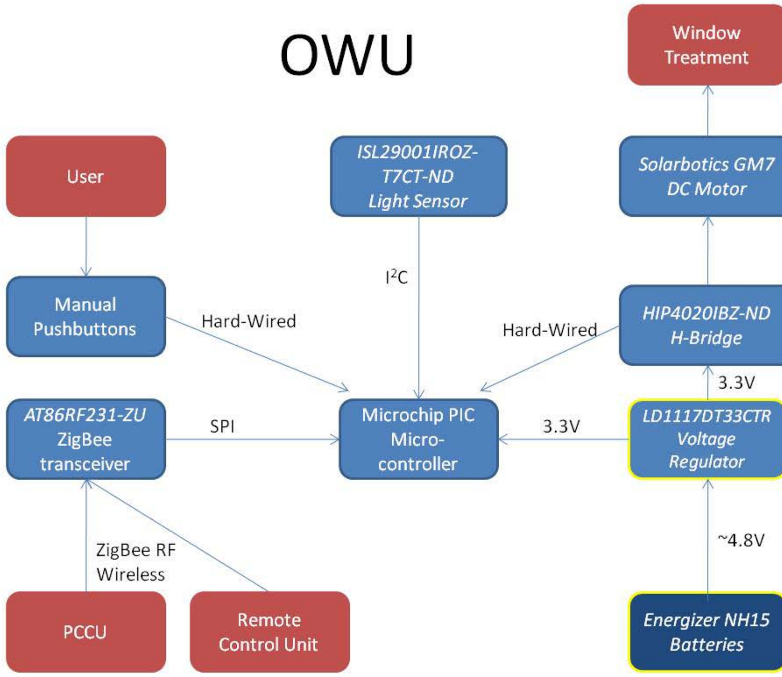

Figure 5.3: Block design of the OWU unit

5.4 Remote Control

Customers will expect to be able to control the Smart Windows system through a wireless remote control. To realize this, we will take advantage of the ZigBee RF wireless interface already in place.

Using the same Atmel ZigBee transceiver IC and ZigBee-ready antenna from Section 5.3.3, a wireless transceiver board will be created. The board will have the same embedded intelligence and clock source as other subsystems (Section 5.3.1). As is common for remote controls, it will be powered through rechargeable AA batteries. If 4 rechargeable batteries are used, the remote can be powered with the same circuitry, voltage, and 3.3V voltage regulator used in Sections 5.1 and 5.3.

The user will interface with the remote through a thumbwheel switch and a push button. The switch will be used to select which window is currently being controlled by the remote control. Such a switch is available from Omron through Digi-key with the part number SW280-ND ($5.65). This thumbwheel switch allows the user to select an input from 0-9. This selection is reported to the microcontroller through a 4-bit binary code using four I/O pins on the microcontroller.

Once the user has selected the correct window, he or she will press a pushbutton switch to change the state of the window treatment. Two buttons will be provided, one to open the window and one to close the window. This pushbutton is available from Panasonic though Digi-key with the part number P12222SCT-ND ($0.33).

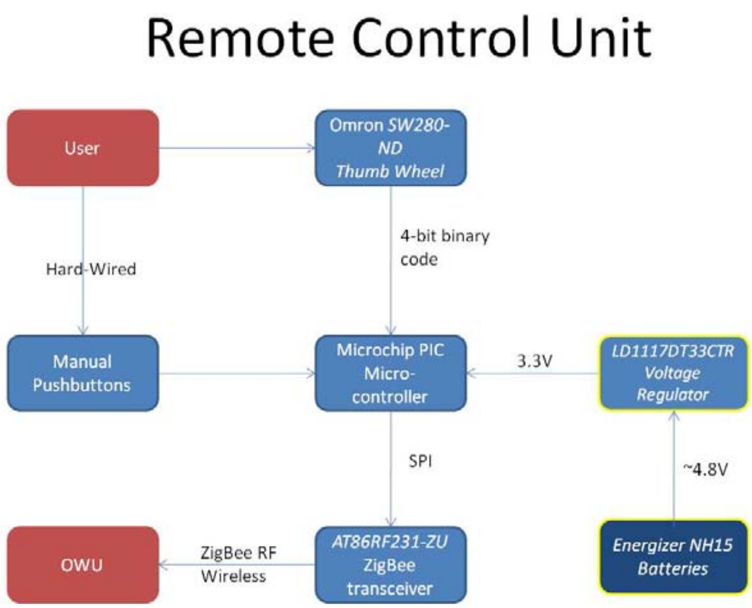

Figure 5.1: Block design of the remote control unit

6 Open Questions

6.1 Window Treatment Actuator

We are currently working on some aspects of the project that are not immediately obvious to us. The most important is the feasibility of our power system. At this point, we wish to use a series of rechargeable batteries so a do-it-yourself installation is possible. Once we have completed our actuator subsystem, we will need to measure current drawn from the batteries per motor cycle and see if a battery source will be viable. We have the option of using a wall outlet if batteries prove insufficient to our needs. If we do end up using a wall outlet, we will need to redesign the circuitry to handle and use the 120VAC source.

In addition to powering concerns, the amount of torque necessary to drive the window treatments has yet to be determined. Once we receive a Solar Shades prototype, we hope to determine this torque. In the meantime, a low-torque motor has been chosen. If this motor proves unacceptable a higher power, higher torque motor will need to be identified.

6.2 PC Application

A big part of this project is creating a user-friendly interface for homeowners to operate. We will need to design a program that receives input from the various windows as well as the user to direct the actions of the windows. Some programming languages will be better than others for this task. The specific programming language to be used for the PC application has not yet been determined.

In addition, the computers COM port will need to be used to access the USB connection. While we know how to make this connection using a HyperTerminal application, we are unsure how to make this connection from a custom application. This process will need to be mastered during the development of the PC application.

7 Major Component Costs

The following is a Table 7 is a compilation of our major component costs. Our project will require various other components such as resistors, capacitors, pushbuttons, and adapters. The costs of these components are negligible.

Component	**Individual Component Cost**
All Boards (Estimated)	$75.00
PIC18LF6722 (x4)	$13.18
Murata CSTCE-series resonator (x4)	$0.61
Energizer Battery (x12)	$3.96
Energizer Battery Charger	$7.00
LD1117D Voltage Regulator (x4)	$0.78
Motor (x2)	$7.00
Thumbwheel Switch	$5.65
H-Bridge Drive Circuit (x2)	$5.29
USB-to-Serial Convertor (x4)	$4.50
ZigBee Transceiver (x4)	$4.73
Light Sensor (x2)	$3.04
Estimated Total Cost	***$261.04***

Table 7. Major component costs.

8 Conclusions

This project brings to the forefront a series of design issues and serious engineering challenges. However, a solution exists to each of these various problems. In discovering and implementing these solutions, we will gain a great deal of technical knowledge as well as problem solving strategies.

In an effort to best minimize costs and maximize functionality, this design has been carefully considered and revised. A wide variety of sources and experts were consulted in constructing this design. To this end, several members of the Notre Dame engineering faculty, especially Professor Schafer, and the resources at Solar Shade deserve thanks for their valuable tools and guidance.

The Smart Windows system, as it is designed here, will be a widely applicable and adaptable system. However, it will also be targeted as a valuable marketing tool for the Solar Shades window treatment.