Wireless Home Control System

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***Abstract*—The presence of wireless technologies and proliferation of mobile controlled devices have inspired a push toward consumer based home automation systems. Wireless Home Control System is a home automation framework designed to compete with popular solutions in the domain. The system features peripheral control modules capable of interacting with lights, outlets, doors, and sensors. All control modules communicate with a central hub that is paired with a mobile device to provide total control to the user. We describe the hardware and software necessary to conceive this system.**

***Keywords*-bluetooth, Home automation, mobile, scalable platform, sensors, power control, wireless.**

1. Introduction

Wireless Home Control System (WHCS) is a solution for any homeowner to be able to remotely control core appliances of their home. WHCS allows the user to control lights, outlets, doors, and sensors around their home. The system's design philosophy emphasizes ease of use, affordability, and effectiveness. An Android phone application developed for WHCS allows users to monitor the state of the installed components and activate them remotely. A central base station equipped with a touch-enabled LCD is present, allowing the users to interact with the system without the need of a phone. Peripheral control modules may be installed into targeted appliances such as lights, outlets, and doors for WHCS to control. As shown in Figure 1, the phone, base station, and peripheral control modules constitute WHCS.

The implementation of such a system required research in a myriad of fields to produce a full-fledged product. A well designed Android application is the key to creating a positive first impression of WHCS. Thus, care was taken to conform to the design philosophies of the Android ecosystem. The alternative interface offered for WHCS is the base station's display. Communication devices form the foundation for the wireless aspect of WHCS, thus an investigation into the advantages of different communication modules was required to realize the system. A network protocol has been developed and implemented in order to form a unified system from the independent modules. The activation of appliances around the home requires high voltage control, so methodologies for properly harnessing the power provided by homes were researched. To extend upon harnessing the home's power, our individual control modules and base station's logic level voltages (5V) depend upon the creation of an efficient way to step down the high voltage supplied from the home.

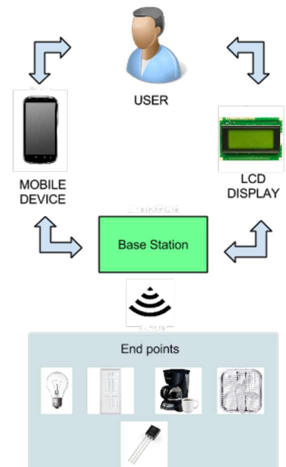


Fig. 1: WHCS System Overview

2. Base Station

The heart of WHCS resides with the base station (BS). When users think of WHCS, they will think of the base station as it is the most visible hardware component of the system. Powered by an AVR Atmega32-A, the base station is responsible for managing, collecting, and displaying information from all of the control modules. If the BS were to fail, WHCS would cease to function.

A. *Subsystems*

The base station has the hardest job in the entire WHCS architecture. It has to juggle a lot of data with limited memory and processing speed. Packets need to be processed and queued to keep the pipeline flowing smoothly. The radio, bluetooth, LCD, and touchpanel need to be managed and updated in real time.

1) NRF24L01+: The NRF radio is directly connected to the Atmega32-A microcontroller through the SPI bus. The radio job is to constantly listen for new packets from the control modules and sending responses in turn. Also, when a command such as "open door" needs to be sent, the radio switches to transmit mode in order to send the corresponding packet.

In WHCS' architecture, the main loop of the base station is not interacting directly with the radio. This is due to the abstraction we built around the low-level radio driver. All driver specific functions are be wrapped in to a façade pattern, network library. This allows WHCS to swap out the underlying network hardware for another, similar radio if needed. Due to this radio being the most critical for WHCS, it needed to have the most attention to detail when constructing the layout and software design. In order to meet these tight constraints, we chose the popular and well support RF24 library. This library is used by many other projects and has a proven track record. Additionally, members already had experience working with the API, therefore the learning curve was quite low.

2) HC-05: The HC-05 Bluetooth module is quite simple in its operations. Data is sent over a two line serial bus and if there is an active connection to a bluetooth enabled device, it is easily able to receive the data and handle it. In this case the device on the other end is expected to be a phone, but not limited to one. As long as the device on the other end of the Bluetooth link follows the WHCS Bluetooth application protocol, then WHCS is able to receive commands from arbitrary devices. In order to pass messages across this medium, a binary protocol has been developed. A simple diagram showing a very high level interaction of a Bluetooth device with the base station is for reference in Figure 14. Once again this underlying protocol is abstracted away from the underlying hardware. For example, if the HC-05 were to fail to meet WHCS' strict requirements, then we would have to switch it for the next best unit - the RN-41. If we wrote the underlying driver to be the "top level" layer that the base station interacts with, then a large amount of code and possibly architecture would have to be swapped out to meet the needs of another hardware device.

In regards to the application level protocol for WHCS, there is a well defined, easy way, for the Bluetooth library to gather information from WHCS' state. This is handled on the top-level flow of the base station by gluing together two different libraries without them knowing about each other. This is a good approach because it decouples the two modules from each other, making their individual implementations separate. Two tightly coupled modules may start to take on the appearance of a "ball of mud." A connected phone is able to accomplish any task that manually interacting with the LCD can handle. This includes controlling the function of individual modules and querying their current state. The BT connection tries to avoid generating too many packets over the NRF radio in response to user events. Instead it merely lookups the cached state from the base station's memory. This is faster and the round trip time is quick. Also, if a bluetooth packet requires a radio packet to be generated, this interaction is asynchronously tracked until the request has been fulfilled.

3) LCD: In what could be considered the "face of WHCS", the LCD module is situated directly over the Atmega32-A. It has the tough job of accurately and quickly conveying any desired information about the state of WHCS' control modules. This was no simple task as not only does it have to display, but with an attached touch-panel, it has to react to user touches. What functionality is exported to the LCD is only limited by the underlying processor speed and the UI library. The high level design of the WHCS LCD only had to worry about what the end goals are for its usage. An example of this abstraction may be viewed in Figure 2.

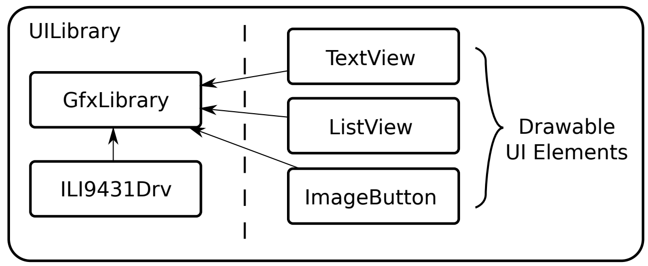


Fig. 2: the level of abstractions for the LCD subsystem

As the state of the WHCS network changes, the base station fires off redraw events in order to keep the LCD up-to-date. These redraws sync the internal state of WHCS with the user viewable interface. The physical connections to the LCD consist of data signaling and an 8-bit wide parallel data bus. There is an optional reset pin that WHCS uses for emergency resets and debugging. The high level interface with the LCD works directly with the high-level UI library and if necessary the underlying graphics library. The base station should never use the direct driver interface as this is subject to change due to hardware revision. In addition, a subtle feature that WHCS may choose to implement would be dynamic power saving through screen dimming. Although we assume the base station has wall power at all times, there may come a time where the system may migrate over to a lower wattage current source, such as power stealing from an HVAC unit. In this case, the system would most certainly have to be power efficient. Despite not needing to worry about power, this function would be simple to implement as only one microcontroller pin is required to control the screen brightness.

4) Touchpanel: In order to provide a way for an end user to be able to control WHCS from the LCD unit, there is a requirement to poll for touch events. This subsystem can be considered a part of the LCD, but the driver is independent from the graphics and ILI9431 (LCD) drivers. These events are be dispatched to the appropriate UI element based on the X and Y position of the touch event. There is an optional Z "position" which represents the pressure, which is used to gather more fine grained information about the touch itself. One of the unfortunate properties of the touchpanel is that it must be actively polled for new touches. This required that the ADC be constantly providing conversions, which raises the dynamic power of the MCU. This isn't a major concern as the base station is expected to have power from the wall most of the time.

The extent of the touchpanel interaction occurs from a `getTouch()` method. This method returns the latest touch event, if any. The base station has full control over where this touch event is dispatched to. Depending on the LCD scene (i.e main menu, boot screen), this event is be handled in different ways.

B. Software Architecture

The code for the base station is the most complicated in WHCS. It has to manage three separate devices simulatenously and be able to service each one in a timely manner. The LCD, NRF radio, and Bluetooth module are all being controlled and commanded by one ATMega32-A chip. There isn't much room for busy waiting or any expensive operations as everything has to be running as fast as possible. Given this, the BS is the least point of failure for the WHCS. This complicated main loop, including early initialization, may be seen in Figure 3.

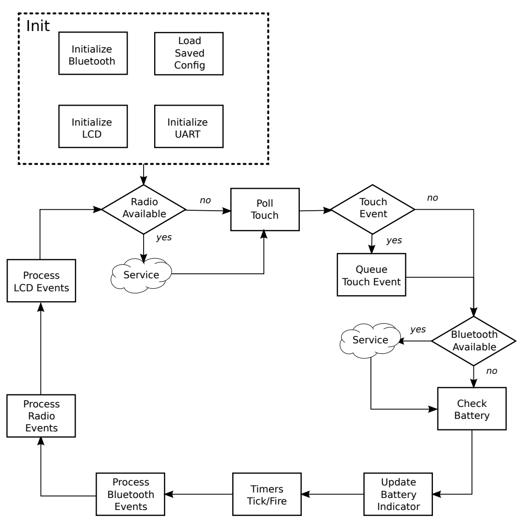


Fig. 3: The high level software flow for the base station

Starting from reset, the base station first loads any saved settings from the EEPROM (saved control modules, behavior settings, LCD settings, etc.), then it brings up all of the main classes (radio, LCD, Bluetooth, and UART). Each subsystem has a unique sequence of "commands" with parameters that are required to configure the device. The NRF radio has to have its power, channel, payload length, and other parameters set before usage. Once these basic options are set, any further configuration is done at run time. This includes switching from listening to transmitting mode and enabling or disabling the automatic acknowledgement feature. The built-in Atmel UART only needs to know the baud rate at which data will be sent and received. The LCD happens to have the most extensive initialization sequence due to required screen configuration, gamma settings, pixel order and other more archaic options.

Once all of the subsystems are brought up correctly, the BS begins the main loop. Radio events, Bluetooth events, and LCD state are all processed as required. For both the Bluetooth and radio, new packets are checked and serviced as needed. From these packets, internal state would updated and any response packets would be generated and sent. Internally, WHCS has an internal event queue with different event types. These events are processed and any responses are generated, if any. These responses could include a confirmation packet over the NRF radio, or a status update through Bluetooth. The base station may also initialize actions despite not receiving events. These could be triggered from timers firing.

All of the above tasks are executing in the same way as single core CPU would: in pseudo-parallel. The faster the whole system runs, the better the appearance of everything executing at once.

C. Control Module Abstraction

For WHCS to function smoothly and scale well, a neat and abstracted interface must be defined to accept *any* type of control module. New control module types should be easily added to the system without affecting older types and there should be a set of generic data structures for managing and storing information on modules. These structures must be carefully defined to wrap more specific control module packets in all of the shared metadata. Think of it like a hierarchy where all of the common attributes and actions shared by control modules have packets that can be sent to any module. Whereas the more specific packets (get temperature, engage door, etc.) would be wrapped up in the generic ones (essentially a derived object from the generic control module.) This can be visualized in Figure 4. The details of a network structure that would enable this clean interface is further described in **??**.

Beyond sending packets, the base station must accurately record and update state for all of the control modules. Depending on the control module, additional state is stored. Each control module has its own state machine that controls its function in relation to the base station.

D. Schematic Breakdown

To tie the whole design of the base station together, the schematic, created in KiCad is broken down below.

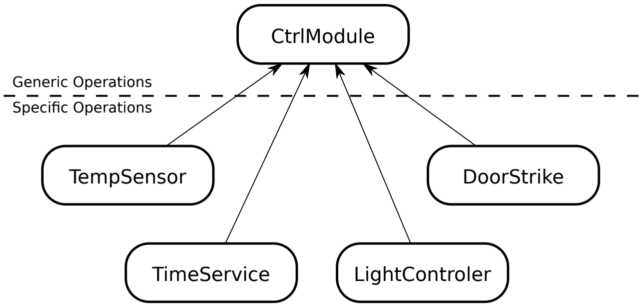


Fig. 4: showing the control module hierarchy for WHCS

In Figure 5 we see a focused view of the Atmega32-A microcontroller with an attached 16MHz crystal and power passives. The crystal has two capacitors that are dependent on the target crystal. These are required to get the correct oscillation for the external crystal. Also the AREF, VCC, and AVCC lines of the MCU have decoupling capacitors. These are used to make sure that the base station performs well under a large current spike. When designing the board, these capacitors should be placed as close as possible to the MCU to avoid a long high-current path through the ground plane. The capacitor on the analog reference pin (AREF) is used to stabilize the reference to make ADC conversions more accurate.

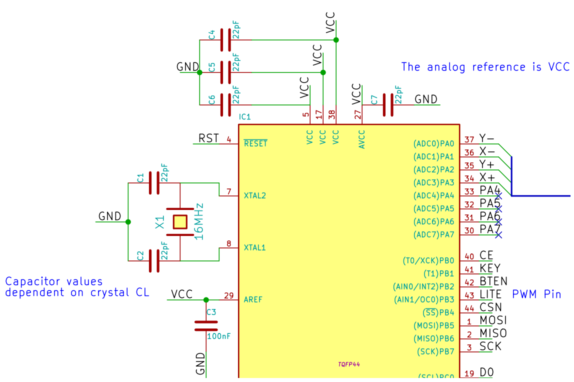


Fig. 5: Base Station crystal and decoupling capacitors

In Figure 6 we see the buses used to connect the LCD to the MCU. This is the most pin heavy component and care must be taken not to mix up any of the signal paths. All of the data control signals are connected to PORTD of the MCU, the touchpanel signals to PORTA (ADC), and the 8-bit parallel data bus completely uses PORTC. There are a few one off signals such as LITE which is a PWM input to control the LCD's backlight brightness.

In Figure 7 we see the 3.3V 3 terminal regulator converting the 5V VCC line down. Additionally, we see the external RESET pull-up resistor and a manual reset push

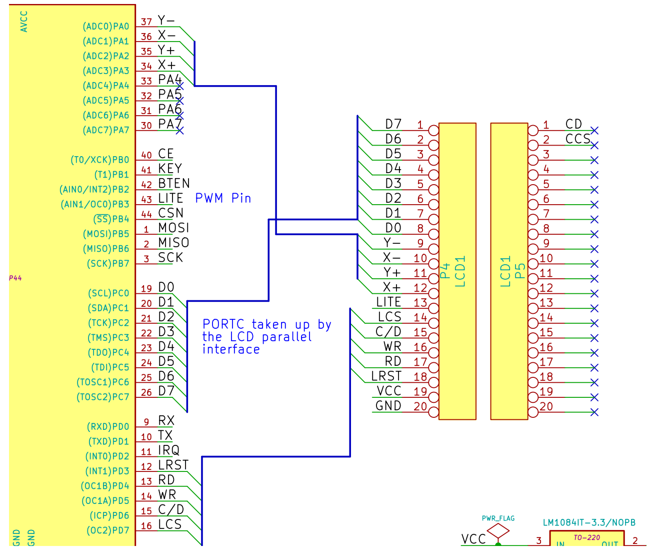


Fig. 6: Base Station LCD header to MCU

button. The left corner has the pinout for the NRF breakout board we are using.

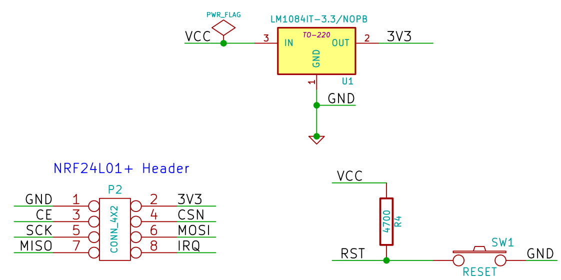


Fig. 7: Base Station power schematic and NRF header

In Figure 8 we see the header for the HC-05. We examine this further because of the unique electrical characteristics of the HC-05 module. The module only accepts 3.3V power and logic. Our MCU is running at 5V, which means we need a 5V to 3.3V logic shifter. To simply implement this, we used a resistor voltage divider which provided the required logic level for the TX pin. The RX pin does not need a shifter because 3.3V is still above the V_{IH} minimum for the MCU.

Finally, in Figure 9 we see the standard ICSP header that most AVR line microcontrollers use. This pin array serves as a quick and easy way to connect an external programmer to our base station while in the field. In this schematic revision, this header can provide power directly to the 3.3V regulator and MCU.

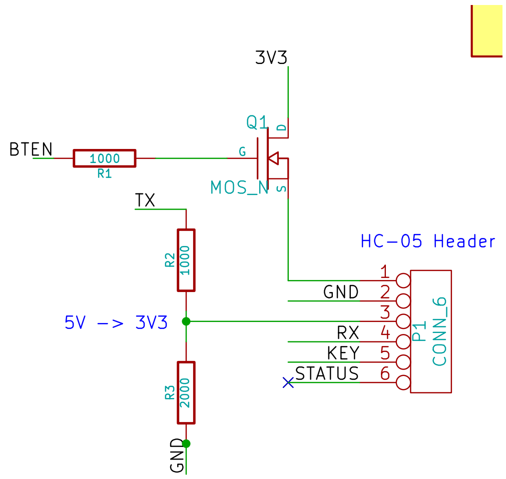


Fig. 8: Base Station HC-05 header

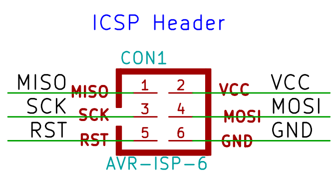


Fig. 9: Base Station ISP header

3. Control Modules

What can be thought of as the "arms of WHCS", the control modules serve as the main devices that seed the network with data. This data is specific to the control module that is emitting it. The base station is more more complex than an individual control module because it needs to be. The control modules should be as lightweight as possible to save cost and keep power usage down. If the control modules were too complex, then the entire cost of WHCS would increase proportionally to the number of control modules.

A. Software Flowchart

The general flow for the control modules is much simpler than the base station just due to the requirements of the system. There isn't as much that needs to be done on each loop iteration. The only main module that the control module needs to work with is the NRF radio. This can be seen in Figure 10. Due to the capabilities for the NRF radio to provide an interrupt signal on the reception of a packet, the control module actually has the ability to sleep when not doing anything. Control modules should be as mobile as possible, which limits their overall functionality and processing power. Without these limits, any battery attached would quickly be drained.

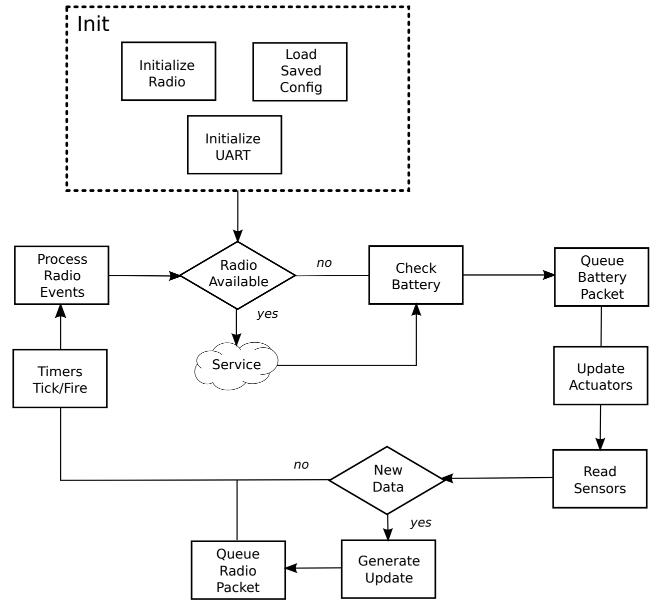


Fig. 10: the high level software flow for a generic control module

B. Electronic Strike

WHCS features an electronic strike which allows control modules to lock and unlock doors within the system. The electronic strike was chosen over an electronic deadbolt because the strike can still be used with a normal door knob. If the electronic strike ever fails during operation the door knob can be unlocked and therefore bypass the strike system. This design principle gets rid of safety hazards that could occur if the WHCS system lost power. The operating mode for the electronic strike is normally open. This means the strike requires power to be unlocked and is otherwise locked. As a result, power is saved within the system which is beneficial because the electronic strike consumes roughly 450 mA at 12V during operation.

C. Sensor Data Collection

The temperature sensor that we used for WHCS is the TMP36. The temperature sensor is simple in design as it has only three pins that require connection. The schematic shown in Figure 11 shows how the temperature sensor is connected to the ATmega328 on the control modules. The VOUT pin of the TMP36 outputs a voltage signal that varies based on the temperature surrounding the component. The voltage range is between 2.7 to 5.5 volts which is supplied through or logic level voltage lines. This sensor has a rated temperature range of -40 to 125 degrees Celsius which is broad enough for a household temperature sensor.

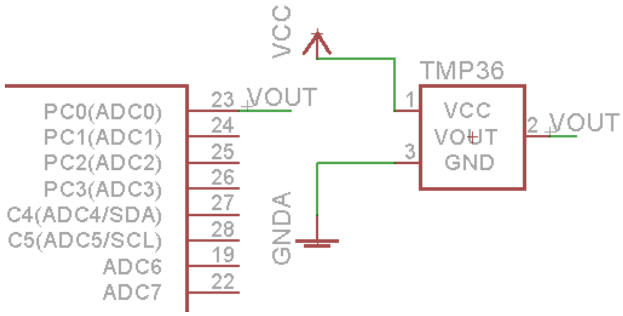


Fig. 11: Temperature Sensor Connection Schematic

D. Light and Outlet Control

The solution to controlling lights and outlets in WHCS is through an AC solid state relay. The solid state relay that we use is capable of switching a load of 120V AC up to 16A. The activation voltage is 1.2V and the activation current is 15mA. The ratings of the chip allow the relay to be controlled directly from the control modules microcontroller GPIO pins. This solid state relays small activation requirements provide low power operation capabilities as well as design simplicity. Figure 12 shows a schematic using this solid state relay.

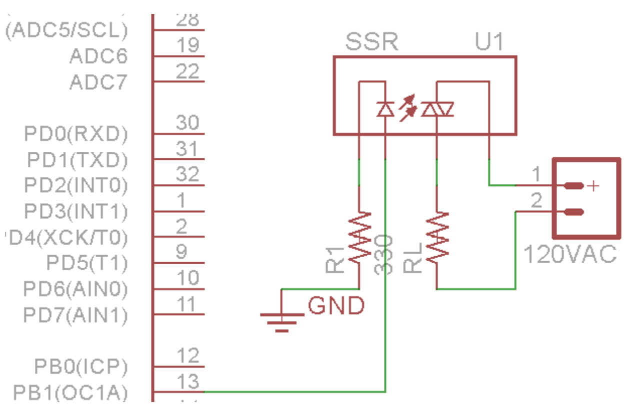


Fig. 12: Wiring Schematic for Solid State Relay

E. Schematic Breakdown

The control modules for WHCS have to be able to support communication via a radio transceiver as well as interaction with their target endpoints. Figure 13 shows the schematic for the control modules that is be implemented in WHCS. The full schematic is available for viewing in **??**. The main component of the schematic is the ATmega328. Everything in the schematic is connected to the microcontroller in some way. In the schematic three different VCC lines are shown. This is because the control modules will have to access to a 3.3V line, a 5V line, and a 12V line. The power board will supply these power lines to the control module. The 5V and 3.3V lines are necessary because they provide power to the logic chips like the microcontroller and the radio transceiver. The 12V line is necessary solely for the electronic strike that we have chosen.

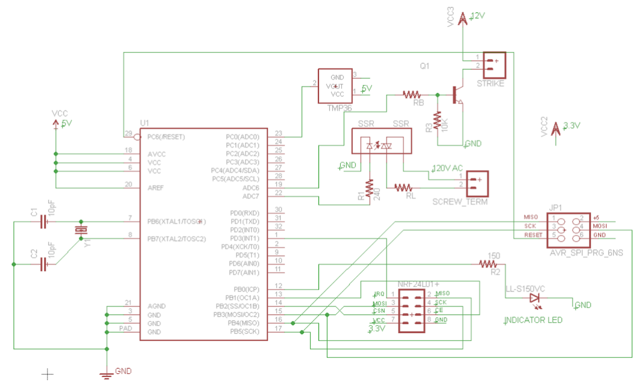


Fig. 13: WHCS Control Module Schematic

4. Android Application

For most WHCS users the mobile application will be the only physical interaction they have with the application. When we set out for development we wanted to make an easy to use application that would attract users to stick with our system. Operability and usability were emphasized in our design process. We wanted an appealing U.I. without complexity, after all we are targeting a simple solution to home automation.

A. Bluetooth Software Design

Bluetooth is the technology allowing the Android application to communicate with the base station. The first step of the Bluetooth lifecycle is to ensure that Bluetooth is enabled. When it has confirmed that Bluetooth is on, the application will the user to connect to a base station. When connecting to a device there are two possibilities for connection, paired devices and non-paired devices. The application will first show the user all devices that their phone has paired with previously such as the base station. If the base station does not show up in the paired devices list, the user will be able to search for active Bluetooth devices and select the base station. At the end of this start up cycle the WHCS application will have an active Bluetooth connection with the base station that can be used for full duplex communication. A socket can be opened within the android application for communication between the two Bluetooth devices.

Once a `BluetoothSocket` has been opened on the Android device the application can begin communicating with the base station. We use a custom communication protocol between the Android device and base station to ensure proper interaction. This protocol allows the Android application to give commands to the base station such as inquire about the state of the control modules or to toggle state within the system. Whenever the Android application wants to send a message to the base station the software creates a packet with a certain structure. The packet contains a byte for letting the base station know that a command is being given, the command itself, any variables for the command, and then a byte for finishing the command. The base station receives one byte at a time due to the serial nature of Bluetooth communication but it is able to parse the packets it receives in order to figure out what action the application is trying to perform. Figure 14 shows a visual representation of the communication between the application and the base station.

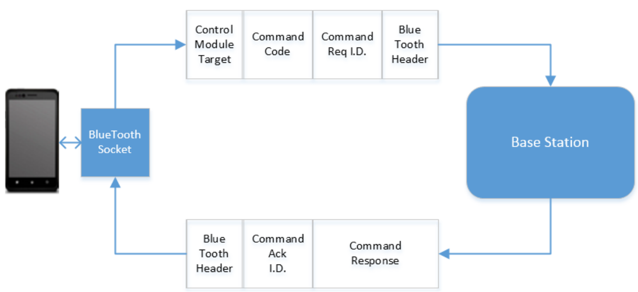


Fig. 14: Visual of Communication Between Android Device and Base Station

B. Speech Recognition

The Android application for WHCS offers speech activation capabilities. These are on top of GUI activation capabilities. The speech activation sequence begins with the press of a button to start the speech recognition. The user is prompted with a microphone and can then give his command. The commands are formatted similarly to light one on. When the user gives commands using the speech method, a notification is given indicating the success of interpreting the speech into a known command. If the users speech does not match a known command, the speech is shown back to the user to show what went wrong. The following flowchart in Figure 15 displays the sequence of events happening when a user performs speech activation.

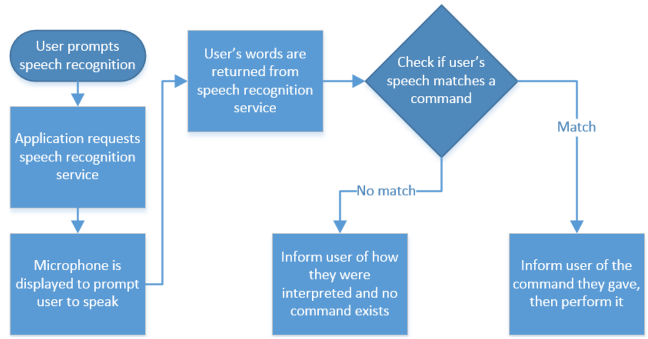


Fig. 15: Android app speech activation chart

5. Power Hardware

In order to power our system we stepped down the 120VAC found in homes to the voltages that our system requires. For our system we need a 12V, 5V, and 3.3V lines. To provide these lines we used a traditional full bridge rectifier design using a 60 Hz 120:14 transformer to convert our AC voltage down to 19.8VDC. We considered using a switched mode power supply, yet based on the increase of complexity of SMPS designs we decided that we would not have enough time to incorporate this type of design for our AC to DC power step down. After having stepped down the power we used TI WEBENCH to convert the 19.8VDC to 12V, 5V, and 3.3V lines. Each line was made using switching regulators in order to have maximum efficiency.

A. Power Consumption

Power consumption wasn't a top priority in our design. While it is important not to be incredibly wasteful to the point that it becomes a problem, power was not something that we decided we wanted to be competitive on. Had we wanted to be more competitive with power, we would have taken a lot more into account and made different design decisions. For example with the microcontrollers we would have looked more carefully into the amount of current that they drew to help us weigh our decisions. MSP430 boards for example would have been attractive because of the low amounts of current that they draw. With that said we made all of our decisions based on their performance and ease of integration. We merely needed to know how much current our system drew to properly design of our switching regulators as well as choose our transformer.

The Figure 16 and Figure 17 were used in making our design decisions.

B. Transformer and Capacitor Choice

To choose the transformer we needed to take into account the apparent power rating as well as the winding ratio. Given that the highest voltage output needed for our design was 12VDC we decided on a 120:14 winding ratio. This gave us about 20VDC to be stepped down by our switching regulators. To choose the apparent power rating we had to consider the current draw. From Figure 17 we find that the max current the system would could ever draw

Operating Voltage	Device	Current Draw (mA)
3.3V	LCD	150
	Bluetooth	35
	nRF	13.5
	Temp Sensor	0.05
5v	Atmega328P	11
	Atmega32A	16
	AC Relay	20
	Strike Relay	5
	Power LED	20
	Board LED	20
12V	Strike	450

Fig. 16: shows the current requirements of each device in our system.

Voltage	Max Current (mA)
3.3V	198.55
5V	76
12V	450

Fig. 17: shows what the max current for each line in our system at any point in time.

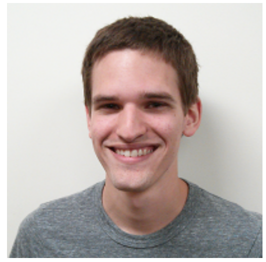
would be below 725 mA. The apparent power rating can be calculated by I*Vrms. Given the information of our system we required an apparent power rating of at least .725*14 = 11. The transformer we chose had an apparent power rating of 20.

We chose our capacitor using the equation $V_r = \frac{I}{2*f*C}$ for an approximation of the expected ripple (Millman-Halkias, pg. 112-114). Using a capacitor of $4700\mu\ F$ gives us a ripple of .887V (for most applications our current draw will be below 500 mA).

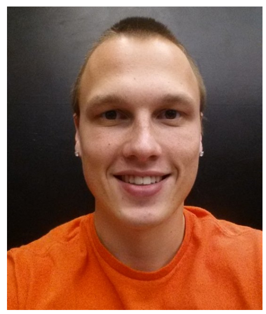
6. Conclusion

Through extensive research, design, and implementation WHCS was realized to meet all requirements set. The Android application was architected successfully for simplistic interaction. All use cases were implemented in order to provide the optimal experience. The base station was fabricated according to specifications. It has proved it is capable of managing all state of WHCS and acting as the middleman between the user and the home. The individual control modules do the tasks that they were created for so that the home can be controlled by the push of a button. Future work includes extending the number and type of control modules supported by WHCS.

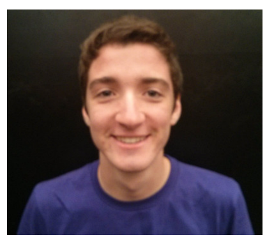
7. Engineering Team



Grant Hernandez is a senior at the University of Central Florida. He will be graduating with a Bachelor of Science in Computer Engineering this summer. In his spare time, Grant writes lots of code, reverse engineers binaries, plays in cyber Capture the Flag competitions, dabbles in computer graphics, and tinkers with embedded systems. He will be attending the University of Florida in fall 2015 to begin his Ph.D in Computer Engineering with a security research lab.



Jimmy Campbell is a senior at the University of Central Florida. He will be receiving a Bachelor of Science in Computer Engineering in August 2015. His interests include embedded programming, mobile development, and web back-end development. Jimmy will be taking a full time position with Microsoft as a Software Development Engineer after graduating.



Joseph Love is currently a senior at the University of Central Florida and will receive his Bachelor of Science in Electrical Engineering in August of 2015. He is currently working with Direct Beam Incorporated and plans to pursue his masters in Electrical Engineering during the Fall of 2015 at UCF with a focus in Electromagnetics.