Gaming Wizard

A Smart Table for Tabletop Gaming

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Group 30

Gabriel Holguin	Computer Engineering
Daniel Kalley	Computer Engineering
Erica Lindbeck	Electrical Engineering
Logan Taylor	Electrical Engineering

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1.0 Executive Summary

Tabletop gaming has experienced a surge in popularity thanks to the rise of several popular web series featuring gameplay and more widespread references in traditional media. With this increase in popularity there is a corresponding increase in demand for new materials to game with, both in terms of game content such as new options for player characters, and gaming accessories such as dice and figurines. We have met this demand with an adaptable system that enhances or simplifies existing game mechanics and provides a variety of new features that can be used to improve immersion in a wide variety of roleplaying games.

The system begins with a 38” x 30” x 36” table on which games can be played. The table itself displays the game in simulation of traditional mediums of gameplay, and the surface of the table facilitates interaction with the imaginary world of the game through touch inputs. This functionality is implemented using a rear diffused illumination touch screen made of clear acrylic, embedded in the top of the table, with a diffusive material attached. In comparison to many previously developed smart tables, this method allows users to generate touch inputs using objects such as figures of characters, in addition to their fingers. The touch screen is illuminated from below in the visual spectrum by a projector, allowing any necessary game maps and features to be displayed. Additionally, the surface is illuminated by infrared illuminators to generate a heat map of touch inputs which is translated into coordinates by blob-detecting software and game software subsystems.

Additionally, several bookkeeping elements of gameplay, such as rolling dice and calculating distances on maps, are taken care of automatically by the game software hosted by a player’s pc, and a smart phone app which turns players’ phones into character controllers using a Bluetooth connection. Thus, time spent on the entertaining aspects of the game rather than performing tedious calculations can be maximized. To simplify performing these calculations across many games, the player app tracks relevant information related to each player’s character such as current location, health, movement speed, and abilities, and saves them between sessions. Similar apps can already be used to track many of these features, but our app is able to track additional pieces of information and integrate them more seamlessly into gameplay.

To enhance immersion in roleplaying tabletop games, we added special effect functionality. Speakers embedded in the table play sound effects for specific actions, and LED lighting around the edges of the table light to denote the use of magic or other special abilities. When a character’s choice of action causes changes in their environment, the map displayed on the table shows the affected area.

This report details the process of designing the Gaming Wizard system, accounting for budgetary and time restrictions as the project was funded solely by group members and most systems were assembled in under 5 months. Special consideration was given to guaranteeing that the system is compatible with a wide variety of current and future games, as well as incorporating standards to interface with the smart phones and computers that must be used to run the Gaming Wizard software. During the design stage we ensured that no components would be forced outside their specified operating ranges during intended operations, checked our power supply for compatibility and added fans to keep the interior of the table cool. During the assembly and testing stages, we ensured that all electrical components were safely handled and securely attached to the table.

2.0 Problem Overview

In an open-ended tabletop role-playing game, each player controls at least one character and cooperates with other players in their party to complete a series of adventures known as a campaign. Traditionally, the physical representation of game settings consists of a gridded board and figures representing the landscape and characters, respectively. Paper character sheets are used to keep track of character abilities, and dice are used to determine the outcomes of events in the game. During gameplay, keeping track of the locations of characters and monsters on the board with respect to each other is vital to various mechanics such as combat, using magic, and interacting with the environment. However, problems arise such as remembering character locations between game sessions or when a piece falls over. Further, counting grid squares to determine distances each turn often causes delays in gameplay and can be a matter of contention when paths do not lie along grid lines.

Another issue that arises with tabletop gaming is the large amount of information that needs to be tracked. This includes things like character attributes, skills, equipment, and the amount and type of dice needed to be rolled for an interaction. These values evolve over the course of the game which normally requires a large amount of erasing and rewriting. Given that an average game involves four players and a game master, this information is tedious to track and slows down gameplay.

Our project seeks to solve these issues by using a “smart” game board that can recognize multiple character locations, represented by physical figures on the game board, track that information, and display the relevant information both on the board and in a phone application. Ideally when a character is moved on the board, the application software recognizes this and asks for a confirmation. The application saves and remembers character locations even after being closed, which greatly reduces the time it takes to reset a board between meetings.

Additionally, the application tracks character information such as attributes and combat statistics. This creates a paperless game that removes the need for constant erasing and rewriting. Combining this with the location information also greatly reduces the time it takes to perform combat interactions, as the board can automatically display the range of an ability or spell once it is selected by the user. Dice rolls can also be simulated in the software, removing the problems of needing a large surface to roll dice on and losing dice.

The proposed smart table hosts the game from a user’s laptop and communicates with players’ phones using Bluetooth connections. From their phones, players and game masters (GMs) use a menu system to create characters, view and modify their stats, and trigger events on the table’s surface corresponding to character movements and abilities. Further, a character’s statistics are saved on the corresponding player’s phone, to reuse the character on different maps that may be loaded onto the board for different scenarios. All character and digital token locations on the board are saved to the GM’s phone or computer when the table is shut down, allowing the group to recreate the game board quickly for subsequent game sessions. The GM has access to additional options such as map selection and enemy creation that are not accessible to players. The current map, along with additional relevant graphical information are projected onto the table’s surface from the interior of the table. The structure of this phone application/computer program/table system is given in Figure 1.

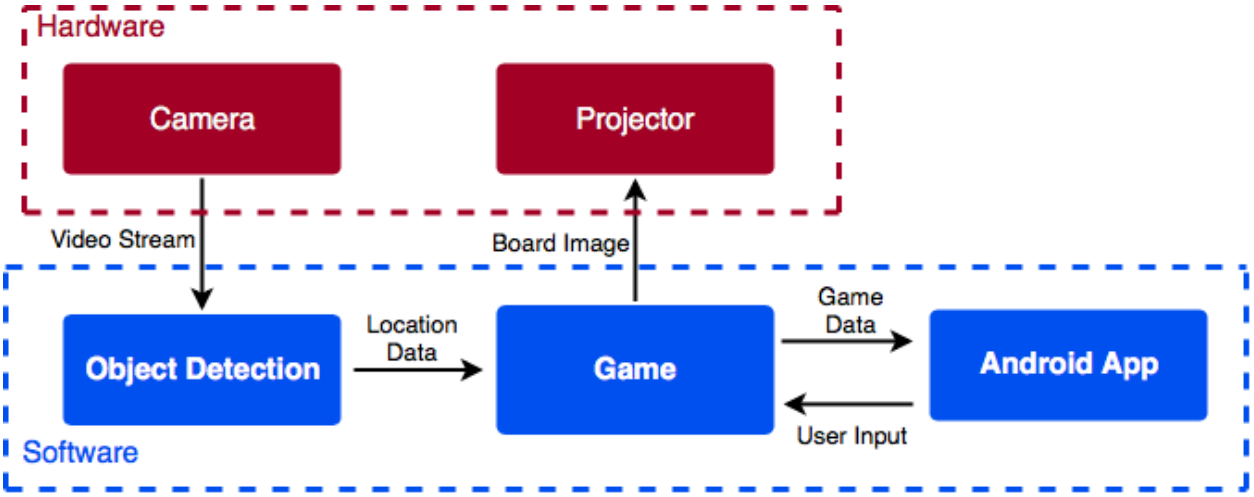


Figure 1: General Software Block Diagram

In order to track characters, figures on the table's touch surface are located through use of Rear Diffused Illumination (Rear DI). In Rear DI, in addition to the image being displayed, infrared light illuminates the table's surface from below and is diffused for even coverage of the surface. The translucent material of the surface allows some light to be transmitted through the surface while some is reflected downwards. When an object is placed on or hovers closely above the table's surface, the transmitted infrared light is reflected downwards by the object and creates a region of higher intensity infrared light, which can be detected by a camera under the surface. The generated heat map is used to determine object and touch locations. This method was selected based on location accuracy requirements, cost efficiency, and the need for object detection in addition to detection of fingers and specially designed styluses. Touch input is also used to select locations for ability usage (e.g. the center of a spells areas of effect) and movement of digital tokens representing enemies or allied non-player characters.

The table relies on a standard electrical outlet for power in order to remain turned on for lengthy game sessions. An automatic cooling system triggers when the inside of the table, which contains most of the electrical components, exceeds safe operating temperatures. This system consists of two fans and an associated temperature sensor. To ensure visibility, manual controls are available to set the baseline brightness of the table's image, but maximum brightness is recommended in virtually all situations.

To improve the quality of gameplay, there are several additional features to the table. Indicator lights on the table are used to denote player turn and ability damage types. Speakers inside the table allow the game master to play ambient music or special effects through the use of a third-party audio player. Finally, a programmable timer was included for timed skill challenges and limiting decision-making time in combat. The incorporation of the many proposed features of the table is detailed in Figure 2.

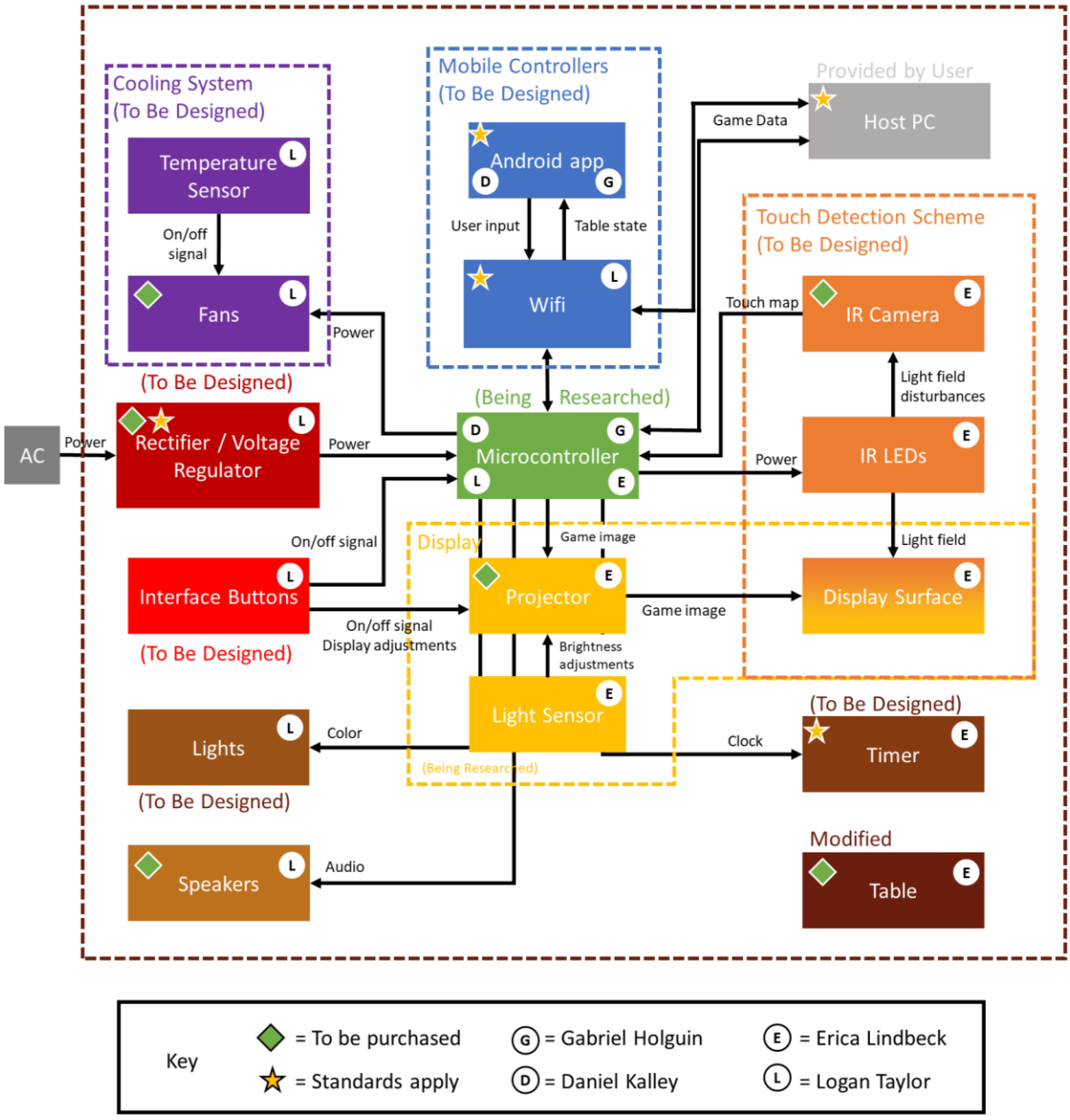


Figure 2: Hardware Block Diagram

3.0 Project Requirements

3.1 Marketing Requirements

As we designed a smart table for tabletop gaming, we had to consider what the most desirable characteristics of such a table would be, given a typical game. As a game usually includes several players and is run by a single game master (GM), support for several simultaneous users was necessary. During an encounter or while exploring a specific location, the players use a map consisting of a top-down view of the environment, divided into squares which represent a 5' square in the environment with a 1" square on the map. This map must be sufficiently large to show a reasonable portion of the environment and contain all of the relevant characters. Setting up the map, placing characters, and looking up character details should be quick processes to avoid delays in gameplay. As each player's character is represented using a miniature figurine of the character with a 1" diameter base, the figure must be accurately located on the map to determine which objects, enemies, and allies are within range of the character's abilities (such as magic spells and weapons), as well as which locations (i.e. grid squares) the character can move to on their turn. A player should be able to easily tell where objects are on the map and distinguish features of the environment such as doors, levers, and walls in order to make decisions about which actions to take on their turn. Finally, the table must be affordable for a dedicated table group and so that the benefits it confers are worth the price. These desirable features are organized in Table 1 as they are the general characteristics which the table must have.

Table 1: Marketing Requirements

Desired Features	Reasoning
Supports Normal Game Groups	Most games are balanced to be played by 4 players with a game master. A larger or smaller group is possible, but the table should be able to support groups of typical size.
Easy to Use	If the table is significantly more complicated than traditional paper/dry erase maps and figurines, there is little to be gained by using it. Setting up a map and placing characters should be comparably quick, and interfaces should allow easy access to desired character and ability information.
Supports Full Length Games	A typical game session is 3-6 hours, though it may last longer. A map is usually not required for the entire session, so the table may not be necessary for the whole session but should be available for the entire duration, just ot be on the safe side.
Map Details Are Easily Distinguished	Map features such as landscape, locations of digital tokens, and areas of effect for character abilities should be easily distinguishable for effective gameplay
Character Locations and Touch Inputs Are Accurate	Locations of characters and choice of target when triggering an ability such as a spell should be accurate to the constraints of the game, which is played on a grid.
Low Cost	The table should be low enough cost that the benefits it brings to gameplay justify the expense, and maintenance (e.g. replacing projector bulbs) is not excessive.

3.2 Engineering Requirements

Engineering requirements of the table which will ensured that the table met marketing requirements are given in Table 2. These requirements were chosen in compliance with the relevant standards given in Table 3, based on our chosen implementation using a Rear DI touch

screen and a phone application. Some of these standards are detailed further in the following section. We encountered more standards as we finalized our design and began its implementation, but we created our design to either initially satisfy standards or be modifiable to meet them.

Table 2: Engineering Constraints

Aspect	Constraint	Reasoning
Touch Surface Dimensions	20”-36” per side	Large enough play area without causing significant detection issues; 20” square game mats are the most common commercially available custom mapmaking product
Table Height	1.5’- 3.5’	Players are expected to sit around the table during gameplay
Maneuverability	Can be safely moved by 2 people	The table will have to be moved for demonstrations and in home without special equipment
Device Lifetime	$\geq$ 3 years	Desirable lifetime given expected cost of development/replacement
Simultaneous Touches Detected	$\geq$ 6	Support 4 player tokens + 2 touch points for user input
Simultaneous Mobile Controllers	$\geq$ 5	Support at least 4 players and a game master
Mobile Controller Range	$\geq$ 10’	Avoid disconnecting walking around a room
Mobile Controller Input Delay	$\leq$ 1 s	Acceptable delay considering inherent wireless communication delays over a stable connection
Touch Input Delay	$\leq$ 0.2 s	Acceptable delay for touch input detection to interact with the table in near-real time
Operating Temperature Inside Table	$\leq$ 32ºC	Safe operating temperature for most electronic devices/components
Time to Cool from Startup (assuming ambient temperature is within operating range, internal temperature at most 10ºC higher than allowable)	15 minutes	Acceptable delay assuming ambient room temperature is within operating range, long enough for fans to significantly cool the interior of the table
Average Projector Bulb Change Time	$\leq$ 6 minutes	Ease of replacement is necessary as projector bulb is an expected point of failure in the long term
Continuous Operation Time	$\geq$ 6 hours	Enough for most game sessions
Display Resolution	$\geq$ 720 x 720 $\geq$ 1080 x 1080 ideal	Possible with available projectors and provides reasonable image quality at expected display dimensions
Object Size for Detection	$\geq$ 0.5” diameter	Must detect fingers and 1” diameter figure bases
Object Location Accuracy	$\leq$ 0.5” from true location	Must be able to accurately place track objects/touches to 1” grid squares
Object Removal/Placement Detection	$\geq$ 95%	Must reliably detect when a figure is moved for character tracking
Locations Tracked and Saved on Exit	$\geq$ 20	Able to store location data for the next game session for 4 player characters and a reasonable number of virtual allies/enemies
Average Time to Set Up New Map	$\leq$ 2 minutes	Acceptable set up time based on average time needed using a traditional map and figures

Table 3: Considered Standards for Engineering Requirements

Standard	Application
IPC-2221B	Generic Standard on Printed Board Design
NASA-STD-8739.3	Soldered Electrical Connections
Bluetooth Special Interest Group Standards	Bluetooth devices must demonstrate and declare compliance with the standards set by the Bluetooth SIG
IEEE 3007.3-2012	IEEE Recommended Practice for Electrical Safety in Industrial and Commercial Power Systems
CUI Power Supply Safety Standards	Standard for power supplies
Android Design Guidelines	Regulates Android applications
Google Java Style Guide	Non-mandatory standard for program formatting
IEEE 29119	Software testing

The relationships between a selected subset of engineering requirements and the marketing requirements are detailed in the House of Quality in Figure 3.

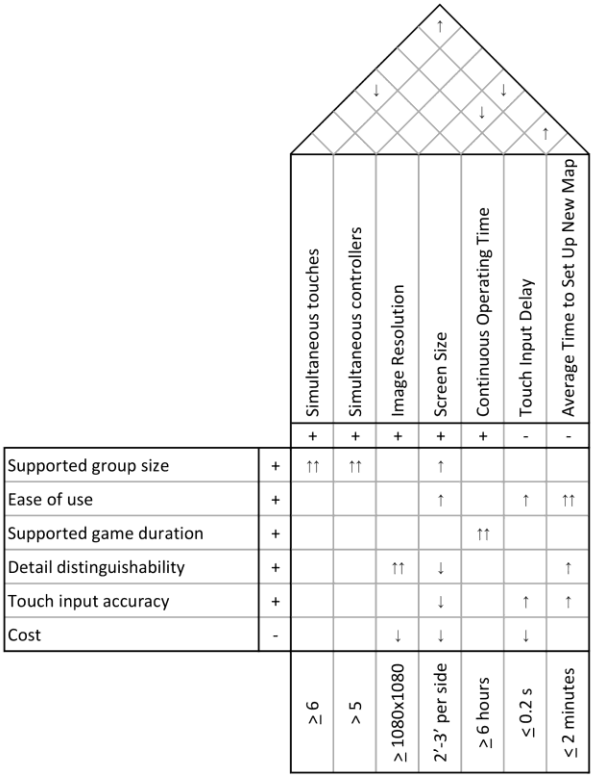


Figure 3: House of Quality for Selected Engineering Constraints

3.3 Standards

Standards define the characteristics of a product, process, or service. They simplify product development, reduce unnecessary duplication, lower costs, increase productivity, promote safety, and permit interchangeability, compatibility, and interoperability. Standard development

organizations such as IEEs facilitate the development and maintenance of official standards but some companies such as NASA choose to also follow their own standards.

3.3.1 Hardware Standards

Various standards were used as a guide for designing and testing the hardware of the device. Standards were selected based on relevance to design decisions such as safety, wireless technology, and soldering techniques. To reduce costs for the project most of the standards chosen are freely available.

3.3.1.1 CUI Power Supply Safety Standards

Devices used within the smart table must be powered with various voltages which presents a level of danger especially when dealing with the alternating current coming from the mains. Standards can be used to protect against fire and electric shock. The CUI power supply safety standards [1] aim to identify the major standards that relate to power supply safety including: IEC 60950-1 (safety of information technology equipment), IEC 62368-1 (audio/video, information and communication technology equipment), IEC 60601-1 (safety of medical electrical equipment), and IEC 61010-1 (safety of measurement, control and laboratory equipment).

Within the document three classes of equipment are defined based on how their power supplies are isolated from dangerous ac mains voltages. Class I devices achieve electric shock protection through basic insulation and protective earth grounding and have conductive parts with a hazardous voltage connected to a protective earth conductor in case of insulation failure. Class II devices use double or reinforced insulation and do no require a ground. Class III devices operate from a safety extra low voltage supply circuit where extra low voltage is defined as a voltage in a secondary circuit not exceeding 42.4Vac or 60Vdc which are the levels when a voltage is considered hazardous. The power supply, although connected from the wall outlet, only provides 12Vdc so this device is considered class III. The only hazardous voltage is coming from the wall but is protected through the use of insulation around the wires so this does not pose a problem.

3.3.1.2 Bluetooth Standards

IEEE used to have a standard for Bluetooth mandated as IEEE 802.15.1, but is no longer regulated under that number. Currently so long as a device meets the criteria set forth by the Bluetooth Special Interest Group, the device will have met the standards necessary. The criteria must be met by the Bluetooth adapter or microcontroller used, which they have.

3.3.1.3 NASA-STD-8739.3 Soldered Electrical Connections

It should first be stated that on October 17, 2011 NASA-STD 8739.3 [2] was replaced by J-STD-001E requirements for soldered electrical and electronic assemblies which is a joint industry standard. However, J-STD-001E is not free to access and the old NASA standard is adequate for the scope of this project. There is no requirement to follow a specific standard for soldering, and it is simply used to gain a better understanding of actual soldering techniques used in industry.

For this project a large number of RGB LEDs will need to be soldered to conductive wires and surface mount parts will need to be soldered to the PCB. Understanding the appearance of an adequate solder connection will be important to ensure strong connections so devices work as intended. Figures in the document show minimum and maximum acceptable amounts of solder for various connections as well as improper wire stripping and how solder connections look when insufficient or excessive heat is used. There is also a list of definitions that are useful when trying to understand the different terms used in soldering.

It is stated multiple times throughout the document to not use pressurized air to cool solder joints. The solder should be left to cool naturally at room temperature. Cooling the joint too quickly can cause it to become fragile or reduce the integrity of the connection. It is also stated that there should be no motion between conductors when solder is applied. This means that when soldering wire to LEDs they should be fixed in place. When it comes to the geometry of a solder joint the fillet should be smooth and concave. About using the correct amount of heat, it is stated that a cold connection will exhibit poor wetting and have a grayish and porous appearance. An overheated connection will have a rough surface and will be dull, chalky, grainy, porous, or pitted. These descriptions will be useful when inspecting the appearance of our solder joints.

3.3.2 Standards for Software Development

Though not as strictly adhered to as hardware standards where the misuse of a standard can cost the functionality of the project, there are some standards for the development of mobile applications that make readability and peer reviewing easier. Android OS has a few developmental standards for mobile app development and C++ has a few of its own syntax and style standards.

3.3.2.1 Android Mobile Application Standards

The two general purpose standards that Android OS developers have to deal with relate to UI design and quality of app. In the case of UI design, it is mostly up to the user's preference, but there are a few guidelines to follow that will help with human interactivity with the app. Style, layout, usability, components, and animations are the five main UI designing basics. For style, color must indicate which elements are interactive and the most important elements should stand out. All text must be legible on the selected background and a general color theme should be followed. For layout, the UI must be predictable in a way that humans can use with consistency. The UI must give some kind of feedback when an input action is performed by the user. In the case of usability, the developer must have a specific target audience in mind but also be user friendly enough with a developer-defined minimum level of technological understanding. Components deal with the layout of the UI in order for the app to be ergonomic on a smart phone and having related navigation bars is equally important. The bottom navigation is also a staple of any good Android OS application. Animations must show spatial and hierarchical relationships between elements and must keep focus on what's important. Animations should not bombard the user with stimulus that will confuse them.

Mobile application quality standards are more important than UI standards when it comes to publishing your app and Table 4 below shows us some of the most important standards apps should follow.

Table 4: Android Application Quality Standards

Area	Description
Standard design	The app must not redefine pre-built internal functions such as the back button
Navigation	Pressing the Home button at any point while the app is running must return the user to the Home screen
Permissions	The app should not request higher access to the user's personal data than the absolute minimum needed to run the app
Installation	If the app is larger than 10MB, it should support installation on a SD card and function the same as if it were installed on phone memory
Audio	While the screen is off or another app is running, audio must not be playing unless that is a feature of the app such as for a music player
App states	While the app is in the background, any service such as Bluetooth or Wi-Fi must halt unless it is understood as a core feature of the app
	When the user opens the app while the app is in the background, it should restore the user to the same point that it was left at before
Stability	No freezing, crashing, or interruptions of the same magnitude should occur when using the app
Performance	If more than two seconds have gone by while loading, some kind of feedback must be indicated to determine the status of still loading
Data	All data that is private must be stored on the app's internal storage and be inaccessible to the developer
Networking	SSL is used for all network traffic and the app must declare a network security configuration beforehand
Cryptography	No custom algorithms are allowed and platform-provided cryptography should be used instead
Content Policy	The app must adhere to Google Play Developer Content Policy [3] when dealing with copyright and other intellectual properties
App Details Page	High quality image must be used and the image must not contain any explicit graphics or resemble an advertisement
Testing	Follow Core Suite [4] testing methods for additional testing methods

Since we currently do not have any plans to commercialize our app, we didn't need to strictly adhere to these standards, but it is a good idea to use best practices any time for development. These standards were our guidelines when developing our app so we could have the option of marketing our app in the future.

3.3.2.2 C++ Language Standards

Since similar to Android app development there are no ISO developed standards for C++, we looked at what are considered standards and best practices by engineers. We took our standards and styles from the Google C++ Style Guide [5]. This gave us a guide as to best practices for implementations into larger projects that we can pull from. Google uses C++ as their main programming language for open-source projects and as such has developed a style for cooperation between multiple engineers.

The reasons these standards exist in the first place is to succeed in a few goals laid out by Google. Firstly, all of the style rules should be enough of a significant net benefit when comparing the style with and without the rule. They must be useful enough to make thousands of engineers adhere to it without being too much of a hassle. Since many people after the initial writer of the code will work on, build on, or just reference the work, all code must be optimized for the reader instead of convenient for the writer. Because of this, it is important to be consistent when writing code and not change styles or syntax midway as the reader can get confused. Consistency is also important for trying to adhere to some general use syntax that the C++ community uses for problems that are common or some idioms.

Since C++ can be complex as a programming language, it is important to avoid dangerous constructs that can risk compromising program correctness. The average C++ programmer would find some of these tricky constructs hard to maintain since the initial programmer might not be there to explain what is going on. All of these rules are mostly in place for cooperation as no one person can do all the work in the world. This also applies to our group as we had multiple programmers working on the same project, so it was important to keep consistent syntax between members. Some of the style and syntax choices are specified in their document are shown in

Table 5 and Table 6 below.

Table 5: C++ Coding Standards

Category	Standard
Header Files	Every .cc file should also have and associated .h file, with the exception of very small files that only have a main
	Headers should be self-contained meaning they should be able to compile on their own.
	To prevent multiple inclusions, all header files should have #define guards and should be able to guarantee uniqueness by basing the guard on the full path name
	#include any headers you may need instead of using forward declarations
	For ordering headers the order is related header -> C system headers -> C++ standard library headers -> other libraries' headers -> your project's headers. Each has a blank line in between the categories
Scoping	Initialize all variables in the declaration and only place variables in the narrowest scope possible
	Using static or global variables should be avoided if possible
Classes	Specify if the class is copyable, move-only, or neither
	Use classes for everything except for passive objects that carry data; then use structs.
	When using inheritance, make the class public
	Make constants public and all other classes' data members private
	Declarations should be in order of access level. public -> protected -> private.
Functions	The output of a function must have a return value or be provided through output parameters
	Functions should have a small focus to do only a few tasks per function call
	If a parameter is passed by Ivalue then it must be labeled with a const before its name
	Function overloading is only used if the reader will be able to figure out the function's happenings without having to question which overload is occurring
	Exceptions make the flow of programs difficult to evaluate so it's best not to use them

Table 6: C++ Code Formatting Standards

Category	Standard
Formatting	The line length of code should not exceed 80 characters. 80 characters is roughly the right size to have the editor open on one side of the screen and have something else on the other
	Tabs should produce 2 spaces since tabs are arbitrary and can be different per computer
	Brackets should be consistently used either next to functions and such or on the line after them, not both types
Naming Conventions	Give variables names that have clear meanings to help future readers
	File names should be all lowercase with no spaces; underscores are fine
	Type names start with a capital letter
	Variable names are all lowercase with no spaces
	Constants should start with a "k" and every word in them should start with an uppercase letter
	Function names have a capital letter for each name
Comments	The code should be written in such a way with naming convention that comments should be sparse throughout the code
	Keep consistency and only use // or /* */ throughout code. It's better not to use both
	It is better to not literally describe what code does unless the code is nonobvious
	Always have file comments at the beginning of a file that describes its contents and licensing

Even if some of these standards were not followed in favor of an individual developer's preferred alternative, consistency was key when writing good readable code.

3.3.3 App Accessibility Standards

The Web Accessibility Initiative (WAI) has produced guidelines for ensuring that web content and mobile applications are accessible to individuals with disabilities such as visual impairment, dyslexia, and epilepsy. These are the Web Content Accessibility Guidelines (WCAG) [6]. Some of these guidelines could not be reasonably accommodated by our mobile application, but those which were relevant were taken into consideration. The guidelines are either A, AA, or AAA quality, with A being the minimum requirements and AAA the strictest. As this app is intended for casual games and not an essential interface for any other services, and we do not have plans to commercialize our product, we were able to disregard the stricter AA and AAA requirements without significant concern, although in a few cases when their features would in general be beneficial to our users they were still considered. In some cases, we disregarded the A level requirements as well for convenience, as this is effectively a prototype design with a niche intended user base, and the A level requirements could not be easily accommodated in our time frame. For example, many guidelines specify that some aspect of a page can be programmatically determined, that is, that other programs can extract that information from our app (e.g. that the app is in

English). However, we do not expect a user to need to extract this information as it typically is only useful to individuals who are so visually impaired that the entire gaming table would be useless to them, and thus they would not be in our user base. In other cases, this information is extractable by default when using any standard development environment. Either way, we are not able to make a complete conformance claim for our end product, but we should be able to reasonably accommodate most of our expected users.

3.3.3.1 Perceivability

There are several relevant guidelines regarding the perceivability of information in our application, detailed in Table 7.

Table 7: Perceivability Guidelines

Aspect	Requirement	Accommodation
Colors	Color should not be the only visual means of conveying a piece of information	All information will be conveyed through explicit wording, although color-coding may also be used
Contrast	Text should have a contrast ratio of at least 4.5:1 for small and medium sized text, and at least 3:1 for large text	All text shall be black and all backgrounds sufficiently light
Images of Text	Images of text should not be used in place of text unless the text is part of a logo of brand name	The only image of text will be in the logo on the splash screen or in user uploaded images beyond our control

Other perceivability guidelines ensure that sound is not disruptive to users and that any images or sounds which contain essential information have corresponding transcriptions to allow those with audio or visual processing difficulties to have an alternative in a medium they can understand. However, any map images which will be used in the game will be uploaded by users, and we may reasonably assume that a user will not upload an image that they cannot distinguish.

3.3.3.2 Operability

There are several relevant guidelines regarding the operability of our application, detailed in Table 8.

Table 8: Navigation Guidelines

Aspect	Requirement	Accommodation
Titles	Each screen has a title describing its topic or purpose	All menus will have a top bar labeling the current menu
Link Purpose	The purpose of any link or button can be determined from the label text alone, except where the purpose is ambiguous or general	All buttons should have straightforward labels (max 5 words) which are understandable by experienced tabletop players
Focus Visible	Any keyboard interface has a mode of operation where the keyboard focus indicator is visible.	Any keyboard interface will either expand to fill the screen or highlight the typing area

Other operability guidelines are related to keyboard usage and reducing the risk of inducing seizures with flashing lights. However, we will not be developing our own keyboard, so the keyboard interface will be determined by the user's phone's settings and thus we will not have any control that would allow us to meet these guidelines. Further, we will have no flashing lights or images in our app, and any changes in display will be prompted by the user's touch input, so there should be no concern about the timing of flashes. The only exception would be the user changing menus too quickly, but we rely on the assumption that if a user knows they are prone to seizures it is reasonable that they would not cause flashing by tapping quickly anyway.

3.3.3.3 Understandability

There are several relevant guidelines which ensure information in our application and its functions are understandable to users, detailed in Table 9.

Table 9: Understandability Guidelines

Aspect	Requirement	Accommodation
Abbreviations	A mechanism is available for identifying the expanded form or meaning of abbreviations is available	The expansion of any abbreviation used in a label/button will be provided when the label/button is pressed
Labels / Instructions	Labels or instructions are provided when content requires user input	Any input will be labelled in accordance with the standard labels of tabletop games when available, and instructions provided for table-specific inputs
Error Identification	If an input error is automatically detected, the item that is in error is identified and the error is described to the user in text.	When an invalid input is given, such as an alphabetic character in a context where only numeric input is reasonable, an informative error box will be displayed
Help	Context-sensitive help is available	When possible, an informative pop-up corresponding to the currently considered action will be displayed

Other understandability guidelines are related to ensuring the layout of the app does not change significantly in an unpredictable fashion that would disorient the users. As any menu will either expand or replace the screen only when the labeled button to access the menu is pressed, and a button to return to the previous menu will be available, there should be no such issues.

3.4 Realistic Design Constraints

There are multiple different realistic design constraints which we had to be aware of and take into account during each stage of our project. These design constraints are different from the standards that we have described previously. This project is considered a prototype for our design, so if we did not include all standards for the implementation, then we would could still make a functioning project. Those standards are meant for cooperation between different engineering teams and for implementation, which meant easier compatibility with hardware components. While the hardware component standards would be a pain to ignore as compatibility would be up to our team to get

working correctly, we could still manage. Software standards on the other hand could be mostly worked around if necessary since we do not plan to make this product commercially available.

Standards make cooperation easier between other groups, but constraints are absolutes. Constraints must be taken into account and while there could be some wiggle room in some cases, failing to take these into account would have meant the failure of a project. While failing to use these realistic design constraints would mean failure, the understanding of these constraints helped with the design criteria, quality of the project, and decision making. Classifying certain criteria helped us to understand which constraints apply to each level of the engineering requirements. These constraints can be broken down into a few general topics that will be covered in the following sections such as:

- Economic
- Time Management
- Environmental
- Social
- Political
- Ethical
- Health
- Safety
- Manufacturability
- Sustainability

Generally, design constraints are issued by the customer, by a development organization, or are external regulations such as laws. They are mostly created to meet certain criteria or to make sure the product meets specific requirements that will allow it to go commercial. Since we were making our own project, we had to act the part of the customer when thinking of realistic design constraints. There are the constraints that do not change, such as safety or ethical, whether a solution is home-built or company developed. Constraints limit the solution for a problem, therefore before making allowances and changing a solution to fit a constraint, it is imperative to make sure that the constraint needs are followed during the design process. The addition of even one more constraint can drastically change a solution and require many more hours of creative and difficult engineering to adhere to. Thus it was important to classify the design constraints into the categories mentioned above to make sure that they were necessary and applicable to our current project.

3.4.1 Economic and Time Constraints

With no financial sponsorship for our project, all financial costs and burdens fell upon our team of four people. When we discussed what our project budget should be, we decided that it should ideally cost under $600, and absolutely not cost more than $1000 for designing, testing, and final implementation. Since we were making this project ourselves, we decided that the designing phase should not constitute more than $100 of our budget. This included having to cut specific materials such as the acrylic or other unforeseen manipulations of materials that required specific tools that we did not have access to. Testing was allotted $200 where we would test a variety specific parts to see if they would work with our project. We could also purchase some redundant inexpensive parts since shipping would cost more if a part were to break or malfunction and need replacing. The shipping cost for most technologies used constituted a significant portion of our budget. We

projected that the final project, if commercially made available, could be made with the budget of around $450 with the acquisition of cheaper parts. Mass production companies can acquire cheaper parts, compared to what we have to work with, because they purchase items in bulk. Since they can acquire items through bulk purchase, much of the shipping costs that we can to pay would be cut down significantly.

Since we have no sponsor, we needed to try and get cheaper products either through deals or accepting slightly worse quality products to use in our project. The projector was definitely our biggest single expenditure, thus we had to try to minimize the expense while not compromising on the performance of the projector. We secured a projector by looking at deals during Black Friday and Cyber Monday, as well as options for used projectors. By comparing projectors that met required specifications for our project we were able to diminish the economic burden placed on us. There were many different projectors that we looked at, as stated in this document, but since this was the most expensive overall part of the project, if the projector failed to meet specifications and performance results, the expenditure would significantly increase as another projector would need to be acquired.

Subsequently, since customers do not have to cover the financial cost of designing and testing, we assume a final product would be cheaper to mass produce. Our expenditure for designing the project was based around materials and tools that we realistically did not have cheap access to. For example, the acrylic had to be cut with a specific tool to accurately and safely change the dimensions in a way that the acrylic will not be damaged. Acrylic is not delicate but can crack easily if an amateur attempted to cut a piece thus we must expend some funds for professionals to cut the pieces to a high degree of accuracy. While this seems like an unnecessary expenditure, the cost for cracking an acrylic glass can severely negatively impact our financial situation. A company that might mass produce these tables would already have pre-made acrylic glass to fit each table or have a cheaper way to cut the glass through a company contract.

The financial cost of testing would also not be pushed onto the customers as testing should be a large expense at the development phase and then less burdensome when trying to update a product. Most of our testing budget must go into testing to see if certain products work with the overall design we are envisioning. Items like LEDs, speakers, IR Cameras, microcontrollers, and cooling fans all fall into this category. While we did do extensive research on products to ensure performance and cost analysis, compatibility may be a problem as we cannot always foresee how each product will interact with each other in a real world test. While these products do have recommended compatibility charts, even then problems could occur when trying to connect to the software.

The time given to our group to design, build, test, and finalize this project was two contiguous semesters of college. For us, the time schedule began around late August 2019 and was completed by April 2020. The project must be fully functional and meet engineering specifications described at that time. The table must be able to track individual character pieces through object detection, and the screen must be a touch display and be able to accurately display the game data within certain specification described in this document. The timeline of goals and milestones has been created to help us follow through with the time constraint given and be able to deliver a working product.

While it does seem as though we have 8 months from August 2019 through April 2020 to get the product meeting engineering specifications, the time we have to work on it was not so easily

defined. A company that would be working on a project such as this would likely dedicate personnel to focus on development of their one project and nothing else, but we do not have the time to do so. Each of us in our Senior Design group has other obligations that we must attend to apart from working on this project. From work, to other classes, or other responsibilities, we all have duties that take up time from working solely on our project. Furthermore, complications arose from restrictions imposed on shipping, travel, and use of University facilities as a result of the COVID-19 crisis.

3.4.2 Environmental, Social, and Political Constraints

Apart from the financial and time constraints placed on us during this project, there were many factors such as environmental, social, and political constraints that we had to contend with. Since our smart gaming table is planned to be used by people who normally play board games inside, we designed and prototyped our table to be safely used indoors. As we were building this prototype in Florida, the conditions outside are less than favorable for electronics. The humidity is high and can damage electronics that are not specifically designed to resist such extreme conditions. The heat is also a problem as we do not want our electronics running too hot since they could potentially be damaged. Since we use this product indoors, with air-conditioning, we can expect the ambient temperature to reach no higher than 85° Fahrenheit (29° Celsius), and the humidity can be expected to be no higher than 20%. Florida sometimes reaches outside temperatures upwards of 95° F (35°C) and humidity levels around 74%. Although the prototype could be modified later to protect against the harsh Florida climate, it would also require more resources to produce.

Our smart gaming table's electronics are not weather protected since we would have had to design those parts to work outside by ourselves, and this would impose extra constraints that would have severely increased our expenses and necessary structural integrity. The printed circuit board especially is at risk from the humidity and high temperatures of Florida. It is inside the table, but gaps for fans an access to the interior mean that connections and microcontroller are sometimes exposed to the open air. As described in this document, we have a cooling system with fans inside of the table that will keep components at a safe temperature. While the fans will help minimize the risk of overheating, the humidity levels can make it so that water accrues inside the fan and may be blown or drip onto sensitive components and connections. Our speakers' output could become muddled due to the humidity and the blob detection might become compromised due to condensation on the acrylic sheet. While being in an air-conditioned building does remove some of the constraints of prototyping in Florida, if the climate outside is severely harsh then indoor conditions may also be affected.

Social constraints for our current project mainly deal with consumer wants and copyright laws. As social constraints can be based on cultural preferences, whether a product will actually be used by anyone must be taken into consideration. Even if a new and innovative product solves a problem better, if no one takes an interest in it then it will become a failure. For our project, we had to look at certain problems that people who play tabletop games face and if they would be willing to spend around $500 on our product. One of the main problems that new players and sometimes veterans face is trying to keep track of all the information that goes into the game, from their own character stats, abilities, and items to visualization of the game world. The information of individual players and their attributes is easily tracked and managed thanks to our companion app, severely lessening the load of mentally tracking such data. The app can also help lower the learning curve for newer players for a more welcoming experience. We believe the price is something a group of players

can split to lessen individual expense since the table would presumably be used every week for a gaming session.

Since we designed our own circuit board layout and are not claiming the electrical components to be manufactured by us, we safely do not violate any copyright laws on that end. Our object detection software has been labeled to be open source and can be used with individual projects. With the exception of free use UI libraries, all software was written by our group. The main constraint for copyright comes from specific game companies, who own the rights to particular terms and game mechanics associated with their games.

As we were not designing anything that is used or potentially going to be used by the military or government, the political constraints for our smart gaming table are minimal. We do not predict that our table will have any impact on any foreign government either. The only use for this smart gaming table should be entertainment and thus there should be no political constraints associated with the project.

3.4.3 Ethical, Health, and Safety Constraints

Our prototype must adhere to ethical, health, and safety constraints that could be problems when dealing with a prototype. Since our prototype is our initial design and it was some of our group members' first time working with soldering electronics, we had to be careful when dealing with these components. For this project, the main constraints in this section are dealing with the storing and collection of player data, the ignorance of electrical safety, and the dangers of exposed circuitry being meddled with by people other than our group, as a consumer might not know the safe way to use any open electrical equipment.

Since we made our game capable of being saved and picked up again at a later time, for a game that is played in for multiple play sessions, we must ensure that we cannot see any personal user data. Since there are many ways for personal data to be stolen or even misused by the creators of an application, it is important to keep to the highest levels of ethical standards when dealing with personal data. A database created by developers should not have access to high-risk personal information such as credit card numbers or passwords. All sensitive data should be encrypted and sent over secure network lines so people cannot steal the information while in transit. If a developer is using a database, sensitive data must also be stored as encrypted on the database so anyone with access to the database cannot see the sensitive data.

Our group uses Bluetooth to form connections to our mobile application which does not require the use of a web database. All storage of the game, assets, and player information is done directly on the user's personal computer. The game executable creates folders for individual player information that can be reused next game session. Using this method means that we do not need for players to create accounts as they will be able to select their in-game character from a list stored on the main computer. Since no sensitive personal data is being sent through Bluetooth, there is no need to encrypt data access from our mobile application to the host computer.

Our principal health constraint for consumer use in this project is how we deal with our ignorance when dealing with new electrical components that we have never worked with before. The equipment that we are using is not high voltage or high current as we will be using an already made wall adapter to supply our power. The wall adapter helps us circumvent the dangerous engineering requirement of working with potentially deadly levels of electricity. By using a preexisting wall adapter, we also make sure that any users of our product do not seriously harm

themselves, which may be a concern if we were to make an adapter. Any electronics are also be protected or concealed enough to the point that people cannot accidentally bump their legs underneath the table on an exposed wire.

Constraints on substance safety must also be followed to try and minimize the risk to ourselves. While the exposure of wires and electrical equipment is a safety hazard for consumers, we also had to protect ourselves when dealing with the equipment necessary for our project. As a step for compliance with safety constraints we had to use materials that were in compliance with RoHS standards. RoHS stands for Restriction of Hazardous Substances, and there are plenty of electronics bound by them. The RoHS bans the excessive use of certain materials that can cause serious harm towards humans. The main elements that the RoHS considers dangerous substances that might have been used in our project and their maximum levels are described in Table 10 below where ppm is parts per million.

Table 10: RoHS Restricted Substances

Element	Maximum levels
Cadmium (Cd)	< 100 ppm
Lead (Pb)	< 1000 ppm
Mercury (Hg)	< 1000 ppm
Hexavalent Chromium (Cr (VI))	< 1000 ppm
Polybrominated Biphenyls (PBB)	< 1000 ppm
Polybrominated Diphenyl Ethers (PBDE)	< 1000 ppm
Bis(2-Ethylhexyl) phthalate (DEHP)	< 1000 ppm
Benzyl butyl phthalate (BBP)	< 1000 ppm
Dibutyl phthalate (DBP)	< 1000 ppm
Diisobutyl phthalate (DIBP)	< 1000 ppm

While we may not have been exposed to relatively large quantities of these substances, the smaller amounts could still be harmful if misused. Cadmium is mainly exposed to manufacturing and construction workers, but can also be encountered by people who recycle electronics. While we did not handle damaged electronics parts, we had to throw away old or failed parts in appropriate recycling containers to ensure cadmium is not grouped with regular trash which would endanger workers. Electrical engineers often use lead to solder electrical equipment and must be careful with skin contact and contact with open sores. Lead poisoning can lead to anemia and kidney damage if in high enough dosage and can lead to dizziness and weakness for lower exposure levels. Soldering can already be dangerous without the mentally addling effects of lead that we must look out for. Low levels of mercury can be found in equipment we are using such as switches or batteries. Similar to cadmium, Cr (VI) is usually exposed to people during welding but can show up when electronics get to unsafe hot temperatures. PBB and PBDE are common in electrical products that need to be flame-retardant. The last four elements, DEHP, BBP, DBP, and DIBP, are all used as insulation plasticizers that make polymers more flexible and increase thermoplasticity.

Apart from elements and substances that could be harmful when developing our prototype we had to consider the harm that the electrical components could bring. Speakers can play music and sound effects chosen by the lead player of a game, but we had to put safe limits on sound output or make sure that the speakers cannot produce high decibel (dB) levels that cause permanent

hearing loss. The safe noise level to minimize hearing loss over 8 hours is 85dB; 85 dB is roughly equivalent to the sound of a boiler room. Hearing loss significantly increases as sound levels go upwards of 85dB, so to be safe we had to constrain our sound level output to never go above 80dB.

The electronics should not be able to run to high enough temperatures as the components and people can come to harm, thus we use cooling fans to reduce the temperature. Cooling fans for electrical components run at around 4000 rpm (rotations per minute). Considering the plastic fan material and the speed, the possibility of permanent injury with this type of fan is low, but safety precautions still had to be taken into account. Hair and other electrical components such as wires could get caught in a fan, which could jam the device or simply break it outright, while potentially causing minor to moderate harm to the user. Our table is made out of wood, but temperatures of our electronics should be nowhere near enough to burn or blacken the wood as most wood start burning at around 300° C, so handling of the table will be safe as long as we keep in mind the weight and size when transporting it.

While working with light sources and infrared technology, it was important to consider the effect that these technologies have on the human body. Most projectors give out a light with a power output of around 6kW (kilowatts), which can easily damage the eyes of someone looking at the projector. Looking directly at the device was not a major concern, but accidently pointing the projector at someone else could cause serious harm. While working on our table, we were also careful when looking from top to bottom if we removed the diffusive layer for whatever reason. After researching IR light, we found that since IR light produces lower energy photons than visible light, it is not harmful to humans to view the the IR Illuminators we are using directly.

3.4.4 Manufacturability and Sustainability Constraints

Manufacturability deals with designing a product in such a way that parts can easily be made or acquired and assembled into the final product. Manufacturability constraints are mainly adhered to in the case of a product that is mass-produced, but they are also important when trying to reproduce other people's work and for simplicity of design. For constraints for our group, manufacturability meant that we had to think about our part acquisition and assembly of our table. The processes that manufacturing consists of after designing is finished are:

- Parts Receiving and Processing
- Subassembly
- Final Assembly
- Inspections and Testing
- Packaging and Shipping

A company must buy or make all of the required parts which are then cataloged and made ready for initial assemblies. To make this process easier, we tried to minimize the number of parts required for our project, which helped reduce this step. The reduction of parts also helped lower prices as fewer parts means that manufacturers could reduce shipping costs of bulk purchases. The next step was subassembly wherein the initial parts were assembled into smaller completed parts such as a microcontroller connecting to a cooling fan. This assembly is not the final product, but it is also easier to test some functions at this step before final assembly. During final assembly, all the smaller assembled pieces were fitted and connected to form the final product. The final assembly in a production line is like that of our own final prototype, so making our final prototype easy to assemble was preferred.

Comprehensively testing the functions of the product was the next step, which involved checking for any issues resulting from mis-assembly or defective parts. Inspections made sure the product adhered to health, safety, and other constraints previously mentioned. Packaging and shipping must also be taken into consideration when building any device nowadays. Most products bought by consumers are shipped to homes all over the world, so the product must be robust enough to survive the trip. This means utilizing parts that are sturdy enough to survive some jostling or encasing the more delicate components into protective cases that shield them through shipping and can be left on during normal use. A table would have problems during shipping as the joints of any structure composed mostly of empty space are easily in danger of being damaged, so packaging must fill the shipping box with soft material and handle with care. To make shipping easier, we must make sure all our components will not fall off or out of the table, unless intended to be assembled by the user in their home.

Sustainability constraints address the need to use components that meet the needs of the device but can still be easily found currently and in the future. If the resources are extremely scarce, or if parts of the product being damaged mean the entire device must be replaced, then the product does not have good sustainability. Some of the parts that we used, such as our IR camera, butchered from a PlayStation Eye, may not be found in the future. Even though these exact parts may not be found, our smart gaming table's design should still work if another IR camera is used. The cost of older electrical devices is always decreasing as technology advances, so finding an IR camera in the future will likely be easier than it is now. Companies can also manufacture their own projector, or since the table does not use all the functions of a regular projector, they can make a device that meets the specific needs of our table.

Our smart table has entirely replaceable electronic components that can be more or less easily interchanged if a part malfunctions. The LEDs, fans, projector, and speakers are all easily acquired, although some parts are not inexpensive. The only product that will be difficult for the consumer to acquire in the future will be our own printed circuit board, but since the documentation of the circuit board is included with our document, the board can be printed again. Since these parts are easy to acquire for students like us then companies would have an easier time obtaining these products with a bulk purchase of replacement parts.

4.0 Previous Projects

There are a few similar smart gaming tables that have been built previously that we were able to learn techniques and mistakes from. While their games are not the same, much of the technology, or at least their concept, is similar enough to what we have available to use in our project. There has been enough advancement in technology since the time these products were built that we had an easier time acquiring better technology for better prices than what these smart tables used. The technologies that have most advanced in recent years for this type of smart table project are the projector and the app development environment for phones. The cost of projectors has significantly been reduced ever since mini-projectors and home projectors have become more popular and affordable to the general public. Apps are also easier than ever to develop with tutorials and extended libraries from community users and from the standard libraries themselves.

We didn't want to focus too much on smart tables from companies with much more resources than we could possibly come up with for this project, so our research for similar products are built by small groups only. Two of these similar smart gaming projects, Multi-Touch Poker Table and Smart Table, are from UCF students that were in Senior Design in years past, like our group is now. We thought that we had the most to learn from fellow students in similar situations to us. They may have had more personal funding or prior knowledge, so it wasn't be a perfect comparison to what we were trying to make. The final project is from a DIY enthusiast that had some prior experience with hardware and software, called Magic Frame: Turn Everything into a Touch Area.

4.1 Multi-Touch Poker Table

When researching techniques for multi-touch sensing we came across the Multi-Touch Poker Table [7] by UCF Alumni Christopher Herod, Nathaniel Boucher, and Raeginald Timones done for Senior Design of Fall 2009. Their objective was to create a low-cost smart gaming table capable of playing Texas Hold'em Poker with a companion app to go along with it. Although not exactly what we are trying to design and create, since our project will have object detection for character figures, we figured it was worth examining their design and implementation for a smart table. Like their project, we are planning to have a touch screen display, but we are also trying to create object detection for ours with open source software for blob detection. While the idea of only having digital tokens for our game characters did come up for discussion, we believed that with more modern technology that we could make it work. For our smart table, we made an Android OS companion app similar to their iOS app for individual players. Table 11 compares what the Multi-Touch Poker Table team used for their design in comparison to the technology we used in our own smart table. While just comparing parts is not ideal, we can get a sense of the starting point of each smart gaming table and their designs.

Table 11: Smart Table Feature Comparison

Feature	Multi-Touch Poker Table	Smart Gaming Table (ours)
Multi-Touch Display	Allows for multiple finger touches at once and dragging digital tokens on screen	Will also allow these same features with the addition of object detection and tracking of character game figures on top of the screen
Projector	Minimum screen resolution of 800x600 with adaptive light output depending on ambience in room	Minimum resolution of 720x720 since our game boards will be square. Light sensor to automatically adjust the brightness of the screen or of the projector's output
IR Camera	Minimum resolution of 640x480 with a frame rate of at least 30FPS	Same resolution but minimum FPS of 60
Computer	Their project has a dedicated PC built inside of their table that runs everything for the game	Our plan is to have one of our home PCs separate from the table since the object detection will most likely take more processing power than we can afford for dedicated hardware with our budget
Table	Cooling system and phone charging station with USB 2.0 inside	Ours will also have dedicated fans for the microprocessor and components for the table. It will also include speakers, LEDs, timers, and buttons for interactions and in-game immersion.
Wireless Device Communication	IEEE 802.11g standard Wi-Fi to connect to iPhones and have input and output data from them	Bluetooth communication with Android OS device for communication with the game

While our idea for having a smart gaming table which uses a touch screen is nothing novel, as seen in this previous project, the idea of having physical object interactions combined with the touch screen will pose a new challenge. Even with open-source software for the object detection, we were still the ones setting up the hardware and trying to make sense of what the detected objects mean for our game. While we could have tried to acquire a projector with much better resolution, since in comparison to the resolution of the Multi-Touch Poker Table there is not much of a difference, there were expenses and over-engineering issues to consider. The cost of projectors jumps up significantly with each significant increase in image resolution. We decided that since our game is less reliant on image quality and 720 x 720 is already sufficiently high quality, we could save money by getting a cheaper product than what was available 10 years ago.

There was no need for a better IR camera for this project since it already does the job it's meant to for a cheap price and getting a better one will not necessarily have any noticeable effect on the final product. The Multi-Touch Poker Table group also decided to have a dedicated PC built into their table which made it seem much more elegant but increased component cost for prototyping. If we were to find out that the PC our group member provided had a problem running the software, we could easily try one of our other group members' PCs instead of swapping components in the table. If this were a product to be mass produced or even produced on demand then having PC components be part of the table would be required, but since the smart table we built is our prototype, we decided that a separate laptop computer would be easier to test with.

4.2 Smart Table

The Smart Table [8] was another smart gaming table designed for Senior Design by UCF Alumni Chris Rodrigue, Phillip Murphy, Jonathan Lundstrom, and Ryan Mulvaney in Spring 2017. This project demonstrated some of the functional aspects of the software that we want to have available in our gaming table. This project was more of a utility or smart feature add-on to an already existing product. These type of products for general use can be compared to fridges with touch screens or Wi-Fi thermometers. They took an existing product that has little to no interaction with other electronics around it and gave it options for interactivity and smart interactions between devices. While their main focus was not building up the smart gaming table with one game in mind, the techniques used helped us understand our own project better. Key interactions that we could learn from them were how they got sensors and LEDs to work with and affect the output display image.

The Smart Table group's project had several features including timekeeping, environmental sensing, current weather status, and some simpler games like Snake. They used Bluetooth for their communication option for input and selection of what to display on screen. Their project worked similarly to a 16x2 LED display that people often use with DIY projects. The screen of their table was composed of a grid type pattern of square blocks that has a RGB LED backboard to it to display the image. While the LED technique might be different to the projector idea we had for our project, we also needed to create individual squares for our game. Similarly, each of our squares represents an area for the game matrix to function on. These blocks of ours have more functionality than display like in the Smart Table project as they also determine the characters' options at that block.

4.3 Magic Frame: Turn Everything into a Touch Area

This DIY project to turn any flat surface into a touch screen was created by user Jean Perardel at hackaday.io. [9] While not entirely reliable, it is a way of touch screen that we could get to work with object detection in a grid as well. The surface that he used was a flat screen TV that would have been easier to use and develop for than a projector and creating our own touch screen with acrylic. The technology used for this DIY project is based on having IR LEDs on one side of the table emit light and having light triangulation with IR receptors on the other side of the table. The IR receptors check for the light from the LEDs and if it cannot see any light then an object is blocking the path. With enough of these IR LEDs and receptors you can triangulate the location of an object.

The problem and the ultimate reason that we decided to seek alternative solutions to this is the lack of accuracy in this method of object detection. In tabletop games multiple characters are on the screen at the same time, so detection of specific characters is an issue with this method. There can be multiple characters physically on the screen that could block the position of another character

if they are close by. Similarly, for our grid game, each character needs to stay in their individual grid block, so we need to keep a record of which character is in each block. This would be difficult to program as the squares are quite small and the light triangulation method might result in ambiguous locations leading to incorrect game data.

4.4 Similar Mobile Apps

The market for tabletop companion mobile applications is widespread and was influential for the design and implementation of our own application. These companion applications are usually only for storing your personal character information or to help lighten the load for remembering people and places in the game. The Game Master can store his planned fights or attributes of the monsters for the fight in some of these apps or create their own with specialized monster creators. On iOS and Android OS some basic apps to help keep track of such information are available, such as Fight Club 5th Edition and Fifth Edition Character Sheet respectively. There are plenty of other examples since tabletop games are becoming increasingly popular, but these emphasize what most of the companion apps are capable of. Table 12 provides a comparison of these apps' features with our intended app's functionality.

Table 12: Mobile App Feature Comparison

	Features of Current Companion Apps	Features Our Mobile App Will Have
Character Sheet	All Companion apps have a dedicated page or two that details a player's information such as attributes, skills, and abilities	We will also have a tab solely for this character sheet as it is the information players most often use in game
Attacks	More advanced companion applications bring in data of weapons and skills from reference books	We will have a template for attacks where players specify range, attribute, die roll, and radius if applicable
Inventory	Basic applications just have a tab with an expanding list as to what is in a player's inventory	Our mobile app will have predefined places to put a few items such as money and then a template to write down other inventory items.
Enemy Characters	Some apps have a compendium to look up certain monsters created by others	We can create templates for monsters so we can have more customizable gameplay
Game Master Settings	The applications are mostly made for players and as such Game Master UI settings are limited to compendiums and note taking	We will have a different UI for the Game Master so they can control the flow of the game and select whose turn it is

Because of the plethora of abilities, weapons, creatures, and character features available in tabletop games, as well as the continual expansions of many games, we believe it is better to have a template for users to input data rather than forming a hard-coded database from existing sources. We also have these templates because we must make certain structured data available to the smart gaming table for tracking game characters. Having a template allows more flexibility in what people want

the game to be like. The Game Master is given a different user interface than players so they can control multiple monsters on the smart gaming table at once. Most apps that are available are commonly informational, but we wanted to develop a true companion app that enhances and simplifies the experience.

5.0 Hardware Design

5.1 Multi-Touch Surface

An essential component of the table is a multi-touch surface capable of accurately detecting and tracking simultaneous touch inputs provided by fingertips and small objects. The inputs resulting from objects will be used to monitor the positions of characters in the game, while the fingertip inputs will direct the character's actions. Although a resistive touchscreen might have been able to meet the detection requirements, and a capacitive touchscreen could detect objects if specialized contact surfaces were created to adhere to the bases of the objects, both methods would leave the sensing apparatus more vulnerable to excessive impacts and require more advanced manufacturing techniques than an infrared light and projection-based touchscreen. Therefore, we have chosen to focus on light-based techniques for our design.

5.1.1 Available Touch Detection Techniques

Upon review of available multi-touch technology, only three methods supported object detection in addition to fingertip detection, and thus were considered for use in the table. Rear Diffused Illumination (Rear DI), Diffused Surface Illumination (DSI), and Light Triangulation (LT) are detailed in the subsequent sections.

5.1.1.1 Rear Diffused Illumination (Rear DI)

Rear Diffused Illumination (Rear DI) [10] uses a clear material (glass or acrylic) with a diffusive material adhered to either the top or bottom as the touch surface. The surface is embedded as the top of a closed box, and infrared illuminators, in the form of LEDs or similar emitters, project light onto the surface from below, illuminating the surface as evenly as possible. The diffusive material allows partial transmission of the IR light, while the rest is reflected downwards. The touch of a user's finger, or an object placed on the surface, reflects the otherwise transmitted light downwards as well, creating a bright spot known as a "blob" of infrared light, which can be seen up by an IR camera at the bottom of the box. Tracking software can then process the blob-filled image to create a map of touch input locations for use by the rest of the game software. This process is illustrated from a side view in Figure 4.

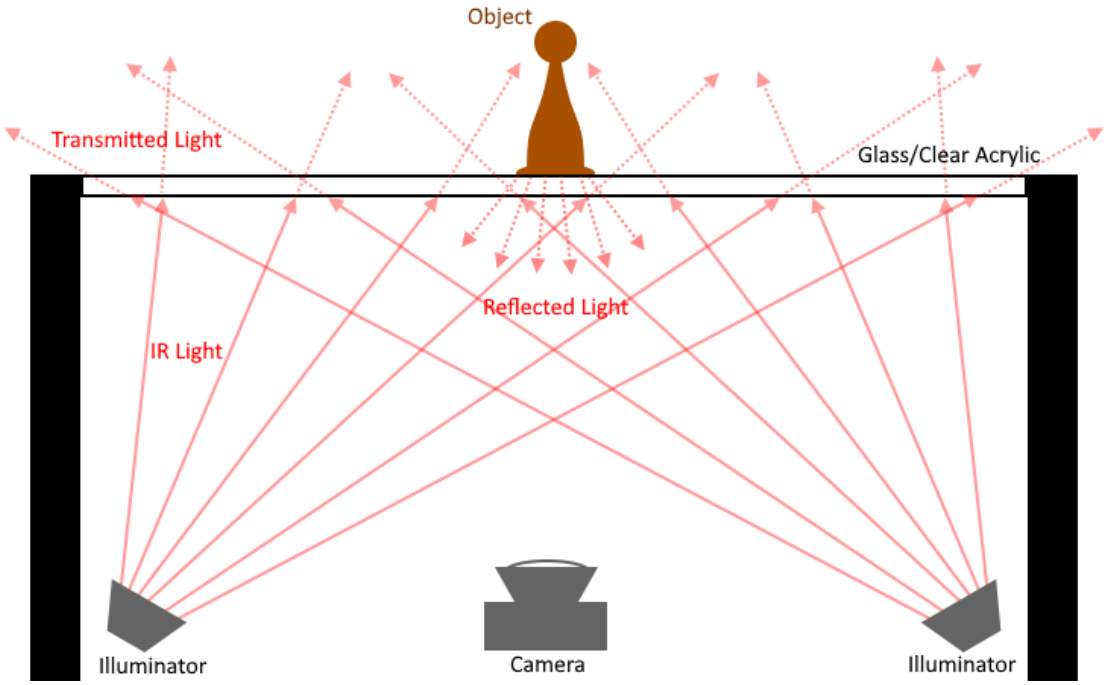


Figure 4: Rear Diffused Illumination Technique

Rear DI's main advantages lie in the low price and availability of the required materials, and the simplicity of the illumination method. Additionally, there is well-tested open-source software available for blob detection and tracking that would simplify the development of the touch/object tracking functionality. Disadvantages lie in the need for a closed-box projection system, difficulties in achieving even illumination and thus equal detection rates across the surface, the possibility of hot spots (false inputs), and the constant low-level reflection decreasing the contrast of blobs, making detection difficult.

Although a related process in the form of Front DI, in which illuminators are placed above the screen and inputs are detected by the shadows cast under the touchscreen by an object's presence, is also capable of multi-touch object detection, the inherent misdetections and dead zones caused by hands reaching across the table to move objects or touch specific locations render it impractical for our purposes.

5.1.1.2 Diffused Surface Illumination (DSI)

In Diffused Surface Illumination (DSI) [11], similarly to Rear DI, a specialized acrylic surface with a diffusive material adhered to either the top or bottom as the touch surface. This special acrylic is embedded with minute reflective particles. Then, when the acrylic is illuminated from an edge by IR LEDs, IR light is internally reflected by the particles and interfaces of the acrylic with air, diffusing evenly through the material out to a distance determined by the quality of the acrylic used (at most about 1.5 feet from an illuminated edge). When a finger or object is place on the top of the surface, IR light is deflected downwards. As in Rear DI, this creates a visual blob which can be detected by an IR camera below the screen. This process is illustrated from a side view in Figure 5.

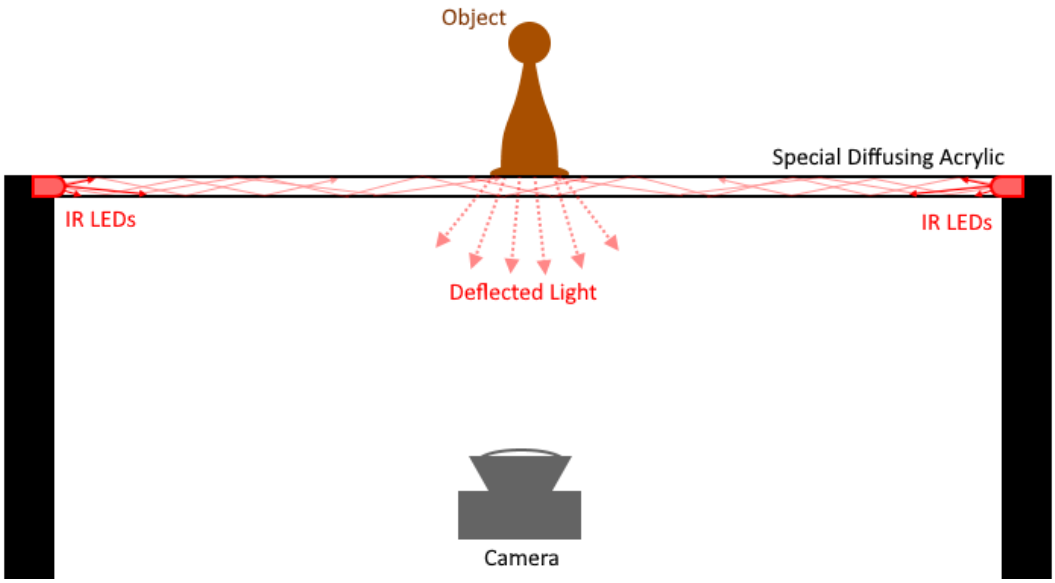


Figure 5: Diffused Surface Illumination Technique

DSI's main advantage is the uniform illumination of the surface, which makes tuning the detection software simpler and more reliable. Further, the same open-source software available for blob detection for Rear DI can also be used for DSI. Disadvantages lie in a similar need for a closed-box projection system, the low level of deflected light resulting in low-contrast blobs, the limited size based on diffusion distance of the acrylic, and the high expense of the specialized acrylic. Depending on the diffusion distance required, and thus the quality of the acrylic, the cost can be between 5 and 40 times that of a glass or clear acrylic sheet of the same size, which can easily increase the cost of the surface by hundreds of dollars given the 4 – 9 square feet required.

5.1.1.3 Light Triangulation (LT)

In contrast to the previous two techniques, light triangulation [9] has no requirements for the material of the touch surface, as all hardware other than the visual display is necessarily placed above the screen. A strip of IR LEDs is placed just above the edge of the active area of the surface and shine across to a strip of sensors on the opposite side of the table. Each LED is lit briefly in sequence, and the sensors which can detect each LED are recorded. Any object or finger on the table will block the light between only a few combinations of LEDs and sensors and knowing those combinations we can extrapolate a region in which the blocking object must lie based on the geometry of the array. With high enough numbers of LEDs and sensors, high resolutions can be achieved. This process is illustrated from a top-down view in Figure 6.

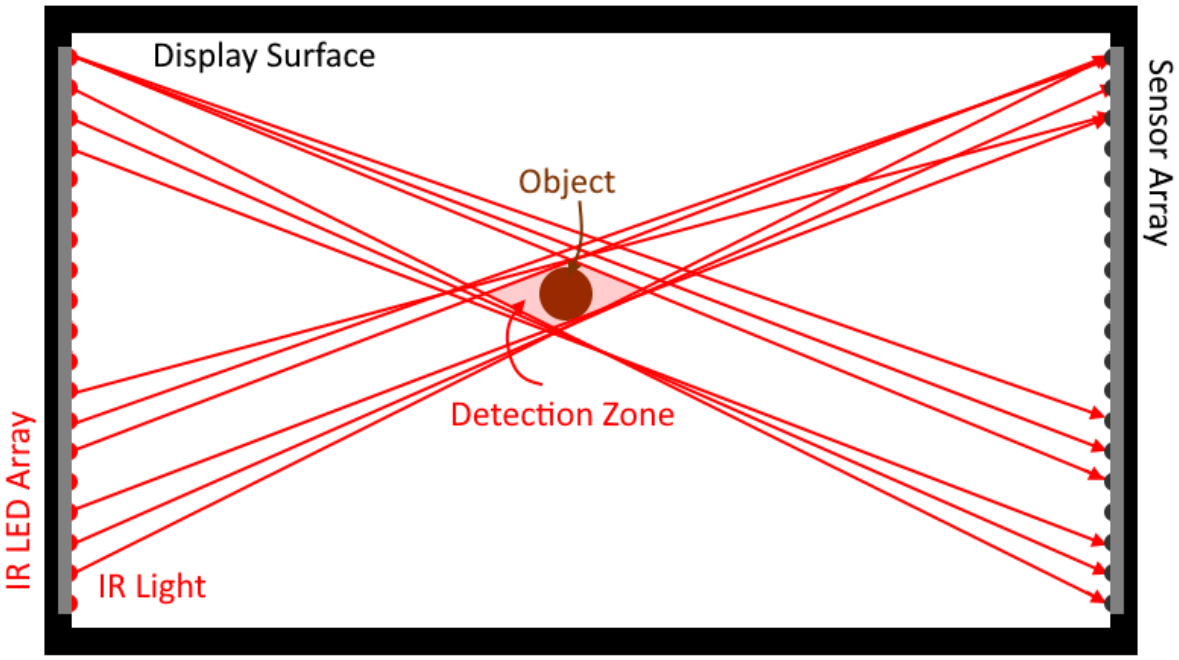


Figure 6: Light Triangulation Technique

LT's main advantage lies in the lack of limitations of visual display options, which would allow the use of a cheap television a projector, and no closed box requirement. However, there are many disadvantages to the technique. Locations near the edge of the screen may not have high detection accuracy, or be complete dead zones, unless the LED and sensor arrays are extended beyond the limits of the active touch-surface area and/or modified to unusual geometries. Objects which lie close together in groups may become indistinguishable as they block the same LED-sensor pairs. Additionally, the standard game figures which are intended to be used with the table typically have short, flat bases, and unusual shapes, as they represent humanoids, animals, and other creatures, so that they may not properly block all LED-sensor pairs that would be required for accurate detection. The sensor array would be more complicated and expensive when compared to a single IR camera as used in Rear DI and DSI. Further, the technique is not widespread and although some pre-existing documentation and software from previous projects using the technique exist, there is very little compared to the plethora of information on Rear DI and DSI. Finally, the large polygons of the generated detection areas are guaranteed to provide a high level of inaccuracy compared to the diffused illumination techniques, in which the blobs typically line up closely with the edges of the contacting object/fingertip.

5.1.2 Touch Detection Scheme Selection

To determine which multi-touch detection scheme would best suit our needs, a weighted decision matrix was used, seen in Table 13. The matrix ranked the possible methods in several categories and weighed these rankings by a chosen importance level of the category. Rear DI had the lowest score, as well as the most first-place and fewest third-place rankings and was thus selected as our multi-touch detection scheme.

Table 13: Multi-Touch Technique Decision Matrix

Category	Importance	Rear DI	DSI	LT
Detection Accuracy	3	2	1	3
Display Surface Options	1	2	3	1
Cost	3	1	3	2
Ease of Implementation / Available Resources	2	1	2	3
Total		**15**	**19**	**22**

5.1.3 Touch and Display Surface Materials

Once Rear DI had been selected, it was necessary to choose materials for the touch and display surface. For our clear material, we could choose between glass and clear acrylic. The clear acrylics we could acquire were lighter and stronger than glass, at roughly a 50% increase in price, as shown in Table 14. The improvements in structural integrity were judged to be worth the price, especially considering the lack of experience we have with table manufacturing, and a clear acrylic surface was selected. OPTIX Acrylic was initially selected for its reputation and minimal thickness, as we intend to place the diffusive material under the acrylic to protect it, and a thick layer means an increased distance between the touched surface and the diffusive surface, which may lead to increased blurring or distortion of touch and object placement inputs. However, the OPTIX acrylic was so thin than it would warp over the wide surface area of the table, and a thicker acrylic had to be special ordered. For this purpose, we switched to the distributor Professional Plastics, as the company could cut to our exact specifications to extremely fine tolerance and had an excellent reputation, along with comparable material cost after shipping.

Table 14: Touch and Display Surface Material Options

Material	Cost	Source	Status
Gardner Glass Products 30-in x 36-in Clear Glass	$18.48	Lowe's	
30". x 36" x .094" Clear Glass	$17.58	Home Depot	
OPTIX 36" x 30" x 0.093" Acrylic Sheet	$32.78	Home Depot	
OPTIX 30" x 36" x 0.08" Clear Acrylic Sheet	$26.49	Lowe's	Tested
0.250" Thick Clear Cast Acrylic Paper-Masked Sheet	$51.99 + $31.95 shipping	Professional Plastics	Selected

For a diffusive surface, some purpose-made rear-projection materials were considered, as well as drafting paper, which has been shown to be effective in previous projects by hobbyists and senior design groups. Considered options are detailed in Table 15.

Table 15: Diffusive Material Options

Material	Cost	Source	Status
30” x 42” x 0.003” Drafting Film Matte, 2-Sided	$8.16	BlikArt	Selected
24” x 36” x 0.005” Drafting Film Matte, 2-Sided	$6.78	BlikArt	Tested
Grey Rosco RP Screen with Finishing	$29.50/ft^2	Full Compass	
36” x 36” Digiline Contrast Projection Film	$52.36	IFOHA	
Carls Gray Rear Projection Film	$64.95	Amazon – Carls Place	

Purpose-fabricated rear-projection materials were found to be exceedingly expensive, too large for our purposes and not easily trimmed, or both. Concerns about possible tears or wrinkles in drafting film were mitigated by the ability to fortify the material with clear silicone, which was cheaply available. Comparatively, drafting film was a negligible expense and if after testing/assembly drafting film proved insufficient for our rear projection needs, it would not be significantly more expensive to order a professional material later than if we had started development with such a material. Thus, drafting film was selected as our initial diffusive material, and was found to be sufficient in testing.

5.1.4 Illumination

To provide the necessary infrared illumination for the Rear DI technique, several pre-built IR illuminators and IR LEDs were considered. The most promising options are detailed in Table 16.

Table 16: IR Illumination Options

IR Source	Cost	Source	Status
EMITTER IR 850NM 100MA RADIAL	$0.39 - $0.50	Digi-Key	Tested
EMITTER IR 940NM 65MA 0805	$0.1575 - $0.49	Digi-Key	Tested
EMITTER IR 850NM 65MA 0603	$0.522 - $0.67	Digi-Key	Tested
JC Infrared Illuminator Silver	$11.99	Amazon - JCHENG SECURITY	
Tendelux 80ft IR Illuminator	$19.98	Amazon - Tendelux	Selected
850nm 6 LEDs 90 Degree Wide Angle IR Illuminator	$21.99	Univivi	

Pre-built illuminators were generally intended for use with night-vision security cameras and had power supply interfaces that would be difficult to integrate into our design, but the Tendelux illuminator came with an adapter for standard wall outlets. Pre-built illuminators were liable to produce issues in the form of hot spots on the screen's surface, resulting in false touch events, but this could be corrected for to some degree with careful placement and adjustments to angles of vision. IR LEDs and emitters on the other hand provided reduced illumination per unit, but greater flexibility in placement, which could reduce the chance of hot spots. However, given the number of other components that required specific placements when installed in the table, and the risk of crushing LEDs when adjusting components if an array was placed on the bottom of the table, this was a riskier design. Eventually several LEDs and emitters were selected for testing based on cost, illumination angle, and brightness, and preliminary testing was carried out with our IR camera, and the 940 nm emitter was judged to be the best suited to our needs, but in full-scale assembly within the table, the placement of other components rendered the use of individual LEDs impractical, so we switched to the Tendelux illuminator instead for the low footprint.

5.1.5 Infrared Camera

To record the blobs and thus detect touch inputs to the table, a camera which viewed only the infrared spectrum was required. Cameras built for infrared imaging were prohibitively expensive, so we considered standard web cameras in which there was no IR-blocking filter or the IR-blocking filter could be removed, and a visible light filter could be added. There was no purpose-made filter for most cameras, but a large filter for another camera could potentially be modified to fit, or a trimmed piece of exposed film negative or floppy disk could be used.

To ensure the accuracy of blob detection, we had to determine a sufficient image resolution. Since we expect the objects and fingertips which we detect to be at least 1/4 inch in diameter and located on a surface that is at most 36 inches on a side, for detection within 1/2 inch we need at least 144 pixels in a dimension. For reliability, we triple that number for a minimum of 432 pixels x 432

pixels. Given standard resolutions, we considered webcams that provide resolutions of at least 640 x 480.

To minimize touch detection times, we wish to maximize the frame rate of the camera at thus the detection rate. Further, if the frame rate is too small, not only will there be noticeable delays in inputs at a single location, certain functions which rely on moving finger inputs to determine the direction of characters' actions may become impossible to implement. As these gestures may take as little as 1/4 of a second, and we wish to track at least 7 frames for gesture inputs, a minimum of 28 frames per second is required. Given standard frame rates, we considered webcams that provided at least 30 frames per second.

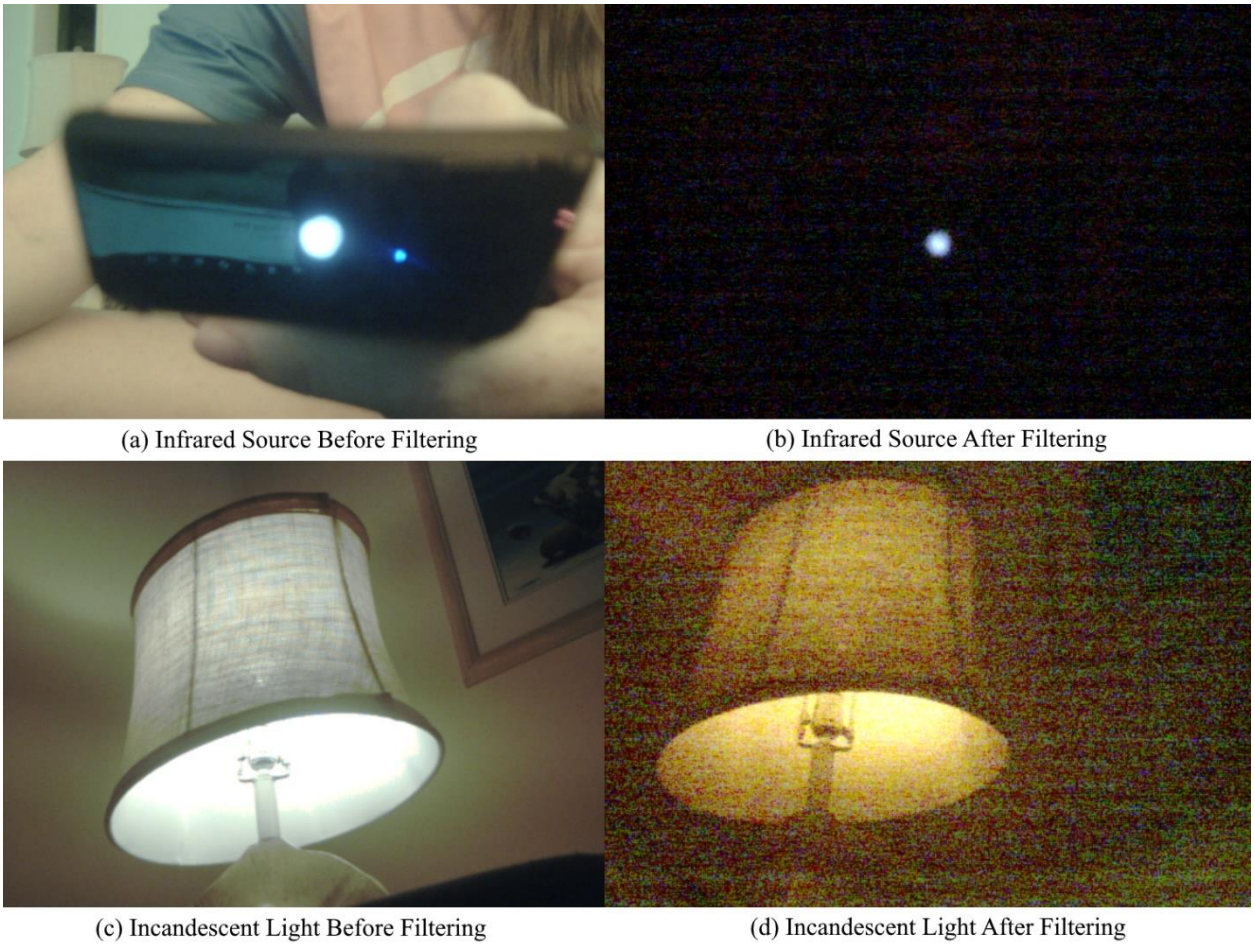
Since we planned to use a user's PC to assist in running the game, a USB interface and PC-compatible driver were the best options for the webcam. To minimize touch detection times, we required that the interface be USB 2.0 or newer. Cameras meeting these requirements are given in Table 17.

Table 17: Camera Options

IR Source	Cost	Source	Status
SainSmart 5MP 1080P Webcam Camera NoIR	$19.99	Amazon - SainSmart	
PlayStation Eye	$8.70	Amazon - PlayStation	Selected
Makerfocus Raspberry Pi Night Vision Webcam	$23.99	Amazon - MakerFocus	
Cimkiz USB Webcam	$9.99	Amazon - CimKiz	
Kodak 35mm Color Negative Film	$3.49	B & H	
3-1/2" Diskettes x 10	~~$18.90~~ $0.00	~~Amazon - Imation~~ Already Owned	Selected
ZoMei 55MM IR 760 Glass Infrared Filter	$23.99	Amazon - ZoMei	

The PlayStation Eye camera was selected based on price and because its use in previous projects means there is ample reference material for conversion from a visible light camera to an infrared camera, as well as a reliable driver for Windows PCs for and additional $3. Further, the camera can record at a resolution of 640 x 480 at a rate of 60 frames per second by default, and the Windows driver we acquired allows us to select the desired frame rate, so it met our specifications nicely. Once the camera was acquired, it was discovered that the infrared spectrum was not strongly filtered out by the hardware, as shown in Figure 7(a), so for initial testing a visible light filter could be added externally rather than risking damage by opening the camera and attempting to replace the existing weak filter. When facing a bright light in the form of an incandescent lamp, sunlight, or LED flashlight, the camera still picks up some object outlines, as shown in Figure 7(d). As these sources are known to produce some levels of infrared radiation, it is unclear to what

degree this is the result of infrared radiation produced by the light sources as opposed to imperfect filtering, as some bright lights can be seen through the filter by eye. The infrared-light blocking filter was then removed and then replaced by visible-light blocking material. Floppy disk material was chosen as the visible light-blocking filter based on price and filter testing.



(a) Infrared Source Before Filtering

(b) Infrared Source After Filtering

(c) Incandescent Light Before Filtering

(d) Incandescent Light After Filtering

Figure 7: Infrared Camera Images

5.1.6 Display Method

To display images onto the touchscreen for the game, using the rear DI method, a projector of some description was necessary. As the table is restricted in height, either a short throw projector or a regular projector combined with a mirror to increase the throw distance was required. New short throw projectors are several hundred or over a thousand dollars more expensive than regular projectors, so the mirror technique was chosen if a new projector was to be acquired. Because the mirror method involves projecting the image at an angle, significant keystone correction was be necessary for undistorted image reproduction. Originally, a high resolution of 1080p was desired to ensure the details of the game could be distinguished. After some examination of available standard projectors, some 720p options were also considered as the image would remain acceptably clear at 1/3 the cost, which could mean hundreds of dollars of savings and a 25% or more reduction in our overall budget as the projector was expected to be the most expensive component.

Despite the increased cost, short throw projectors were considered as the implementation would be simpler and more reliable than the mirror method, as well as providing more flexibility in the dimensions of the table. Any cosmetic damage to the projector was irrelevant as the projector would be enclosed in the box of the table and not visible. Minor discoloration in the image could be tolerated and guarantees on remaining lamp lifetime were enough for our purposes. These were the only expected reductions in product quality relevant to our requirements. Some reputable vendors of refurbished projectors were identified, and candidate refurbished projectors selected which had comparable prices to a new standard projector.

In addition to image quality and throw ratio considerations, control methods were also taken into account, as we wished to be able to easily turn the projector on and off and adjust the display brightness once the projector had been installed in the table. Every projector considered came with an infrared remote which we could modify or use to design a control system. Our top options are detailed in Table 18. The final selection was made in November in the hopes of acquiring an exceptional projector cheaply during Black Friday/Cyber Monday sales, as there was little concern about the compatibility of the projector with the rest of the design, and it was not particularly necessary to test other components at the early stages.

Table 18: Projector Options

Projector	Resolution	Throw Ratio	Keystone	Cost	Source
VANKYO Performance V600	1920 x 1080	1.5	± 15°	$249.99	Amazon - Vankyo
YABER Native 1080P LED Projector	1920 x 1080	1.3	± 50°	$239.99	Amazon - YABER
Crenova Native 1080p LED Projector	1920 x 1080	1.0	± 15°	$249.99	Amazon - Crenova
BenQ MP780ST DLP Short-Throw Projector	1280 x 800	0.5	± 40°	$189.56	eBay - voltarea
BenQ MX810ST MX713ST DLP Short-Throw Projector	1024 x 768	0.6	± 30°	$178.76	eBay - voltarea
Plain Square Mirror by ArtMinds				$6.49	Michaels

As no particularly strong contenders went on sale in November, we decided to go with a used short-throw projector. The used projectors were cheaper than comparable new projectors and organizing the hardware inside the table is simpler when using a short throw projector, as the mirror method poses challenges in terms of placing items out of the path of the projected light. Additionally, most projectors in our price range have only auto-keystoning options which may struggle to adjust the display accurately when facing an angled mirror. After narrowing down the

field to used short-throw projectors and identifying a couple of reputable dealers, two BenQ projectors emerged as the top contenders, the BenQ MP780ST and the BenQ MX810ST. The prices of both are comparable, so the choice comes down purely to projector specifications. The projectors are similarly sized and have the same brightness rating. They also both have some serial control ports that we may be able to use to adjust the projector brightness and other settings from the outside of the table. The MP780ST has a slightly higher resolution, greater keystoning range, and a shorter throw ratio. In contrast, the MX810ST supports smaller minimum image dimensions, has a longer lamp life, and a greater contrast ratio. The minimum image dimensions for the MP780ST are slightly larger than we need, so that displaying the image in the projector-supported size range would require scaling our table so large it could not easily be sat around or maneuvered, while adjusting to a smaller size may result in an unfocused image. The keystoning and throw ratio of both projectors are enough for our intended design, so overall the BenQ MX810ST DLP Short-Throw Projector was a better choice and therefore selected. The dealer we ordered from guaranteed that the projector lamp had at most 1190 hours of use, so at least 2310 usable hours remain. We estimate that the table will be used on average 4.5 hours per game, and at most 3 games per week. With 52 weeks in a year, the used projector lamp should then last 2310/(4.5*3*52) = 3.29 years, which is sufficient for our intended minimum device lifetime of 3 years. Table 19 provides the detailed specifications of the MX810ST projector.

Table 19: Projector Specifications

Projector			
Brightness	2500 ANSI Lumens	**Keystone**	Auto/Manual, $\pm$ 30^{o}
Native Resolution	1024 x 768	**Aspect Ratio**	4:3
Contrast Ratio	4600:1	**Dimensions**	11.4” x 5.03” x 9.9”
Display	DLP	**Power Supply**	100 to 240 VAC, 50/60 Hz
Lamp Life	3500 hours	**Throw Ratio**	0.6

5.1.7 Touch Surface Prototyping

Hardware prototyping began with the touch detection scheme. The infrared camera was the first element of the multi-touch scheme to be developed in order to determine its sensitivity to IR light and to have a method of validating the IR illumination scheme. The array of IR LEDs for illumination of the touch surface was then designed to try to achieve as uniform an illumination as possible and thus make the job of the touch-detection software as easy as possible. The table surface was then assembled, with the diffusive surface attached to the clear acrylic sheet and then placed temporarily in a closed box to begin testing. At this point adjustments to the LED array and diffusive material could be adjusted to optimize both the display clarity and touch input detection accuracy.

Several configurations of the LED array were tested to determine which provided the best illumination of the touch surface. The configurations chosen for testing were the square, offset square, ring, and cross configurations detailed in Figure 8, in addition to a configuration consisting of two lines along the length of the table. The illumination of the touch surface by each configuration was recorded using the infrared camera and the results compared. During final assembly, some modifications may be made to the configuration as some area of the table will be occupied by other components, especially the projector and camera. As a result of the testing, and

after a comparison of the impact on illumination caused by the removal of a section of LEDs, the offset square configuration was selected.

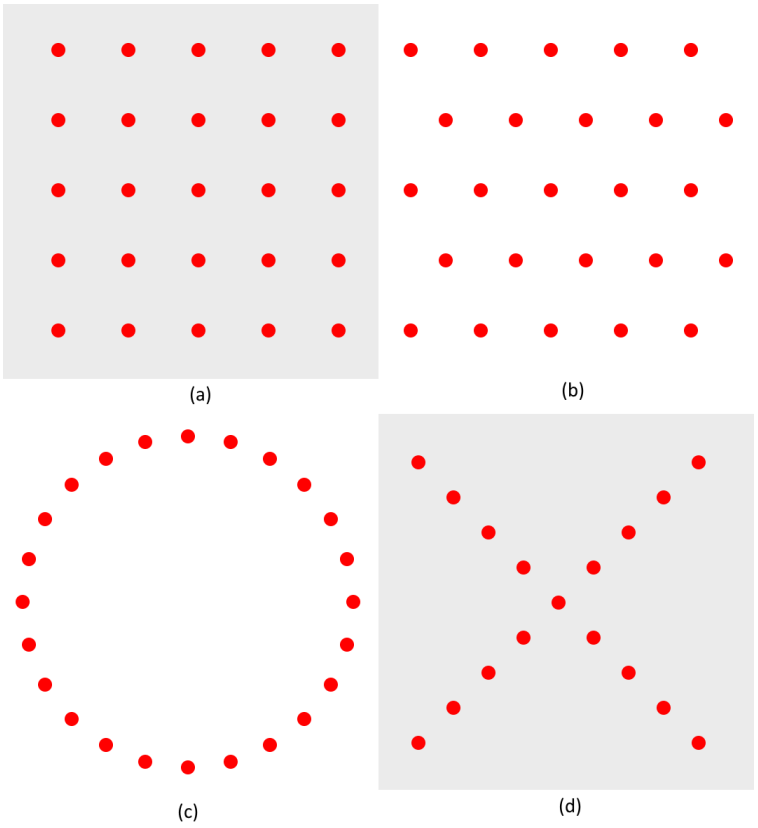


Figure 8: Infrared LED Configurations
(a) Square (b) Offset Square (c) Ring (d) Cross

However, as mentioned previously, with other components installed in the table, the IR LED array could not be adequately arranged without causing significant difficulty in accessing other components, and we switched to the pre-built infrared illuminator. Eventually we ordered two illuminators to even out the illumination of the surface, with one on each side of the interior.

5.2 Table

The physical structure supporting the rest of the hardware had to be chosen to provide enough space for all components and a reasonable throw distance for the projector, without becoming too tall or bulky for users to sit around during gameplay. The unique needs of the project left three main options for the table: commission a custom table, purchase a standard pre-built table and modify it, or build a table from scratch. Commissioning a table would guarantee the best results, as none of the group members have significant experience with woodworking. However, this option is also the most expensive, and thus was discarded early on.

When searching for pre-built structures to modify, we looked for as many characteristics matching those we desire as possible. Glass-top tables, cabinets, and wheeled tables are especially desirable. Glass-top tables may need no replacement of the top surface, or at the very least be easy to replace with an appropriate acrylic. Cabinets fulfill the requirement of an accessible closed box without modification, come in appropriate sizes, and are easily ordered to custom specifications, although

custom ordering is quite expensive. Wheeled tables provided maneuverability while remaining stable. In all cases the material and structure of the table were required to be such that modifications can be safely made, such as wood or particleboard, in the areas requiring modification. After searching half a dozen retailers and online marketplaces, no glass-top tables, cabinets, or wheeled tables were found which would provide significant benefits over building from scratch. However, a shelving unit already in the possession of one of the group members was found to be a good base for a modified design.

The shelving unit consists of a metal frame perforated with holes along the length of each strut. These perforations provide connection points for shelving support structures. Each original shelf is composed of particle board, easily removed and replaced with more appropriate materials. The surface area of each shelf is 2 feet by 4 feet, and the total height of the shelving unit is 3 feet. Each shelf is held in place by a supporting metal framework underneath its edges, which can be left in place at the top of the unit to hold our touch surface and surrounding table top, as well as at the bottom of the unit to support a ground-level shelf which will hold most of the table's electrical hardware.

The framework for each shelf's support is 3/8 inch deep, and thus we can use an acrylic sheet up to 3/8 inch thick while maintaining a closed box structure for the touch surface. As our intended less than 1/10 inch thick, this depth is sufficient. As the projector produces an image with a 4:3 aspect ratio, a 24 inches tall image will be 32 inches wide. After trimming the acrylic to this size, 16 inches of top surface remains uncovered. We address this deficiency by adding two 8 inch by 24 inch wood panels, one on either die of the acrylic, to create a small table area on which users may place cups, snacks, dice, and other small items. Any slight gaps left between the surface of the table and the frame will be filled with foam to prevent the acrylic and wood panels from sliding and sustaining damage. The boundaries between surface materials and the frame will be covered by thin wooden trim for aesthetic purposes and to ensure a light-proof seal. A hinged door will be added to one side to allow easy access to the interior of the table.

However, the shelf-based design has several issues. Attaching wheels would be difficult as they could not be bolted to or through the metal frame, and would therefore have to be attached closer to the center of the table, resulting in reduced stability and greater strain on the joints between the frame and the bottom shelf holding the electrical hardware, and a failure at this joints would cause potentially irreparable damage to the wiring of the table. Additionally, the dimensions of the shelf are not ideal, and the shortest dimension is slightly shorter than we would like and limits the touch surface area, while the longer dimension is much longer than we would like and forces us to purchase extra material and may cause issues when illuminating the surface from the interior. Overall, a table built from scratch was preferred.

Due to the lack of experience among the group, and the need for an enclosed space for rear DI, the initial from-scratch table design is simplistic but functional and can be seen in Figure 9.

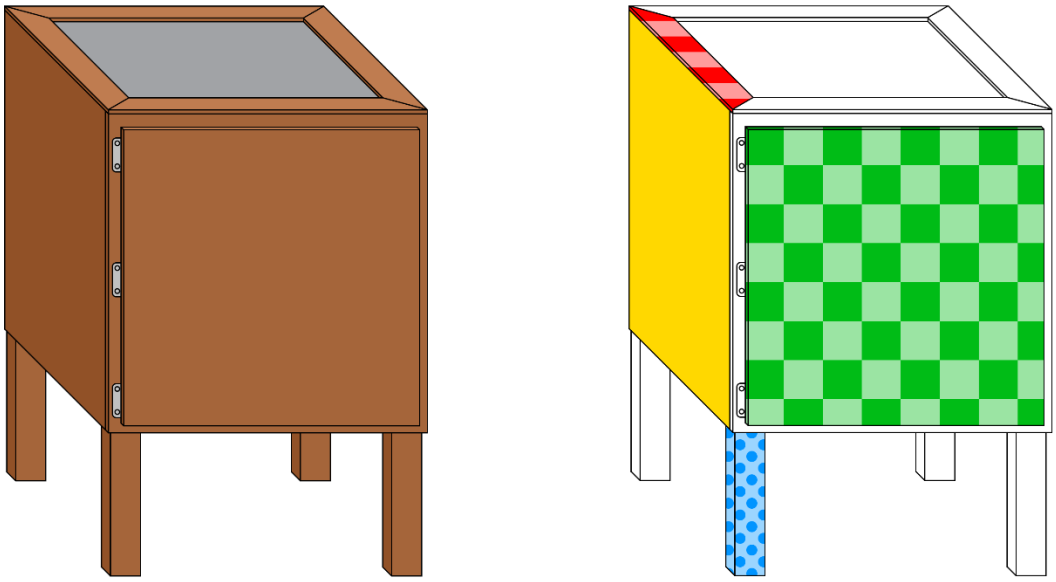


Figure 9: Initial From-Scratch Table Design: Colorized (left) and Significant Components Highlighted (right)

In the initial design, each side panel of the table (solid yellow) is made of plywood to provide a stable structure for embedding fans, buttons, etc. and to support the top of the table. The bottom of the table (not pictured at the angle shown) is made of the same plywood as the side panels and bears most of the weight of the electronic hardware such as the projector and microcontroller. The legs of the table (dotted blue) are used to provide a stable structure and enough depth to securely fasten the other components together. A door (checkered green) of thin plywood is placed on one side of the table to allow easy access to internal electronic hardware for the purposes of installation, troubleshooting, and maintenance. The door is attached on one side by hinges and held closed by a Velcro closure when not in use. Craft foam placed around the edges of the door prevents impact damage when the door swings shut and blocks light from leaking into the box when the door is closed. A frame (striped red) at the top of the table is added for both aesthetic and structural reasons, covering the tops of the legs to create a rectangular touch surface. The frame provide support for the acrylic which rests in a groove at the top of the table. Modifications in the form of handles on the sides and wheels on the bottom were considered to be added after construction if the smooth box design proved difficult to maneuver safely. The exact dimensions of the table were not determined until after the acquisition of the projector, to ensure the visual display would completely cover the touch surface and the necessary throw distance could be guaranteed. Once this was done, the design of Figure 9 was scaled and constructed. During construction, a few other adjustments to the design were made. Mainly these consisted of the removal of exterior protrusions of the legs as the table's interior provided three feet of height already, the placement of the top portion of the table inside the walls rather than resting on top, and the addition of some additional 1-inch thick framework for greater structural stability. Major assistance in assembly and advice resulting in the changes for stability was provided by Graeme Lindbeck, father of one of the group members with previous woodworking experience. The major dimensions are given in Figure 10. It is worth noting that the actual dimensions of the table prototype vary slightly from the listed dimensions due to inaccuracies in woodworking.

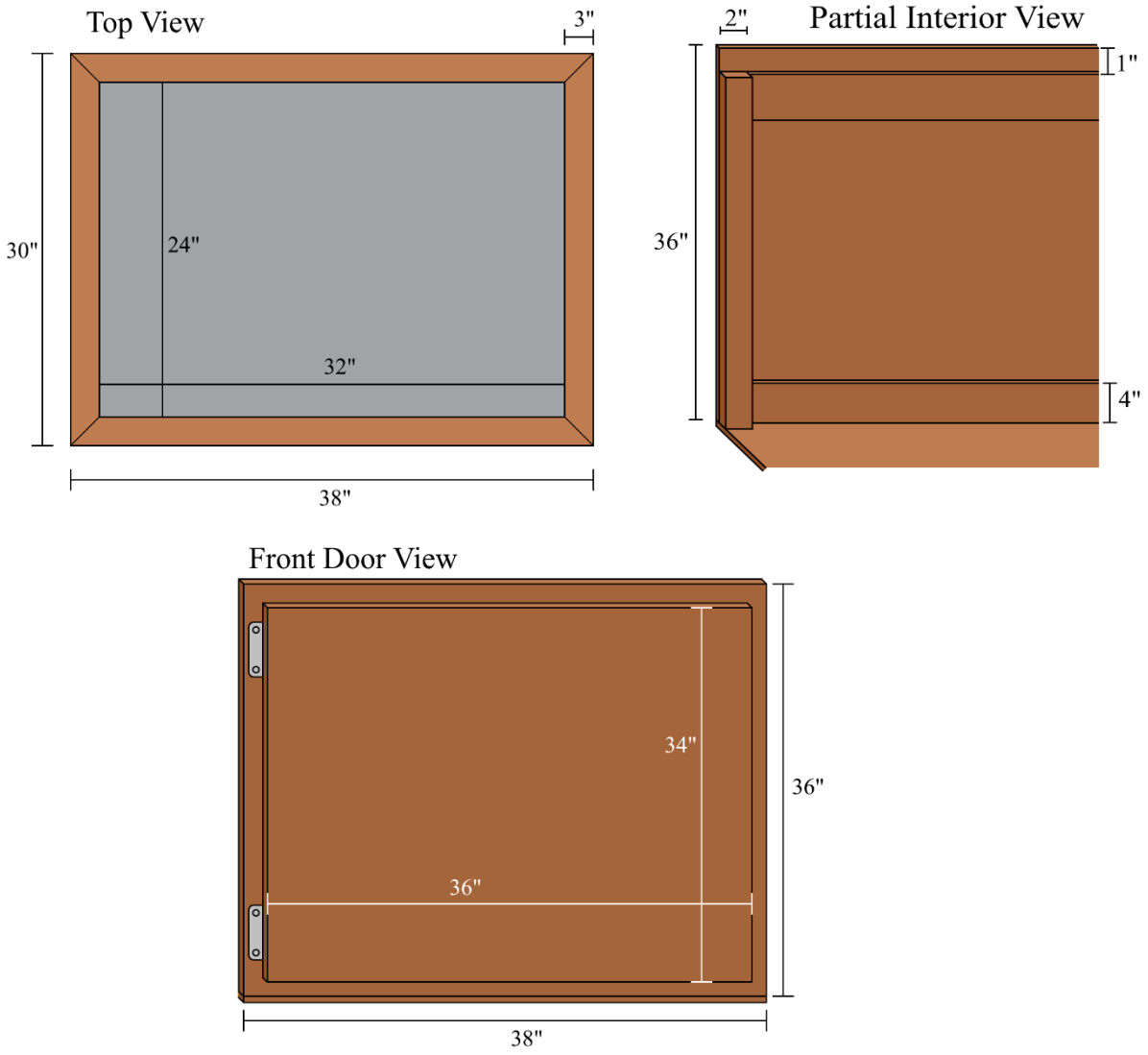


Figure 10: Major Table Dimensions

From the projector's specifications, we knew the native image resolution has a 4:3 aspect ratio. 24 inches for the smaller dimension was selected to meet minimum display size requirements and to make sure the table could fit through most standard doors. A 24 inch by 32 inch image will have a 40 inch diagonal. From the projector's user manual, we determine that a throw distance of 494 mm, or just under 19.5 inches is required for a 40 inch diagonal image. Further, the projector is 9.9 inches long. Allowing 6 inches to plug cables into at the rear of the projector without damage, the closed box portion of the table must be at least 35.4 inches tall, which we round up to 36 inches for simplicity. As we initially expected to add a few inches to the table's height by attaching wheels beneath the table, we definitively did not want to lengthen the legs past the bottom of the enclosed chamber. This further simplified construction and prevents the table from becoming too tall to reasonably sit around. The legs were chosen to be 2 inches square, on recommendation from hardware store professionals with woodworking experience. On similar advice, 1/4-inch-thick plywood was chosen for the sides, of the table, as well as the door for ease of ordering. 1/2-inch

thick plywood was used for the bottom to prevent warping when the table was lifted, which might have caused problems with image detection as the camera moved. The frame of the surface was then chosen to be 3 inches wide and 1 inch thick to provide a stable base for the acrylic, as well as an attachment point to reinforce the siding. Three inches are left on each side of the door for strong hinges and a fastener to hold the door closed. One inch of overlap is left between the door and the table siding to block light and leave room for foam padding as necessary. However, once the table was assembled and other systems were installed, the idea of a door swinging around in a three-foot radius was found to be rather impractical. Thus we replaced the wooden door with a light-blocking curtain on a curtain rod installed just inside the door. To ease the process of maneuvering the table, chest handles were installed on opposite ends of the table. The table was assembled using a combination of screws, nails, dowels and wood glue. A summary of the materials and tools used in construction is given in Table 20. Tools for construction such as drills, screwdrivers, and clamps were already owned or borrowed by team members.

Table 20: Table Materials

Part	Unit Cost	Number	Total Cost	Source
Sandeply 1/4" x 4’ x 8’ Plywood	$22.92	3	$68.76	Home Depot
2” x 4” x 12’ Lumber	$6.92	1	$6.92	Lowe’s
Wood glue	$5.98	1	$5.98	Lowe’s
Screws	$1.08	1	$1.08	Lowe’s
Hinges (2 pk)	$3.49	1	$3.49	Ace Hardware
Caster Wheels (x2)	$4.99	2	$9.98	Ace Hardware
Handles	$3.59	2	$7.18	Ace Hardware
Paint	$10.28	1	$10.28	Lowe’s
Total			**$113.67**	

The plywood chosen was selected for its low cost and its smooth surface, which has already been prepared for painting. The ease of painting is an important consideration as we have no experience staining wood, and thus to improve the appearance of the table, wooden surfaces of the table could be either painted or shrouded in decorative fabric. However, the appearance of the table was not paramount and no such decorative measures were taken in the end.

5.3 Microcontroller

A microcontroller unit (MCU) is a small computer contained within an integrated circuit chip. These chips generally contain a central processing unit (CPU), memory, and programmable input/output peripherals. When many people think of a microcontroller, they think of something like an Arduino board. These do contain microcontrollers, specifically the ATmega328 for the Arduino Uno, but also contain pin headers and other accessories for easy powering and programming. These are known as development boards and are primarily used for prototyping

This project uses a custom printed circuit board (PCB) containing an MCU. The MCU is used for reading a temperature sensor, controlling fans, prompting LED effects, running a timer, and potentially playing sound effects on a speaker. The main advantage of using the MCU for these

things is speed. It is also useful to keep these simpler functions separate while the single board computer is used for more complicated things like object detection and controlling what is displayed on the projector. The following sections detail the process of selecting an MCU for this project.

Various microcontroller units were considered based on factors such as number of inputs/outputs, functionality, and cost. Other factors such as familiarity and online resources such as tutorials and example code were also considered. The goal was to find an MCU with good enough performance, memory, and enough I/O lines for the planned features while keeping costs down.

5.3.1 ATmega328

The ATmega328 is a single-chip microcontroller created by Atmel (currently owned by Microchip Technology). It has an 8-bit reduced instruction set computer (RISC) architecture and achieves one million instructions per second per megahertz. Some features of the ATmega328 include 32KB ISP flash memory with read-while-write capabilities, 1KB EEPROM, 2KB SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible timer/counters with compare modes, internal and external interrupts, serial programmable USART, a byte-oriented 2-wire serial interface, SPI serial port, 6-channel 10-bit A/D converter (8-channels in TQFP and QFN/MLF packages), programmable watchdog timer with internal oscillator, and five software selectable power saving modes. The device operates between 1.8 and 5.5 volts.

This microcontroller was a good potential candidate for this project. One potential benefit of using this microcontroller is there are a large amount of resources and tutorials available due to this device being used in the Arduino Uno development board. 32KB of flash memory is also plenty considering the simple operations the microcontroller will be performing. A 16MHz crystal would need to be used as an external clock due to the internal RC oscillator being unreliable but this is a very cheap device and not a problem. A potential problem using this microcontroller is the number of I/O lines. The device will have multiple outputs operating at the same time including a display for a timer that will take a large number of lines to control various segments.

5.3.2 MSP430FR6989

The MSP430FR6989 is an ultra-low-power (ULP) device with a Ferroelectric Random-Access Memory (FRAM) platform that combines embedded FRAM and holistic ULP system architecture to increase performance and consume less power than other MCUs. Features of this device include a wide supply voltage range (3.6 to 1.8V), optimized ULP modes, ULP FRAM, intelligent digital peripherals, high-performance analog, multifunction input/output ports, code security and encryption, enhanced serial communication, and a flexible clock system.

The main benefit of using this device is familiarity due to using it in UCF's Embedded Systems course. In that course multiple features of the device were tested including adjusting the clock settings, timing interrupts, using UART, I^2C, and SPI, using analog-to-digital conversion, and using an LCD pixel display. All of this was programed at the register level in Code Composer Studio and implemented using the MSP430FR6989 Launchpad Development Kit. The development kit is similar to Arduino in that it combines the MCU with multiple peripherals and pin headers that allow for quick prototyping. Even though there are less online resources for this MCU compared to the chips used in the Arduino boards it is still a strong candidate for this project due to the large pin count and familiarity.

5.3.3 ATmega2560

The ATmega2560 is a high-performance, low-power Microchip 8-bit AVR RISC-based microcontroller that combines 256KB ISP flash memory, 8KB SRAM, 4KB EEPROM, 86 general purpose I/O lines, 32 general purpose working registers, real time counter, six flexible timer/counters with compare modes, PWM, 4 USARTs, byte oriented 2-wire serial interface, 16-channel 10-bit A/D converter, and a JTAG interface for on-chip debugging. The device achieves a throughput of 16 MIPS at 16 MHz and operates between 4.5-5.5 volts.

This MCU is similar to the ATmega328 but has an increased number of I/O ports and more memory. Like the ATmega328 this device has a large number of helpful tutorials and resources due to it being used in the Arduino Mega development board. Another benefit is the ability to use the Arduino board to protype and test various peripherals before committing to a PCB. The increased number of I/O lines remedies the problems faced when using the ATmega328 so this was the best candidate out of the three MCUs considered.

5.3.4 Microcontroller Comparison

A comparative summary of the MCU parameters is given in Table 20 below.

Table 20: Microcontroller Comparison

	ATmega328P	MSP430FR6989	ATmega2560
CPU type	8-bit AVR	16-bit ULP	8-bit AVR
Performance	20 MIPS at 20 MHz	16 MIPS at 16 MHz	16 MIPS at 20 MHz
Flash memory	32 KB	128 KB	256 KB
SRAM	2 KB	2 KB	8 KB
EEPROM	1 KB	0 KB	4 KB
Pin count	28	100	100
Maximum operating frequency	20 MHz	16 MHz	20 MHz
Maximum I/O pins	23	83	86
External interrupts	2		11
Cost	$2	$8	$12

5.3.5 Uploading Bootloader to MCU

When a chip is received from the manufacturer it is blank and is unable to run programs. To solve this problem a bootloader is required. This is the first program that runs when an MCU is reset and allows the MCU to receive new programs through some means of communication. To simplify programming the MCU on the PCB the bootloader from the Arduino Mega will be used. This allows us to reuse the same programs that were used when prototyping on the development board. A guide was found that shows how to use SPI to burn the Arduino Mega bootloader from an Arduino Uno to the target chip. The pins in a given row are connected. The VCC and GND pins must also be connected. To implement this a 6-pin header will be created to be used as an In-Circuit Serial Programming Interface (ICSP).

5.3.6 Communicating with the MCU

Once the bootloader had been burned there needed to be a way to upload software that will be run by the MCU. For the Arduino Mega a second MCU called the ATmega16U2 is used specifically for USB-to-serial conversion. If it wasn't for this chip the ATMega2560 would not be able to recognize the USB input. Implementing this in our design would require many more parts, increase complexity, and increase the cost of manufacturing the PCB. Instead an already built USB-to-serial chip module will be used. The chip will allow the MCU to interface with a pc through UART. A module based on FTDIs FT232RL chip was chosen. The module contains all of the required pins discussed in the next section and LEDs that indicate when data is being transmitted.

The two most common protocols for serial communication with MCUs are transistor-transistor logic (TTL), also known as UART, which uses +5V and 0V for its voltage levels, and RS-232 which uses ±12V for its voltage levels and is primarily used for long distance communication. It was previously decided that UART would be used to communicate with the MCU. The ATMega2560 has UART built in so this was easy to implement. Multiple connections will be required including: receive (RX), transmit (TX), and Data Terminal Ready (DTR) along with the 5V and GND connections. The DTR pin is connected to reset of the MCU and when connecting the USB-to-serial chip will set the DTR pin to low. A capacitor is placed in series with the reset line so the reset pin will return to 5V. The receive pin of the USB-to-serial module is connected to the transmit pin of the MCU and the transmit pin of the module is connected to the receive pin of the MCU.

5.3.7 Standalone MCU Schematic

Once it had been determined how the MCU would be programmed and how the PC would communicate with the MCU a standalone MCU schematic could be created. This schematic shown in Figure 11 includes:

- The ATMega2560 MCU
- A 16 MHz crystal oscillator
- A 6-pin header for burning the bootloader
- A reset button and auto reset circuit
- Two 5-pin headers for UART communication
- Decoupling capacitors
- A 14-pin header for a 7-segment display
- A 4-pin header for timer control
- An 8-pin header for connecting to the LED driver
- A power indicator LED

These subsystems are labeled in the schematic and arranged so that they are in close proximity to relevant pins. The 16 MHz crystal is needed because the internal oscillator of the ATMega2560 is not reliable and only runs at 8 MHz. The pin header for the boot loader allows for an easy temporary connection. Two headers are used for communication. The first one is dedicated to uploading programs and the second one is used for receiving UART commands during gameplay. Decoupling capacitors are required to reduce noise from the chip and traces. The digital pin header is used for the 7-segment LED timer and the analog pin header is used for any ADC that may be required. Finally, an LED is connected from VCC to GND and acts as a power indicator. The

initial design was used as a foundation and was updated to its final form based on which pins were necessary for the peripherals being used.

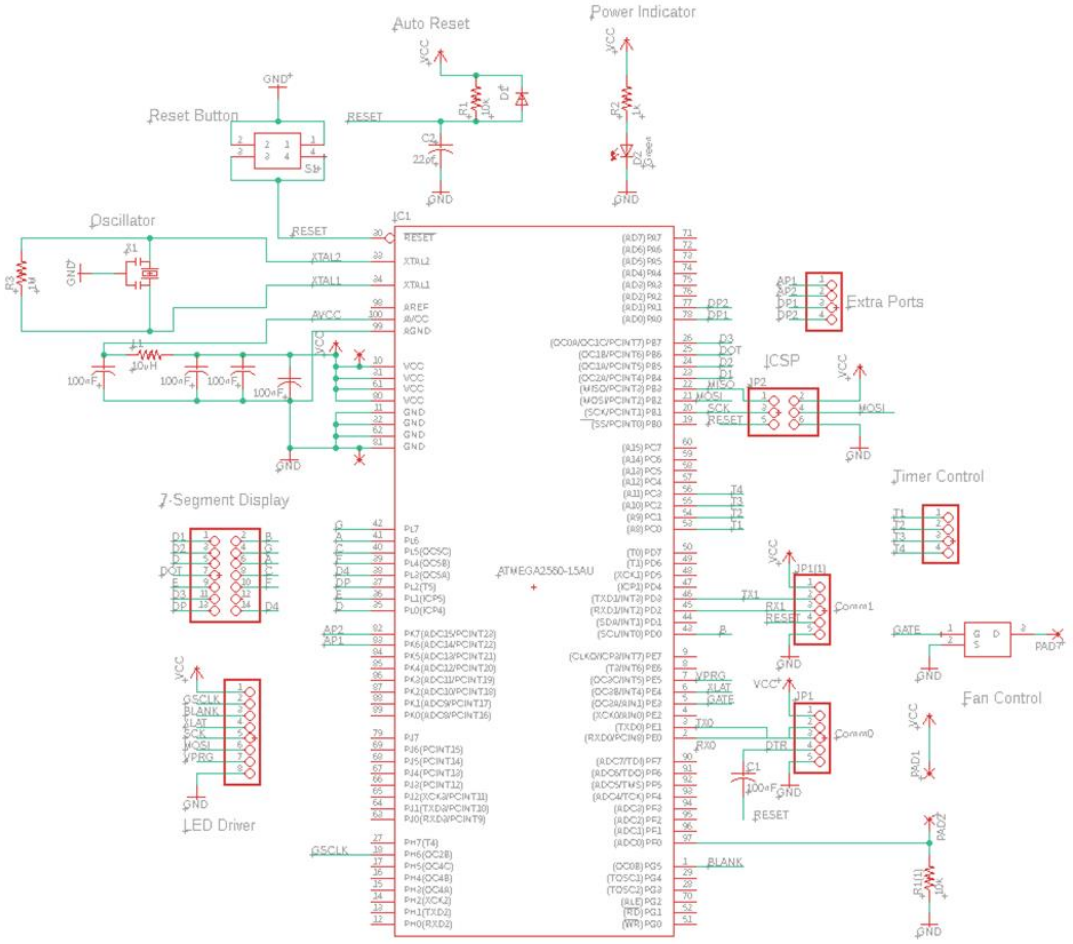


Figure 11: Microcontroller Schematic

5.4 Cooling System

A serious concern for this project is the heat generated by the various devices, especially the projector. This problem is magnified by the fact the components will be enclosed within the table. To reduce this heat two fans are be used, one for intake and one for outtake. The fans are attached to opposite sides of the table so air will flow through the table and cool the enclosure. It was decided that a 12V fan would be used instead of a 5V fan to make sure enough air is flowing to reduce the temperature. Many of the lower voltage fans are used for computer cases which have less air volume so these fans will likely make little difference in a large enclosure. The chosen fan has a current draw of 0.25A and runs at a speed of 1600 rpm. It has an estimated air flow of 73CFM which is acceptable for this size of enclosure. The size of each fan is 120x120x25mm (4.72x4.72x4.13in) which easily fits within the side of the table. If the cooling was not sufficient another set of fans could be added, though it was not determined to be necessary. The fans only cost $6 so extras could be purchased just in case.

5.4.1 Temperature-Based Control System

Controlling the fans so they only run while the enclosure is above a certain temperature gets rid of unnecessary power usage. In order to do this, there needs to be a way to detect the temperature of the environment. This is where the thermistor comes into play. Thermistors are temperature dependent variable resistors and are a cheap way of detecting changes in temperature. The most common type of thermistor is the Negative Temperature Coefficient (NTC) thermistor. For an NTC thermistor, increasing the temperature decreases resistance, and decreasing the temperature increases resistance. A chart can be used to determine which temperature corresponds to each resistance value. These charts are given in the data sheet for the thermistor. There is also a tolerance, usually 1-10%, that corresponds to the possible range of measured resistances for a specific temperature.

In order to control the fans using the thermistor the devices need to interface with the MCU in some way. Two problems arise from this: the MCU detects changes in voltage, not resistance, and the MCU cannot supply enough current to run the fans. The solution to the first problem is to use a voltage divider containing the thermistor and another known resistor value. The voltage divider is then connected to the MCU as an analog input. As the temperature increases, the thermistor's resistance decreases, and the voltage at the input will increase. The ATmega2560 uses 10-bit analog to digital conversion. This means the input value will be somewhere between 0 and 1023 where 0 represents 0 volts and 1023 represents 5 volts.

The value of the ADC changes linearly with the input voltage so by using the voltage divider equation and the resistance of the thermistor given in the datasheet we can determine what voltage turns on the fan. For example, it is determined from the datasheet that the resistance of the thermistor at 30 degrees Celsius is 8k. If a 10k resistor is used in the voltage divider for the second resistor, and 5V is used for voltage source, the voltage of the divider at this temperature will be about 2.78V. Dividing this by 5 volts and multiplying it by 1024 gives the ADC value corresponding to that voltage which in this case is 569.

The solution to the second problem, the lack of current supplied by the MCU, is the use of a MOSFET. A MOSFET has three terminals, gate, drain, and source, and by supplying a high enough voltage to the gate, current is able to flow through the device. Using these properties, the gate can be connected to a digital output on the MCU and once the voltage at the analog input reaches the desired level specified in the firmware, the output will become high which turns on the MOSFET. By connecting the 12V power source, the fan, and the MOSFET drain and source in series the fan will run when the MOSFET turns on.

Using the MCU to control the MOSFET also allows the use of Pulse Width Modulation (PWM). This allows us to send repeated pulses instead of a constant current to the gate of the MOSFET which affects the speed of the fan because it is being run intermittently based on the duty cycle. The higher the duty cycle the faster the fan will run up to a max of 100% which corresponds to the output being always on. Therefore, the MCU can be programmed to have the fan run at different speeds based on temperature by controlling a PWM output. PWM on the ATmega2560 is based on an 8-bit value that ranges from 0 to 255. An example of different duty cycles and their corresponding PWM values is shown in Figure 12.

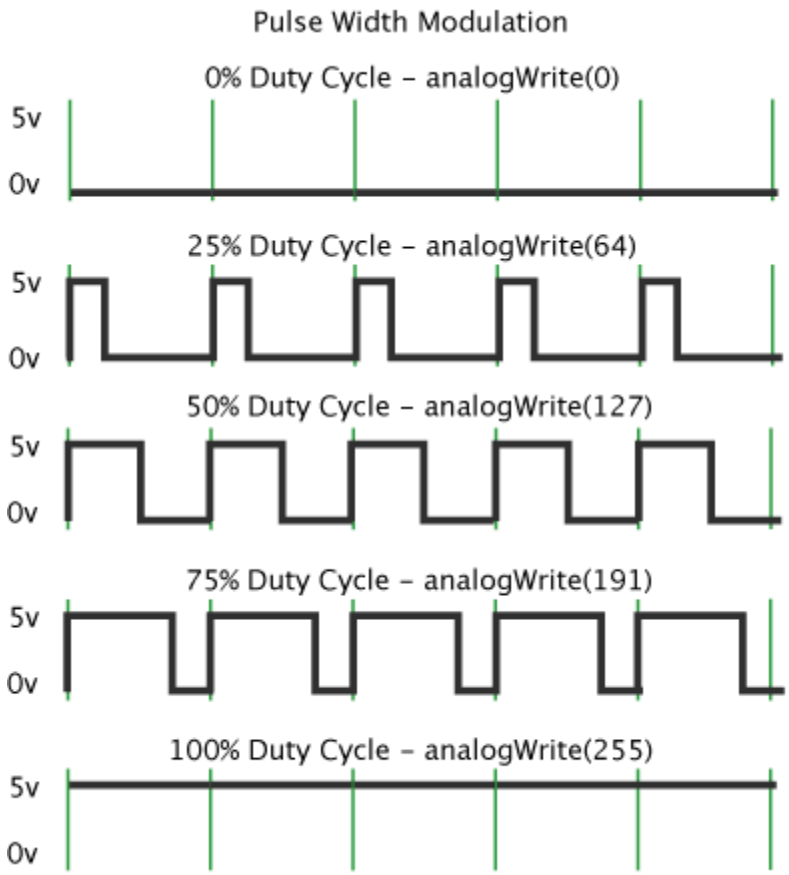


Figure 12: Example of 8-bit PWM
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5.4.2 Prototype of Temperature Control Subsystem

A prototype of the temperature control subsystem was created on a breadboard. The prototype uses the Arduino Mega development board which contains the ATmega2560 chip that will be used in the final design. The transistor used is the F12N10L which is a logic level N-Channel MOSFET with a gate threshold voltage of 1 - 2V and a maximum drain current of 12A. The fan is powered by a 12V AC adapter directly connected to the breadboard. The Arduino Mega requires 5V and is powered through USB. The fan was connected between the 12V rail and the drain of the MOSFET. The gate of the MOSFET was connected to a PWM port on the Arduino and the source connected to ground. By applying a high output to the gate, current can flow through the MOSFET and the fan turns on. A 10kΩ thermistor was connected between the 5V output and a voltage divider created using a 10k resistor. The voltage divider was connected to an analog port on the Arduino. The Arduino Mega's 10-bit ADC, as explained in the previous section, can be utilized through the analog read function in the IDE. The ambient temperature was measured to be 77 degrees Fahrenheit which coincidentally is the temperature when the thermistor has a resistance of 10k.

Before connecting the fan, the ADC from the voltage divider was tested and read 510 on the serial communications monitor. This is very close to the expected value of 512. The bit controlling the digital pin going to the gate of the MOSFET was then configured so that it would be set high if the value of the analog read function became greater than or equal to 570. To test this the thermistor

was touched to increase the temperature. The serial monitor read 1 which corresponds to high when the ADC value reached 570 as expected. Finally, the fan was connected as mentioned above and the entire circuit was tested. The fan only ran while the ADC value was greater than 570. Therefore, the prototype was a success.

It was decided that the MOSFET for the temperature control circuit would be part of the PCB. In order to do this a surface mount logic level MOSFET that could handle at least 0.5A of current was required. It was determined that the FDN359 N-channel logic level MOSFET would be used. This MOSFET has a maximum drain current of 2.7A and a gate threshold voltage of 1 – 3V which are well within acceptable ranges. It also comes in a surface mount package so it takes up less room than the F12N10L. Once a MOSFET was decided on, a schematic of the temperature control circuit could be constructed. The schematic shown in Figure 13 contains the MOSFET, a 2-pin header for connecting the fan, solder points for connecting the thermistor and a voltage divider. The reason the thermistor will be soldered instead of making it part of the PCB is so the device can be placed in the optimal position to detect the temperature of the enclosure.

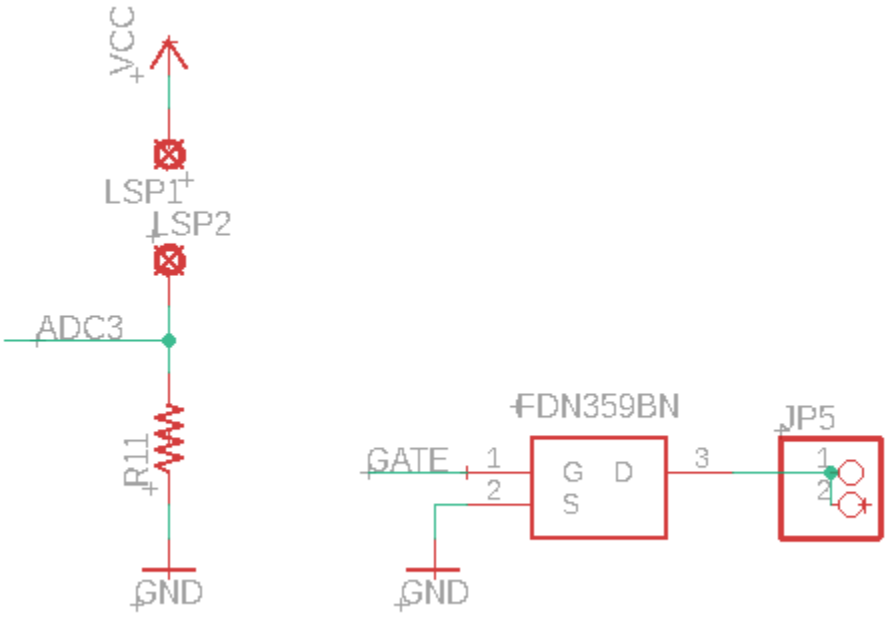


Figure 13: Temperature Control Circuit Schematic

5.5 Timer

A timer was added to the table for use in timed skill challenges and limiting turn durations. To display the time separately from the touch screen and phone apps, some sort of display unit is required. This display unit need not be very large, so we considered both LCD displays and LED displays. Since the table may need to operate in dim lighting, if we used an LCD display unit we must have chosen one with a backlight for visibility. Among LED displays, we considered 7-segment displays and dot matrix displays. Among the three categories, an LCD display provides\d the most flexibility as it could be used to display any black and white design that fits in the display window. If we decided later in development to generate some additional output, such as a welcome

message as the table is turned on, or an error message when some problem is detected, this would provide another method of communication with the user. A dot matrix LED display could also be used for a wide variety of designs, but they would have to be less cohesive and smaller than a design for an LCD display. A seven-segment LED display would be the most restrictive, able to display only a small set of alphanumeric characters in a few fixed positions. However, the more restrictive the display unit, the simpler the implementation, as a seven-segment LED display can be connected to the microcontroller by a relatively small number of binary I/O pins, whereas a dot matrix LED display or an LCD display typically requires serial digital communications to transmit the complicated design. Further, seven-segment displays are the cheapest option out of the three. Since we should be able to display complicated outputs on the table's surface, in apps, and on the host PC, a complex output for the timer should not be necessary. Thus, we chose a seven-segment display for our timer.

The timer shows 2 digits of minutes and 2 digits of seconds, as the longest time challenges are expected to be 30 minutes or less. To indicate that the timer has finished counting down, the display flashes 00:00 until stopped. A four-digit seven-segment LED display is used to show the full duration and simplified the timer construction. The four-digit seven-segment LED display has 8 input pins for the seven segments plus decimal point, and common anodes for each digit in addition to the colon between minutes and seconds. Multiplexing is used to set each digit and the display must be constantly refreshed at a high rate to avoid flickering. As decimal points are not needed, 12 pins are used. The timer interface relies on 4 buttons attached to the table. The explicit functions of the buttons are: power on/off, start/pause time, increment minutes, increment seconds. Powering the timer off and on again resets the timer to 00:00. The timer's logic and timing were intended to be provided by the microcontroller, with 16 I/O ports required in total, but eventually a Raspberry Pi 3 was used after damage and delays in late stage testing as we were not able to replace the microcontroller or its associated PCB in time after a burnout.

The timer relies on a single "time" counter, which is set by the user via incrementation, and which decrements each second as the timer is run. The timer has 4 states corresponding to different stages of operation. Each state may accept only a certain subset of possible of inputs, based on expected changes during the state's operation. These states are detailed in Table 21.

Table 21: Timer Operating States

Timer States	
State 1 - Off	
Input	**Function**
Button pressed: Power on/off	Enter state 2, set time = 00:00, update display
State 2 – On, Setting Time	
Input	**Function**
Button pressed: Power on/off	Turn off display, enter state 1
Button pressed: Increment minutes	Add 60 seconds to time, update display
Button pressed: Increment seconds	Add a second to time, update display
Button pressed: Start/pause time	Enter state 3
State 2 – On, Counting Down	
Input	**Function**
Clock tick (1/second)	If time = 0, enter state 4 Else, decrement time by 1, update display
Button pressed: Power on/off	Turn off display, enter state 1
Button pressed: Increment minutes	Add 60 seconds to time, update display
Button pressed: Increment seconds	Add a second to time, update display
Button pressed: Start/pause time	Enter state 2
State 4 – On, Timing Complete	
Input	**Function**
Clock tick (2/second)	Flash 00:00 to indicate time is complete
Button pressed: Power on/off	Turn off display, enter state 1
Button pressed: Start/pause time	Enter state 2, update display

A prototype timer was created using a breadboard to connect components and used an already-acquired Raspberry Pi as the controller. The individual components of the timer were first tested in this setting. Once the microcontroller was acquired, the code was to be adapted and programmed into the microcontroller. However, the COVID-19 crisis introduced some severe delays in assembling peripherals to our system, so the Raspberry Pi system was used in the final prototype.

5.6 Brightness Adjustment

To maintain visibility of the game screen, the brightness of the displayed image can be adjusted. Manual adjustments can be made using two buttons on a remote, one to increase brightness and one to decrease brightness. Initially we planned for an ambient light sensor to detect changes in the room's lighting and automatically adjust the brightness of the image when a significant change occurs, if the maximum/minimum brightness has not been achieved. This was to be accomplished by sampling the ambient brightness once per second and comparing the sample at time t to a coarse array of brightness levels, assigning it to the brightness level L(t). If the current level differed from the previous level, the image brightness would be increased or decreased proportional to the number of levels of difference, i.e. L(t) – L(t-1). The manual adjustment would be treated as an offset to the levels, e.g. one manual increase would result in brightness levels previously assigned to L(t) being assigned to L(t)+1. Some of the considered light sensors are given in Table 22.

Table 22: Light Sensor Options

Light Sensor	Cost	Source	Status
APDS-9005-020	$0.51712	Digi-Key – Broadcom Limited	
APDS-9306-065	$0.52601	Digi-Key – Broadcom Limited	Ordered
VEML7700TR-ND	$0.6996	Digi-Key – Vishay Semiconductor	
APDS-9300-020	$0.7272	Digi-Key – Broadcom Limited	
OPT3002DNPR	$0.792	Digi-Key – Texas Instruments	
OPT3006YMFR	$0.885	Digi-Key – Texas Instruments	

The levels were to be chosen once the projector has been acquired and are selected based on testing in development. However, at this point it was determined that the projector should remain at maximum brightness because that level wasn't blinding even in a dim room, while it was necessary in a bright room. The automatic brightness adjustment feature was therefore discarded for being relatively useless.

5.7 Special Effect Lighting

Lighting effects are used for player actions such as attacking and casting spells. RGB LEDs line the edges of the table and are controlled by the MCU. When an action is done on the player's phone a signal is first sent through Bluetooth to the single board computer. The computer then sends a signal to the MCU that selects which function the MCU will perform and a preprogrammed LED effect will occur.

LEDs are current driven devices. This means the illumination is determined by the amount of current flowing through it. LED drivers regulate this current at the desired level to make sure the current stays constant. In total 20 RGB LEDs will be controlled. If we tried to control these directly from the MCU it would take a very large number of pins which is impractical. LED drivers can be combined with SPI and PWM to reduce the number of output lines needed from the MCU. Two potential LED driver devices were looked at: the TLC5940 and WS2812B.

5.7.1 TLC5940

The TLC5940 is a 16-channel, constant-current sink LED driver that is capable of driving 120 mA per channel. It is a PWM unit with 12-bit duty control and 6-bit current limit control. The IC also contains integrated dot correction circuitry to compensate for variations in LED brightness. This is useful when there is a display containing an array of pixels that need to have uniform brightness but is not very important for this project. The device is controlled using Serial Peripheral Interface (SPI) and can be daisy chained together to increase the number of LEDs that are being controlled. Each IC has the ability to control 5 RGB LEDs since each LED requires 3 channels. The device has the ability to control the brightness and color of each individual LED which is important when trying to create effects such as simulating light moving around the table. There are many tutorials online about how to use this IC and overall it was a strong contender for this project

5.7.2 WS2812B

The WS2812B is an intelligent control LED light source where the control circuit and RGB chip are integrated into a package of 5050 components. It includes an intelligent digital port data latch and signal reshaping amplification circuit. It also includes a precision internal oscillator and a 12V voltage programmable constant current control circuit.

The device only requires a single data line and can be connected in series to form chains of LEDs. There is a delay as the signal propagates through the chain but this is not noticeable when using a small amount. Unfortunately, the communication protocol this device uses is not standard and is not supported by most microcontrollers. This means data transmission must be implemented by the software in a process known as bit banging. This can be challenging with low clock rates due to the high data rate of the protocol (800kbps). Therefore, although this device would be easier to wire than the TLC5940 discussed in the previous section the difficulties of using a custom protocol outweigh the benefits and this device will not be used for this project.

5.7.3 Led Effects Hardware and Software Design

It was decided the TLC5940 LED driver would be used to control the LED effects. The reason for using this IC is to reduce the number of outputs needed from the MCU by utilizing channels on the chip instead of directly connecting LEDs to the MCU. It also allows the ability to daisy chain multiple ICs together to control more LEDs if necessary. A tutorial was found that discussed how the chip could be controlled with an Arduino Uno and this was used as the basis for the design [12]. The next few paragraphs will give a more detailed explanation about how the chip works and how to set it up in the firmware.

The TLC5940 has 16 channels each with its own 12-bit PWM value (an example of PWM can be seen in Figure 12. The PWM value ranges from 0 to 4095 and the higher the value is the brighter the LED connected to that channel will be. By connecting the red green and blue leads of the RGB LED to three different channels the color of the LED can be precisely controlled (common anode LEDs must be used). There are a massive 2^{36} color combinations in total (4096x4096x4096). Each channel is also given a 6-bit (0 to 63) value for dot correction. Dot correction is used to compensate for the fact that the brightness for a given current will vary for each LED. It automatically adjusts the brightness variations between LED channels and other drivers in the SPI chain. The correction data is stored in a table on EEPROM that is integrated into the chip.

The device is controlled by a clock signal going from the MCU to the GSCLK pin. The frequency of this signal is 16 MHz for the ATmega2560 (an external 16 MHz crystal oscillator must be used) but this can be divided to generate lower frequencies. This clock continuously counts up from 0 to 4095 and is reset by pulsing the blank pin on the TLC5940. After every cycle, which takes 256µs, the PWM value for each channel can be updated. This means the brightness and colors of the LEDs are changing about 3900 times per second. This is much faster than what would be possible using the pins on the MCU.

Now that the inner workings of the TLC5940 have been established the steps needed for proper setup in the firmware are presented. The steps are as follows:

- Establish ports on the MCU for the XLAT, GSCLK, VPRG, MOSI, and SCLK pins.
- Determine the bit order, data mode, and clock divider for the SPI

- Create a subroutine for dot correction. VPRG must be set to high while dot correction values are transmitted and XLAT must be toggled on and off to write the data to the dot correction register.
- Set up two timers for updating PWM values. The first timer is connected to GSCLK and counts from 0 to 4095. The other timer is much slower and will control the interrupt that transmits data via SPI every cycle and toggles the Blank and XLAT pins.

Care must be taken when populating bytes to be transmitted with SPI because the dot correction and PWM values are 6 and 12 bits respectively whereas a byte is 8 bits. A timing diagram can be found in the datasheet for two cascaded devices that shows how the XLAT and Blank pins are used to clock in data [13]. The diagram was not included in this report due to copywrite protection.

Another important feature of the TLC5940 is the ability to control the maximum current for each channel. The maximum current is determined by the I_{ref} pin and is given by an equation found in the datasheet: Imax = 43.4 / R. The R in the equation represents a resistor going from the I_{ref} pin to ground. For this design a 2.2k resistor will be used which gives a max current of about 20mA. Therefore, if 20 RGB LEDs are used, and each has 3 channels, the maximum current draw would be 1.2A. However, due to PWM this would not be a constant current and the LEDs are only in use periodically.

5.7.4 Prototype of LED Effects System

The TLC5940 IC has a 28-pin PDIP package that allows for testing on a breadboard. A prototype shown in

Figure 14 was constructed using an Arduino mega with 5 RGB LEDs to be controlled by the LED driver. The system was powered by an AC adapter connected through a barrel jack and a 5V linear regulator. The goal of this prototype was to gain a better understanding of the timing diagram found in the datasheet of the IC and to test different possible effects for the game. Basic effects such as setting all of the LEDs to one color were first tested. Then effects that could potentially be used in the game were tested. A list of the tests performed is given in Table 24. Certain pins on the Arduino must be used for access to specific timers or for SPI functions. This is why the ports used in the figure below appear to be nonsensical. Table 23 shows which digital pins on the Arduino were used, the corresponding pin number on the ATmega2560, and the pin on the TLC5940 that they are connected to.

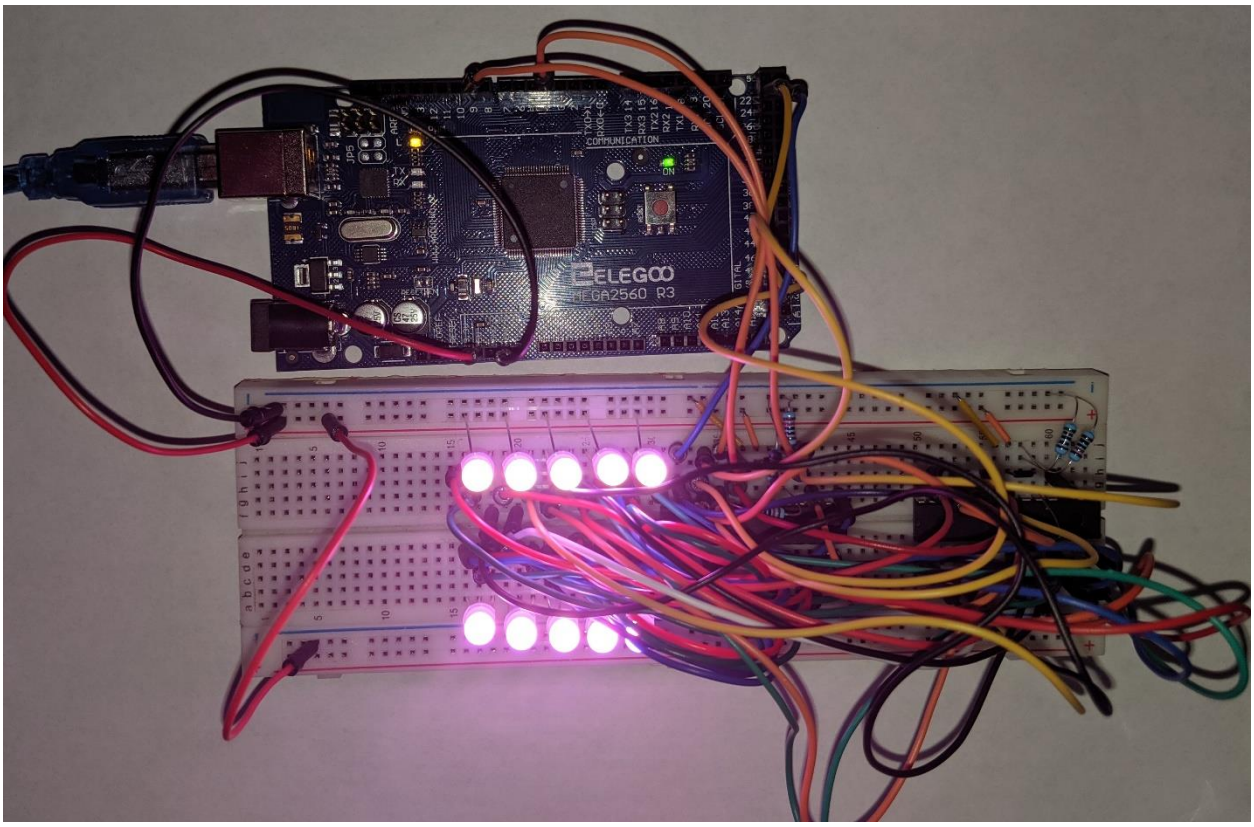
Table 23: Pin Connections for LED Effect Prototyping

Arduino Mega Pin	Port & Bit	ATmega2560 Pin	TLC5940 Pin
Digital Pin 22	PA0	Pin 78	XLAT
Digital Pin 9	PH6	Pin 18	GSCLK
Digital Pin 23	PA1	Pin 77	VPRG
Digital Pin 51	PB2	Pin 21	MOSI
Digital Pin 52	PB1	Pin 20	SPI CLK
Digital Pin 4	PG5	Pin 1	Blank

Table 24: LED Effects Tested Using Prototype

Test	LED Effect
1	All red
2	All green
3	All blue
4	LEDs flash white twice
5	Green light moves through row of LEDs
6	LEDs glow blue with increasing intensity and then dim
7	Random behavior

Figure 14: Prototype of LED effects system



5.7.5 LED Effects System Final Design

After using an Arduino to become familiar with the TLC5940 a schematic shown in Figure 15 was built in Eagle. It was designed so each driver would be placed on an individual board. Each board had a header for both input and output. This allowed the LED drivers to be easily daisy chained.

The schematic also included the resistors for the reference current and a 100nF decoupling capacitor. Solder points for all 16 channels of the LED driver were also included: 15 for RGB LEDs and one for a single-color LED for the player indicator.

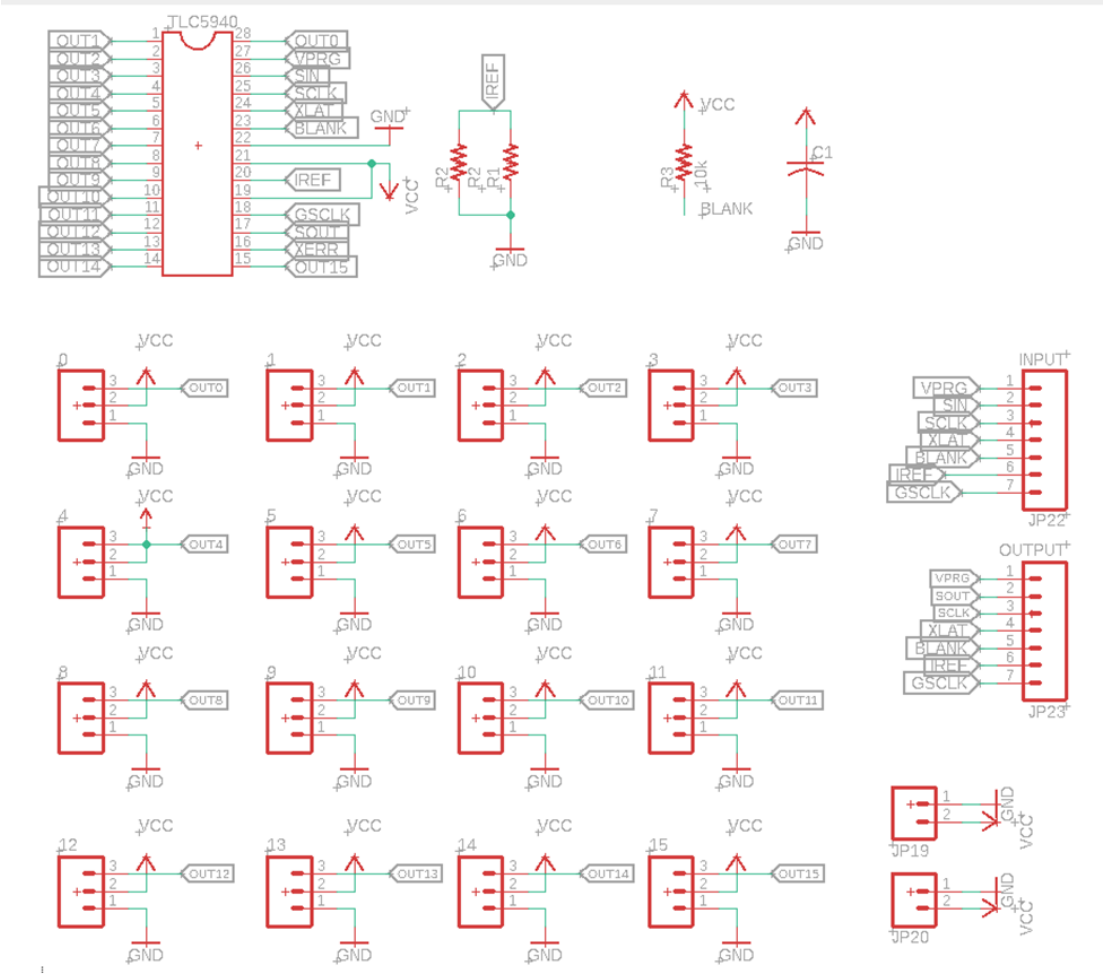


Figure 15: Effect Lighting Schematic

5.8 Sound Design

Sound effects are used to complement character actions such as combat and using magic. These sound effects accompany the LED effects. However, they are controlled using software on the PC as opposed to being controlled using the MCU. This is mostly due to memory limitations with the MCU because sound files take up large amounts of memory. Free use sound effects are used and if music is needed then royalty free music is used. To play the sound effects speakers are connected directly to the PC using a 3.5mm jack. Pressing an action on the user's phone will play the corresponding sound effect. A list of sound effects and their associated damage types is given in Table 25.

Table 25: List of Possible Sound Effects

Action	Sound Effect
Bludgeoning, Slashing	Swords Clashing
Piercing	Bow Drawn
Necrotic	Generic Cast
Thunder, Lightning	Electricity Crackling
Fire, Radiant	Fireball Sound
Cold	Icy Sound
Force, Psychic	Magic Missiles
Acid, Poison	Bubbling Acid

5.9 Power Supply

As we plan to use a commercial projector and laptop as components of our system, and we do not wish to put forth excessive effort designing a custom power source, running the risk of permanent damage to our most expensive components, the table will use a standard wall outlet for power. In order to convert power coming from the wall outlet to DC power an AC adapter is needed. For safety purposes instead of creating our own design an adapter will be purchased. To determine which adapter to buy the output voltage was compared to the highest voltage required by an individual component in the design. These components include the microcontroller, the LED drivers, the fans, and the 7-segment display. The projector is be connected directly to a power strip and was not considered. Out of the previously mentioned devices the highest voltage requirement was 12V for the fans. Therefore, the AC adapter needs to supply 12 volts. A 12V power supply with a maximum current of 2A was selected. The device connects to a power strip along with the projector and is used with a series of voltage regulators to provide the required voltages for all peripherals.

5.9.1 Voltage Regulator

The 12 volts coming from the AC adapter is too high to be used for the MCU and other peripherals. A step-down converter, also called a buck converter, was needed to step down the 12 volts to 5 volts while also regulating this voltage. The Texas Instruments Webench® Power Designer gives recommendations for designing voltage regulators based on desired specifications such as input voltage, output voltage, and max current. Using the Power Designer multiple possible regulator configurations were compared to determine which one would best fit our design. Three step-down voltage regulator ICs, the LM2576, TPS562208, and TPS565201, were considered and are discussed below.

The LM2576 is a monolithic integrated circuit that provides the active functions for a step-down switching regulator and is capable of driving a 3A load. A switching regulator is different from a linear voltage regulator in that it uses a switching element, such as a MOSFET, to transform the incoming power supply into a pulsed voltage [14]. They can regulate the output more efficiently than linear regulators and generate less heat. Out of the three ICs considered the LM2576 required the lowest part count making it the simplest choice. There is also familiarity with this IC due to using it in coursework.

The TPS562208 is a simple, easy-to-use, 2A synchronous step-down converter. It operates in force continuous conduction mode where the switching frequency is maintained at an almost constant

level over the entire load range and is optimized to achieve low standby current. A synchronous buck converter is a modified version of the basic buck converter circuit topology where the diode is replaced by a switch. This is more expensive but improves efficiency. Overall the TPS562208 was a good option that balances cost, efficiency, and complexity.

The TPS565201 is another synchronous step-down converter. It has a higher maximum load at 5A and has higher efficiency than both of the other options with an estimated efficiency of 96.4%. It is optimized to operate with minimum external component counts and a low standby current. This device employs D-CAP2 control which provides fast transient response and requires no external compensation components. It also allows the use of low-equivalent series resistance specialty polymer capacitors and ceramic output capacitors. Like the TPS562208 it operates in pulse skip mode to maintain high efficiency even when operating with a light load.

Table 26 below shows a comparison of the three ICs that were considered. The LM2576 has the lowest BOM count, which is appealing, but lacks in efficiency. A low efficiency means the device would run hot and this is undesirable especially since the table will be in use for potentially hours at a time. The TPS562208 has a much better efficiency and has the lowest cost of the three devices. The number of external components required to use the device increases but the IC is smaller so the total area used actually goes down by quite a bit. Finally, the TPS565201 has the highest efficiency, has a higher max output current, and is only 74 cents more than the TPS562208. The high efficiency means the device will be able to run for long periods of time without generating too much heat and the higher max current gives us room to add more power consuming devices such as LEDs. Therefore, this is the IC that we chose as our step-down voltage regulator.

Table 26: Comparison of Voltage Regulators

IC	BOM Area (mm^2)	BOM Count	Cost ($)	Efficiency (%)	V_{in} Range (V)	V_{out} range (V)	I_{out} Max (A)
LM2576-5.0	679	5	2.67	83.9	5.4 - 40	5	3
TPS562208	188	9	1.16	92.2	4.5 - 17	0.77 - 7	2
TPS565201	186	9	1.9	96.4	4.5 - 17	0.77 - 7	5

5.9.2 Voltage Regulator Design

Along with the TPS565201 IC external components such as resistors and capacitors must be used to give the desired output voltage. Using the recommended configuration from the Texas Instruments Power Designer a schematic was built in Eagle and is shown in Figure 16 A barrel jack is used to accommodate a 2.1 x 5.5mm plug. This will receive a regulated 12V from the AC adapter. The output voltage of the barrel jack leads to a toggle switch which is used as an on/off switch for the MCU. When the switch is in the on state the 12V is connected to the input of the voltage regulator. Two parallel decoupling capacitors are used for the input and output of the regulator as recommended. The purpose of decoupling capacitors is to suppress high frequency noise. An inductor is also placed at the output of the regulator. The main purpose of inductors in switching regulators is to maintain current flow during the off state. They can also be used to create a higher output voltage than input voltage but that is not relevant to this design. The output voltage is determined by Equation 1, found in the datasheet for the TPS565201:

Equation 1: Output Voltage Equation

$$V_{out} = 0.760 * \left(1 + \frac{R1}{R2}\right)$$

The datasheet explicitly states to use a 54.9k resistor for R1 and a 10k resistor for R2 to get an output voltage of 5V. Using the equation above, the output voltage with the recommended resistors is about 4.93V. This is suitable for the desired applications. Two 4-pin headers are also included. These serve as ports for peripherals such as the fans. This allows us to easily remove and reconnect these devices by providing solderless connections as optimal positioning is determined.

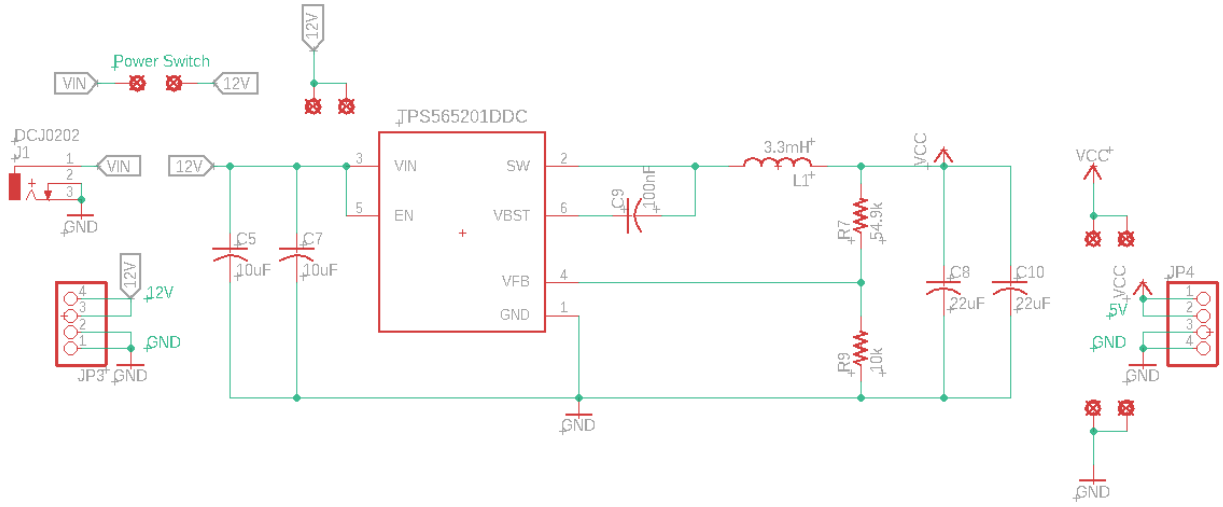


Figure 16: Schematic of Step-Down Voltage Regulator

5.10 PCB Design

Three different PCBs were designed for the MCU, the LED drivers, and the voltage regulator. The PCBs consisted of a top and bottom layer and used trace thickness of between 12 and 20 mils. All of the traces were manually routed. The design check in Eagle was used to make sure the boards could be manufactured, and no errors appeared. PCB layouts for the MCU, LED driver, and voltage regulator boards are shown in Figure 17, Figure 18, and Figure 19.

JLCPCB was selected to manufacture the boards due to its cheap pricing and quick turnarounds. Parts were selected based on their inventory and there were no issues getting the desired parts. There was some concern about order completion as their facilities were shut down for a few weeks as part of the COVID-19 crisis, but we were able to order the boards and parts, just without the assembly services which we originally intended due to unavailability.

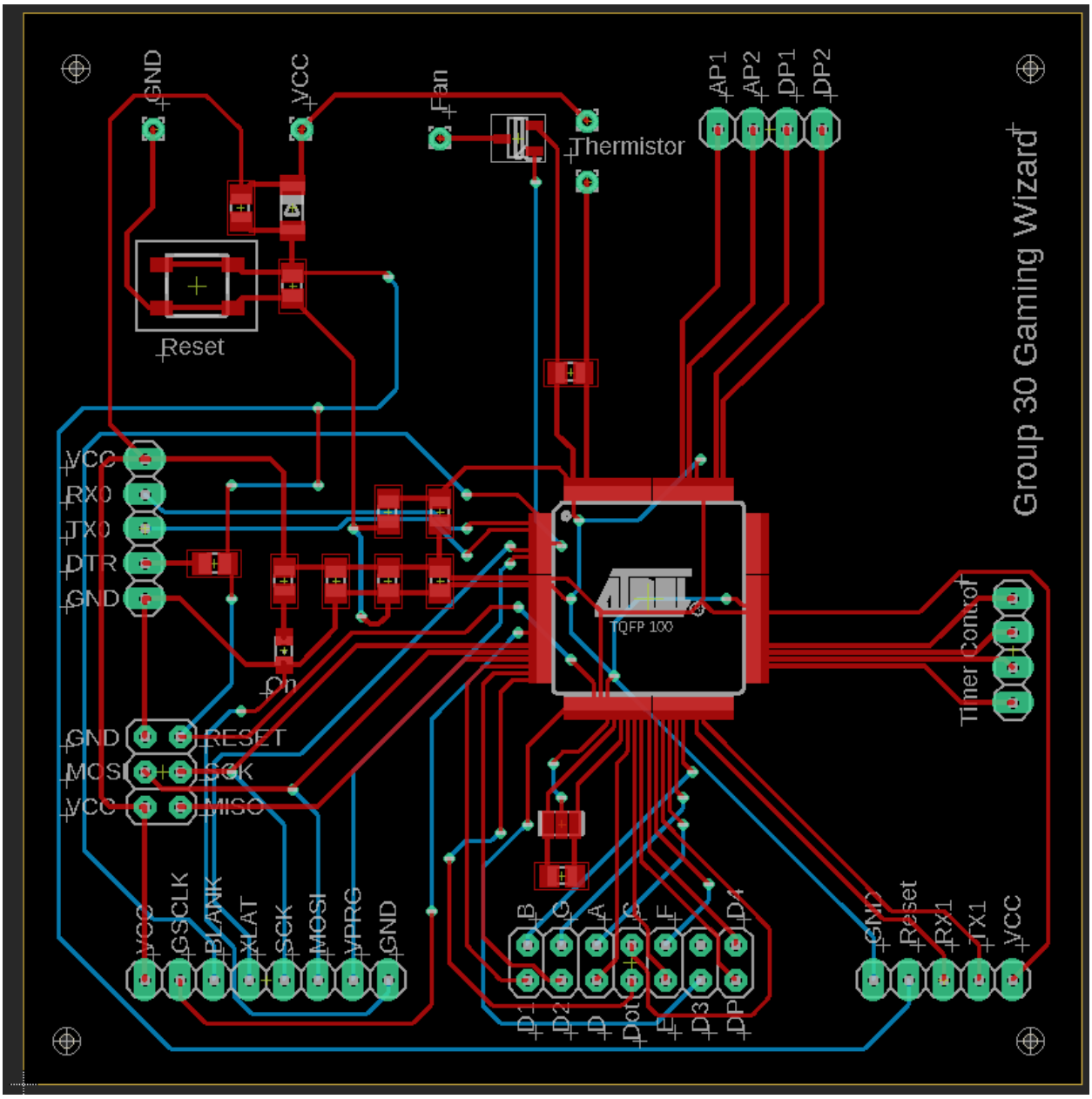


Figure 17: MCU PCB

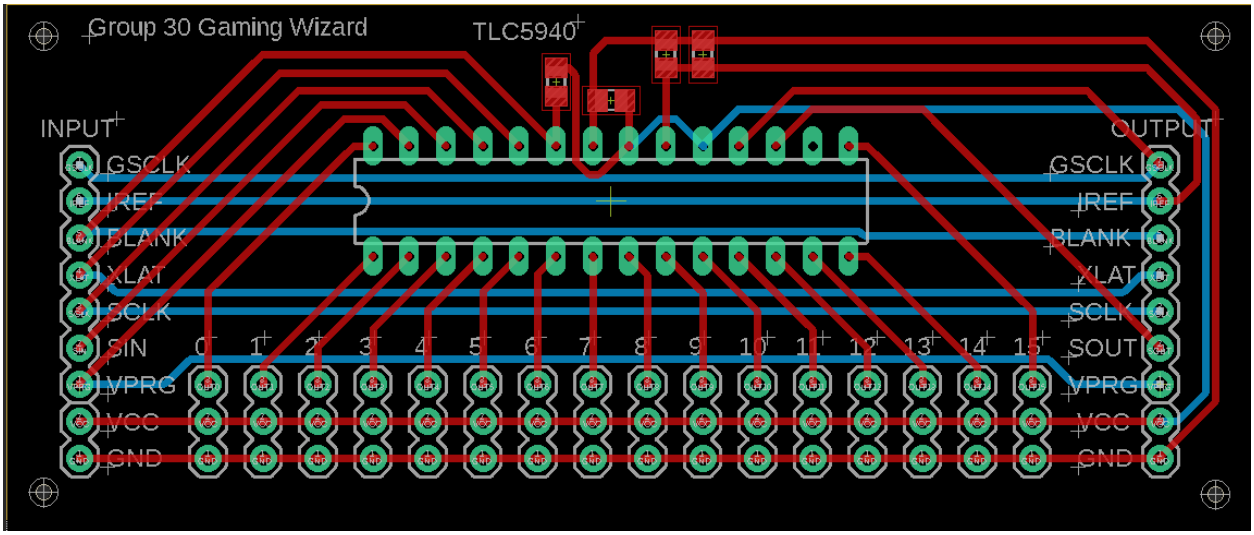


Figure 18: LED Driver PCB

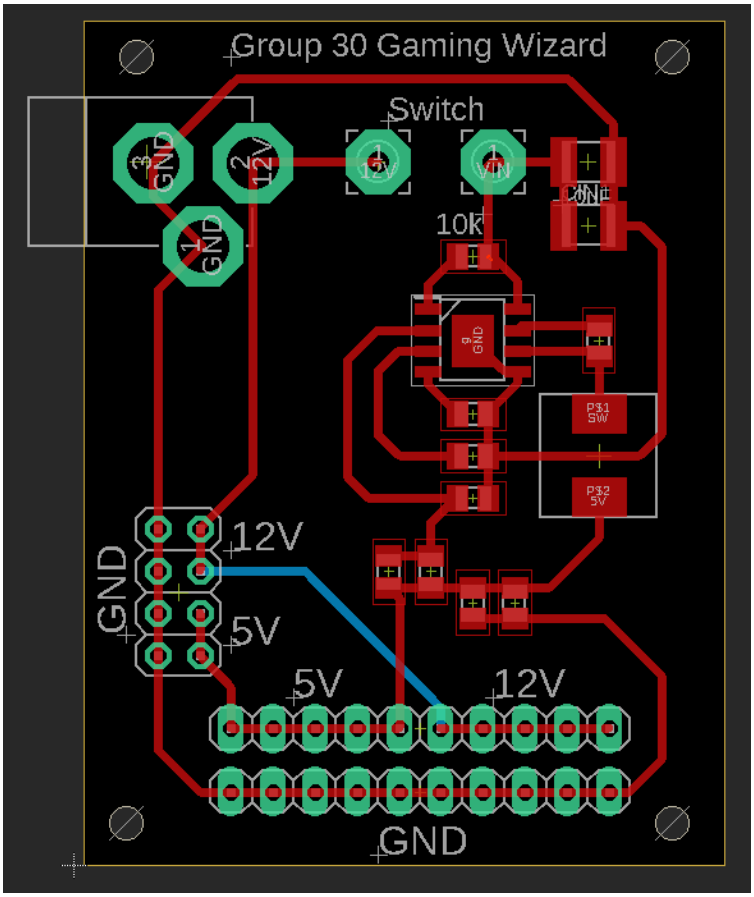


Figure 19: Voltage Regulator PCB

5.11 Serial Communication Protocols

Serial communications are a way for electronic devices to communicate with each other by streaming data one bit at a time using a hardwired connection. The main benefits of using serial

communications over parallel communications, which transfers multiple bits at the same time, is that it requires fewer input/output (I/O) lines and is easier to implement. There are two types of serial communications: asynchronous and synchronous. In asynchronous communications the data is transferred without support from an external clock signal which means the rising and falling edges are not guaranteed to coincide. For synchronous communications all devices share a common clock by always pairing data lines with a clock signal. This is more straightforward and faster than asynchronous communications but requires at least one extra wire between communicating devices. Three types of serial communication protocols are explored below: UART, I^2C, and SPI. The advantages and disadvantages of each protocol are then compared in Table 28.

5.11.1 UART

Universal Asynchronous Receiver and Transmitter (UART) is a simple asynchronous communication protocol commonly found inside microcontrollers. There are three ways it can operate between devices: simplex, half duplex, and full duplex. In simplex mode data is only transmitted in one direction using one wire. In half duplex mode data is transmitted in either direction but still uses one wire so the devices must take turns transmitting and receiving. Finally, in full duplex mode two wires are used so data is transmitted in both directions simultaneously. Figure 20 shows a transmission pattern for 0X1F using UART. The scheme works like this: the line is idle at high, the line drops to low for one bit duration to signal the start bit, the data is transmitted one bit at a time, and finally, a stop bit with a value of high is transmitted to signal the end of the transmission. The bit duration is defined by the transmitter's clock rate and is known as the baud rate. The most commonly used baud rate is 9600 which means a bit lasts 1/9600 seconds. Table 27 shows a list of parameters for UART and the most popular configuration for those parameters.

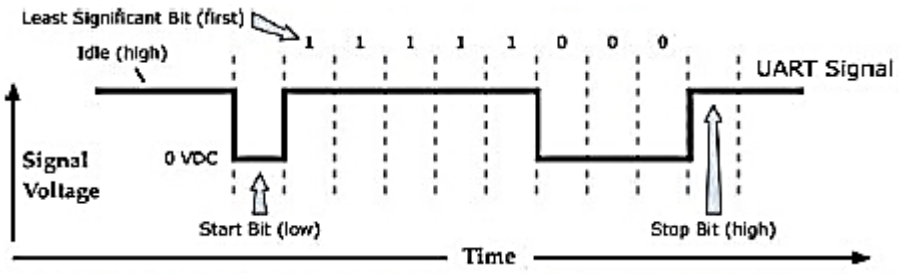


Figure 20: UART Operation
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Table 27: UART Parameters

Parameter	Meaning	Popular Configuration
Baud rate	Transmission speed	9600
Data size	Number of bits	8-bit
First bit	Significant bit	LSB
Parity	Bits to detect errors	None
Stop bit	Signals end of transmission	1-bit
Flow control	Mechanism to pace transmission	None

5.11.2 I^2C

Inter-Integrated Circuit (I^2C) communication is a synchronous serial communications protocol similar to UART mainly used with modules and sensors. It is based on a bus topology and has two wires: Serial Data (SDA) and Serial Clock (SCL). The clock line is used for synchronizing transmission and the data line is the line through which bits of data are sent or received.

In the bus topology all devices plug into the same set of wires as shown in Figure 21. This topology is useful because it allows multiple devices to be connected to the bus. Each device is assigned a 7-bit address so they can be distinguished from each other. One device is designated as the master and the other devices are designated as slaves. The master initiates all transmissions, reads from or writes from the other devices, and is responsible from driving the clock signal.

The SDA and SCL lines are pulled up via pull-up resistors and read high if no action is done. To start and end transmissions the master uses start and stop signals. These are unique signals that can't occur during the data bits. To begin transmission the master transmits the start signal and then sends each slave the 7-bit address of the slave and a read/write bit to the slave it wants to communicate with. The slave compares the address with its own and if there is a match the slave returns an ACK bit which switches the SDA line to low for one bit. If there is not a match the SDA line remains high. The master then sends or receives the 8-bit data frame. After each data frame has been transferred the receiving device returns another ACK bit to acknowledge successful transmission. To end transmission the master sends a stop signal by switching SCL high before switching SDA high.

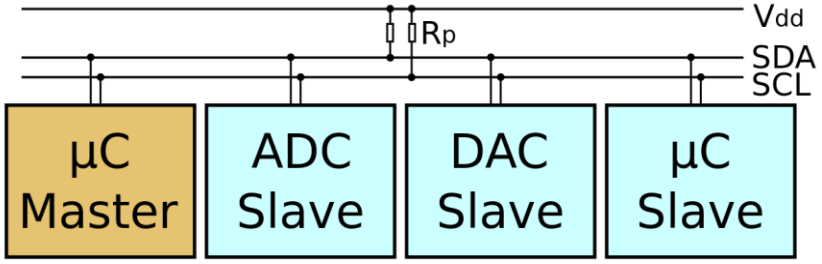

Figure 21: I^2C Configuration
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5.11.3 SPI

Serial Peripheral Interface (SPI) is another synchronous serial communications protocol similar to I^2C that is specifically designed for microcontrollers. It operates at full duplex where data is sent and received simultaneously using two data wires. A fourth line known as the chip select is used to choose which device is being communicated with. The devices that are not selected place high-impedance on their data out lines to not interfere. Therefore, the SPI interface uses four wires: Serial Data Out, Serial Data In, Serial Clock, and Chip Select. When the master interfaces with only one device the device's chip select signal can be connected to low to save a pin at the master in what is known as 3-pin SPI. SPI is not an official standard so the names of each wire may be different. For example, the data lines are sometimes called Master Out/Slave In (MOSI) and Slave In/Master Out (SIMO). Figure 22 shows an example of three devices using SPI in a daisy chain configuration (output of one device is wired to input of another device).

SPI is implemented using two shift registers: one at the master and one at the device. Communication works by exchanging the contents of the two shift registers. Bits coming out of the master's shift register goes into the device's shift register and vice versa. Transmitting a byte consists of latch/shift actions repeated eight times. There are four modes of operation based on combinations of the clock polarity and what triggers the latch and communicate actions (clock phase). The two types of polarity are clock idle at low and clock idle at high. The two types of clock phase are latch at trailing edge/communicate at leading edge and latch at leading edge/communicate at trailing edge.

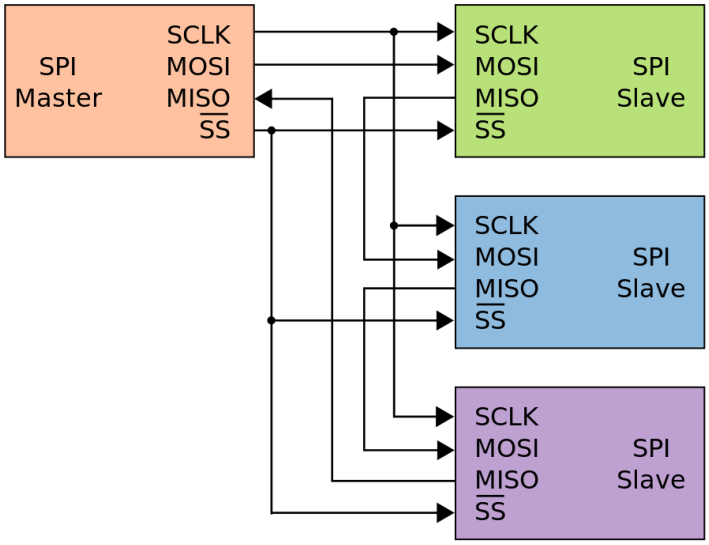

Figure 22: SPI Configuration
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5.11.4 Summary

The advantages and disadvantages of the three serial communication protocols discussed are summarized in Table 28. Understanding these protocols was useful for this project because there are many different electronic devices being used, each with different protocol compatibilities. Being able to communicate between these devices to create a coherent product was essential.

Table 28: Serial Communications Summary

Protocol	Advantages	Disadvantages
UART	Simple to operate	Size of data from is limited to 9 bits
	Well documented	Cannot use multiple master systems and slaves
	No clock needed	baud rates of each UART must be within 10% of each other to prevent data loss
	Parity bit allows for error checking	Low speed
I2C	Simple to operate	Limited speed
	Low pin/signal count even with numerous devices	Requires space on PCB for resistors
	Supports multi master and multi slave communication	Becomes complex when many slaves are implemented
	Adapts to needs of various slave devices	
SPI	Faster than asynchronous serial	More pins needed than other protocols
	Receiving device can be as simple as a shift register	No acknowledgment mechanism
	Supports multiple slaves	No form of error check
	Data is transmitted continuously (no start and stop bits)	Only one master allowed. Slaves cannot communicate with each other.
	Data can be transmitted and received simultaneously	

5.12 Wireless Communication Protocols

The smart table requires the ability to have multiple smart phones connected wirelessly and simultaneously. Information such as player actions and character statistics need to be sent from the phones to the table with as short of a delay as possible. Two possible wireless technologies, Bluetooth 5.0 and IEEE 802.11ac (Wi-Fi 5), were compared and a decision was made on which technology would be incorporated into our design. These technologies were selected because they are both used by most modern mobile devices.

5.12.1 Bluetooth 5.0

Bluetooth is a wireless technology that uses ultra high frequency radio waves to connect fixed and mobile devices over short distances. It operates in the 2.4 to 2.485 GHz ISM band and uses frequency hopping, which is a technique where the signal moves from one frequency to the next at regular intervals. The data is split into portions called packets and is transmitted across 79 bands that are 1 MHz in size. This technique allows transmissions to avoid interference from other signals using the same frequency band such as Wi-Fi. The hopping occurs at 1600 times per second and hops over all of the available frequencies using a pre-determined pseudo-random hop sequence based on the address of the master node in the network.

Bluetooth uses a master-slave structure where one master may communicate with up to seven slaves in something called a piconet. Packet exchange is based on the master's clock which all the devices share. Multiple piconets can be connected to form a scatternet where devices can simultaneously be a master for one network and a slave for another. This network configuration is shown in Figure 23. Bluetooth pairing is a scheme that allows devices to connect easily and

quickly. Pairing is usually initiated manually by a device user and a link is made visible to other devices.

Bluetooth standardization was previously defined by IEEE 802.15.1 but is now managed by the Bluetooth Special Interest Group and to market something as a Bluetooth device a manufacturer must meet the Bluetooth SIG standards. Bluetooth 5.0 was first presented by the Bluetooth SIG in June 2016. It mainly focused on improving technology for Internet of Things (IoT) and boasted four times the range, two times the speed, and eight times the broadcasting message capacity of older versions of Bluetooth.

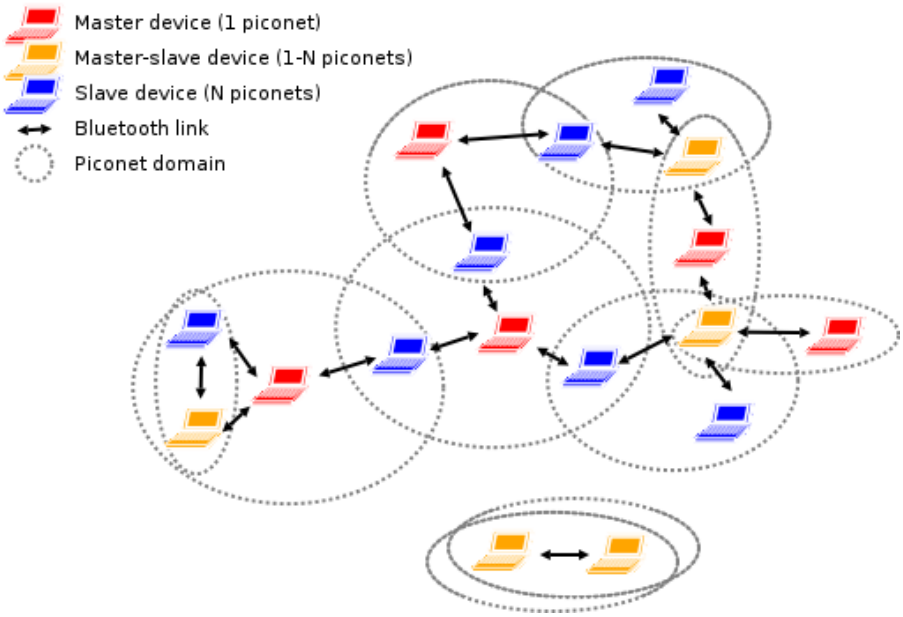

Figure 23: Bluetooth Scatternet Configuration
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5.12.2 Wi-Fi IEEE 802.11ac

Wi-Fi is a radio frequency technology based on the IEEE 802.11 [15] family of standards. It most commonly uses the 2.4 and 5 GHz super high frequency ISM bands. It is a major form of communication used within most homes for connecting to the internet. Wi-Fi uses an access point that acts as the base that communicates with Wi-Fi enabled devices. The data is then routed onto a local area network normally via ethernet. Home Wi-Fi systems often use an Ethernet router that provides the Wi-Fi access point and links to the internet via a firewall. Many routers now provide dual band Wi-Fi connectivity and automatically select the optimal channel and frequency (2.4 or 5 GHz).

There are two basic Wi-Fi network types: local area network (LAN) and ad hoc network. In a LAN based network an access point is linked onto a local area network to provide wireless as well as wired connectivity. In many cases only wireless connections are used in what is known as a Wireless Local Area Network (WLAN). An Ad hoc network allows devices to connect directly without the use of a server. In this case users communicate with each other and not with a larger wired network. One of the peripherals takes the role of master and the others act as slaves. Ad-hoc mode is also known as Peer-to-peer mode. Another standard called Wi-Fi Direct builds on ad-hoc

mode and makes it easier to discover and connect to nearby devices. Wi-Fi Direct allows two devices to establish a direct Wi-Fi connection without requiring a wireless router. This is a single hop communication as opposed to the multihop used by ad hoc networks. This mode is the most similar to Bluetooth.

802.11ac is a variant contained within the 802.11-2016 standard that was released in 2013. The organization Wi-Fi alliance labeled this standard Wi-Fi 5. 802.11ac improves upon 802.11n (Wi-Fi 4) in the following ways:

- More channel bonding, increased from 40 MHz to 160 MHz.
- Denser modulation, using 256 Quadrature Amplitude Modulation (QAM), up from 64QAM.
- More Multiple Input Multiple Output (MIMO), using eight spacial streams, up from four.

Wireless speed is the product of three factors: channel bandwidth, constellation density, and the number of spacial streams. 802.11 ac increased the boundaries of these parameters to allow for much greater speeds (1300 Mbps up from 450 Mbps). However, this protocol only works in the 5 GHz band which lowers the range.

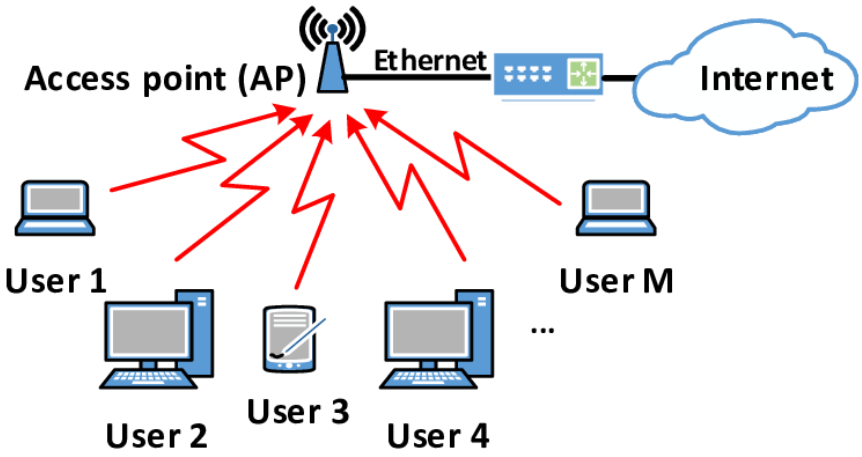

Figure 24: LAN Network
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5.12.3 Wireless Technology Comparison

Bluetooth and Wi-Fi technologies were compared to determine which one would best support our use case. In our case the cost can be neglected because the computer used supports both Bluetooth and Wi-Fi, and the smartphones are guaranteed to have both these technologies. Power consumption could also be ignored for the purposes of comparison because the table is connected to a wall outlet. The ranges for both protocols are plenty sufficient for the purpose of this project. A benefit of Wi-Fi is that it boasts less latency and a higher data rate compared to Bluetooth. This is important because there should be as little of a delay as possible when performing actions. However, during implementation, the Wi-Fi Direct protocol proved impossible to incorporate into our software, so we decided to switch to Bluetooth. A summary of the comparisons between Wi-Fi and Bluetooth are shown in Table 29.

Table 29: Wireless Communication Protocol Comparison

Specification	Bluetooth 5.0	Wi-Fi IEEE 802.11ac
Frequency	2.4 GHz	5 GHz
Cost	Low	High
Channel Bandwidth	1 MHz	22 MHz
Range	5-30 meters	20m indoors
Power consumption	Low	Medium
Latency	200ms	150ms
Bit-rate	2.1Mbps	600 Mbps

6.0 Software Design

6.1 Software Overview

The tabletop game software is comprised of three different subsystems. As seen in the detailed software block diagram in Figure 25, the subsystems are the object detection, game software, and the android app. The game and object detection subsystems will both be located on the computer system. The different subsystems run on different threads to allows for simultaneous execution. Specifically, this enables the object detection subsystem to generate locations while the game software handles requests from the mobile app subsystem. The game subsystem receives player piece location data from the object detection subsystem, and it receives explicit user commands through the connection with the app. The game software must be able to maintain the location of each player, maintain the location of all digital non-player controlled (NPC) entities, maintain a connection to all players, send the correct images to be displayed by the projector, and manage all request from users. The object detection software uses a video stream provided by a camera and converts that stream into location data that is sent to the game software. The video stream faces the bottom of the display and looks for blobs that contrast with background illumination to distinguish objects. The user app is the endpoint where users are able to directly communicate with the software. The app acts as a replacement to the character sheet which is traditionally a physical piece of paper. The character sheet stores all the character information. The app contains functionality to turn what would normally be spoken word in the game to digital actions on the display. Communications between the app and computer systems is carried out using the Bluetooth protocol.

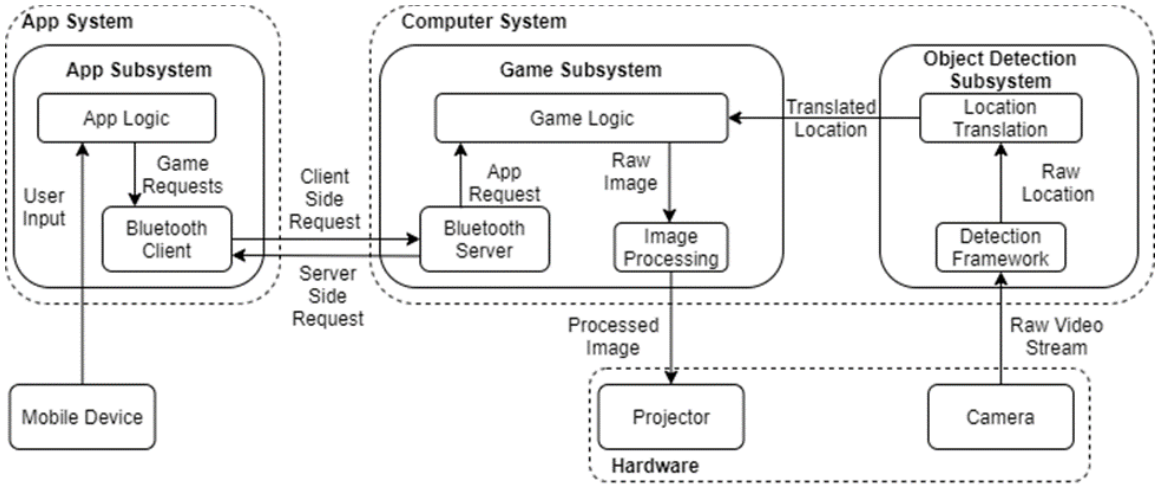

Figure 25: Detailed Software Block Diagram

6.2 Object and Touch Detection

Figure 26 displays the use case for the object detection subsystem. The key feature for this subsystem is the ability to track user pieces on a display. This can be accomplished by using third-party open source object detection framework. The framework is able to track cursors and blobs. For each tracking object the framework must be able to transmit the data readings. The input to this subsystem is a camera feed and the output is the object detector class. This class is created to

handle data transfer and manipulation for the project's software. The third-party framework must accommodate the rear DI tracking scheme as that is the scheme used to track objects in this project.

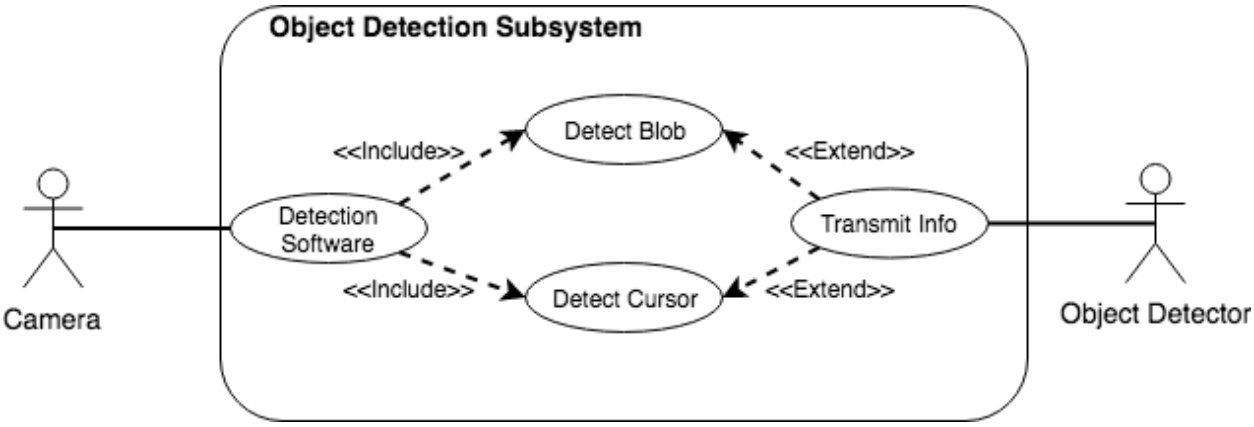

Figure 26: Object Detection Use Case Diagram

6.2.1 Framework Discussion

6.2.1.1 CCV

The CCV (Community Core Vision) [16] framework was developed by a group called The Natural User Interface Group. The current version was released in November of 2014. They are a community dedicated to open source software related to research into human computer interactions. CCV provides a solution to tracking objects. After some configurations in the operating environment, the software ideally spots white blobs through a video input stream where there is no background noise. This applies directly to the rear DI scheme because the video input is the touchscreen where only touches or objects on the screen reflect enough light to become a blob.

The software requires a Pentium 4 processor of better, 512 MB of ram, a camera, and windows QuickTime. There is a list of supported cameras for the software. They do also include a more option implying that any camera can work with the correct configurations. The software does support GPU acceleration to improve latency and capacity of tracking objects. The recommended GPU is listed as a modern GPU which can be assumed to be a GPU made any time after the software was created. The software does offer cross platform support to for Windows, Mac, or Linux systems. The original development platform was Windows and Windows also has the most amount of stable releases.

The software provides a graphical user interface that displays the video input and the tracked object output. However, for this project only the raw data is required as tracking of objects is done within the software. The interface is useful for testing the hardware setup for the display. There is a method that allows object locations to be outputted as raw coordinates. Those raw coordinates will be translated to more useful values in the project's software. The software also tracks the size of each blob that is detected and output those values as well. The sizes can be used to identify what an object is; however, for this project the sizes are used to better determine the location on the game map.

6.2.1.2 Scene

Scene [17] is an open source free to use software that tracks objects. It comes with a graphical user interface as a way to show the manipulations that the software has done to the input frames. Similar to CCV, the interface was used for testing purposes rather than directly implemented into the software. The interface design was actually provided to Scene by CCV.

The software is developed to take any video stream input and process those frames through different techniques to determine the difference between the foreground and the background. After the foreground and background objects are sorted, the background is eliminated. Blobs are then formed using only the foreground elements of the video stream. The blobs are packaged and transferred through the TUIO framework. The video source that the software receives in this project is an already black background with only the blobs in the foreground.

The techniques used to determine and eliminate the background elements of the video stream are simple gaussian, fuzzy gaussian, or mixture gaussian techniques to remove background objects. They are referred to as subtraction background methods. These methods use statistical analysis of image matrices to determine what pixels belong to the background and foreground. Of the three methods, fuzzy gaussian is the only method that does not eventually incorporate stationary objects into the background. However, simple and mixture gaussian are able to pick up on and track moving objects with accuracy. There are also two self-organizing background subtraction algorithms options; adaptive and fuzzy adaptive. These options use neural networks to determine what pixels should be considered foreground and background.

6.2.1.3 TouchLib

TouchLib [18] is a free to use library to implement a multitouch interactive display. The website for TouchLib explicitly says that the library works for FTIR and DI configurations. This library is provided by The Natural User Interface Group who also created CCV. The last published version of the library was in February of 2016. This option does not come with a graphical user interface.

The library provides a configuration application to properly set up hardware for accurate touch readings. Demos are provided as examples on how to create different applications with the framework. The benefit of using a library is the flexibility to create an application that only functions for a specific purpose. The solution is smaller and more efficient in terms of computations. Testing was more difficult with the lack of a graphical interface. Instead, methods were created in order to test functionality of the software. Development time was increased with this option over an already built application. Similar to the other object detection software options, transmission of blob objects is done through TUIO.

6.2.1.4 Conclusion

Scene is a robust solution for the problem that is present in our project. The images that are processed already have the background eliminated and desired blobs brought to the foreground. The background elimination techniques are unnecessary and to save computation are disabled. However, by disabling them the solution becomes functionally the same as CCV. Unexpected difficulties could have come from modifying the software to the extent that would be necessary to eliminate the irrelevant functionality. TouchLib was a tempting choice because it provides freedom to create apps that only include features required. Development time would increase with more software needing to be created and tested. The last version of the library being from 2016 was troublesome in that support may not be readily available and any complications may result in major time loss. If time was not a constraint, this option would have been explored for the customization

ability that it inherently brings. A fully developed and tested software would cut down on development time. The only time requirement was to setup the configurations for the hardware system and test to make sure that the software is reading the input stream and providing an output stream. CCV does just that and provides the desired functionality for DI. There was no need to create or repurpose software because the package has everything included. The only additionally software needed was to set up the other subsystems to allow for TUIO communication. This software would have been developed regardless of the decision as each option uses the TUIO protocol. CCV was chosen to cut down on software development time for design, implementation, and testing.

6.2.2 TUIO

The TUIO (Tangible User Interface Objects) [19] protocol is an open source framework. The framework is free under the less restrictive L-GPL license. The protocol defines two different message classes; Set and Alive. Set details location data for current alive objects. Attributes such as coordinate location, orientation, and directional velocities are recorded and sent in these messages. Alive messages show the current alive objects being tracked; therefore, comparing consecutive readings can identify the addition or removal of objects from the display. This allows the software to not create add or remove messages to reduce the number of messages being sent. This will avoid information loss due to packet loss through transmission. Transmission is also defined in this protocol to be through a TCP connection.

The CCV software utilizes this framework to package and transmit object detected. This format provides dimensional values that describe an ellipse that is created within the bounding box of the blob. The bounding box is way for the software to enclose the blob detected into a range of pixels. The box will have a width and height equal to the maximum dimensions of the blob. The center point of the box is the center point of the blob and it is with respect to the top left corner of the image. The top left corner of the image is located at (0,0). After the bounding box is created, an ellipse is inscribed, and the area of this ellipse approximates the area of the blob. The bounding box is oriented based on the direction that the object is placed on the display. An angle is associated with this bounding box and dimensions are normalized after a rotation for the box.

Tuio objects need to provide a variety of information about different attributes that describe the ellipse approximation. This project requires the ability locate objects at more than just the center point of that object, but also all surrounding pixels that the object overlaps into. Therefore, the (x,y) coordinates for the center point of the blob as well as the ellipse dimensions are needed. All of these attributes are normalized and returned as floating-point values.

Tuio does not maintain the exact values for the height and width because the Tuio objects provide the necessary values to allow the programmers to calculate it themselves. The coordinate normalization is done using Equation 2, found on the TUIO website, taking the sensors location and dividing it by the corresponding sensor dimension. This will produce a floating-point value that will be between 0 and 1.

Equation 2: TUIO (x,y) Coordinate Normalization

$$x = sensor\_x \,/\, sensor\_width$$

$$y = sensor\_y \,/\, sensor\_height$$

The (x, y) coordinates provide the location of the center of the blob. This location can be used to determine what grid space the center of the blob is located in. For the majority of cases, the center point location will be enough to determine the grid space the player piece is meant to be in. However, there may be times that the center point is on the grid lines or close enough to cause issues. The solution to this problem lies in the area of the blob.

Similar to the coordinates, this area value returned is a floating-point value. The value is found using the normalized width and height as well as the approximate area of the blob in pixels. Equation 3, found on the TUIO website, shows how the area is achieved.

Equation 3: TUIO Area Normalization

$$Area = Pixels \ / \ (width * height)$$

TUIO uses inheritance to create a set of related classes for maintaining detected object states. Blobs are maintained in a TuioBlob objects. This object inherits attributes and methods from the TuioPoint class. Specifically, the TuioPoint class maintains fields for the object as if it were a single point on the display. The fields track the center point of the blob. The TuioBlob class maintains all the values need to describe the ellipse approximation.

6.2.3 Object Detector Class

CCV is the open source software used for this project. The software incorporates the TUIO API to transmit objects. On the framework's end, a TuioClient object is used to transmit blobs. The blobs are sent through a TCP socket using the TuioSender object that is instantiated by the TuioClient. To read the broadcast, an ObjectDetector class was created. The object detector class also uses the TUIO API and generates a TuioClient that adds a TuioListener. This listener receives the blobs by creating a TCP socket endpoint. The transmitted blobs are then placed into local fields that are manipulated by a decoding method. The high-level flow of communication can be seen in Figure 27. The transfer of blobs begins with the video stream input and ends with the GetLocation() function implemented in the ObjectDetector class.

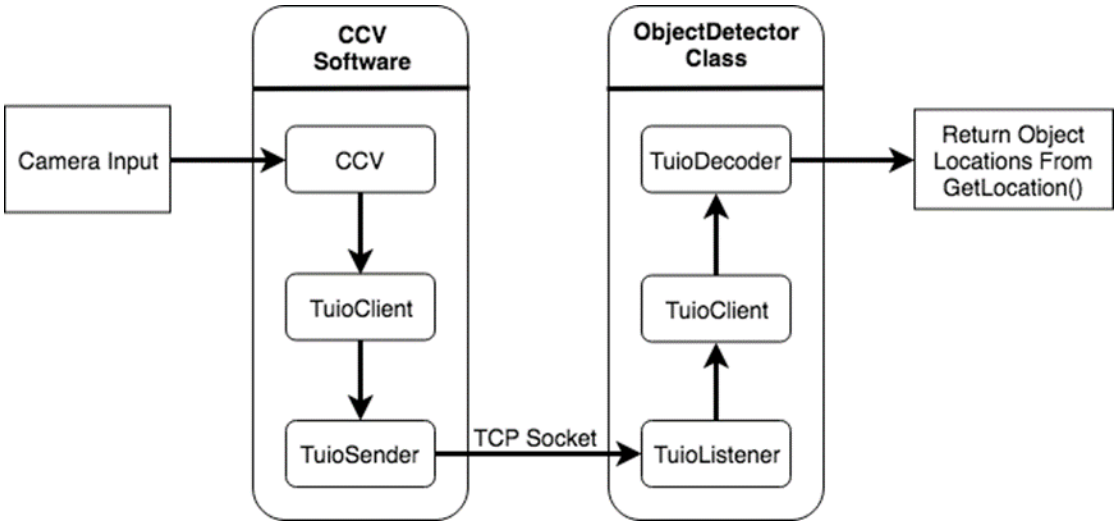

Figure 27: CCV and ObjectDetector Communication

The TuioListener is an abstract class provided by the TUIO API. There are a few methods that need to be implemented to allow for functionality. These methods are shown in Not all methods were programmed to have functionality. This project's software only requires the methods related to Tuio cursors; therefore, methods related to other Tuio objects could be left empty.

Table 30. Not all methods were programmed to have functionality. This project's software only requires the methods related to Tuio cursors; therefore, methods related to other Tuio objects could be left empty.

Table 30: TuioListener Methods

Method	Method Purpose
addTuioObject(TuioObject *tobj)	Handles objects becoming visible
removeTuioObject(TuioObject *tobj)	Handles objects being removed
updateTuioObject(TuioObject *tobj)	Handles moved objects
addTuioCursor(TuioCursor *tcur)	Handles new cursors
removeTuioCursor(TuioCursor *tcur)	Handles removing cursors
updateTuioCursor(TuioCursor *tcur)	Handles moving cursors
addTuioBlob(TuioBlob *tblb)	Handles newly detected blobs
removeTuioBlob(TuioBlob *tblb)	Handles blobs being removed
updateTuioBlob(TuioBlob *tblb)	Handles moving blobs
refresh(TuioTime bundleTime)	Marks end of a Tuio Transmission

The constructor sets up the Tuio objects to initiate communication with the CCV software. When blobs are received by the Tuio protocol, they are passed over a UDP socket and listened for on the Game's TuioClient instance. When an object is heard, the session ID, or temporary object ID, is compared to the internal list of objects to determine if the object is new or being updated. It will then call the appropriate method for adding, removing, or updating an object. When a new object is detected that object must be processed by the game and therefore will be added to a shared data queue to wait for processing. The update message for each object occurs with every refresh of the

CCV software. Therefore, a threshold of half a grid space in both the vertical and horizontal direction must be passed to reprocess the point. That threshold is 16 pixels in the vertical direction and 21 pixels in the horizontal direction. It can be assumed that objects will not being moving frequently and any movement equal to or greater than the threshold is an intended movement of an object. The x and y positions received by CCV are normalized and therefore must be processed to actual screen locations. This is a simple task as it just requires the x position to be multiplied by the output x resolution and y position to be multiplied by the output y resolution. The output resolution will be 1280 pixels x 720 pixels. shows the methods needed by the object detector class to translate the TUIO object into usable values for the game. The vector of locations is encapsulated to avoid any unnecessary manipulation of the values.

Table 31 shows the methods needed by the object detector class to translate the TUIO object into usable values for the game. The vector of locations is encapsulated to avoid any unnecessary manipulation of the values.

Table 31: Object Detector Class Methods

Method	Method Purpose
ObjectDetector(): void	The constructor that boots up the TuioListener and prepares the game to receive input from the object detection software.
addTuioCursor(TuioCursor *tcur)	Handles new cursors
removeTuioCursor(TuioCursor *tcur)	Handles removing cursors
updateTuioCursor(TuioCursor *tcur)	Handles moving cursors

Table 32 references the encapsulated fields that are maintained by the object detector class. These fields are used to create the ability to communicate with CCV and store the messages. The TuioClient creates the connection with the CCV software on the default port of 3333 using UDP. This data is stored in the objects map. After decoding, the values are stored in the toprocess list.

Table 32: Object Detector Class Fields

Attribute	Descriptions
Private TuioClient client	The object used to connect to CCV.
private std::list<Location> toprocess	The list of the decoded blob locations to process.
private std::map<int, Location> objects	A map of all currently tracked objects indexed by the objects ID.

6.2.3.1 Blob Decoder

The blob decoder method takes in as an input a set of blobs that represent the current array of objects on the display. The method returns a set of coordinate points that can be used to distinguish a location on the display. The location coordinates within the blobs are normalized using the sensor's width and height. To decode these normalized points, the points are multiplied by the output display's width and height. These values are known constants that can be easily accessed by the object detector class. The TuioBlob object has the location coordinates as well as blob dimensions saved as attributes. The attributes are private members of the class that can only be

read using the no argument get methods provided. The blobs that are being decoded contain all the information required to decode them.

6.3 Mobile App

The mobile app software is the input endpoint point for a player's gameplay decisions. The decisions are collected through a series of menus that are navigable depending if the player is the GM or player character. For the normal player, those states are either character development or action. During an action state the player has the decision to move or attack. A selection needs to be made as well as confirmation of the physical action. The Game Master needs to act as non-player characters during encounters. This implies that the Game Master has very similar menus that the normal player has as well as additional menus to help with the logistics of the game. The Game Master requires the ability to initiate the save game protocol as well as create and place NPCs. The use case for this subsystem can be seen in Figure 28. All-important functionality that was implemented is displayed.

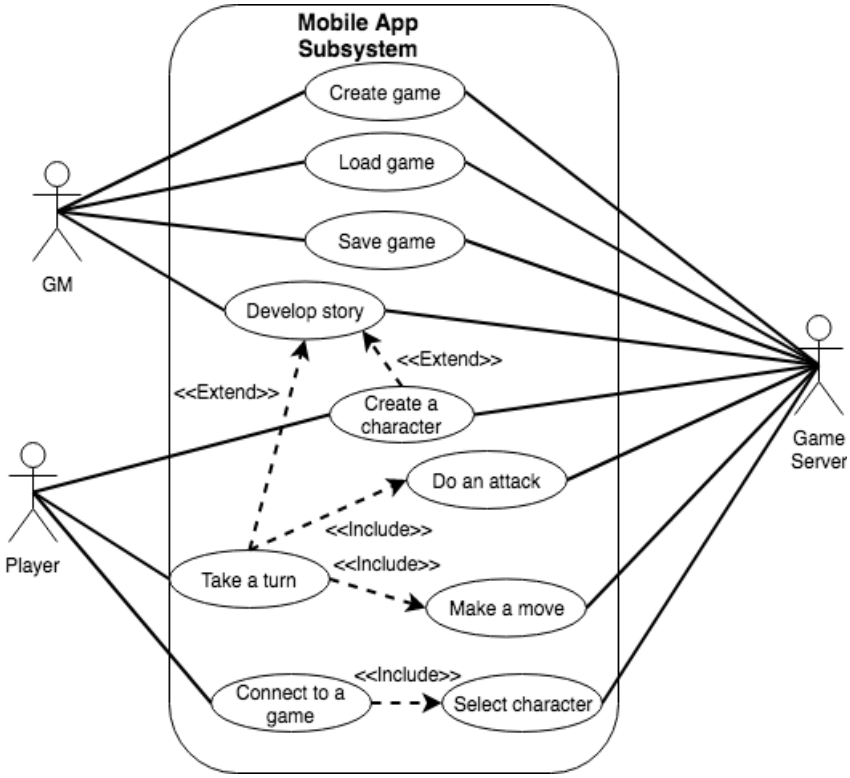

Figure 28: Mobile App Use Case Diagram

The app launches into a visual of the app's logo. In the background, the main menu components are populated by a start-up procedure. Once the image is fully created, it is shown to the user. The first menu that appears for all users contains the option to join session, pair through Bluetooth, or use the app in offline mode. Every player selects the option to connect to the server first then choose a role. The next set of menus depends on the state of the campaign. If the campaign is newly created, then the players begin a character development process. If the campaign already exists, then the players see a selection of character names that they can select from. The player's mobile device is then be linked to that character. During gameplay, a menu is shown that provides different options for the player to select from. Depending on the choice, the app requests the game

to do a specific action through Bluetooth. Table 33 lists the major methods for the app and their purpose.

Table 33: Mobile App Methods

Method	Method Purpose
startup(void): void	Creates the Bluetooth Connection screen
createGame(void): void	Creates a menu to record game data. Sends game data to server to generate game.
saveGame(Player/GM): void	Starts the save game protocol for players.
joinSession(View): void	Connects mobile device to server.
createCharacter(View): void	Creates a screen to create a character.
attack(Player/NPC): void	Sends an attack command to PC with damage type and damage amount
move(Player/NPC): int[*]	Sends a move command to PC with speed(range of movement) and current position
placeCharacter(Player/NPC): int[*]	Sends a place command to PC to place character anywhere on map

The fields for the app, detailed in Table 34, are used to maintain different components as well as the specific subclass that the device is utilizing. Only after a game has begun does a player have an instance of the GM or Player class. These classes define more menus that can be displayed. A device can only ever have an instance of either the GM or the Player class. There will never be a time where both exist. This allows for security that no player can hijack the game by gaining access to the GM interface. Other fields for the player stats are maintained to create faster collection of data when communicating with the game software.

Table 34: Mobile App Fields

Attribute	Descriptions
private GM gmInstance	The instance of the GM interface class.
private Player playerInstance	The instance of the player interface class.
private Widget widgets[*]	A list of all interface components.
private Int stats[*]	A list of all stats being displayed and maintained.

The methods and fields can be split into three different stages. The starting class is where the Bluetooth connection is established. Regardless of the type, namely being a player or GM, each user can interact with the main menu. Only after the game has been started do the menus differ. At that point, the different subclasses are instantiated. The differences in the menus is accompanied with difference in functionality. As seen in Figure 28, the GM has the ability to create, load, save, and develop the game. This functionality must be limited to the GM of the game. The separation of the methods and fields discussed above can be seen in the class diagram in Figure 29.

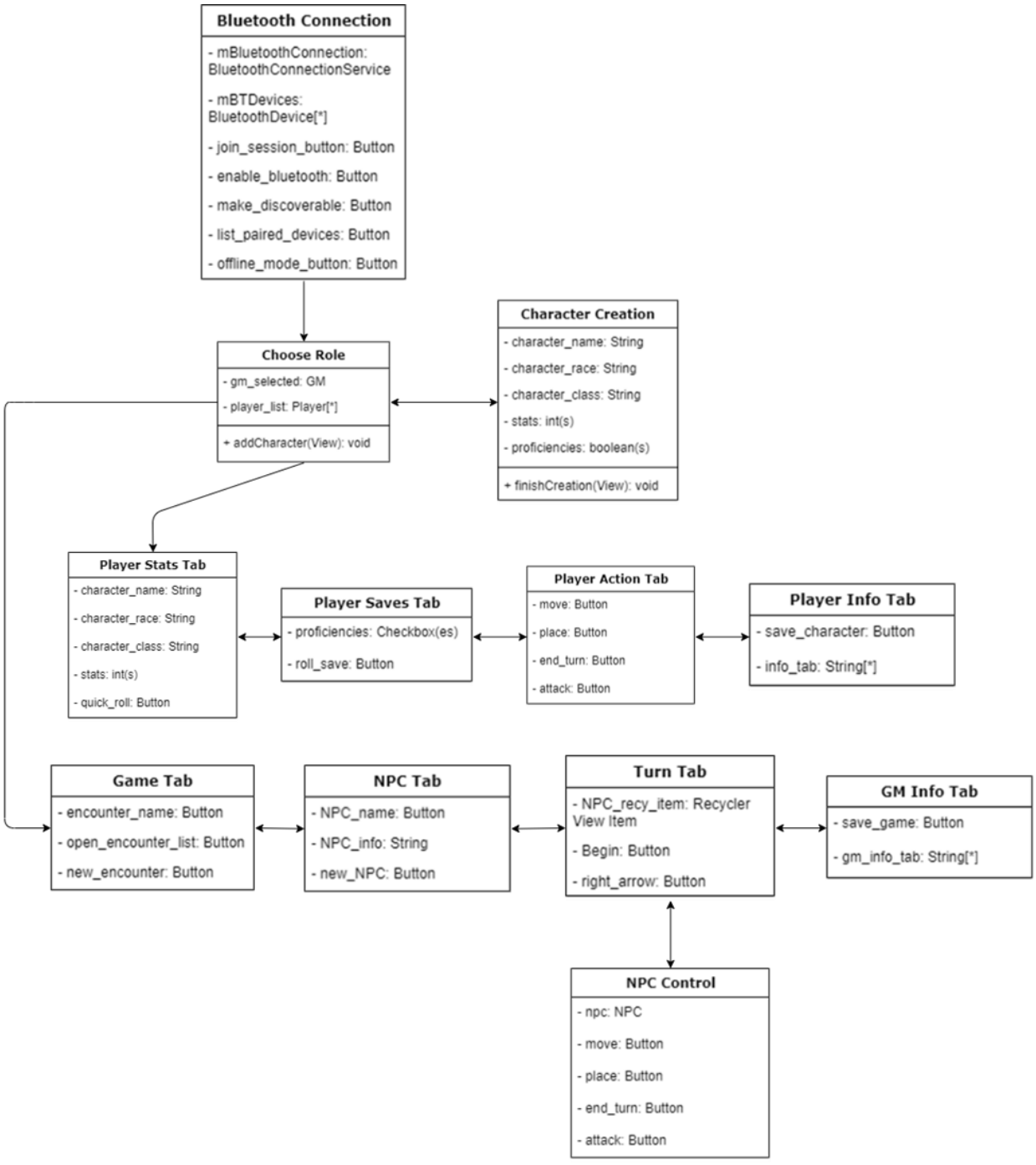

Figure 29: Mobile App Class Diagram

he mobile app remains looping through a set of menus. Each player only has access to turn actions when their turn is active. The state diagram seen in Figure 30 shows the relationship between the different menus. To move from the start menu to the idle menu the game must begin. The idle menu is the menu that is seen while not actively doing any actions. The state only returns to the start menu when a game has ended. On a player's turn, the player chooses a primary turn action. This leads the state to either an attack json sent or a move json sent. The player then has the choice

to end their turn or conduct a secondary action if it is their turn still. Also, the player has the option to update their player stats at any time.

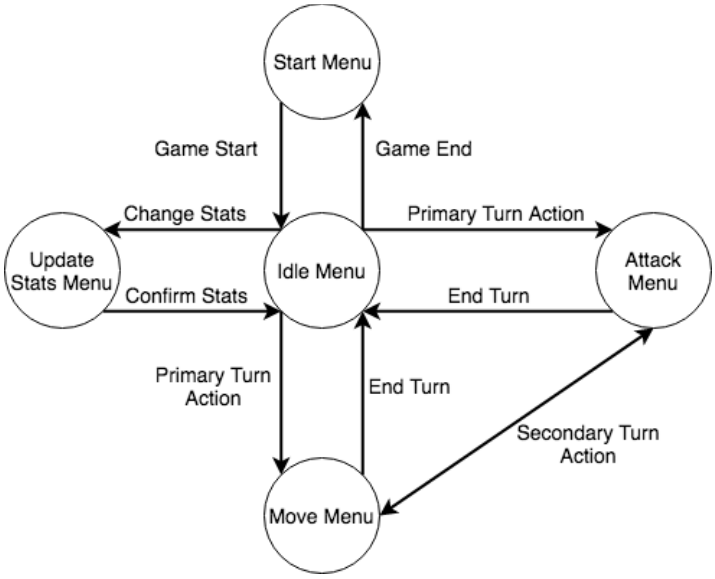

Figure 30: Mobile App State Diagram

When deciding which application environment to program our mobile app with we had two realistic options to choose from, Apple iOS or Android OS. There are less popular mobile operating systems, but most of them are based on Android's Open Source Project (AOSP) or, like Chrome OS, limit the application development to work with a browser only. As we are tried to limit our use of Wi-Fi and instead use Bluetooth for our interactions with the mobile application, a non-browser mobile OS is preferred. The main contributors to our decision included accessibility, financial, and developmental tools.

Since we developed a smart table where the use of a smart phone with our application is required, we needed to bring the app to the greatest percentage of people by choosing either iOS or Android OS. We could extrapolate this data by checking the amount of sales of each OS device per yearly quarter to see which OS is being used the most and check trends in purchases for the future. In Figure 31: Smartphone Sales, 2007 - 2018, we see that Android is clearly leading in number of sales for their OS in the recent decade. This means that there are many more users of Android OS than Apple iOS. We also can see a steady increase in the popularity of Android OS whereas iOS is barely changing in terms of sales per year, so we can assume that there will be even more Android users in the future. This seemed to indicate that if we chose Android OS over iOS, more people would likely have access to our overall game through the app.

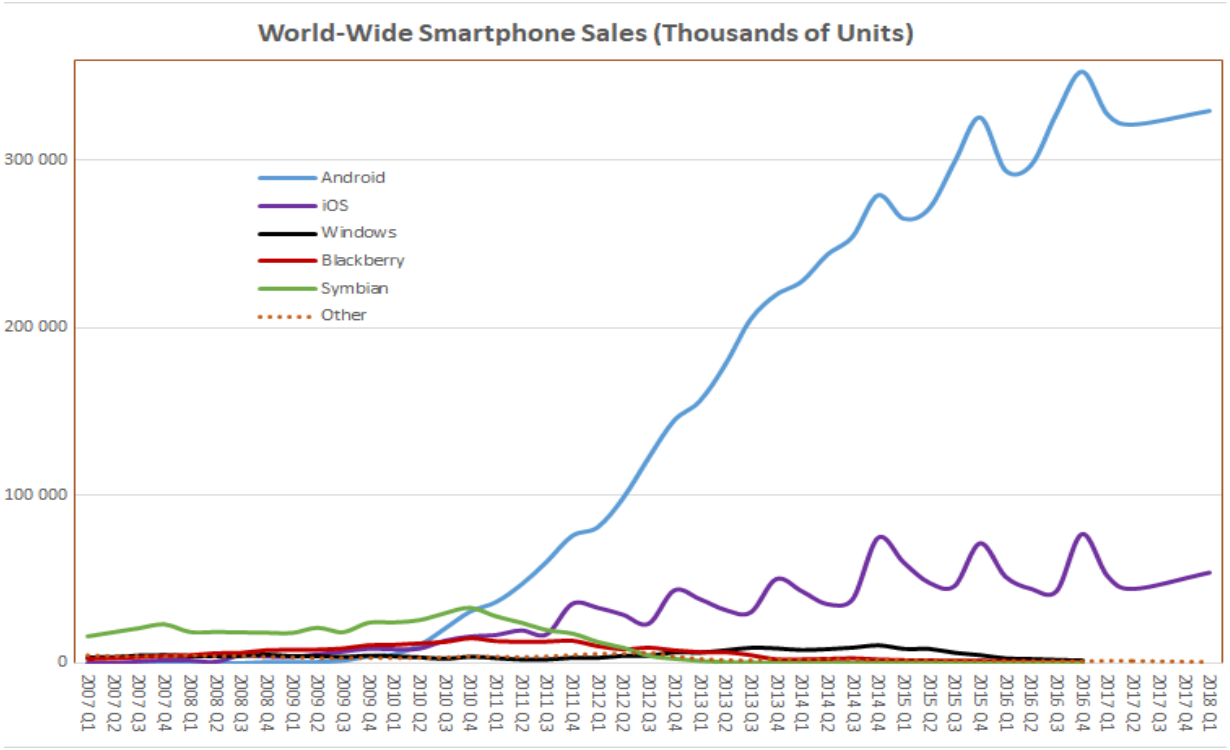

Figure 31: Smartphone Sales, 2007 - 2018
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6.3.1 Android OS Overview

Even though Android is clearly leading in terms of rising sales, there are some problems with just assuming there are more Android OS users. A major problem that Android developers face is software updates and obsolete units. Since Android OS is open-source, phone manufacturers have to choose whether or not to integrate a new software update with their older models of phones. Since Apple manufactures their own phones they have a greater incentive than Android manufacturers to integrate older models with their newest update since the sale of those older models is still a large enough profit for them. On the other hand, Android phone manufacturers have less revenue coming in from older models since they have more competition each update cycle. This leaves older generations of Android phones obsolete much faster than those of Apple, with many still on older versions of the OS.

In Figure 32, we can see that only 10% of Android OS users are on the most recent big update that includes more features and changes than previous updates. This creates a problem when trying to develop an app for the platform. While we could program our app to work with the most recent update, it is not guaranteed to work with previous versions of the OS, so we would be losing a large number of potential people who can play our game. The solution to reaching a bigger audience when developing for Android is to program the app on a lower version of the OS since future updates are backwards compatible with apps in previous updates. So if we were to program our app for Oreo 8.0 we would have a potential 40% of Android users able to play our game. Just for one quarter in Figure 31, 40% of Android sales which totaled around 350 million are 140 million users a quarter in the more recent years.

Version	Codename	API	Distribution
2.3.3 - 2.3.7	Gingerbread	10	0.3%
4.0.3 - 4.0.4	Ice Cream Sandwich	15	0.3%
4.1.x	Jelly Bean	16	1.2%
4.2.x		17	1.5%
4.3		18	0.5%
4.4	KitKat	19	6.9%
5.0	Lollipop	21	3.0%
5.1		22	11.5%
6.0	Marshmallow	23	16.9%
7.0	Nougat	24	11.4%
7.1		25	7.8%
8.0	Oreo	26	12.9%
8.1		27	15.4%
9	Pie	28	10.4%

Figure 32: Android OS Version Distribution
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6.3.2 Apple iOS Overview

Apple iOS does have some distribution of OS versions since they usually have a major update every year alongside the release of their new phone. Although app developers still deal with some problems with updates and incompatibility, the problem is much less wide spread than Android OS. This happens because Apple is closed-source, making all production and applications of devices with the OS happen in house. This means that Apple does not have to worry about manufacturers changing their phones to fit different AOSP derived OSs'. With this in-house production comes an easier time when updating older models of phones to the newer update. This makes it so that phones that released around the same window of now obsolete Android phones are still being updated to the new OS. The Apple Devloper site [20] provides the distribution of OSs' for iPhones that released in the past four years. 55% of users are running iOS 13, 38% are running iOS 12, and the remaining 7% are running earlier versions. We see that iOS users are primarily using the two most recent updates compared to the many versions in use by Android users.

From Figure 31, we see that the total sales for Apple iPhones is around 60 million per quarter, so around 56 million (93%) of users are on iOS 12 or higher. Unlike Android OS, apps developed to work for previous generations may not be automatically compatible for future generations as Apple introduces new features and requirements with each update that an app must follow. App developers must decide to keep supporting each iOS when a major update occurs. Even though the sales are lower for iPhones, the adoption rate of previous devices for new updates is much higher than Android. As long as an iOS app works with the two most recent updates, then you are likely to reach most iPhone users.

6.3.3 Financial Costs

Since Android OS is open source, the developmental costs are much cheaper than the closed source iOS. Android Studio is the free IDE required to develop an Android OS app. It is available for free for Windows and is based on Java for coding. To publish your mobile app on the Google Play Store, there is a one-time developer fee of $25. For iOS, you must own a MAC in order to develop an app for iOS. On the MAC OS, Xcode is the free IDE used with the Swift programming language to code iOS apps. App developers for iOS are charged an annual developer fee of $99 to submit their app to the App store. Although we would only get a one-year fee requirement for our project, if we ever wanted to update our app in the future, we would need to renew with another developer fee.

6.3.4 Developmental Tool Differences

Android and iOS have different approaches when it comes to tools when developing apps. Since the computer's OS is also different there are many differences in UI and file management for mobile app development.

6.3.4.1 Android Studio

When developing for an Android OS app, programmers must use Java to handle creating user interfaces (UI) and interactions between the App and external communications like Wi-Fi or Bluetooth. Android Studio has a set of software tools called Android SDK which includes their required libraries, a debugger, an emulator, and some tutorials to help a new developer. The Android SDK also includes a feature that allows you to choose which version update of Android to support. The debugger has a log for error messages, a pane for seeing variables and threads, and testing frameworks. The emulator allows you to test your program in a virtual environment before pushing onto the Google Play store. Unfortunately, the emulator cannot simulate external communications like Wi-Fi or Bluetooth so a developer must have a physical phone to test those features. The Android emulator can also specify different versions of the Android OS to test for backwards compatibility of an app. Each Android virtual device has its own storage and cache for each instance of the virtual machine. The basic tutorial can help a new developer create an app with features such as adapting screen size for different phones, UI, and performing background tasks not dependent on the UI.

6.3.4.2 Xcode

Developing for iOS uses Xcode for an IDE in comparison to Android Studio. Apple apps are programmed using Swift which Apple incorporated back in 2014 to help users create their own iPhone apps. Swift is a good language for beginners as it has many safeguards in place to minimize errors and allow fast execution of code through optimization. Xcode itself has many easy to use design tools to help ease in a new mobile app developer. The declarative syntax helps distinguish what each element of the UI should do. For designing new UI elements, Xcode has a drag and drop feature that allows for easy creation of visual UI designs. Xcode has a simulator that can prototype the entire created UI and app testing that will test background app functionality. Like Android Studio, Xcode cannot simulate WI-FI or Bluetooth functionality to external sources because those functionalities need specific hardware to run.

6.3.4.3 Feature Comparison

Both of these IDEs have similar features such as emulation or simulation, but they also have a few differences that make them distinct. Android Studio offers a Gradle-based build system which allows custom builds through the use of plugins created or downloaded by the user. Android Studio

also allows multiple APK generation and variants. Android OS has more community resources because it is open source allowing more people to share their builds and plugins for Android Studio. Unique to Xcode is an assistant editor and asset catalog that allows for easy creation of UI elements. UI is one of the most difficult part of any app creation to make interact correctly with the features and look comprehensive enough for new users. The catalog greatly helps cut down on the time required to build a UI and instead allows developers to focus on features and interactions between the app and input from external communication like Bluetooth.

Based on user experience, Xcode does more than Android Studio in terms of a friendly development environment and easy to use assets. In terms of each programming language, Android Studio's Java based coding is more familiar to programmers trying to make their first mobile app. Although the programming language might feel more familiar in Android Studio, Xcode more than makes up for it using its storyboard seamless IDE integration with the simulation. However, because of this integration, Xcode can be quite slow when compiling since it is connected to the simulator which slows down while trying to compile simple changes in code. Swift is a very strict language that updates to change library functions which can make a previously working apps crash or not compile at all in different versions. The overall financial requirement is much greater for iOS than Android OS, and was have been especially as no user had a MAC to begin with.

6.3.5 OS Selection

With both OS options researched we compiled Table 35 and compare the benefits and disadvantages of each. With this comparison we could choose which OS to use in our project.

Table 35: iOS vs Android

	iOS	Android OS
Benefits	+ Simpler and streamlined Xcode helps new developers, especially when creating visual UI	+ Simple one time developer fee
	+ Brand loyalty of customers and distribution of customers is for the most recent two big updates	+ Updates are backwards compatible with apps made in previous versions
	+ Simulation of code is possible using Xcode programmed with Swift	+ Emulation of different versions is possible with Android Studio
		+ Increasing sales for OS means more potential future users.
		+ In our group, we all have Windows, so we have free access to Android Studio
Disadvantages	- No one in our group has a MAC so we would need to borrow one since purchasing one is too expensive	- Fragmentation of users mean fewer people on each update
	- An annual developer fee of $99	- More difficult to make UI in Android Studio
	- Smaller percentage of people have iOS based on number of sales per quarter	

The benefits and disadvantages are not equally important, and we decided to go with Android OS for our mobile app. The lack of a MAC and the high annual developer fee for Apple iOS is what ultimately made the decision. While we could most likely borrow a MAC from someone we know or even UCF, there might have been a reason that we cannot one day and all progress or testing on the app portion of our project would halt.

6.3.6 App User Interface Framework

Because the app was built in C++, a third-party open source library was required for the interface. Although the project only developed an android app, some third-party libraries do enable the ability to run the same code on different platforms. This allows the same look to be ported to different platforms such as an iOS environment or even a desktop environment. This ability to have the same look across different platforms comes from the frameworks process of drawing their own components based on the operating system the code is running on. This also helps the performance and ability to look like other native applications. Two open source frameworks that were considered are QT and wxWidgets.

6.3.6.1 QT

QT [21] is a cross platform, open source user interface framework. QT is developed in C++ and performance is just under native libraries in terms of speed of creating components. There are two license options that QT allows developers to use, a commercial license and free license under the L-GPL licenses. To use QT for free, source code must be visible to the users or the QT libraries need to by dynamically linked to the source code. In other words, if the library functions need to be modified to better work with the project, the project must be made open source. This allows other developers to see modifications made and help the framework overall. If the libraries do not need to be modified, then the libraries can be dynamically linked to the project which shows that no modifications were made to the framework. The goal of QT is to provide a framework that can easily be ported across platforms. Therefore, they provide plenty of documentation on how to use the different library classes and their methods, how to start a project, and how to compile and build the projects. Regarding the android app, QT provides documentation that shows how to convert a C++ project to a build compatible with android development.

6.3.6.2 wxWidgets

The user interface framework wxWidgets [22] is also cross platform and open sourced. It is developed and compiled through the C++ language making the speed of the code comparable with built in user interface libraries. wxWidgets is completely free for both free and commercial products under the L-GPL license with an exception that code does not need to be distributed to users. In other words, the framework libraries can be modified without the need to show other developers what changes have been made. The framework has the benefit of age being created in 1992. There are many popular programs that use this framework. It is important to note that these programs are all for desktop platforms. Android development is not fully supported, and documentation is not at a level that would create ease of use while developing.

6.3.6.3 Android Studio Layout Editor

The Android Studio layout editor [23] is a drag and drop user interface that aims to provide easy to create and implement interfaces. As seen in Figure 33, programmers drag components from the component selection tool and place them on the window in the graphical component view. Once placed, the component view displays the component without the added graphic and an instance of that component is added to the list in the component tree. The editor provides built-in basic

components for development and the ability to create subclasses from those components. This leads to the ability to modify components to better fit the needs of the application or to create entirely new components.

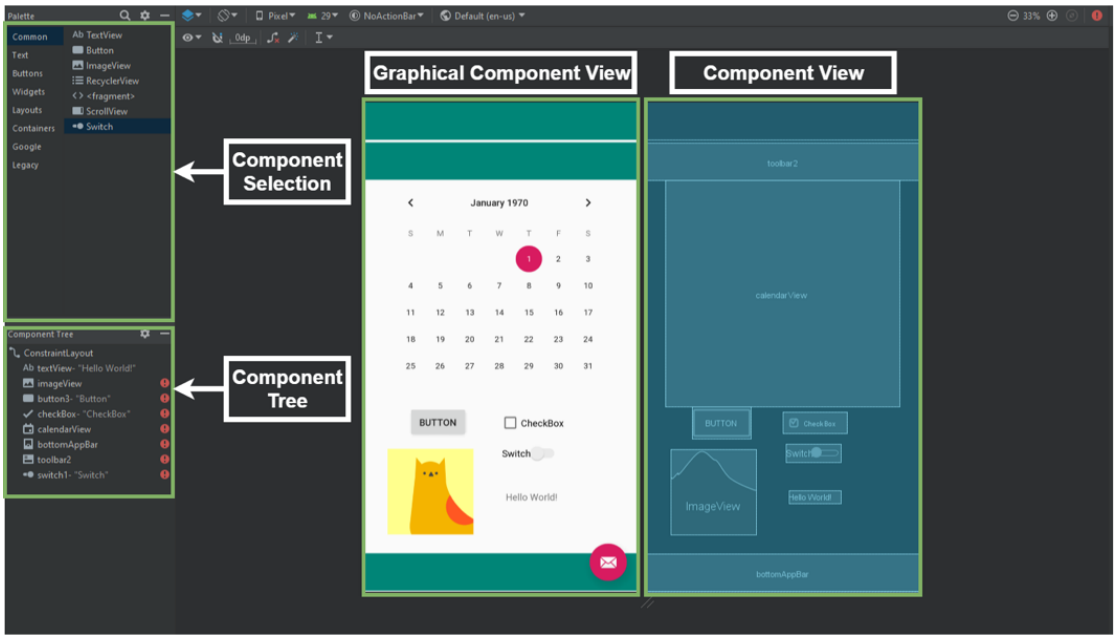

Figure 33: Android Studio Layout Editor
Reproduced from work created and shared by the Android Open Source Project and used according to terms described in the Creative Commons 2.5 Attribution License

6.3.6.4 User Interface Framework Selection

Although this project involved developing only an Android app, iOS development is still possible for the future and was included in the decision. Therefore, Android Studio layout editor was initially ruled out because it constrains the user interface to only apply to android devices. However, time constraints did play a factor in interface development, therefore, Android Studio layout editor was used to develop the Android user interface. The other frameworks were ruled out because they would require significantly more time to learn and implement.

6.3.7 App User Interface Design

The app is designed to provide easy, logical access to character information for both players and game masters, as well as additional controls for game setup and turn assignment for game masters. The logic and functions available to users through the app are detailed in Figure 34. Some functions are available offline (i.e. when not connected to the table) to allow users to prepare for games at any time and from any location. Each function may expand a sub-menu or series of sub-menus as required by the complexity of the information being accessed.

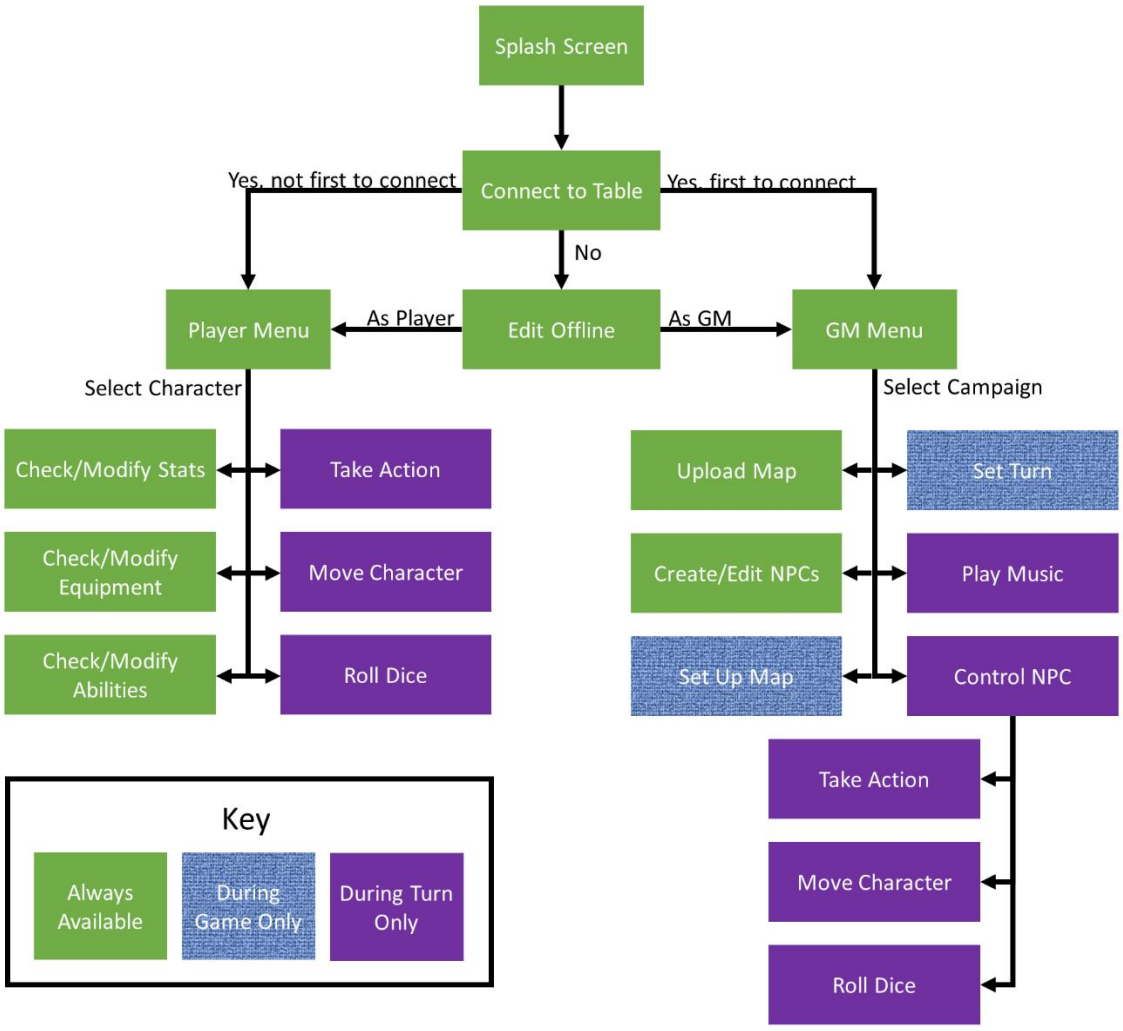

Figure 34: App Interface Logic and Functions

The app is styled to be reminiscent of the paper and pencil format of the original game. The splash screen and main screens for GM(middle) and players(right) are depicted in Figure 35, for a 1080 x 1920 pixel display (a standard resolution for modern mobile devices). The GM screen depicts the turn order and the player screen depicts the stats of the player. The splash screen design and player screens use a traditional paper aesthetic and are easily adapted to a variety of display dimensions.

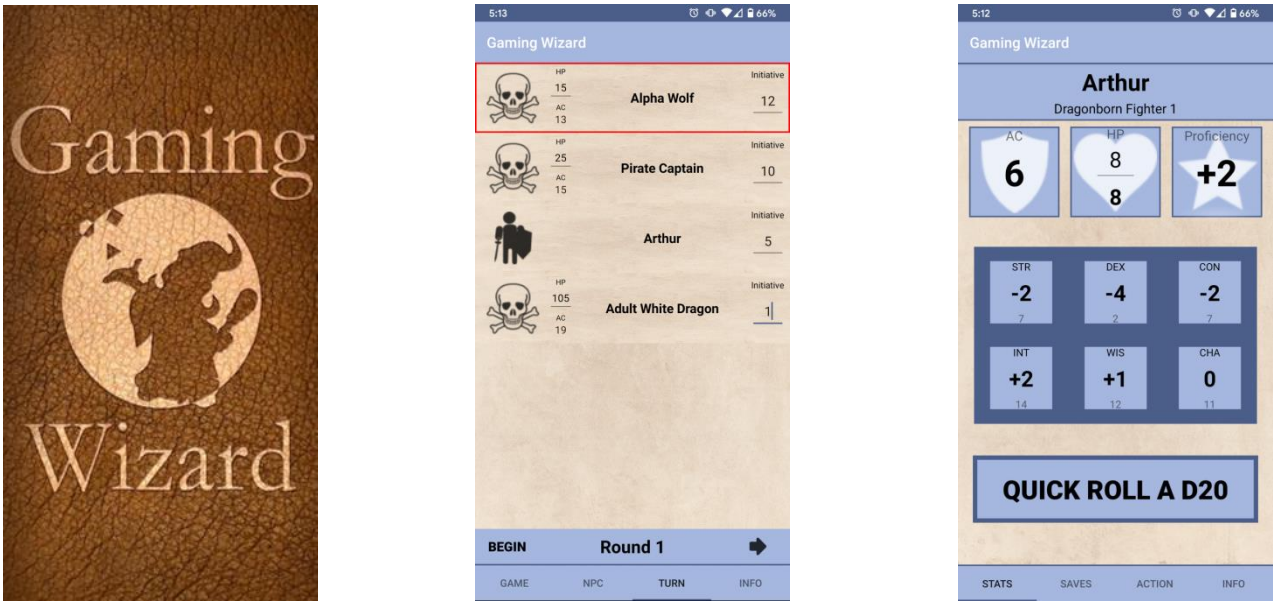

Figure 35: User Interface Designs

6.4 Game Software

6.4.1 Game Software Endpoints

Figure 36 shows the use case for the game software subsystem. The diagram lists major functionality that the game subsystem handles. The actors on the left side of the system represent the inputs to the system while the actor on the right side represents the output. Each actor is an endpoint managed by the software. The input endpoints are the mobile app and object detector class. The output endpoint is the display. Since the game is heavily dependent on user input, the game handles the mobile app endpoint by being in constant contact with each user's app. Bluetooth protocols are in place to distinguish user devices and create communication channels. The users communicate turn information which is then processed to properly display images. The GM initiates protocols for creating, saving, and loading games. All players need to be able to connect to the network. The game software maintains memory of player piece movements. Updated player piece locations are detected through the object detection software and sent to the object detector class to be stored through a socket. Some functionality manipulates the displayed images to create a more coherent game experience. That functionality includes methods such as update map, display map, and display attack or range spaces.

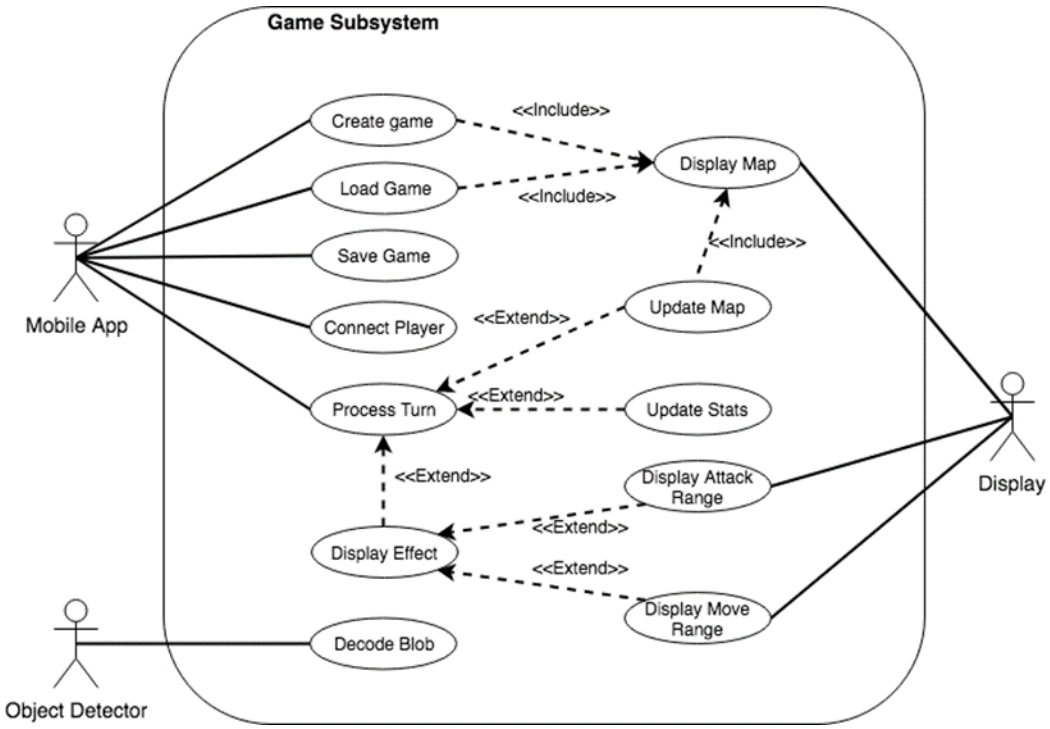

Figure 36: Game Use Case Diagram

6.4.2 Game Software Class Descriptions

The game software can be broken up into different classes that encapsulate the different aspects of the program. By grouping the major functionality seen in Figure 36, four classes are used to incorporate all functionality. Those classes are the player class, game class, Bluetooth class, and display class. The basic class structure can be seen in Figure 37. The player class is used to keep a local record of the character traits and provide methods for user actions. The game class handles the logistics of the game logic. More specifically, the game class maintains the instances of each of the other classes and controls logic flow to each of the classes. The Bluetooth class is an object that creates a server network that is broadcast to the nearby Android devices. The display class handles all display-related methods and attributes.

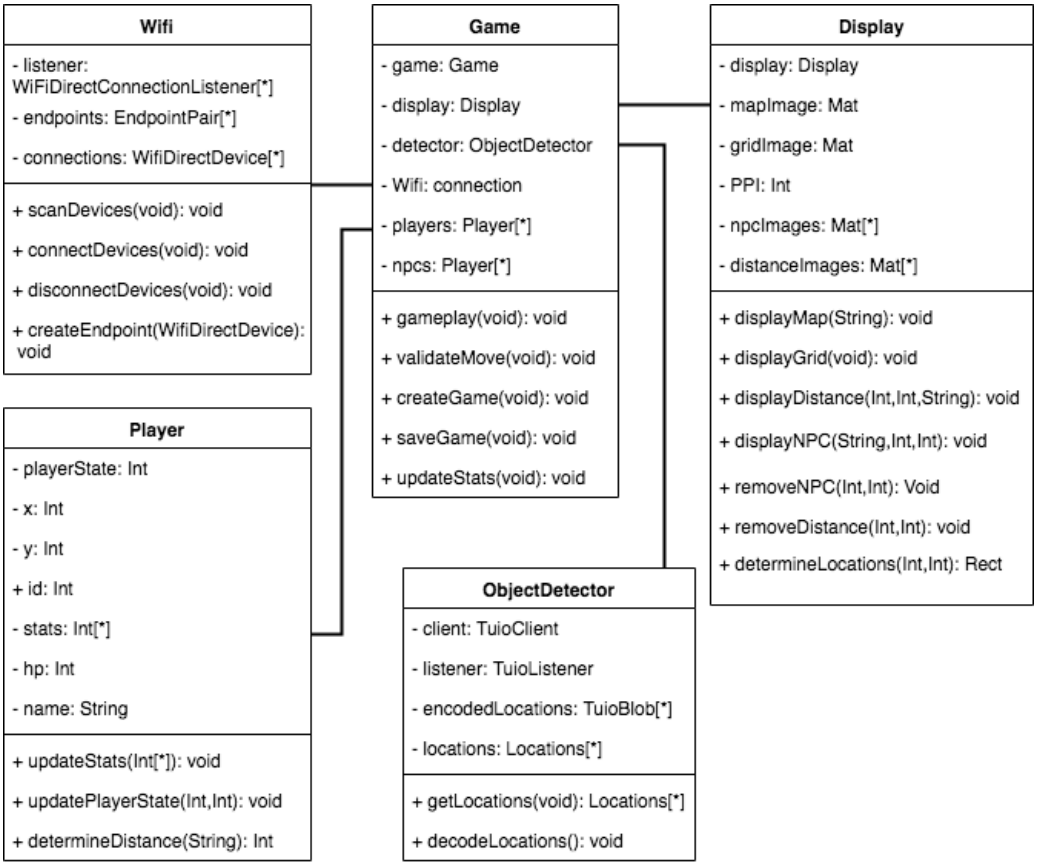

Figure 37: Game Software Class Diagram

6.4.2.1 Player Class

The player class holds the information about the user's character and methods to manipulate that information. The methods required for the player class can be seen in There are several public getter and setter methods that have been omitted from the table because they do not provide the major functionality of the class. The table instead holds the methods that are important for the Game class. These methods include createPlayer which takes in a json object for the player's stats and updates the player's local field for the first time. Similarly, the updatePlayer takes in a json object and updates the player's local field with the new information. This assumes that the field has been populated before the current call. The isGM method is used to determine if the current Player instance is the GM as the GM has different protocols compared to normal players.

Table 36. There are several public getter and setter methods that have been omitted from the table because they do not provide the major functionality of the class. The table instead holds the methods that are important for the Game class. These methods include createPlayer which takes in a json object for the player's stats and updates the player's local field for the first time. Similarly, the updatePlayer takes in a json object and updates the player's local field with the new information. This assumes that the field has been populated before the current call. The isGM method is used to determine if the current Player instance is the GM as the GM has different protocols compared to normal players.

Table 36: Player Class Methods

Method	Method Purpose
Player(): Player	Player constructor that will instantiate a player object and return a reference to that object.
createPlayer(json attributes): void	Method that takes in a vector of values and updates the corresponding field elements.
updatePlayer (json attributes): void	Method that calculates player state based on a combination of a dice roll and hit points.
isGM(): bool	Returns true if the player instance is the GM, otherwise returns false.

The class fields act as a replacement for the traditionally character sheet. The character stats, if the player is the GM, and the player ID are maintained. There are many values on the character sheet that will not be displayed in Table 37 as they are encapsulated in the attributes field.

Table 37: Player Class Fields

Attribute	Descriptions
private bool GM	A Boolean that signals if the current Player instance is the GM.
private json attributes	A json object that holds all player data for the game.
private int id	A unique ID for each player

The json object for attributes is where all the character information is stored. Examples of the player information includes basic abilities such as strength, dexterity, constitution, intelligence, wisdom, and charisma. The id field will be used for distinguishing the different players. The player id needs to be readable from other classes to ensure that the correct player instance is being manipulated. The object detector class maps blobs to players and this is achieved by mapping to the unique id value. The player id is generated based on the mobile device. The Bluetooth connection already requires a unique id for each device and this id can be repurposed for the player id as well.

Encapsulation is utilized in this class and public getter and setter functions are needed for each of the field elements. Methods in the Game and Display classes rely on field data from this class. However, they are not granted direct access to the fields to avoid any corruption in the data. The Game class requires the ability to read the player's id to select the correct player object to manipulate. The player stats are also used to determine gameplay events such as attacks. Some player stats need to be updated throughout the game. The only class that is granted permission to modify the fields is the Player class. Each field therefore requires methods to set those values. The player can also have different states that are dependent on the player's health and a physical dice roll. There is a menu to insert the dice roll on the mobile app so that the Player class can properly handle calculations needed to update the player state.

The Player class oversees managing player actions. These player actions come with values associated with either hit points or range of action. When performing an attack action, the attack range is based on player stats and so is the hit point damage applied during that attack. Similarly,

when performing a move action, the player has a set range based on their player stats to move. Players have the option to perform both actions on any given turn assuming NPCs are present on the board. If the game state is not currently in combat, then the attack action is not an option. Players also have the choice of just performing a single action. Since there are a few options, the player needs to select what action they would like to perform through the mobile app. The Game class must then to ask for the distance in order to display the range and continue gameplay.

NPCs are controlled by the game leader through the mobile app. For all purposes they act as a normal Player. A subclass is not required as no different functionality is required. A problem that was faced was in the unique id. The same procedure as was discussed above cannot be done for NPCs. Since each NPC technically is owned by the game leader, they would all have the same unique id which would void the uniqueness of the id. As a result, each character has a unique ID that is part of their attributes. Therefore, each device has a unique ID to determine where messages are going and coming from. The character ID will be used to distinguish characters for the GM.

6.4.2.2 Game Class

The game class is the starting point for the game logic and manipulation. When the program is launched, an instance of the game class is instantiated, and the game setup begins. The key steps to setup are to start the Bluetooth server to allow for connections to the game, display the startup menus, and tracking blob locations to allow for touch control. The constructor for this class is used for setup. The class is also in charge of validating player actions on the display and processing any input from a player's mobile app. The major methods for game functionality are shown in Table 38.

Table 38: Game Class Methods

Method	Method Purpose
Game(): Game	Game class constructor that instantiates a game object, runs the setup process, and returns a reference of that object.
gameplay(): void	Processes the gameplay requests.
createGame(): void	Method to begin a game's startup
saveGame(): void	Saves all states of each class into a file and stores the save file on the game leaders app.
loadGame(File *gameData): void	Takes a save file and generates all objects stored in the file.
messageHandler(char * message): void	Method to read and handle actions dictated by the input message.
processPoint(int x, int y, int mode): void	Method to match a blob object queued to the correct action in the software logic.

Since the game class maintains the major functionality of the game, there are private field elements for each of the objects required for player and display interactions. The players and NPCs are also

maintained in this class. The Players are maintained in a vector of Player objects and the NPCs are maintained in a json object. The fields can be seen in Table 39.

Table 39: Game Class Fields

Attribute	Descriptions
private Game instance	The object itself.
private Display display	The object that will maintain all display objects.
private Bluetooth bluetooth	The object that will send and receive input over a Bluetooth server
private ObjectDetector detector	The object used to detect objects on the display
private int gameState	Holds the state of the game. 0 mapping to normal play, 1 mapping to combat.
private std::vector<Player> players	A vector of user player objects
private json NPCs	A json object of NPCs

6.4.2.2.1 Game Constructor

The game constructor should only be called by the main function when the system is powered on. When the game constructor is called, the first task is to allocate memory for the object if it does not exist. There should only ever be one instance of the game class running at any given time. Before the memory is allocated, the constructor checks for any instance of the object already existing. If the object does not exist, it creates the object and stores it in the private field. The constructor then continues to setup only if the instance was just generated. Setup creates an instance of the Bluetooth, Display, Player, and ObjectDetector class. Once all of the necessary fields are stored, the gameplay method is called so that the game can begin. The gameplay method call indicates the end of the constructor and finalizes the connection of all players for the game. Figure 38 illustrates the flow of the constructor beginning with the power on event and the call from main.

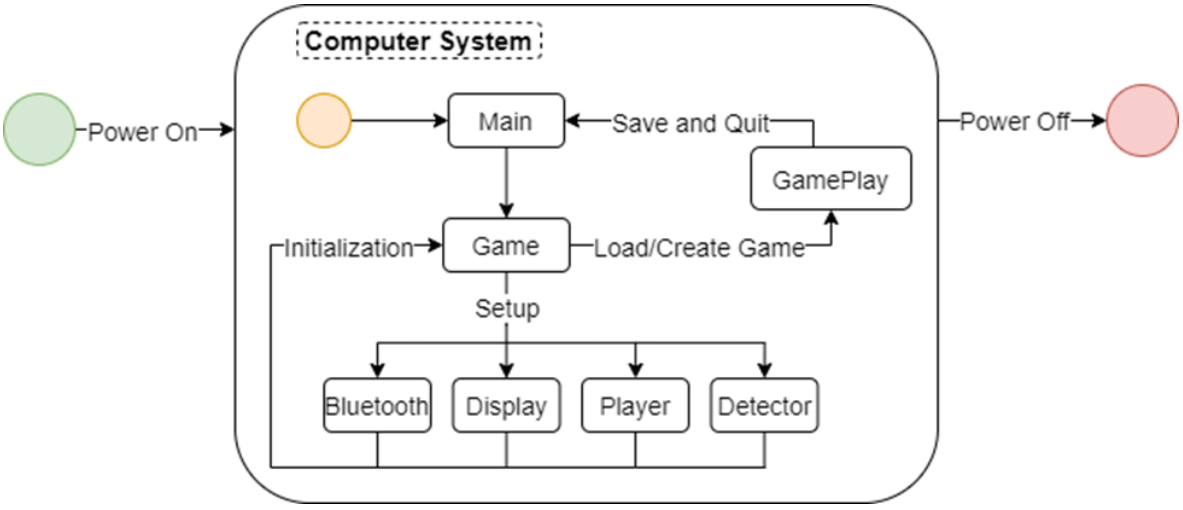

Figure 38: Game Constructor Flowchart

6.4.2.2.2 Gameplay

The gameplay method is the main functionality of the game. It maintains ordered player turns and processes all user input. At this point, the game has an instance and all players are connected. The turn order is decided by the game master and maintained in this class. In a round, each player takes a turn. The parts of the turn that have a digital action are movement and attacks. Both of which call a Display class method to highlight spaces. The game then waits for the user to choose a physical space or move their player piece on the display. The location of the action is collected by the object detector class. The location then passes through the process point method. If the state is combat, then the attack action can be done by itself, before, or after the movement action. If this is the case, the player is asked again what action they are going to take, and the process repeats.

6.4.2.2.3 Validate Movement Method

Since movement and attack locations are user inputted, there must be a verification method for valid input. This is accomplished by taking the player's original location, the distance the player can travel or attack, and the new location found by the object detection software. Using the initial position of the player and the distance that they can move or attack, a boundary can be formed. Verifying that the new position is within the boundary can easily be done. Verifying location must go beyond simply checking the location to the boundary formed. The display shows a map that the player pieces are placed on with a grid overlay that is divided into 1" by 1" squares. Ideally, players place their pieces perfectly within each of those squares. Realistically, players are not perfect, and placement verification should not harm the flow of the game if it does not need to. If a piece is slightly overlapping another square, the game won't ask the user to fix the position. However, if the piece is greatly overlapping another square to the point that it cannot distinguish which square was intended, the game must request clarification from the user.

As a way to mitigate the issue of greatly overlapping squares, an algorithm will be in place to decide on the grid space that the piece occupies the most space in. The only assumption this makes is that the user will attempt to place the piece mostly in their desired location. This can only be manipulated if the user intentionally places the piece mostly in the wrong grid space. At that point, the game will just assume that they are in the other grid space and continue operating as expected.

A case to observe is when two player pieces are overlapping the same grid space. This can be seen in the valid placement case of Figure 39. The circles represent player pieces and the shaded region represents the grid space with the most piece area. The circles are shown in green to signify that they are valid placements. Although the two pieces occupy the same space, one piece occupies more area than the other and that piece is deemed the true owner of that space. Specifically, grid space C2 in the figure has both player pieces within the space. As shown by the shading, P2 has a majority of area within C2 making it the owner of the space. It can be generalized that if a player piece has a majority of its area within a grid space it will be deemed the owner of that grid space.

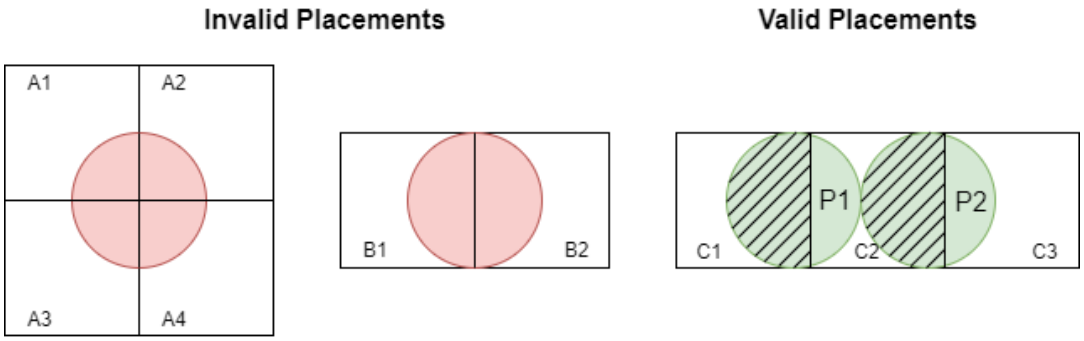

Figure 39: Player Piece Placements

Cases of invalid player piece placement are shown in the invalid placements section of Figure 39. The player pieces are the circles in the figure and are shown in red to signify invalid placement. The placements create a problem programmatically as the area distribution is near equally distributed across multiple grid spaces. In the first instance, the player piece occupies four grid spaces equally. Similarly, in the second instance, the player piece occupies two spaces equally. It is not possible to determine which square was intended by the player using only the piece area because the distribution is even. There also cannot be a deterministic solution to this problem such as always pick the top left most space that the player piece occupies. This assumes more than the software should and will break the flow of the game when the deterministic nature of the solution is wrong. Therefore, in order to maintain proper game flow, all spaces that the piece is overlapping in are highlighted and the player is notified that they need to fix the position of their player piece. This avoids any desync between the players and the software where the game software believes the player piece is in a specific location and the player believes that the piece is in a different location.

The case where two player pieces occupy exactly half of a single space can never occur because of the algorithm already discussed. Two player turns will be done sequentially and not simultaneously. When the first player has the option to move their piece, the piece placement is verified. If the piece is occupying equal area in two adjacent squares, the game prompts the user to fix their placement. They then fix the placement of the piece so that it occupies less than 50% of the area in the square that would be shared. Since that square has space for more than 50% of the second player's piece, they can place that piece in the shared square without with occupying most of the area.

6.4.2.2.4 Create, Save, and Load Game

The game class also handles the save and load methods. Both methods are initiated by a request from the game master's mobile app. The Game class then handles the request. Figure 40 shows the basic process of the save game method. The game first checks to see if the mobile device has a past save data file. If the file exists, it is overwritten, otherwise it is created. The different object fields are iterated through and their contents are recorded into the save file. This save file is then transmitted to the game master's device for storage. Each of the objects is deleted to free memory. Finally, all devices are disconnected to setup for the next game or shut down.

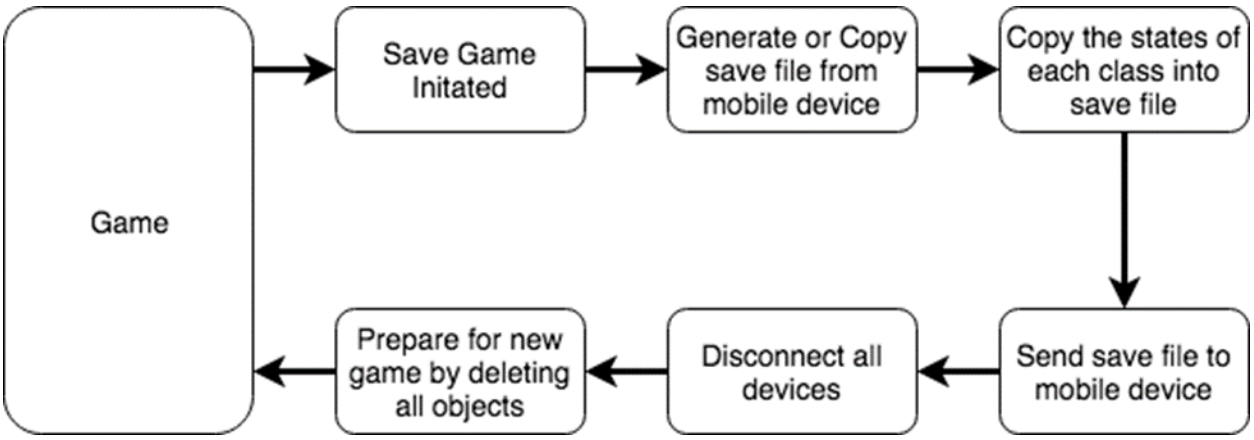

Figure 40: Save Game Flowchart

When loading a game, the save file is transmitted from the game leader's device and is processed by the load game method. The file is parsed and each of the object fields is populated with the save data. After the objects are populated, all player devices are connected to the server and the display begins its setup. After the display setup, the game is ready to resume.

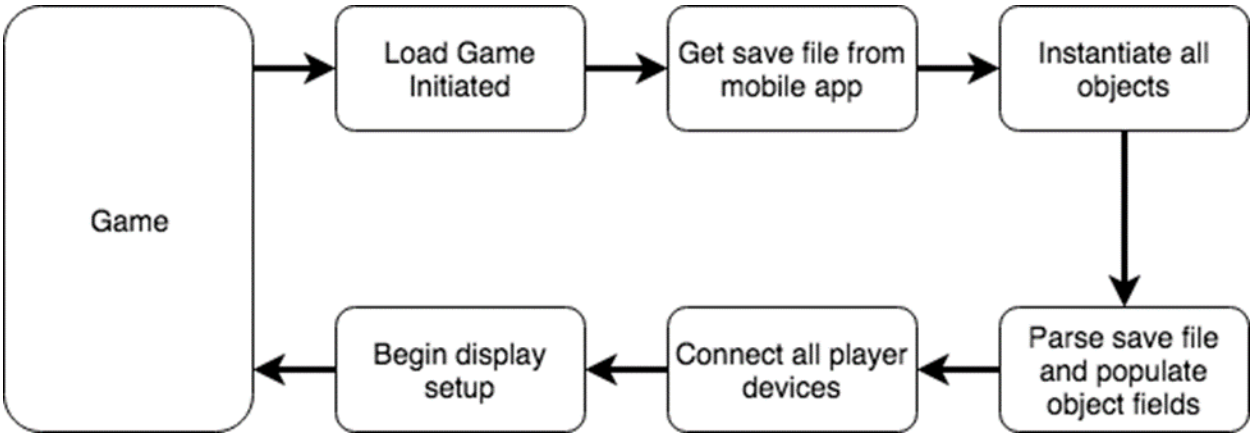

Figure 41: Load Game Flowchart

Create game acts very similar to load game. Besides the obvious difference of no save file, create game initiates the start of the game. The start of the game begins by receiving the number of players playing and the map to be displayed from the game leader. The next step is to setup the character sheet with all character statistics and place pieces in a starting location. While all these steps are occurring, the Game call receives and populates class elements with information about each player to begin tracking gameplay.

6.4.2.3 Display Class

The display class holds the methods required to do all image processing required for gameplay. A third-party image processing library is used to do the image overlaying portion of the image processing. This third-party library is OpenCV [24]. OpenCV is an open source computer vision software library. CCV also uses OpenCV in their object detection protocols. The library has support for all major platforms; Windows, Linux, and Mac OS. The framework has been released in C++, Java, and Python. The free use of OpenCV is allowed under the condition that the

copyright notices listed at the top of each file is not to be removed from the files. Also, the library can be modified as well. Any additions to the software can be made to better fit the cases required in this project's software. Some concerns that have been seen when researching other projects using OpenCV is that C++ has some issues importing and using library methods. However, all methods needed for this project's implementation were imported without issue.

OpenCV was used to create the displayed image through their image processing methods. Specifically, the methods to read in, write out, show, and add images together. These methods can be seen in Table 40. These four methods are able to provide the necessary manipulations required to update and display images for the users. The addWeighted() method is used to merge two images with a different opacity. The base image has the higher opacity while the image being overlaid on top has a lower opacity creating a merging effect.

Table 40: OpenCV Methods

Method	Method Purpose
imread(String filename, int flags): Mat	Reads in an image into a Mat type using the filename path.
imwrite(String filename, InputArray image, std::vector<int> params): bool	Creates an image file of the input array at the given filename path. Params can be a list of parameters to save the file with. On success a True Boolean is returned.
addWeighted(InputArray src1, double alpha, InputArray src2, double beta, double gamma, InputArray dest, int dype): void	Merges src1 and src2 into a dest array based on the parameters of alpha, beta, and gamma.

The OpenCV methods were incorporated in the Display class methods to produce the desired functionality. All methods shown in Table 41 were implemented. They represent the major functionality of the Display class and give descriptions of the goals of the Display class. Methods requiring a location require processing from the object detection software to provide accurate pixel location.

Table 41: Display Class Methods

Method	Method Purpose
Display(): Display	Constructor to instantiate display object and return a reference of that object.
displayMap(String URL): void	Creates a map image object from the passed in URL and displays the image to the display.
displayGridLines(): void	Overlays the gridline image object on top of the map image object.
displayDistance(int x, int y, int distance, String Color): void	Creates a set of images of the color passed in. Overlays those images centered around the x and y given to the distance given.
displayNPC(String URL, int x, int y): void	Displays a passed NPC image from the URL at the passed x and y location.
removeNPC(int x, int y): void	Removes an NPC image at an x and y location
removeDistance(int x, int y): void	Removes the distance images surrounding the x and y location.

Table 42 shows all privately maintained fields for the class. These fields enable the class to manage the different layers of images and provide the ability to determine their locations. The map and grid line images are maintained to avoid corrupting the original files. The PPI is maintained so that when dynamically creating images, the scale is correct. A list of npc and distance images is maintained. This is referenced when creating images.

Table 42: Display Class Fields

Attribute	Descriptions
private Display instance	The instance of the display object .
private Mat mapImage	The map image object.
private Mat gridImage	The gridline image object.
private int PPI	The PPI for the current display
private std::vector<Mat> npcImages	A vector of NPC image objects
private std::vector<Mat> distanceImages	A vector of Distance image objects

6.4.2.3.1 Display Constructor

The display constructor creates memory for the display object. There should only be one instance of this object to play the game. Therefore, when the constructor is called, it checks the private field instance to determine if a display instance already exists. Otherwise it creates an instance, saves that instance in the private field and returns a reference of that instance for the calling class.

6.4.2.3.2 Methods to Display Images

The map image that is projected on to the touch display is provided by the user through the mobile app. To not destroy the original map image, secondary images are overlaid on top. Therefore, the map image is the base background image. An important layer that needs to be added to make the map playable is the 1” by 1” grid of spaces. Each space represents a valid position that a player

can place their figure. The 1” by 1” grid must be to scale because the physical game pieces need to fit within them properly.

An image can simply be thought as an area of pixels. A specification required to translate an image’s pixels into physical distances is pixels per inch (PPI). This value depends on the native resolution of the projector as well as the length and width of the display region. To find the PPI, let the native resolution of the projector be represented by R and the length, in inches, of the display side be represented by L. shown below will produce the PPI for a projector with the native resolution R projecting on to a square display with a side length of L. For this project, the native resolution of the projector is 720p and the side length of the display is 24”. The PPI is 30 pixels per inch and each space will require 900 pixels. It is important to note that the PPI for a projector is not unique. This is because a projector will only output the number of pixels provided by its native resolution. The same number of pixels will always be displayed onto any display surface. Therefore, the display surface size is the varying factor for PPI. PPI is the same as DPI (dots per inch); however, the display will be dealing with pixels so thinking in terms of pixels is more useful.

Equation 4 shown below will produce the PPI for a projector with the native resolution R projecting on to a square display with a side length of L. For this project, the native resolution of the projector is 720p and the side length of the display is 24”. The PPI is 30 pixels per inch and each space will require 900 pixels. It is important to note that the PPI for a projector is not unique. This is because a projector will only output the number of pixels provided by its native resolution. The same number of pixels will always be displayed onto any display surface. Therefore, the display surface size is the varying factor for PPI. PPI is the same as DPI (dots per inch); however, the display will be dealing with pixels so thinking in terms of pixels is more useful.

Equation 4: PPI

$$PPI = R/L$$

The grid that is overlaid onto the map image is a separate image created with all parts transparent except for the gridlines. To accomplish proper scaling, the PPI found above is the exact dimension in pixels needed for the 1” by 1” grid spaces. The first and last two rows of pixels are used to create the horizontal grid lines. Likewise, the first and last two columns of pixels are used to create the vertical gird lines. This produces a grid with line width equal to four pixels. To determine the width in inches, the inverse of the PPI is taken. Each line has a width of four times the inverse of PPI, which is 0.13”.

The ability to distinguish grid spaces is a required property that is needed to properly track gameplay and overlay smaller images. A matrix numbering system is used to identify each space. Specifically, each space is identified by its row and column value with the top left space being position (0,0). The playable region will be 24” by 24” with 1” by 1” spaces creating a total of 576 spaces. The row and column indices vary from 0 to 23. Although the exact pixels are not used, it can be easily determined what pixels are occupying a given space. The exact pixels can be represented by four different values corresponding to each of the four corners of the space; top left, tl, top right, tr, bottom left, bl, and bottom right, br. Given an arbitrary space (n, m), the four points can be found using to create a rectangle object that holds the pixel locations on the display.

Equation 5.

When overlaying smaller images on to the map, the region that the image needs to occupy must be a value passed to the overlaying function. The determine location method takes in a grid space location and applies the equations shown in to create a rectangle object that holds the pixel locations on the display.

Equation 5 to create a rectangle object that holds the pixel locations on the display.

Equation 5: Grid Space Coordinates

$$tl = (PPI * n, PPI * m) \qquad tr = \big(PPI * n, PPI * (m + 1)\big)$$

$$bl = (PPI * (n + 1), PPI * m) \qquad br = (PPI * (n + 1), PPI * (m + 1))$$

No padding needs to be done to the images to create a buffer along the edge of the image. The table design takes care of the buffer needed for the display and the table. It creates a slight buffer for all edges of the display because the display surface is resting on a lip of the table. This relieves any issues that may have occurred had the display been flush with the table.

The actual overlaying is done by generating a new image each time there is a change. This is done using library methods that copy an image on to another image. The general flow is to create an object for the new image, store that object in local fields, and add the image to the display. This process begins with the function call from the Game class and the flow is depicted in Figure 44.

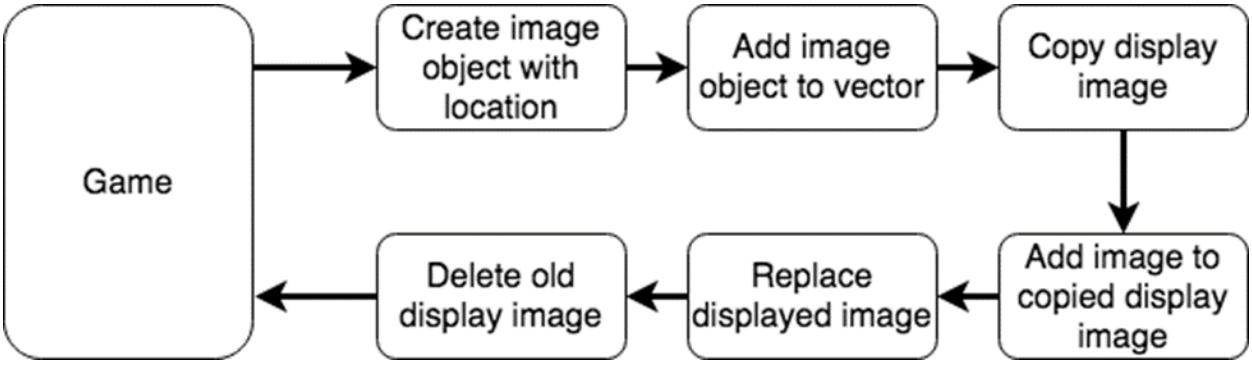

Figure 42: Image Addition Flow

This process occurs in such a way that the layers are presented in the correct order. Following Table 43, the gridlines are added on top of the map image first, followed by any distance indicator spaces and lastly any NPCs that are currently on the board. This avoids any NPCs accidently hiding under any other image. They are considered players and their locations should always be known and visible. To create a more natural look, the distance indicators are not solid spaces of a single color. Instead, the distance indicator image is blended with the map to give the map a highlighted affect. This allows the map image to avoid being completely blocked out by the highlighting, and still remain different enough to be noticeable. The last concern with the image formation is when adding the NPC image and the distance indicator that it blocks the grid lines. This issue is resolved by only placing the images inside the area that is bounded by the gridlines. Therefore, the NPC and distance indicator images do not occupy the 900-pixel area that each space provides. Instead they occupy a 676-pixel area because each dimension is reduced by 4 pixels to bound the area by the grid lines.

Table 43: Display Image Level

Layer	Level
NPC Image	4 : Top
Distance Indicator Images	3
Grid Image	2
Map Image	1 : Base

Figure 43 shows an example of the overlaying levels. The slanted red line represents the map image. Every other layer of the image can clearly be seen on top of the red lines showing that they are the base image. The next layer is the grid lines which are shown by the black lines. The distance indicator shown by the green shaded region is entirely within the grid lines. There is no overlap of the regions. The distance indicator does not have full opacity to allow the background images to be seen as well. Finally, the NPC image is represented by the blue circle which is on top of every layer.

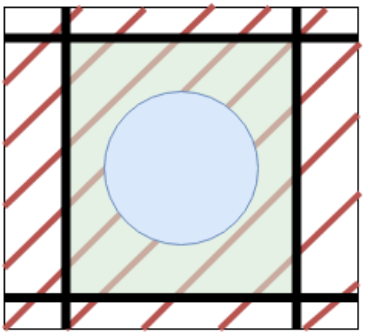

Figure 43: Overlaying Example

It is important to fully generate the new image before removing the old image. This avoids any gaps between images that would appear as a flicker. This process has smooth transitions and instead has instantaneous changes from image to image. The majority of the image should remain the same making the actually transition not seem as abrupt. As a way to create some effects, when populating a list of images, periodically the image can be refreshed so that a large chunk of space is not modified in a single refresh. For example, the distance indicator spaces are centered around the player's piece. If the spaces are populated in a circle motion being updated each time the radius expands one space, then there is an effect of the distance spaces radiating from the player's piece. This can be ensured by creating a small delay between refreshes as well.

6.4.2.3.3 Methods to Remove Images

To make removing images more straightforward, when an image is added to the display an object is created that holds all the details about the image and its location on the display. When removing images, information about the image needs to be passed in. Identifying information includes the image's type and its location on the display. From this information, the image object is found and freed and a new display image is generated and updated. This general process can be seen in Figure 44.

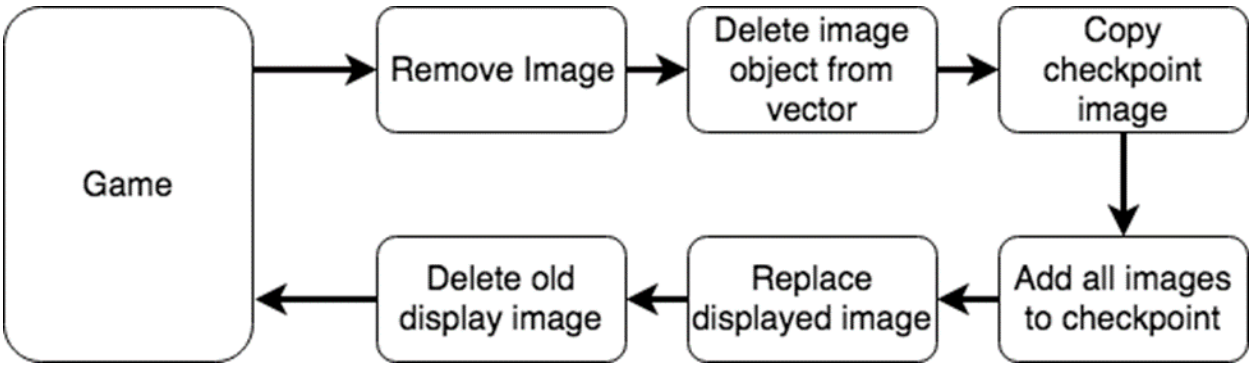

Figure 44: Image Removal Flow

A major concern with this process is performance time for images that require many layers to be copied. To increase the performance of this process, checkpoints are made. Images that remain on the display for long periods of time are saved. For example, the map with gridlines is be the base of every updated image. If a checkpoint image is used, then the steps to generate the map with gridlines is bypassed. The time to create checkpoints can be generalized for the gameplay. During a turn, the distance indicators only occur when the characters attack and move. Once the position is selected, they are removed. Therefore, the step before adding the distance indicators is to save the current state of the displayed image and then modify it. Once a space is chosen, then the image can revert back to the state before it showed the distances. The only unavoidable state is during an attack when an NPC must be removed. If there are multiple NPC's on the display, there is no way to know which one will be attacked and removed first, and the state cannot be saved to preemptively save time.

6.4.2.4 Bluetooth Class

The game software acts as the server for all the Bluetooth communications. All mobile devices connect to the computer and the computer's game software processes and responds to requests made by the mobile devices. To more efficiently develop this functionality, an external library of Bluetooth functions was obtained. This class runs on the Windows operating system; therefore, the Windows SDK was used to implement the functionality of this class. The Windows SDK provides libraries that enable the Bluetooth protocol.

Specifically, the Winsock2 library was used to create the server. The first step in creating the Bluetooth server is to create a socket that is linked to the Bluetooth protocol. Once the socket is created, the socket is set to the non-blocking state to avoid getting stuck in a blocking socket functions. Blocking socket functions, such as send and receive, wait until data is sent or received before returning. This potentially could freeze the thread. The non-blocking approach has a timeout that returns from those functions. The socket is then bound to a port on the computer that is reserved for Bluetooth communication. For the RFCOMM protocol, Windows has allotted 30 ports for servers. To allow for connections, the socket is then set to listen state for a specified number of devices. For our application the number is set to five to match the maximum number of players. To advertise the server to nearby devices, a globally unique identifier (GUID) is generated and linked to a service that was registered on Windows. Windows then broadcasts that service to nearby devices. The Android app scans for devices with that the GUID to begin connection. Under the Bluetooth standard, devices can only connect to other devices that have previously been paired together. Therefore, a pairing process must be conducted before a connection request can be made.

However, this process only needs to be completed once, assuming that the user does not manually forget the device on their computer.

The game controls communication with two different procedures, a server and client procedure. The server procedure handles accepting Bluetooth connections and disconnecting Bluetooth connections. The client procedure handles read, write and close actions. When the socket receives a connection request, an accept flag is raised and the server accepts the connection. When a socket receives data, it is placed into a buffer. It will then raise a read flag and the client procedure processes the data that was received. Sockets also have an out-data buffer and when its filled, the socket cannot send any more data. After the data in the buffer is sent and emptied, a write flag is raised, and the client procedure can send data again. Therefore, upon initial connection it is assumed that the buffer is empty and ready to be filled. A socket can receive a shutdown message which disables the read function, the write function, or both the read and write functions. When both are shut down, the socket is being closed and the connection should be terminated. Once the connection is terminated, the socket should be released to free resources.

The messages sent between devices follow the JSON format. Each JSON holds an action field that describes what the message is pertaining to and many other fields holding game data. For the save and load functions, the entire description for each player and GM are transmitted. The user's computer will be the storage point for game data. When a save action is initiated, the game will communicate with all devices requesting their player or GM data back.

Table 44 lists some of methods to create the Bluetooth server . The constructor is used to set up essential variables and buffers used for Bluetooth. Once the constructor's procedure is complete, a startup function is called to begin the Bluetooth server. This function goes through socket creation, socket binding, socket listening, and launching the server procedure. The server is an infinite loop processing connection requests for new connections and any reconnections if needed. When a connection is made, the server creates a thread that runs that device's client procedure. The client procedure is another infinite loop handling the read and write requests for that device. The scanDevices method scans the area for nearby devices to display already paired devices.

Table 44: Bluetooth Class Methods

Method	Method Purpose
Bluetooth(): Bluetooth*	Constructor to instantiate Wifi object and return a reference of that object. The Constructor will turn on the broadcast to Wi-Fi direct enabled devices.
scanDevices(): void	A method to scan for nearby devices.
startup(): void	The procedure to setup the Bluetooth server, listen for device connection, and begin the server procedure.
Client(): void	A procedure to handle client device actions such as receiving and sending data.
Server(): void	A procedure to handle accepting connection requests from devices.

The class needs to maintain all devices connected. Table 45 shows the fields that are maintained by the class. The connections field is a variable length list that holds each of the devices. The order of the list is based on the order of connection to the server. To pair a device with a player profile, when a player object is being created, the ID associated with the connection is maintained. Two lists of character arrays are used to hold the data being sent and received. Whenever there needs to be a message sent from the game to a specific player, the ID is used to fill that players send buffer. Likewise, whenever the game receives a message from a specific player, their receive buffer is filled.

Table 45: Bluetooth Class Fields

Attribute	Descriptions
private std::vector<SOCKET> connections	The list of devices connected to the network.
private std::vector<char []> sendBuffer	A list of character buffers to hold the data being sent out.
private std::vector<char []> receiveBuffer	A list of character buffers to hold the data being received.

6.4.3 Programming Language Selection

An obvious choice for the paradigm of programming languages to be used for the project's software is object-oriented. The paradigm offers the ability to use the powerful tool of inheritance. Inheritance allows for classes to be derived from other classes. This allows functionality to pass down from parent classes to subclasses. Function overloading allows parent classes to act as frameworks for subclasses without creating specific methods for functionality. This allows subclasses to be customized to the extent that they are different from the parent. If inheritance or class creation is not required for a specific functionality, the paradigm allows programmers to fall back to an imperative style of programming. The imperative paradigm is a style where statements are listed in sequential order and executed until completion. The C programming language is an example of the paradigm. It is important to note that the programming team is very familiar with the C programming language and that style of programming. The android app subsystem requires a graphical user interface. Therefore, the language choice either needs to implement their own user interface libraries or allow for third-party frameworks. Some popular object-oriented languages that are common industry that were considered are Java and C++.

6.4.3.1 C++

C++ is an object-oriented programming language with good portability and community support including libraries that help in UI development and object tracking. Besides basic syntax variations, the addition of classes and inheritance is the major difference between the two. In C memory management was completely controlled by the programmer and required constant checks to verify integrity of the memory space to avoid memory leaks and crashes. C++ introduced class constructors and destructors for created objects as a way to relieve some of the requirements put on the programmers for memory management. These two methods work similar to the memory allocation functions, malloc() and calloc(), and memory freeing functions, free(), in C. The difference is that they create and destroy objects and do not required the size of memory to build. The compiler will maintain the different object sizes and when their constructor and destructors are called the memory associated with that object will be allocated or freed. Each class has a constructor and destructor inherently and they can be overloaded to include additional

functionality. Some modern languages have custo garbage collection. C++ does not have this built-in feature. The C++ language can be modified to become non-standard, but include additional useful functionality. Windows has their own version of C++ to allow for the windows API to run properly. There are some versions of C++ that implement a garbage collector. These versions will be ignored as in depth research would be required for non-standard builds of C++. Garbage collection algorithms could create performance issues within the software especially being a non-standard algorithm.

C++ was developed before it became popular to include user interface libraries as standard libraries of the language. Therefore, third-party libraries are required to create any graphical interfaces. Some popular libraries are QT and wxWidgets. These libraries enable the ability to construct different interface components through simply function calls. Documentation is available from each of their respective websites. Since the interface would be for the mobile app, documentation is available for porting C++ projects through Android Studio to build an app.

6.4.3.2 Java

Java is a popular language with plenty of documentation available from its creator, Oracle, about built-in libraries and classes. Java runs on the Java virtual machine, the JVM, which adds a level of virtualization to programs. This virtualization allows Java to implement their own garbage collector that will maintain memory management for the programmer. All memory accesses run through the JVM which allows Java to implement their own memory replacement algorithms. The garbage collector can be troublesome in some cases where it will release memory before it should. This potentially can cause some negative performance issues if the memory released was important to the software.

Java was developed to have built-in interface libraries called Swing [25]. Swing aims to be a platform independent framework to allow similar looks across different platforms. There is plenty of documentation on methods and class information all provided on the Oracle website. Also, Java is the native language for android app development. There would be an advantage to developing the app in Java as no porting would be required.

6.4.3.3 Conclusion

After looking at the two languages, C++ was the chosen language. It requires memory management to be left up to the programming team; however, there was no concern about built-in features taking control of the program. Different options were explored when dealing with the graphical user interface libraries, but libraries were available to create a design that could be seen across multiple platforms. If development were to ever move or expand to a different platform, design code would not have to be changed. Lastly, the programming team has experience with the C programming language and the transition to C++ would not be harsh as learning a new language.

6.4.3.4 Visual Studio IDE

For our game running on Windows, we used the Visual Studio IDE to code, test, and finalize our software written with C++. Microsoft has the proprietary rights to Visual Studio which is used to create computer programs, websites, and mobile applications. For our purposes, we did not use Visual Studio to create our mobile application as we had the IDE specific for Android OS, Android Studio for that purpose. Visual Studio has many features that are convenient to a developer to create their own Windows applications.

Visual Studio is integrated with a Microsoft development platform called Windows API that has beneficial features that streamline the development process. Since the platform is so heavily integrated with and built for Windows, it can do some things that other IDEs cannot. Most external IDEs only have access to the base features of Windows such as file management, threads, and processes unless given permission to do otherwise. Windows API allows Visual Studio to handle tasks such as powering on/off the system, creating a background process called a Windows service, and managing user accounts. A Windows service can run in the background regardless of which user is signed-in and is helpful in trying to start our game as soon as we turn our computer instead of loading a file. Windows API helps with built-in functions to ease the UI development process in allowing graphics to easily be placed on displays. The UI is given functions that control the size of a window, scrolling, and IO which helps in displaying on our screen instead of a regular monitor or TV display. The Windows API also includes features that made feedback directed at players such as loading and toolbars easy to develop.

Visual Studio includes a few convenient programming tools that helped us develop our game software with higher quality and simplicity in mind. While all of our team has programmed in C before, C++ has some additional features and upgrades that we needed to get used to while coding our project. The native syntax highlighter and code completion assists new developers in any supported language. While experienced programmers might consider these features as crutches, while getting used to a new programming language these tools not only help developers fix mistakes but also provided hints as to why certain syntax is not allowed. The IDE has native help guides to get started on creating a new application as well. If all else fails, the community of online programmers has probably experienced a similar issue to an error that a developer encounters. Stack Overflow [26] is a great website that can help all levels of developers with syntax, logical, or semantic errors.

Visual Studio offers debugging and testing tools for its developmental environment. The debugger offered works as a source-level debugger and a machine-level debugger for any supported Visual Studio programming language. The debugger can be run during the execution of a developer's code which then assists with variable and stack management. Setting breakpoints allows the debugger to take a break during execution which can then be told to keep running after a developer finishes analyzing the previous results. The debugger also supports step-execution that creates breakpoints after each line of code allowing execution of one line of code at a time. Visual Studio also has tools for easier unit-testing including a test explorer, Microsoft's own unit test framework for C++, and code coverage. The test explorer allows a developer to see all the unit test results with Microsoft's framework. After running all of the unit-tests, the code coverage feature alerts the programmer of code that has not been tested with the current unit-tests. There are more add-ins and plugins designed for Visual Studio that extend the range of capabilities the native IDE supports.

6.4.4 Multithreading

Since we believed that the execution of our game would be taxing on our CPU (Central Processing Unit), we explored the option of multithread programming. Multithreading is the ability to use more than one core of a CPU at one time to break up the load of execution through the distribution of threads. This leads to faster overall execution of the code, as it allows resources not would normally be idle to be utilized. The problem that can be encountered with multithreading is when two or more threads are trying to use the same resources at one time. For example, if two different threads, running on separate CPUs, need the ALU (Arithmetic Logic Unit) then one thread will

have to wait until the other is finished before using the resource which can slow down overall execution if the code primarily uses a single hardware unit. There are two main types of multithreading that are worth discussing for our group and they are interleaved multithreading and simultaneous multithreading.

Interleaved multithreading's main purpose is to get rid of data dependencies that can clog the execution of a program. All threads on each CPU should not wait for the output of a thread that is outside the range of the current core. This means that a thread in core one of the CPU will not rely on the output of threads from cores two through four. For every cycle of the CPU there is a context switch for the code which results in no pipeline flushing. The problem with interleaved multithreading is its performance for single threads, so if there is a long thread then the process will actually take more time to execute than single core processing. Interleaved multithreading also requires specific hardware to run. CPUs need to have multiple register banks and other hardware necessities that are necessary for interleaved multithreading.

Simultaneous multithreading uses parallelisms to superscalar fetch multiple threads on each CPU cycle. The idea for simultaneous multithreading comes from the fact that threads create unused issue slots when normally executed which are then allowed to be used for another thread on the same CPU. In simultaneous multithreading's single-thread mode, the CPU is operating at full performance for that CPU core. This leads to easier handling of pipeline bubbles and long latencies, but simultaneous multithreading is also the most complex to establish in a program. The CPU also has hardware requirements that need to be met in order to use simultaneous multithreading in which the CPU needs to be able to fetch more than one thread at a time for this type of multithreading.

Since we chose C++ as our programming language for our Windows game, we researched what it would take to optimize our game using multithreading. The native C++ language does not have built-in support for multithreaded programs. However, Visual Studio has an external add-in library called MFC (Microsoft Foundation Class), which allows C++ developers to use multithreading. Developers can create their own threads to handle background or maintenance tasks. We were able to use multithreading in our project by giving each thread that has to deal with object detection to one core, while the game itself could run on another. Although multithreading was useful in speeding up execution, debugging and testing became harder the more cores utilized.

6.5 Windows API

As stated previously in this document when discussing the Visual Studio IDE, Windows API is a Microsoft development platform open to use for personal projects. The Windows API is a collection of other APIs (application programming interfaces) that are collectively used in the Window's operating system. Microsoft offers developer support for Windows API through their software development kit named Microsoft Windows SDK. The Microsoft Windows SDK, specifically the one we used called Windows 10 SDK, contains libraries and functions that we could use for our project. The SDK also includes documentation for describing functions' applications and tools to simplify common tasks and better implement our communication protocol. Windows 10 SDK is available for free for anyone with a legitimate Windows 10 Home, Professional, Education, or Enterprise license which all of our group have access to. Table 46 below shows the twelve basic categories that all Windows API functions fall into which are collected into groups and their purpose for a developer.

The API modules that are described in Table 46 mostly work with the interactions of the application and Windows OS. Some APIs work with networking or external devices, but Microsoft has developed different technologies for interactions with different Windows applications. COM (Component Object Model) is the binary-interface that allows inter-process communication object creation. These objects can be used across machines that the object was not created in. This could useful if we ever need to communicate our application with another computer to host a game. To easier create better and more elegant UI elements, Microsoft has the Universal Windows Platform (UWP). Using the UWP for app design was another option when designing an app instead of using just Windows API.

Some functions and APIs are no longer supported, or the features they implement could be implemented more easily through the Visual Studio IDE or external libraries. APIs such as the User Input or Diagnostics fall into these categories. Audio and some visual functions such as show on screen were also easier thanks to these IDEs. Sensor data collection and interpretation of that data is done with our printed circuit board instead of Windows API. We also do not have a need for the security API as no personal or sensitive data is being accessed, sent, or received. Some of the categories in Table 46 do not have functions and instead are programs or other recourses such as Windows Installer that creates the installer exe for a client.

Table 46: Windows API Categories

Category	General Purpose
User Interface	Displays output for the user, creates prompts for user input, and handles all other tasks that handle interactions between an application and the user.
Windows Environment (Shell)	Controls the windows of a user application. Can set data from windows user such as audio, images, and time on Windows files from a developer.
User Input and Messaging	Direct Manipulation pre-declares certain behaviors for an application such as pan and zoom. Direct Manipulation also handles putting touch detection on a separate thread than the UI thread.
Data Access and Storage	Handles transferring files and data between a client and server, disk management, and offline file management.
Diagnostics	This API handles troubleshooting applications by debugging, error handling, and network monitoring.
Graphics and Multimedia	Handles the audio, video, and graphics part of the user application through the use of Core Audio and DirectX. Allows developers to integrate their own audio devices such as speakers.
Devices	Sends signals through a distributed bus for controlling peripherals such as a temperature sensors, LEDs, or cameras.
System Services	Gives the developer access to use the recourses of the computer such as memory and threads for their application. It also allows power management to not draw too much power for the application.
Security and Identity	Allows the developer to secure their application through the use of encryption and passwords at logon. Authentication of users is also included in the features in this API for a developer.
Application Installation and Servicing	Windows Installer allows a developer to create an installer that someone can download to install their application. The installer can be set for the application to get updates from the internet.
System Admin and Management	This API extends and enhances the functions given by the Application Installation and Servicing API. The restart manager and task scheduler are two of the tools that a developer has access to.
Networking and Internet	Enables the communication between a network and an application. The communication protocols supported include Wi-Fi, Bluetooth, and Wi-Fi direct.

6.5.1 Application with our Project

In this section, we describe the various functions and methods that were useful to us from the Windows API library.

6.5.1.1 User Interface Integration

The UI elements from this API that we used were focused on UI and a few error handling message functions as described in Table 47.

Table 47: User Interface API Functions

Function	Description
CreateMenu(): HMENU	Creates an empty menu
InsertMenuItemA(HMENU hmenu, UINT item, BOOL fByPosition, LPCMENUITEMINFOA lpmi): BOOL	Inserts a new menu item to the handle identifier for the menu with an identifier for position and information of the new menu item. Returns BOOL true on succeed. Must call DrawMenuBar when changing the window.
DrawMenuBar(HWND hWnd): BOOL	Updates the window specified, true returns if succeed.
EndMenu(): BOOL	Ends the active menu. True returns if succeed
MessageBox(HWND hWnd, LPCTSTR lpText, LPCTSTR lpCaption, UINT uType): int	Creates a modal dialog box that has a set of buttons, an owner window, a title, and text to be displayed. The int that is returned describes which button was pressed.

The menu functions allow us to set up the initial game with a menu and to change parameters of the current game. The message boxes inform the player of any errors that occurs within the game or options that the game master can choose. Animations and images are difficult to make using this API so we used the Visual Studio IDE helper to create the other UI elements.

6.5.1.2 Windows Environment (Shell) Integration

The shell elements allowed us to create handles for specific icons, unique file names, and loading a specific Windows profile on startup as shown in Table 48.

Table 48: Shell Functions

Function	Description
ExtractIconA(HINSTANCE hInst, LPCSTR pszExeFileName, UINT nIconIndex): HICON	Returns a handle to the icon specified with the string.
LoadUserProfileA(HANDLE hToken, LPPROFILEINFOA lpProfileInfo): USERENVAPI BOOL	Takes a token for the user and a struct for the profile info and loads the specified user profile. True returns if successful.
PathMakeUniqueName(PWSTR pszUniqueName, UINT cchMax, PCWSTR pszTemplate, PCWSTR pszLongPlate, PCWSTR pszDir): BOOL	From a template, creates a unique file path that a developer can use for creating new files. True returns if successful.

Extracting icons helps us manage our non-physical characters such as monster creatures. We load a profile automatically when starting the computer for our game. Since we use the host's PC for storing files with game data, creating unique paths is important to not overwrite files.

6.5.1.3 Data Access and Storage Integration

The functions in Table 49 let us manage offline files since our game runs solely on the host's PC instead of a database.

Table 49: Data Access and Storage Functions

Function	Description
GetDiskFreeSpaceExA(LPCSTR lpDirectoryName, PULARGE_INTEGER lpFreeBytesAvailableToCaller, PULARGE_INTEGER lpTotalNumberOfBytes, PULARGE_INTEGER lpTotalNumberOfFreeBytes): BOOL	Gets the information required to create a new directory and files on a host computer by accessing the space available to the game. True returns if successful.
CreateDirectoryExA(LPCSTR lpTemplateDirectory, LPCSTR lpNewDirectory, LPSECURITY_ATTRIBUTES lpSecurityAttributes): BOOL	Creates a new directory to store game files with the specified template to create unique directories every time. Returns errors if directory exists already or path not found.
SetCurrentDirectory(LPCTSTR lpPathName): BOOL	Takes the path of directory in the host's computer and changes the current directory for the current process. True returns if successful.
CreateFileA(LPCSTR lpFileName, DWORD dwDesiredAccess, DWORD dwShareMode, LPSECURITY_ATTRIBUTES lpSecurityAttributes, DWORD dwCreationDisposition, DWORD dwFlagsAndAttributes, HANDLE hTemplateFile): HANDLE	Creates a new file to write data into using the new file name, access security, and a file template. Returns a handle to the new file.

We need to check if the host's PC has enough storage to handle our game and to create offline files so the game can be run again for a future session if needed.

6.5.1.4 System Services Integration

Alongside the functions shown in Table 50 below, we must use a thread manager in the IDE to give priority to threads.

Table 50: System Services Functions

Function	Description
CreateThread(LPSECURITY_ATTRIBUTES lpThreadAttributes, SIZE_T dwStackSize, LPTHREAD_START_ROUTINE lpStartAddress, __drv_aliasesMem LPVOID lpParameter, DWORD dwCreationFlags, LPDWORD lpThreadId): HANDLE	Creates a thread using the security attributes, initial stack size and address, a pointer to the variable being passed, and a thread id intensifier. Returns a handle to the new thread if success
AttachThreadInput(DWORD idAttach, DWORD idAttachTo, BOOL fAttach): BOOL	Takes an identifier of the thread being attached and the identifier of which thread to attach to. Returns non-zero value if succeeds
GetSystemTime(LPSYSTEMTIME lpSystemTime): void	Takes a pointer to the system time struct, SYSTEMTIME, and puts the current time in that pointer's data)

The first two functions are a part of the thread management that our project must perform to make sure events don't overlap or happen before they are scheduled to. System time is used as part of our interface for displaying game information such as turn order and options.

6.6 GitHub

GitHub is a free hosting service provided by Microsoft that we used for developmental software control during our project. GitHub offers collaboration services that are great for development teams including version control, code review, and code merging. Version control allows a developer to see all changes from one version of the code to another. This helps not only keep track of who is contributing to the changes but also to roll back the version to a previously working state if there is a program breaking bug. Code review allows people to purpose changes which will then be either approved or denied for changing the overall code. This can also help with peer review for syntax, logical, or semantic errors. Code merging allows the use of status checks to make sure that branches of code are protected and will work before they are pushed onto the project.

7.0 Test Plan

7.1 Hardware Testing

All components of the multi-touch table were tested independently to ensure functionality before integrating them into larger subsystems. Each subsystem was then tested before being installed in the table and integrated into the overall system. More realistic test cases were generated for the entire system once then table was complete, detailed in section 7.3. These tests were carried out indoors in a group member's home as the table is designed to be used in a consumer's home or similar setting, and the UCF Senior Design Lab was not accessible due to campus closures.

7.1.1 IR Camera

Prior to modifying the camera to record the infrared spectrum, the appropriate driver was installed, and the camera was connected to the testing PC using a USB 2.0 port to verify that a video feed can be captured with the desired image quality and frame rate. This test is passed if the video feed accurately captures the scene and the feed maintains at least 640 x 480 pixels at 30 frames per second. The camera was pointed at and infrared LED to ensure that IR light could be detected after the IR filter was removed. This test was passed as the camera feed showed a lit LED while human eyes detected no such light. After replacing the IR-blocking filter with a visible spectrum-blocking filter, the camera was pointed again at visible scenes to ensure the visible spectrum-blocking filter was functional. This test was passed as the video feed was a uniform color when no infrared sources are present. Finally, the IR light detection test was repeated to ensure the visible light-blocking filter is not also blocking the infrared light, with the same pass/fail criterion.

7.1.2 IR Illumination

The IR LEDs were powered using a 5 V source and a breadboard circuit according to their datasheet specifications, while the pre-built illuminators were powered by a wall outlet through an included adapter. The illuminating setups were pointed at various objects and a white wall with an area marked out to match the touch surface dimensions. The IR camera was used to verify that the wall and objects were illuminated. This test was passed if the change in illumination when the illuminators were on vs when they are off was easily distinguishable on the IR camera feed. Adjustments were made to the LED array to illuminate the area as evenly as possible. This test was repeated on the inside of the table once construction is complete, leading to the selection of a pair of pre-built illuminators and their final positions.

7.1.3 Surface Material

Test images were projected onto the touch surface/diffusive material in a lamp-lit room to ensure that rear projection would produce a visible image with clarity matching the requirements specification. This test was passed if text 1" tall could be read from 2' from the edge of the table at a 30^{o} angle. The material was then illuminated with the IR LEDs, and objects and fingertips placed on the other side. The IR camera was used to ensure blobs would appear that could be used for touch detection. This test was passed once blobs could be distinguished by the blob-detection software in at least 95% of the test trials.

7.1.4 Power Supply

A multimeter was used to verify that the power supply provided the desired output voltages, current, and wattages with an appropriate test load. This test was passed as the measurements fell within $\pm$10% of the desired values.

7.1.5 Light Sensor

The light sensor was to be powered using a 9 V battery and a breadboard circuit according to its datasheet specifications and placed under a lamp of adjustable brightness in an otherwise unlit room. The lamp's brightness would be varied repeatedly to ensure corresponding changes in current flowing from the sensor in accordance with its datasheet. The test would be passed if appropriate changes in current are observed. However, with the automatic brightness adjustment feature discarded, this test was rendered useless.

7.1.6 Timer

7.1.6.2 Timer Display

The quad seven-segment LED display was tested using a breadboard circuit by first lighting each relevant segment individually. When all segments lit as expected, this test was passed. The display was then connected to the Raspberry Pi for program testing. First we displayed 20 pre-generated random numbers, to ensure the display refreshed at an appropriate rate which avoided flickering, and that multiplexing was properly implemented. When the displayed numbers matched what had been sent, and no discernible flashing occurred, the test was passed. This test was also used to confirm that functions for commanding various numbers are correct in the software.

7.1.6.2 Timer Buttons

Each button of the timer was tested to ensure that they could generate interrupts for the microcontroller. The buttons were connected to visible LEDs in a breadboard circuit and used to turn the LEDs on and off. The test was passed when the lights turned on and off as expected in all cases. Once the microcontroller was acquired and the timer is programmed, each button was tested to ensure they triggered events as expected on the software side, i.e. the power button turned the timer on and off, the time increment buttons added the appropriate value to the "time" variable, and the clear button reset the "time" variable to 0. Each button was pressed in each of the operating modes. The test was passed when all observed behaviors matched expected behaviors detailed in the timer design section. Further, the rollover events triggered by incrementing by 1 minute at 99:xx, incrementing by 1 second at yy:59, and incrementing by 1 second at 99:59 were tested for 5 randomly selected choices of xx and yy, to check that the rollover behavior was well-defined and properly implemented. The test was passed when all rollovers occurred as expected.

7.1.7 Speakers

The speakers were connected to a PC and the sound effects chosen for the game were played to verify that the speakers were functional prior to installation in the table. This test was passed when the sound effects were relatively undistorted compared to the laptop's built-in speakers. Once integrated into the overall system the same sounds effects were played again to ensure nothing was damaged and that the sounds were not muffled and made inaudible by the table. This test was passed when the slight muffling could be countered by increasing the volume while maintaining little to no discernible distortion.

7.1.8 Accent Lights

The accent lights were connected to the controller and an array of color and effect commands which were to be used in the game were sent to the lights, such as "light orange for 1 second." This test was passed when accurate responses to the commands were verified.

7.1.9 Temperature Sensor and Fans

The fans are powered in accordance with their datasheet to make sure they are not dead on arrival. This test was passed when the fans turned on as expected when powered. The temperature sensor was tested by comparing its readings to those of a traditional thermometer for accuracy. This test was passed when there was less than 1% difference in actual and measured temperature within the operating range of the table. The temperature sensor was set to trigger a fan response in temperatures exceeding the maximum operating temperature of 32^{o}C. The temperature sensor was then warmed using a finger to ensure the response triggered, then allowed to cool to ensure the fans turn off again. The test was passed when the fans turned on and off when the temperature sensor crossed the 32^{o}C threshold.

7.1.10 Wireless Communications

The wireless connectivity which allows communication between mobile devices and the table was tested by first ensuring that mobile devices could locate the access point and establish a connection. This test was passed when our Android phones could find the access point and establish a connection.

7.1.11 Table

The physical structure of the table was tested prior to the installation of critical components at risk of damage. First uneven forces were applied to the sides and top of the table in the form of a single individual pushing or pulling on specific areas. The test is passed when the table displayed no visible damage and all structural elements remained securely attached. Maneuverability was verified by having two healthy individuals move the table, before and after adding significant electrical systems. The test was passed when the table was moved over 10 feet in one trip, and then through a doorway without injury or damage. After installation the security of each critical component's fastening was tested by light pushing or pulling as appropriate. This test was passed when the components remained fastened and did not move significantly unless designed to be removed by such a force.

7.2 Software Testing

The software can be divided into two distinct groups for testing; the mobile app and the computer applications. The mobile app was be built using Android Studio and within Android Studio is the ability emulate the app. This allowed some testing to be done locally on a test machine for the app. The computer applications required some methods to test the results of important functionality.

7.2.1 Mobile App Testing

Mobile app testing verified the functionality of the user interface on the app. Much of the functionality of the app requires a communication link to the game software, and that was tested in a later section. The user interface can be tested through the emulation software within Android Studio. Each menu was executed and traced to verify that each window is appearing when it should and disappearing when its purpose has finished. Local variables tied to each window were checked to verify that the state of each window is maintained. This could be done by setting constant values for different fields on each window that requires input data. Then we cycled through different windows before coming back to each window with inputted data and verified that data was all showing and not lost.

7.2.3 Communication of App to Game Software Testing

The mobile app connects to the computer program to set up a Bluetooth connection. The connection can be tested by looping through the process and outputting the details of the connection when the connection is made. The connection should be maintained throughout the length of a full game. That connection can either be held with no disconnections or with a process to reconnect upon a random disconnection. A testing procedure was created to initiate the Bluetooth connection and have the computer output any connection drops without a successful reconnection during the duration of the test.

The Bluetooth connection was only half of the protocols required for communication. The socket connection also needed to be verified. This could be done by going through the procedures of setting up a socket and outputting values that link to that socket channel. Data could be sent through the channel to verify that each end can send and receive data. Max datagrams for each method were passed to verify the integrity of files of all sizes. A series of transfers were taken, and transfer timings were recorded. These timings were used to calculate the average transfer speed of 250 milliseconds as well as view the longest transfer time. The longest transfer time was roughly 500 milliseconds and the fastest transfer time was roughly 5 milliseconds. These are important metrics when evaluating the functionality of the communication link. The speeds measured for each message are fast enough to show no noticeable lag of communication.

7.2.4 Object Detection Testing

According to the engineering constraints in Table 2, there are three constraints related to the object detection software that had to be be verified.

- Objects of 0.5” diameter or larger must be able to be detected
- An object location must be within 0.5” of its true location
- Object movement must be accurately detected with 95% or higher certainty

Testing the accuracy of the software required both physical testing as well as software testing. A testing module was written to test features independent from the game logic. The game logic constrains the functionality of the software to allow the software to directly relate to what is required. Excluding the game logic allows the software to detect objects across the entire display without any methods for interfering. However, the methods which turn coordinates into grid space translations had to remain active to test correctness of that method. The testing module read all objects and output the results into a file that could then be checked for accuracy. Physical movement of objects on the display was required to test the software because the data input is dependent on physical objects.

The playable area of the display should not have any dead zones where objects are not detectable or incorrectly detected. Detection over the entire display had to be verified. To check for any issues with the display, testing was done by placing objects in locations across the entire display and checking if the software could detect each object. Verification was done by running the testing module and verifying the output data with the input object locations. Testing the edge of the playable area confirmed that the range of the camera was correct. An issue that may arise after moving the table is that the calibration of the software may not be accurate enough the translation will be incorrect. If this is the case, all translation data should be off by the same margin. This will be a sign to recalibrate the system and restart testing.

To verify that objects of a certain size are detected, object of the minimum diameter threshold and smaller were placed on the display and the data was analyzed to see if all objects were detected. If the software can detect objects at the minimum size, it is able to detect objects of larger sizes. After the coordinates are translated to grid placements, it was verified that the object is located with the minimum range of its true location by comparing actual placements to detected placements. The final constraint required movement of objects on the display. This requirement was tested by physically creating movements on the display. To accurately test this condition, at least 100 movements had to be tested and at least 95 of those movements had to be detected. These constraints were tested in differing environmental brightnesses to confirm that there would be no noise distortion with the setup.

Once the detection over playable area was confirmed to be functioning as intended and constraints had been verified, then the game logic was reenabled. Methods related to invalid piece placement checking were tested by creating a loop that constantly looks for a player piece to be moved. For each iteration of the loop, a piece could be either placed in an invalid location or a valid location and the behavior of the software can be observed. Invalid locations could be defined as pieces placed nearly equal in between two or more grid spaces. Valid locations could be defined as pieces placed within the grid space or at most 40% in another space. The results of these actions should have been in line with the protocols defined in the software design. Invalid locations should have created a prompt to be fixed and valid locations should have been accepted. The tests were independent of the mobile app; therefore, prompts could be outputted to either the console or an output file. These tests were conducted over the entire playable area. An example of a specific case used to observe the software's behavior was placing a piece partially out of the playable area.

7.2.5 Save and Load Game Data Testing

There is one engineering constraint from Table 2 that relates to save and load game data.

- There must be at least 20 locations tracked and saved on exit

Since NPCs are digitally created and tracked, there is a maximum of 4 physical locations tracked. All other locations are for the NPCs. Testing was conducted by placing the save and load game methods within a loop. The software had access to the expected result files and be able to check on each iteration. The goal was to verify that within the save and load game data methods there were no bugs that caused corruption of the data or save files. By iterating many times in one set time period, it was be observed whether there were any issues to the save files that may arise from the code being run in frequent succession.

7.2.6 Display Testing

To test the display software, a testing script was made to manipulate the displayed image. Different display images were generated by adding and removing overlaid images. The goal was for change sin display images to not have a high latency and the placement of overlaid images to be in the correct locations. To test this, the latency for creating an image with the greatest number of components was timed. After the image was generated and displayed, the locations of each component were recorded and compared to the test data. The latencies were also timed for adding and removing a single component to verify that the methodology for creating the display image was fast enough. The methods for displaying the move and attack ranges were tested by running the methods in a loop. After each iteration, the displayed image will be checked for correctness.

When updating the map or starting a game, the starting locations for player pieces were highlighted. These methods were also be tested to verify that the location given to the software matches the location on the display.

7.3 System Testing

To test the overall systems of the table in a comprehensive fashion, several test cases representing possible gameplay scenarios were generated. The extent of this testing was reduced from our original intention due to constraints imposed by county lockdowns. The range of parameters possible in the test cases are given in the following sections. 5 scenarios were generated, each by randomly selecting a parameter value from each relevant category, as each scenario tests a wide number of sub-cases. Unless otherwise noted, all choices are made by random selection with equal probability from the possible options.

7.3.1 Game Options

In each game, there will be exactly one Game Master (GM) and one player (limited by available mobile devise). There were also 1 – 2 maps set up for gameplay. The player had 1 – 3 characters to choose from. Once the number of characters is chosen, then the specific traits of these characters are determined. Then the number of maps is chosen, and a subset of the maps is set up.

7.3.2 Player Character Options

We assigned each player character a race and background. We considered 10 race options, some of which have 2 or more subraces to choose from. Some races provided character features to choose between. Each character's race determines their maximum movement each turn. There were also 15 backgrounds to choose from. Each background provided the character with a few skills, items, and features. After race and background selection, the character was assigned 6 ability modifiers in accordance with popular gaming conventions. Each modifier was determined from a corresponding ability score. The ability scores were determined by generating a random integer from a pseudo-normal distribution centered around 10.5 and limited to the range 3-18, then adding race-based modifiers (for example, a tall race may have provided an increased strength score). Once a race and background had been selected, a first class for the character was chosen, and the character was given 1-20 levels in that class. Resulting class feature options, including equipment, abilities, and subclass were selected. If the number of levels was great enough, some random ability score increases may also have been applied. For each level the character gained, there was a 30% chance of adding a random piece of equipment. Further, for each level the character gained, the amount of currency in their inventory increased. These additions were made on the basis that a high-leveled character has typically been part of a game long enough to have acquired greater resources than a new, low-leveled character.

7.3.3 Map Options

Each game used between 1 and 3 maps. Each map was between 10 and 24 squares on the shorter side, and 10 and 32 squares on the longer side. The background for the map was selected at random from 10 images, cropped to the appropriate size given the number of squares and the projected image resolution.

7.3.4 Game Master Options

For each map, between 1 and 5 non-player characters (NPCs) were created and controlled by the game master. Each non-player character was selected at random from a list of 5options, with duplicates allowed. Each of these 5 options provided the non-player character's ability scores and

modifiers, a few skills, and possible actions such as attacks and spells that the character may take on their turn. If the non-player character was a humanoid, rather than another type of creature (e.g. a bear), they may also have been given some additional random equipment or abilities.

7.3.5 Game Simulation

All player and non-player characters were then placed randomly on the map by first selecting a random x-coordinate and then a random y-coordinate. If the space was already occupied, by another character, an object, or terrain obstacle (e.g. a tree, boulder, or river), the random selection was repeated, until an unoccupied space was chosen. A turn order was randomly assigned to all characters on the map. On their turn, each character took a random action which was available at their current location, including potential movement to put targetable character in range of their chosen action. This may have involved showing the character's movement range, the range of their chosen action/ability, and selecting the target for the action. This may have also triggered special effects, such as sounds effects (a whoosh as a fireball spell is cast, a clang when a sword is used to attack, etc.) and lighting effects (e.g. twinkling lights for spells, a warm glow as a fire is lit, etc.). This process was repeated for 1-5 iterations, known hereafter as rounds, in which each player character and non-player character takes a turn. Possible actions for each character included picking up or dropping usable items to test the ability to modify a character's inventory and available actions during a game. The map was then saved, the table was powered off and on again, and the map was reloaded. 1-3 more rounds were simulated to ensure no unexpected changes to abilities occur during the saving/loading process. At the end of the game simulation, the map was erased from the table, to ensure updates to character abilities and inventories were saved independently.

8.0 User's Guide

8.1 Desktop Application User's Guide

The first menu is the Main Menu shown in Figure 45. By pressing the New Game button, the game will begin the process of creating a new game. The Load Game button will bring up a menu that displays a list of all previously saved games to choose from. The Quit button will close the application.

Figure 45: Main Menu

The Pair Devices menu is shown in Figure 46. The Add New Device button will spawn a dialog box that will allow the user to pair an unknown device to the computer. The Refresh button will rescan for nearby known devices and display them in the list. The Ready button should be pressed once all unknown devices have been paired and it will move on to the next menu to choose a Game Master. The Main Menu button will return the game to the Main Menu.

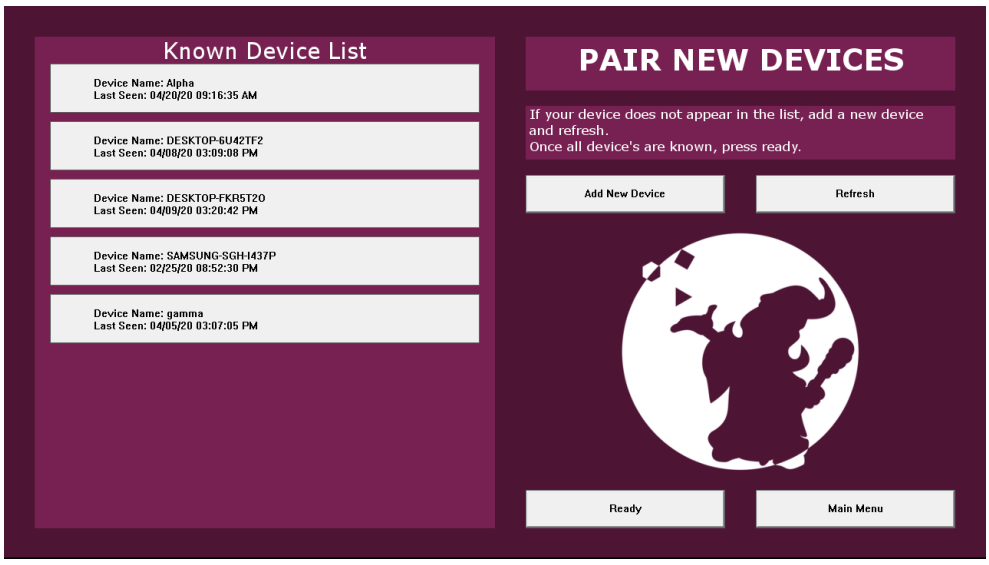

Figure 46: Pair Devices

The choose a Game Master menu is shown in Figure 47. A Game Master can be chosen by selecting one of the connected devices in the Connected Device List. The device chosen will be displayed in the region titled GM Selected. Once a GM is selected, the players can press the Ready button to move on to map selection. The refresh button will reload the list to display any newly connected devices. The Main Menu button will return the game to the Main Menu.

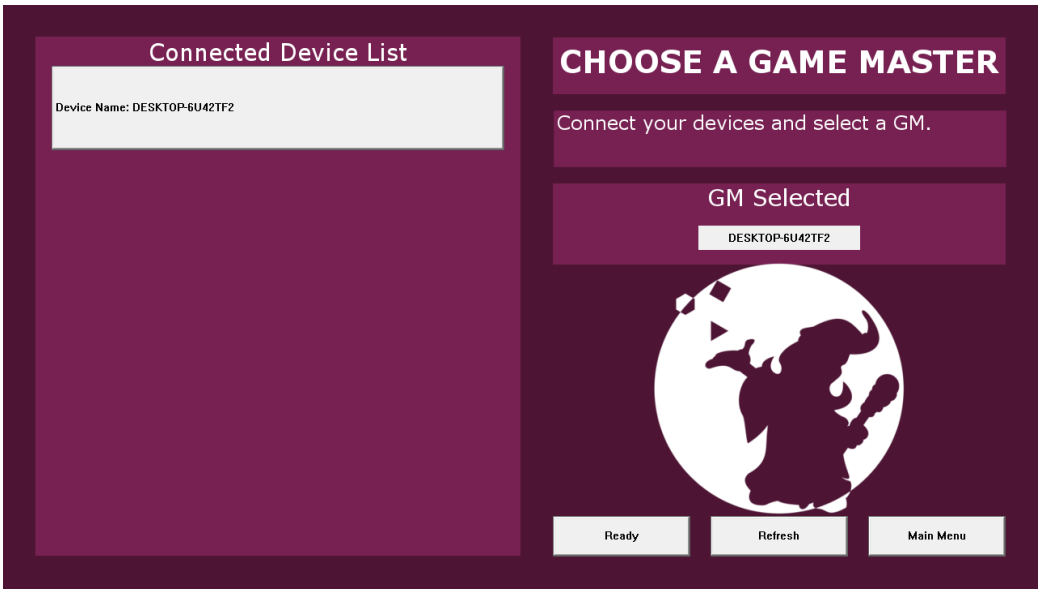

Figure 47: Choose a Game Master

The Map Selection menu is shown in Figure 48. The Open Map button will pull up a Windows open file dialog box. Any image on the host computer can be chosen as the playing map. Once a map has been chosen, the players should select the Ready button to display the chosen map. The Main Menu button will return the game to the Main Menu.

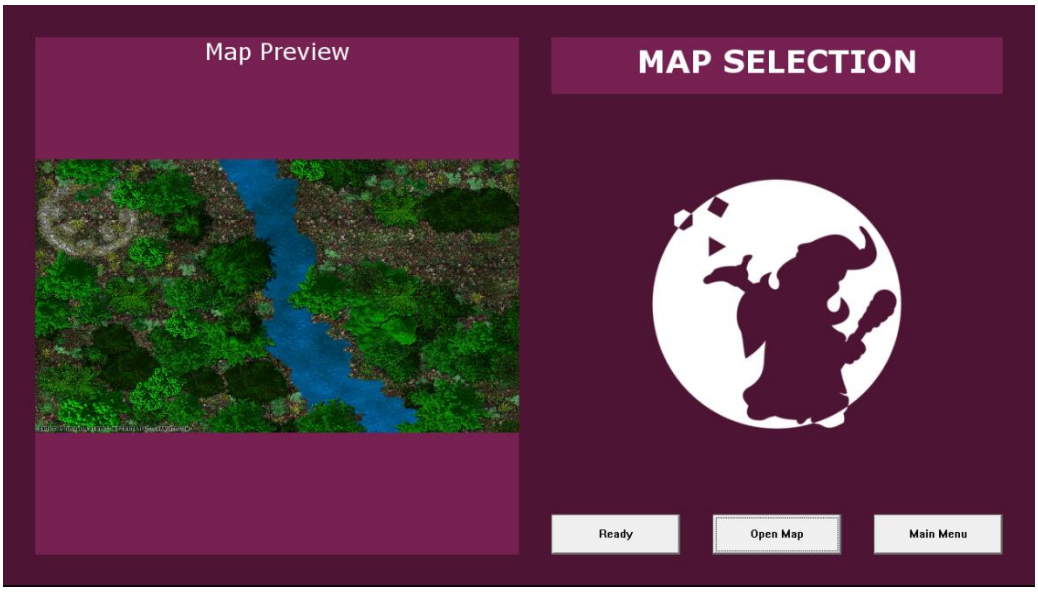

Figure 48: Map Selection

Once the map is shown, it will be the image selected in the previous menu with a grid overlay. Some game map variations are shown in Figure 49. These variations show different NPCs spawned. Also, the Move and Attack valid regions.

Figure 49: Map Variations

By pressing the "ESC" key on the keyboard a pause menu will appear. That menu is shown in Figure 50. There are five different options that the players can choose from. Resume Game will close the pause menu and continue with the game. Save Game will save the current state of the game. Change Map will bring the game back to the map selection menu shown in Figure 50. Main Menu will bring the game back to the main menu. Quit to Desktop will close the application.

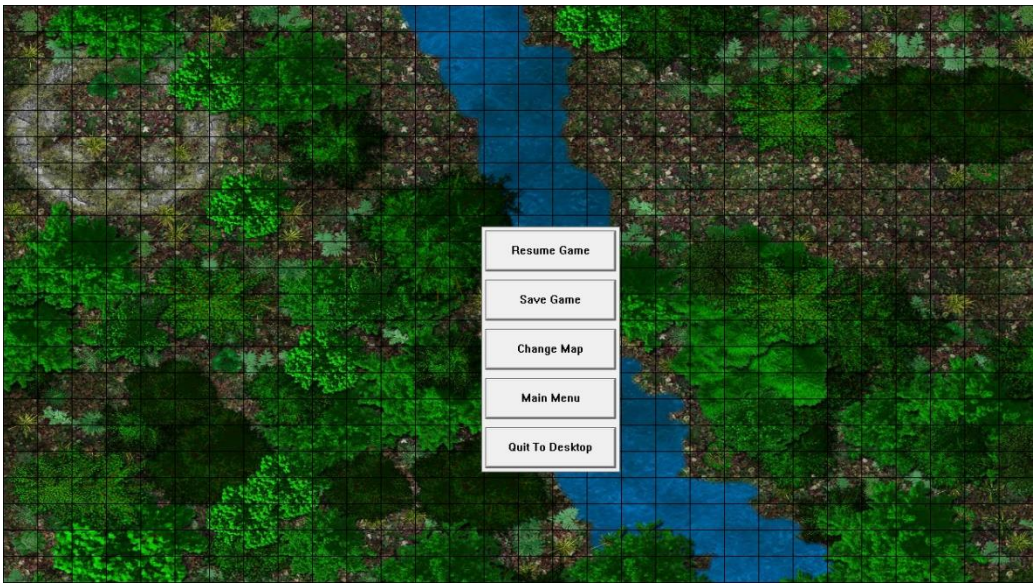

Figure 50: Pause Menu

The Load Game Menu shown in Figure 51 is displayed by selecting Load Game on the Main Menu. The players can select from the list of Saved Games. The red "X" will prompt the players to delete the save file. The Next and Previous page buttons will navigate through multiple pages of save files if they exist. Once a save is selected the Ready button can be selected to move on to selecting the Game Master device. The Main Menu button will bring the game back to the Main Menu.

Figure 51: Load Menu

8.2 Android Application User's Guide

The first screen after the splash screen is the Bluetooth connection screen shown below in Figure 52. By pressing the Enable Bluetooth and Make Discoverable buttons, the android phone can be initially paired with the PC. Once you click the List Paired Devices button, it will display the devices paired to the android phone that will then be used to establish a socket connection. Click on the name of the PC and a connection will be attempted to be created. Once the connection is successful, The "Connection Established" message appears and the Join Session button can be clicked to move onto the next screen. There is also an Offline Mode button that allows the player to use the app completely without Bluetooth and will save the player's information to the phone instead of the PC.

Figure 52: Bluetooth Connection Screen

The choose role screen is where the user is taken after they join the session, which is shown below in Figure 53. The information for the players and GM is grabbed from the PC via Bluetooth, and if any characters are available, they will be clickable. A player can choose between GM and player character, but the Game session should only have one GM, so multiple GMs should not be chosen. Click on a role to move onto the next screen.

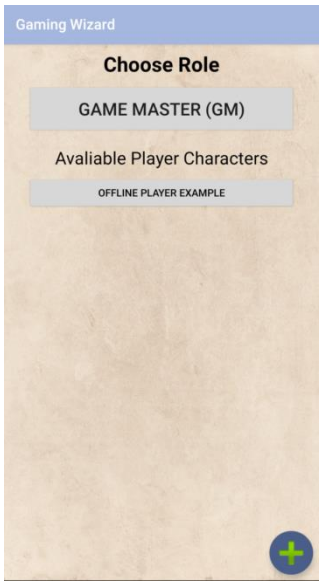

Figure 53: Choose Role Screen

The "plus" button on the choose role screen brings the user to the character creation screen presented in Figure 54 below. The player can input their character's name, class, race, and stats here for their new character. They may also choose up to four skills to be proficient in. Proficiency in a skill adds the skill's modifier with a character's proficiency bonus. After clicking on the Finish Character Creation button, the user is taken back to the choose role screen where the new character will be available.

Figure 54: Character Creation Screen

When choosing a character, the user is taken to a four tabbed display screen shown below in Figure 55. The left most tab displays the character's name, class, race, level, and stats. The user can click on any of these stats to changes them. The text is either editable or a pop up will display prompting the user to change the stats. The Quick Roll A D20 button will automatically roll a d20 dice and show the result on the bottom of the screen. The second tab, left middle, is the saves tab where a player can see their proficiencies in skills and make a saving through by choosing a skill in the "Select Skill" dropdown menu and hitting the Roll Save button. The result will display in a toast message at the bottom of the screen and is calculated by: D20 + skill modifier + character proficiency bonus (if proficient in skill selected).

The third tab, right middle, displays the character's attacks and the actions they can take during their turn. Move, Place, End Turn, and attack buttons all do nothing when it is not the character's turn, but will allow the player to do those actions in the PC when it is their turn. Holding the Move button will bring up a popup box to change the character's speed and the New Attack button will add a new attack button to the character. The last tab, right most, is for a player to store information about their character and to save their character to the PC with the most recent information with the Save Character button.

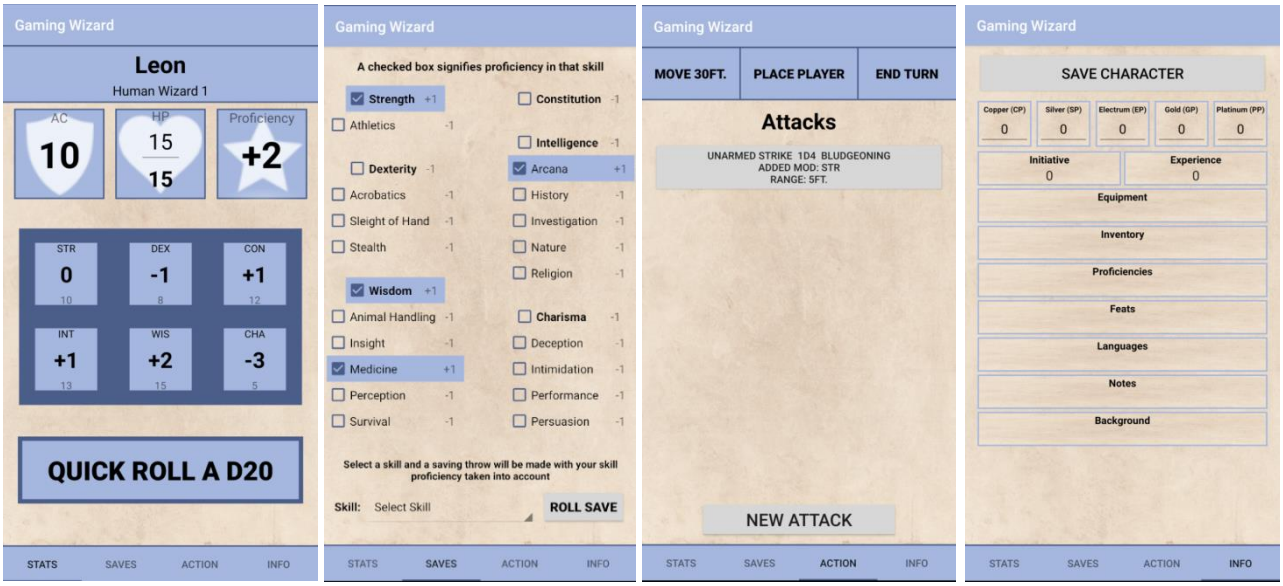

Figure 55: Player Screens

When choosing the GM role, the user is taken to a four tabbed display screen shown below in Figure 56. On the first tab, a GM can select an encounter, which will clear the PC screen of the previous encounter and set the NPCs in that encounter in the third tab. The GM can select the New Encounter button which will pop up the dialog to create a new encounter with NPCs from the list in the second tab. The second tab, NPC, displays a bestiary of all the NPCs currently available in the game session. When clicking the name of the NPC, information regarding that NPC will be displayed under it, clicking it again will hide the information. The "plus" button will bring up a pop up that allows the user to specify the name, stats, and attacks of a new NPC which will then be displayed in alphabetical order under Bestiary.

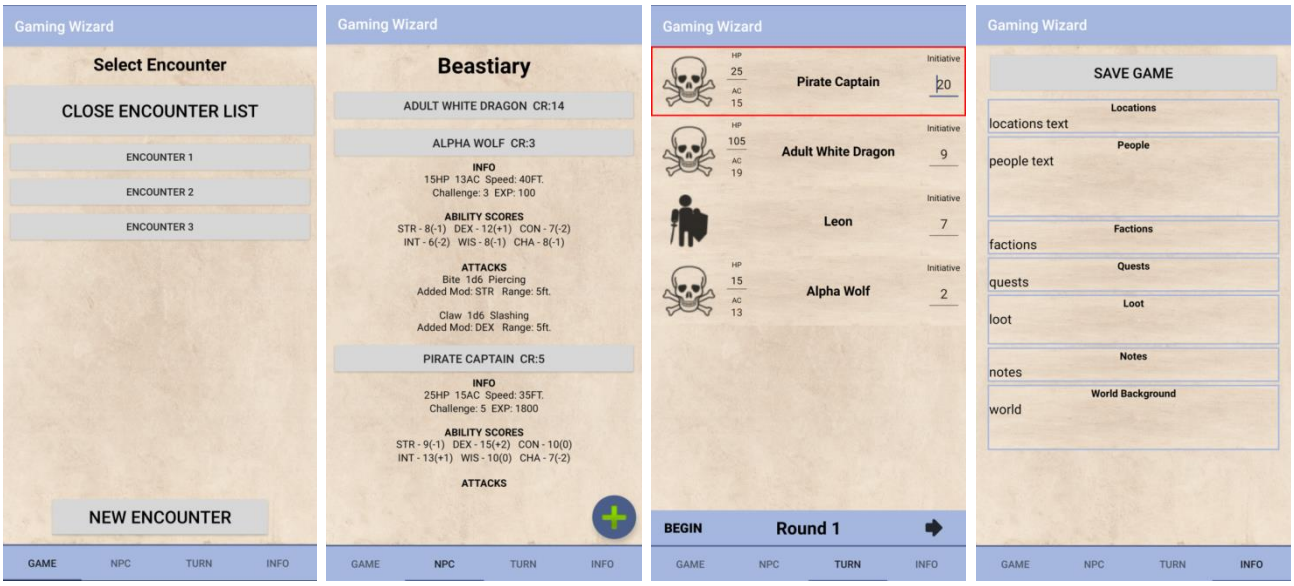

Figure 56: GM Screens

The third tab, Turn, displays the NPCs and players in the selected encounter. The GM can change the initiative for the characters and hit the Begin button which will order the turns by highest initiative first and begin the encounter. The right arrow button will make it the next character's turn in the turn order. Clicking on an NPC, Pirate Captain in this case, will bring the GM to the NPC control screen displayed in Figure 57 below. In the NPC control screen the GM controls the NPC similarly to how a player controls their character. The GM can change the name, stats, and attacks of the NPC selected and if it is this character's turn, they can move, place, or attack in the PC app. The last tab in Figure 56, Info, is where the GM stores information about the game session and game world. The Save Game button will also initiate the save game protocol in the PC app which will save the most recent information for all players and the GM.

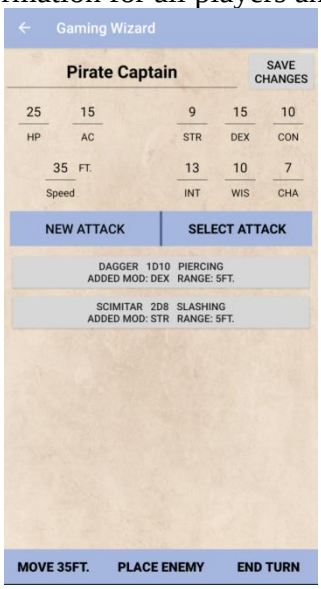

Figure 57: NPC Control Screen

9.0 Budget

With our design complete, a bill of materials is given in Table 51.

Table 51: Bill of Materials

Item	Source	Cost	Number	Tax	Shipping	Total
BenQ MX810ST Projector	ebay - voltarea	$ 178.76	1	$ -	$ -	$ 178.76
PS Eye Camera	Amazon	$ 8.70	1	$ -	$ -	$ 8.70
Camera Driver	Code Lab	$ 3.00	1	$ -	$ -	$ 3.00
Floppy Disk	Donated	$ -	1	$ -	$ -	$ -
Drafting Paper	Blick Art	$ 14.94	1	$ 1.82	$ 9.95	$ 26.71
PCBs	JLCPCB	$ 10.00	1	$ -	$ 17.70	$ 27.70
Assorted PCB Components	LCSC via JLCPCB, Donated	$ 17.15	1	$ -	$ 19.32	$ 36.47
Tendelux IR Illuminator	Amazon	$ 19.98	2	$ -	$ -	$ 39.96
7-Segment LED Display	Digi-Key	$ 3.96	1	$ -	$ -	$ 3.96
Raspberry Pi 3	Donated	$ -	1	$ -	$ -	$ -
TLC5940 DIP	nooelec	$ 12.95	1	$ -	$ -	$ 12.95
RGB LEDs	EDGELEC	$ 8.99	1	$ -	$ -	$ 8.99
12V Fans (2 pack)	Pano-Mounts	$ 12.99	1	$ -	$ -	$ 12.99
Arduino Mega	Elegoo	$ 14.99	1	$ -	$ -	$ 14.99
RFP12N10LMOSFETS	Riddle Electronics	$ 6.95	1	$ -	$ -	$ 6.95
12V 3A AC Adapter	IBERLS	$ 11.89	1	$ -	$ -	$ 11.89
TABLE						
1/4" x 48" x 96" ply	Home Depot	$ 22.92	2	$ 2.98	$ -	$ 48.82
1/2" x 48" x 48" ply	Home Depot	$ 16.08	1	$ 1.05	$ -	$ 17.13
2x2 (leg)	Lowe's	$ 6.30	4	$ 1.64	$ -	$ 26.84
1x4 (inner brace)	Lowe's	$ 7.86	2	$ 1.02	$ -	$ 16.74
1x3 (top frame)	Lowe's	$ 6.76	2	$ 0.88	$ -	$ 14.40
Screws	Lowe's	$ 2.58	3	$ 0.50	$ -	$ 8.24
Nails	Ace Hardware	$ 2.75	1	$ 0.18	$ -	$ 2.93
Acrylic	Professional Plastics	$ 51.99	1	$ 5.46	$ 31.95	$ 89.40
Styrofoam Block	Michaels	$ 12.99	1	$ 0.84	$ -	$ 13.83
Curtain Rod	Walmart	$ 4.99	1	$ 0.32	$ -	$ 5.31
Blackout Curtain	Donated	$ -	1	$ -	$ -	$ -
Grand Total				**$ 16.69**	**$ 78.92**	**$ 637.66**

This bill of materials does not include small items such as resistors and wires, which we were able to obtain for free or already owned. We also exclude tools which were used in construction such as soldering irons, drills, and saws, which were already owned by group members or donated. Our bill of materials comes to a total of just under $640, meeting our target of $700, which was updated from $600 as we decided to improve certain components during construction.

10.0 Milestones

The milestones are broken into two semesters, senior design 1 and senior design 2. Research, design, and testing milestones of the project in senior design 1 are shown in Table 52, and integration milestones for senior design 2 are described in Table 53.

Table 52: Senior Design 1 Milestones

Number	Task	Member	Start	End	Status
1	Gather Project Ideas	Group	8/26/2019	9/2/2019	Done
2	Research Viability of Ideas	Group	9/2/2019	9/9/2019	Done
3	Role Assignment and Idea Choice	Group	9/9/2019	9/12/2019	Done
4	Divide and Conquer	Group	9/12/2019	9/20/2019	Done
5	60 Page Draft	Group	9/23/2019	11/1/2019	Done
6	Gather Project Requirements	Erica	9/23/2019	9/30/2019	Done
7	Research Previous Projects	Gabriel	9/23/2019	10/7/2019	Done
8	Research Hardware and Software Standards	Logan/ Gabriel	9/23/2019	10/14/2019	Done
9	Research and Design Initial Software Technologies	Daniel	9/23/2019	10/21/2019	Done
10	Research Touch Detection	Erica	9/30/2019	10/14/2019	Done
11	Research Microcontrollers, Cooling Systems, Timers, and Communication Protocols	Logan	10/7/2019	10/28/2019	Done
12	Research Programing Environment and Tools	Gabriel	10/14/2019	10/28/2019	Done
13	Describe Hardware Prototyping and Testing	Erica	10/14/2019	10/28/2019	Done
14	Create Initial Software Testing Plan	Daniel	10/21/2019	10/28/2019	Done
15	100 Page Draft	Group	11/1/2019	11/15/2019	Done
16	Realistic Design Constraints	Gabriel	11/1/2019	11/12/2019	Done
17	Initial Prototyping and Ordering of Hardware Components	Erica/ Logan	11/1/2019	11/12/2019	Done
18	Expanding on Software Design and Testing Procedures	Daniel	11/1/2019	11/12/2019	Done
19	Initial User Interface Design	Erica	11/7/2019	11/12/2019	Done
20	Final Document Due	Group	11/15/2019	12/4/2019	Done
21	Testing of Hardware Components	Logan/ Erica	11/15/2019	11/22/2019	Done
22	PCB Design Finalization	Logan	11/15/2019	11/28/2019	Done
23	External Software Library Research	Daniel/ Gabriel	11/15/2019	11/28/2019	Done
24	Physical Table Design and Prototype	Erica	11/15/2019	11/28/2019	Done
25	Expansion on Software Design	Daniel	11/15/2019	11/28/2019	Done

Table 53: Senior Design 2 Milestones

Number	Task	Member	Start	End	Status
1	Build and Test Hardware Subsystems	Logan/ Erica	12/5/2019	1/10/2020	Done
2	Initial Software Writing and Debugging for Windows and Android App	Daniel/ Gabriel	12/5/2019	1/10/2020	Done
3	Build Physical Table	Group	12/5/2019	1/10/2020	Done
4	Final Report	Group	1/10/2020	4/22/2020	Done
5	Combine Subsystems Into Initial Prototype	Group	1/10/2020	1/20/2020	Done
6	Testing and Subsequent Redesign of Parts if Necessary	Group	1/20/2020	3/16/2020	Done
7	Finalize Prototype	Group	3/16/2020	4/10/2020	Done
8	Critical Design Review	Group	2/1/2020	2/11/2020	Done
9	Midterm Demo	Group	3/1/2020	3/20/2020	Done
10	Conference Paper	Group	4/1/2020	4/13/2020	Done
11	Final Presentation	Group	4/1/2020	4/13/2020	Done
12	Final Documentation	Group	4/10/2020	4/21/2020	Done
13	Website	Group	4/10/2020	4/21/2020	Done

Appendices

Appendix A: Copyright Permissions

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Figure 20

https://commons.wikimedia.org/wiki/File:UART_XBee_Data_format.jpg

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Figure 21

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Figure 22
https://commons.wikimedia.org/wiki/File:SPI_three_slaves_daisy_chained.svg

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Figure 23
https://commons.wikimedia.org/wiki/File:Bluetooth_network_topology.png

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Figure 24
https://commons.wikimedia.org/wiki/File:Wlan_www.png

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Figure 31
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Figure 32
https://developer.android.com/about/dashboards

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Figure 33
https://developer.android.com/studio/write/layout-editor

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