ECE 445
Fall 2021

Team 24 - Design Document:

The Educational Entanglement Device

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1. Introduction

1.1 Problem

There is currently no practical demonstration for quantum entanglement, a physical phenomenon that occurs when a group of photons are in a way such that the quantum state of each photon of the group cannot be described independently of the state of the others[1]. For example, say two objects are entangled where both objects can either be a square or a circle and have a color of red or blue. If a person decided to try and measure the shape or color of both the objects they would find that there is a correlation between these two entangled objects no matter the distance between them. However if one person decided to measure the shape of an object and another person tries to measure the color of the entangled object there would be no correlation between them. This property of entanglement is difficult to display in a classical fashion.

1.2 Solution

We will create an 'entanglement simulator' for public demonstrations and outreach. Since this demonstration is built in the real world everything needs to follow classical physics because there is no real way to visually demonstrate entanglement classically. This demonstration will emulate two entangled photons moving in two different directions through the two different LED strips. Each photon will be simulated using two LED lights on each strip which are separated by a 6 inch difference to represent the superposition of the photon's time state and initially have the same color (purple, a mix between blue and red) to represent the superposition of color. A user can emulate measuring the photon's time state by pressing on the capacitive sensors on the two LED strips which would cause one of the lights to disappear, illustrating that the photon is no longer in a superposition since it has been measured. The user can also choose to measure the color of the photon by touching the area between the 2 LEDs which would change the lights to either red or blue. The two separate photons would have correlated outputs if both users decide to use the same measurement on the photon otherwise the results would be random.

Using the measurement from both photons a secret key can be generated. This simple key will consist of 1 byte worth of data and will be generated once at least eight measurements are made on the two different photons using the same method. The bits of the key will depend on the measurement's outputs, for example if the user's measured the position of the 'photon' and the light that stays lit up is closer to the source than destination then it can be treated as a 0 otherwise it would be a 1. Once the key is generated one user can type a single ascii character on the keyboard and have this message encrypted using this key and send it to the other user who can decrypt it using their key to demonstrate how quantum properties can be used in cryptography.

1.3 Visual Aid:

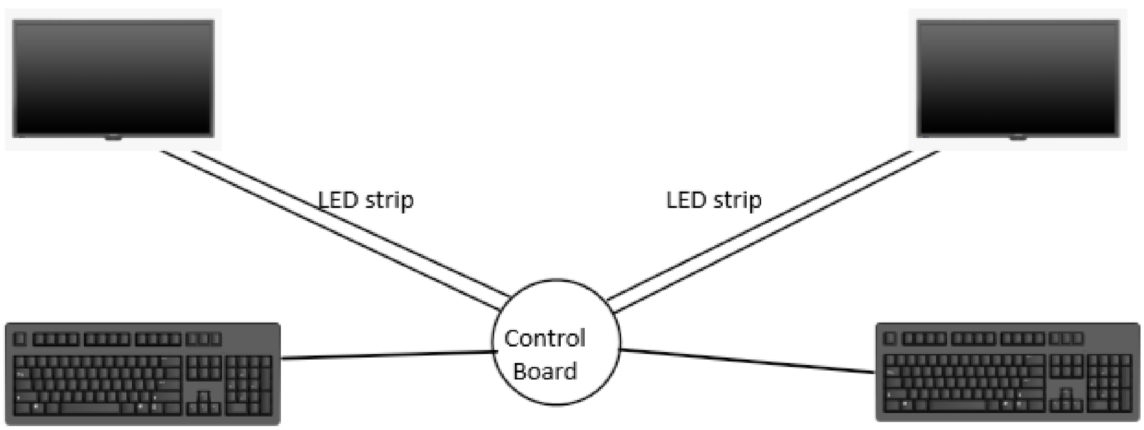

Figure 1: Basic Visual of the Educational Entanglement Device Prototype

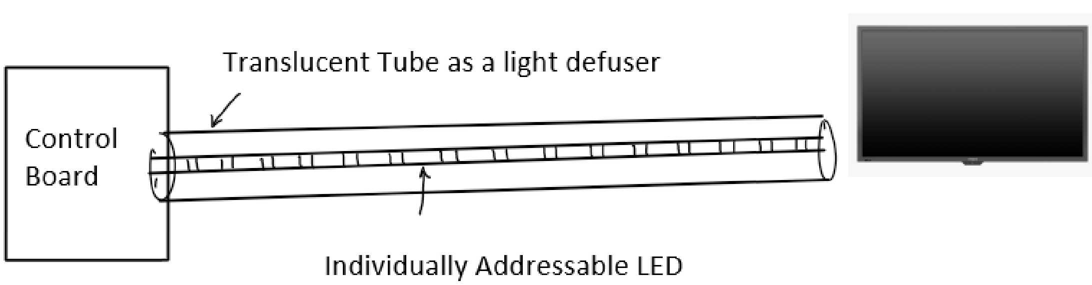

Figure 2: Visual of one arm of the device from the inside

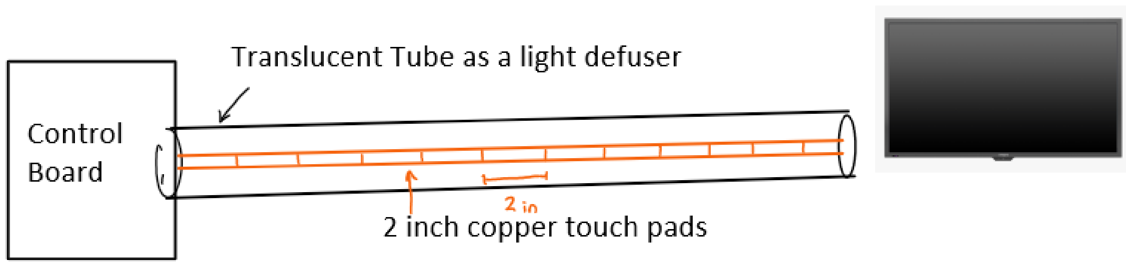

Figure 3: Visual of one arm of the device from the outside

The Educational Entanglement Device: It would feature a central ’source’, out of which come two LED strings, in opposite directions. Correlated light pulses would travel down each string (visible to the observers). The participants could then ‘measure’ the pulses in one of a couple different ways (by touching the strands in a particular way, since we'd like the participants to be able to touch anywhere along a 3' stretch of the string, but with 2 ± 0.1" resolution of where they touched), yielding one of a couple results (in accordance with quantum mechanics). These would then be shown on a local display to each of the participants. In addition to demonstrating the basic correlations of entanglement, such a system can also implement a basic quantum cryptography protocol. If the two participants make the same type of measurement, they get the same (but random) result. These can then be used to generate a shared random key, which the project could then use to allow them to send a short encrypted message ("one-time pad").

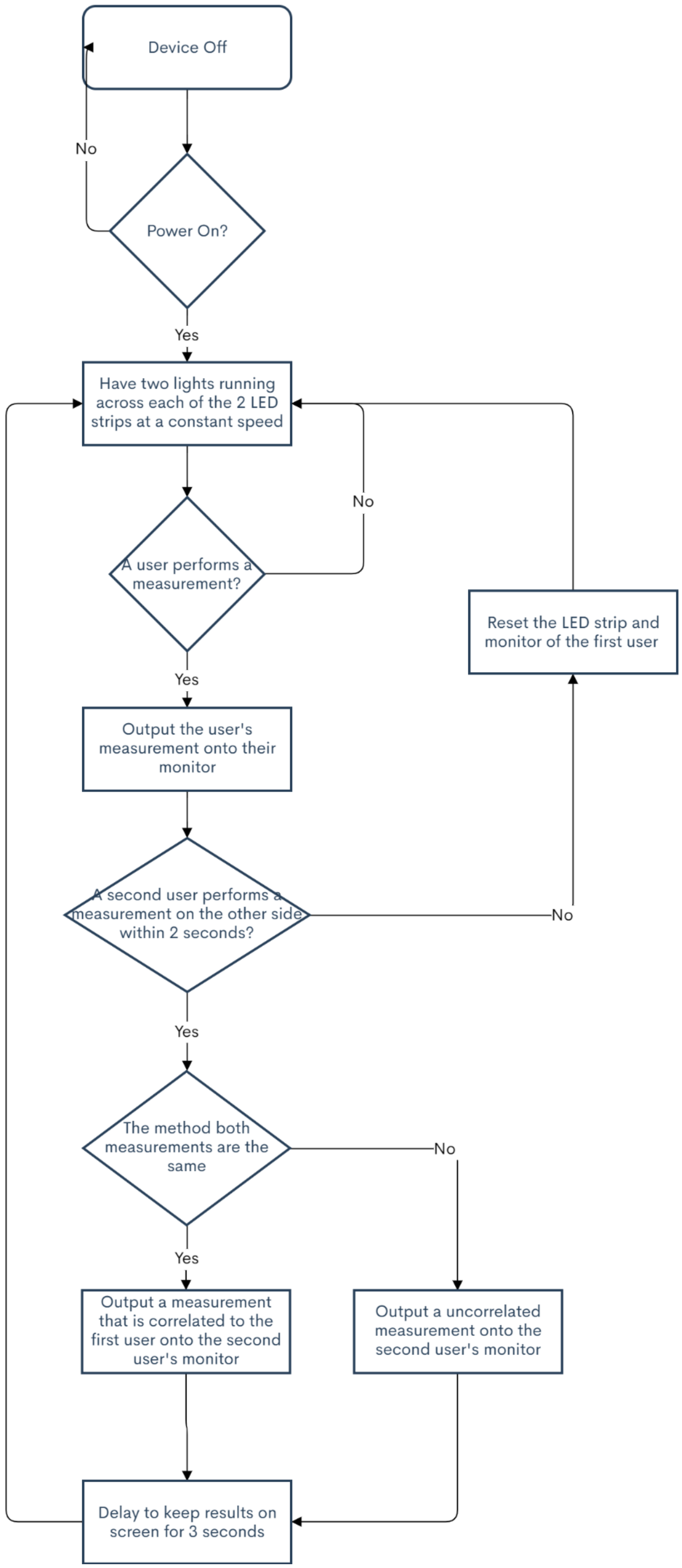

Figure 4: Flow chart of software

1.4 High-level requirements list:

- **Can be easily assembled and disassembled:** Since this project will be quite large and is used as a display, we want to make sure that the different parts can be easily removed and added together so that the whole experience does not require too many people and tools.
- **Ability to display a user's measurement onto a monitor:** A user will perform a measurement on the simulated particle by touching a sensor along the LED arm which would cause the result of their measurement to be displayed on the monitor.
- **Ability to customize the repetition rate, pulse separation, and hold time:** Since our demo can be used by different institutions who want to demonstrate quantum entanglement, we want to make sure that our project has enough customizability to change the rate of repeating the demo, how far away the two light strands are from one another, and how long the downtime is between each measurement

2. Design

2.1 Block Diagram:

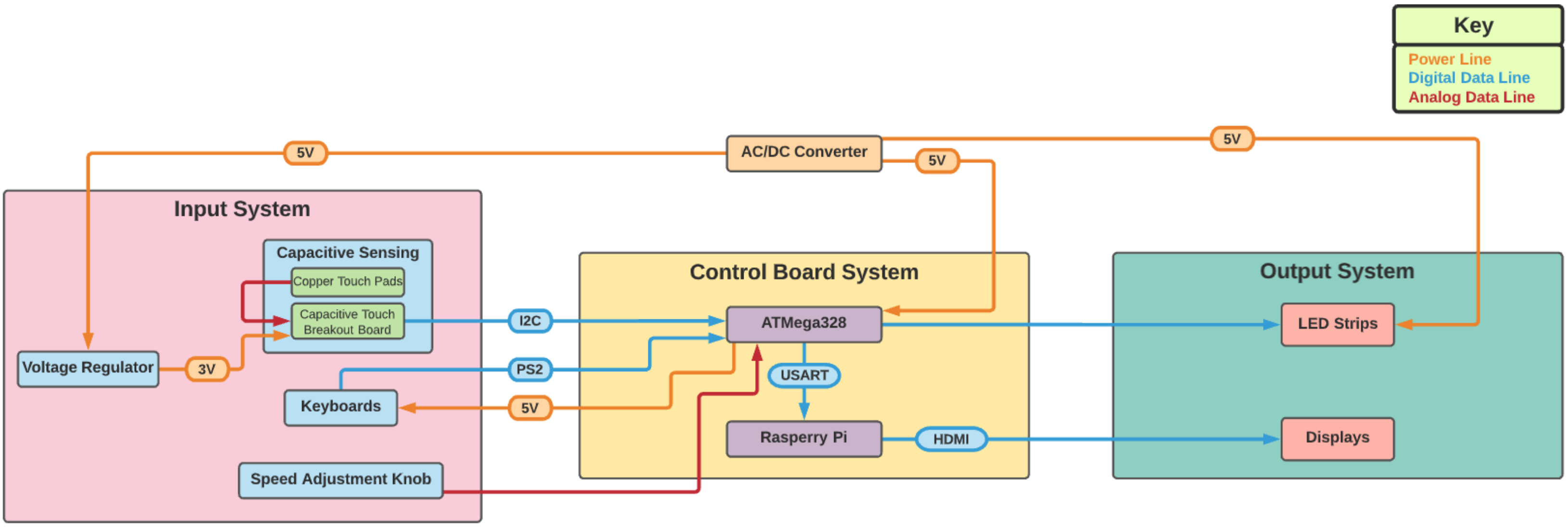

Figure 5: Block Diagram

The design[3] presented in the block diagram contains a power system, control board system, input system and output system. The power system will convert AC power from the wall to DC power for the various modules after regulating the voltage. The Control board system takes input from the Input systems which allows users to interact with the entanglement device and cryptography demo. Once measurements have been made the Control board system then outputs the data to the Output system to display the resulting measurement and encrypted message.

2.2 Schematic:

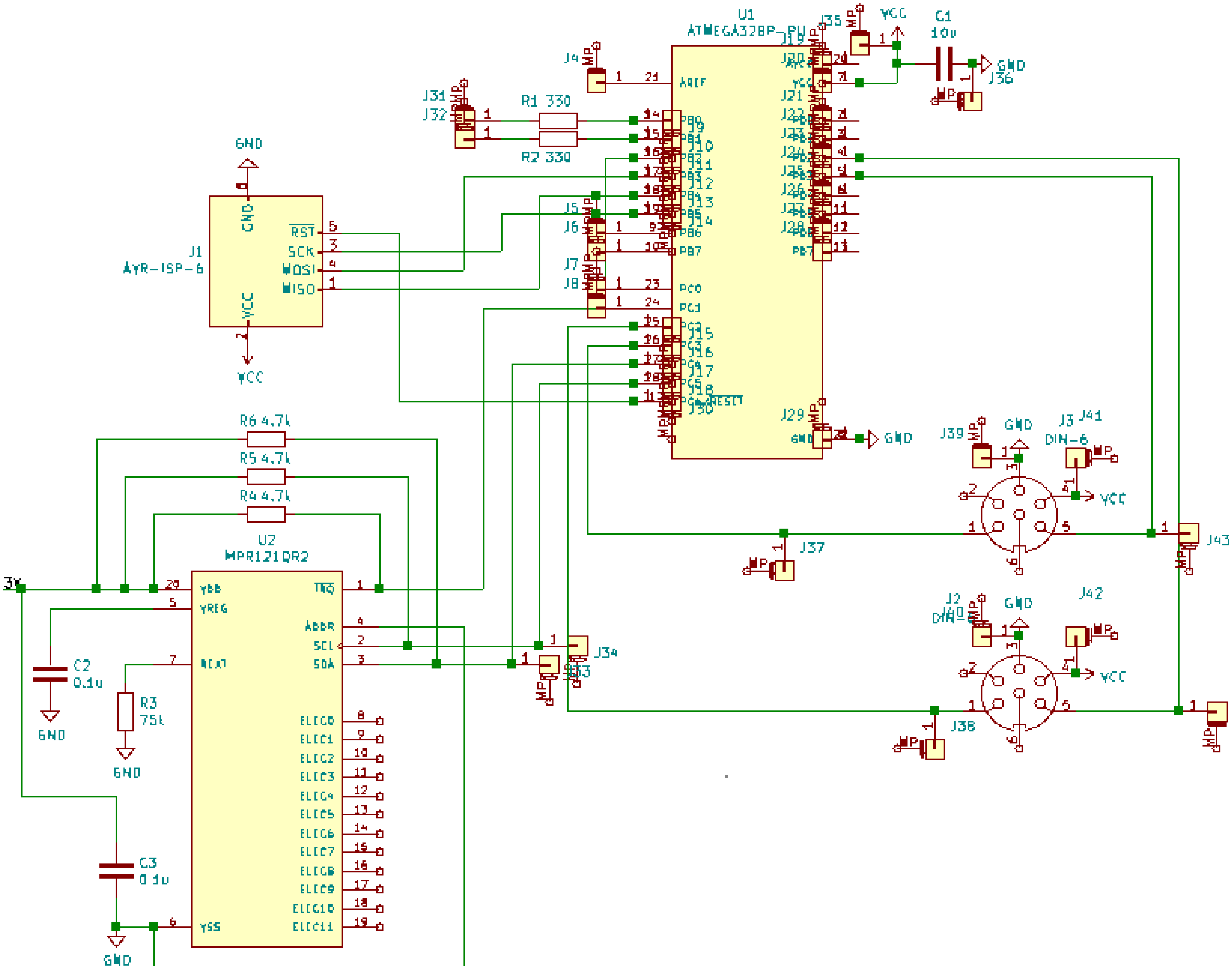

Figure 6: Schematic

2.3 Subsystem Overviews:

2.3.1 AC/DC Converter:

Overview - The AC/DC converter will be used by our project to convert all AC power that we are getting from the wall plug and converting it into DC power that can be used to power our microcontroller, touch sensors, and LED strips. The AC/DC converter must be able to output 200W $\pm$ 5% and deliver it to the voltage regulation system.

2.4 Control Board System:

The control board system will be a printed circuit board which will be designed to accommodate both LED and USB communication, and will act as the interface between the input system and the output system in order to achieve the desired behavior of the overall project. This will include the addressable control of the LED strips to create a traveling light effect, interpreting user input data from the keyboards, and the capacitive touch pads in order to inform attributes of the outputs such as the contents of the messages to be displayed, and the way in which the traveling lights move and what color they appear as. The Raspberry Pi 4 will connect the Control Board system with the monitor through a HDMI signal and will control what is displayed based on the Input System. The microcontroller will send signals to the Raspberry Pi board for the display when there is a signal from the Input System.

2.4.1 USB Interface:

Overview - The USB interface provides a means of receiving user input data from keyboards, and delivering that data to the board microcontroller whereupon it can be utilized as cryptographic messages.

2.4.2 Board Microcontroller

Overview - The board microcontroller is the central processing element of this project. It receives and interprets data from all of the input systems and sensors, including digital touch flag signals from the capacitive touch breakout board, digital keystroke signals through an SPI USB interface, and analog voltage and current signals from the speed adjustment potentiometer. Based on this input data, the board microcontroller sends control signals to all of the output systems and color value signals to the LED strips.

2.4.3 Raspberry Pi 4

The Raspberry Pi 4 will be used strictly for interfacing the monitors with our control system via HDMI. It will be responsible for outputting the user's measurements coming in from the capacitive touch sensors to the two monitors.

2.5 Input System:

The input system consists of a capacitive sensing module and two keyboards which both deliver data to the control board system. The capacitive sensing module uses a capacitive touch breakout board which is able to detect when several different externally connected copper pads are touched, and relays this information to the board microcontroller. The keyboards simply provide standard text input to the control board system for use in cryptographic messages.

2.5.1 Capacitive Touch Sensing:

Overview - The touch sensor allows users to interact with the LED strips to simulate a measurement on the ‘entangled photon’.

2.5.2 Keyboard:

Overview - The keyboard will be used to simulate cryptography by having a user type a character on one side. This message will then be encrypted using the key generated from as stated in the solution and sent to the other user on the other end of the entanglement simulator through the microcontroller.

2.5.3 Speed Adjustment Potentiometer Knob:

Overview - This is a potentiometer that the user can turn that will change the speed of the lights that will be traveling back and forth between the two displays as requested by Professor Kwiat

2.5.4 Voltage Regulator:

Overview - Our voltage regulator must be able to properly maintain a safe range of power to each component that requires it so that each component is properly and efficiently powered.

2.6 Output System:

The Output System consists of our LED display and LED strips. This is the most important system in terms of showing off the functionality of our project, as the display and light strips are what simulate the ‘entangled photon’. Our display will be used to show different numbers for the entanglement demo as well as letters when demonstrating the encrypted cryptography message. The light strips will be used to simulate the ‘entangled photon’ being split and sending the two parts in different directions.

2.6.1 LED Displays:

Overview - The LED display is connected to the microcontroller and will output the user's measurement of the 'entangled photon' to the screen.

2.6.2 LED Strips:

Overview - The LED strips are used to simulate the 'entangled photon' being split going down two seperate directions. The LEDs must have a light density of at least 30 LEDs/ft as a request from our sponsor. This component will be an Off The Shelf (OTS) part.

2.7 Requirements and Verification:

2.7.1 Control Board System:

Requirement	**Verification**
A refresh rate of at least 30Hz	We will use an oscilloscope to measure the vertical and horizontal sync and convert those measurements into refresh rate and make sure they are within the tolerance range
The USB interface must be able to deliver keystroke data that matches the input from the user to the microcontroller, dropping less than 5% of the data from the keyboard, or one in every twenty keystrokes.	Echo all keystrokes onto a screen for both keyboards at the same time to test both USB interfaces
The microcontroller must be able to output two UART signals to the LEDs	Plug in the two different addressable LEDs and send signals from the microcontroller to the LEDs to see if they change states.
The microcontroller must be able to receive the inputs from two USB keyboards	Echo keyboard strokes onto the monitor

2.7.2 Input System:

Requirement	**Verification**
The copper touch pads, along with the capacitive sense breakout boards should be able to deliver touch flag data to the microcontroller with at least 97.5% accuracy.	Touch all the pads 100 times and check the number of state changes within the software comparing them with the number of times we touch all the pads
The keyboard should have a latency of < 200ms between the keyboard stroke and the microcontroller. It should be able to send a signal 99% of the time when a key is pressed.	We will be estimating the scan rate of the keyboard using an online website [4] and determine the pull rate from the keyboard protocol to estimate the latency of the keyboard

With the knob turned to 100%, the velocity of the lights should move at the full speed of 5 m/s ± 0.1 . When the knob is turned to 0%, the velocity of the lights should move at the minimum speed of 0.1 m/s ± 0.1. With any other setting between 0 and 100% be within 0.1 and 5 /s.	We will time how long it takes for one LED light to move from one end to the other in software. Using that time measurement and the length of the LED strip, we can convert that measurement into m/s.

2.7.3 Output System:

Requirement	**Verification**
The resolution of the LED display must be able to display a letter with such a clarity that each letter and number can be easily distinguished from one another from 10 feet away.	We will display an image of a letter onto the screen and walk 10 meters away and see if the image is still recognizable
The resolution of the LED display must be able to display a letter with such a clarity that each letter and number can be easily distinguished from one another from 10 feet away.	We will display an image of a letter onto the screen and walk 10 meters away and see if the image is still recognizable

2.8 Tolerance Analysis:

2.8.1 Power Tolerance Analysis:

The biggest issue our project faces will fall under being able to scale up a larger version of our project using the same PCB based on our control board system. As part of our sponsorship, we have been asked to create a working prototype on a much smaller scale. Upon successful completion of this prototype, we will be granted funds that can be used to create a much larger scale version of the prototype, with better LEDs, better monitors, and its own keyboards.

The issue is making this PCB able to handle both the smaller and larger version of the project we will be building. Our prototype will have two monitors, 2 3’ LED strips, 2 keyboards, and the rest of our components. In order to scale up, our PCB needs to be able to handle 2 LED strips that can range up to 10 ft in length each.

The critical part of this design would be the power system. Each individual LED consumes around an average of 0.2W of power, increasing approximately linearly. One of the requirements of our projects given by our sponsor was that the density of the LED strips needed to be at least 30 LEDs/ft. This would mean for every foot of LED we use 6Ws of power is consumed. For the full scaled version with a total of 20 feet of LEDs this would be we require a minimum of 120W of power just for the LEDs alone.

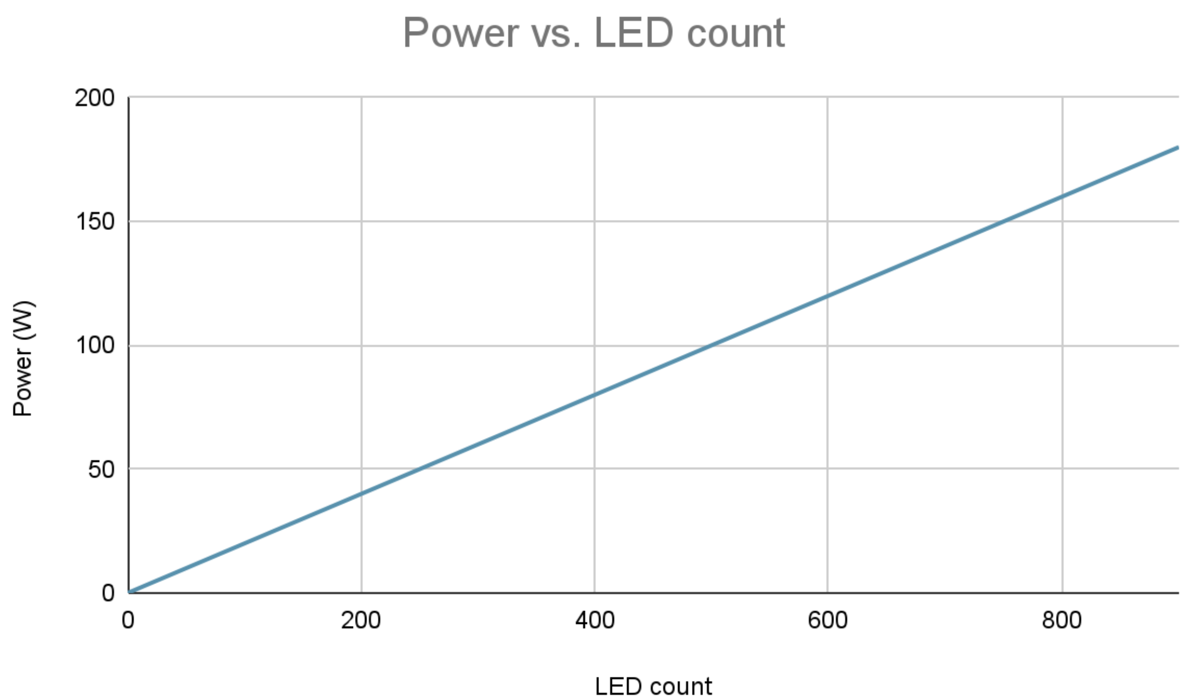

Figure 7: Relationship between Power and Number of LEDs

The best way we can circumvent this problem is by purchasing a power supply that can handle at least 200W to accommodate all components of our project, with there being some wiggle room if we decided to increase the length/density of the LEDs even further, which is in line with our high level requirement that discusses the customizability of our project if it were to be built at other educational institutions.

2.8.2 Capacitive Touch Tolerance Analysis:

One of the issues introduced to our team was how the overall length of the LEDs would affect how well our capacitive touch sensors would be able to transmit accurate data to our control system. The longer the length of the copper wires between the touchpad and the breakout board, the less reliable the signal strength from the touchpad to the microcontroller would be.

This is important to our project because we are building a 3 ft version for our prototype and demo, but a 10ft version for our sponsor. The touch capacitors need to be able to transmit accurate data for both sets of lengths, otherwise our project wouldn't have the scalability and versatility that we are aiming for.

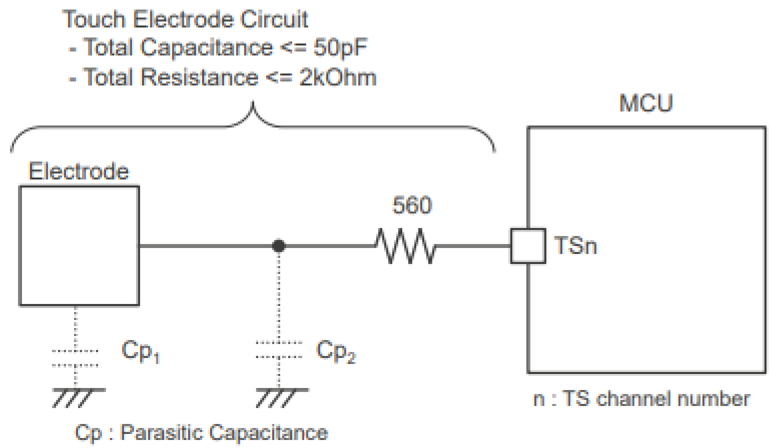

Figure 8: Capacitive touch diagram w/ total resistance

With some touch capacitive boards on the market, they do not have the capability of transmitting accurate data over distances greater than 4 ft in wiring. However, as is the case with our touch capacitive boards that we will be using, they have the capability of being able to transfer accurate measurements over lengths greater than 4 ft shown by the calculation below:

$$R = \frac{\rho l}{A} = \frac{1.7 * 10^{-8} * 3\,m}{6.45*10^{-5} m^{2}} = 0.00079069767\ \Omega$$

As shown by the calculation, we can see that the resistance of the copper wire is negligible. The main problem would be the power drop from the capacitive touch sensor due to the length of the wire since a human's capacitance is about 100 pF. However, after setting up a small demo in the lab, we were able to determine that a distance of 1.5m worth of copper wire was able to still translate a signal using the capacitive touch sensor, and that our microcontroller will still be able to read and translate the data being read when a user touches the copper in our project.

3.1 Cost Analysis

We have estimated that an engineer would be making around $50/hr, and with there being 3 people working on this project at an average of 20 hours/week for 15 weeks with a 2.5 times overhead, our project has an estimated building cost of $112,500.

Part	Price	Quantity	Final Cost
Raspberry Pi 4 Starter Kit	$109.99	1	$109.99
Microcontroller ATMEGA328-PU	$2.58	1	$2.58
Capacitive Touch Sensor Breakout	$7.95	4	$31.80
5m Copper Tape	$4.95	3	$14.85
3’ LED Strips	$17.99	2	$35.98
PS2 connectors	7.95	2	$15.9
Knob	$5.18	1	$5.18
AC/DC Converter	$29.99	1	$29.99
DC/DC Regulator	$0.70	1	$0.70
36” Frosted Acrylic Round Tubes	$9.00	2	$18.00
Resistors and Other PCB parts	$1.00	10	$10.00
Heavy Duty Clear Tape	$8.47	1	$8.47
Clock oscillator	$1.24	1	$1.24
Total			$270.26

Table 1: Cost breakdown for each part

3.2 Schedule

Week	Benjamin	Andrew	Ian
Week of 9/27	Find parts and finish up Design Document	Find parts and finish up Design Document	Start work on PCB schematic
Week of 10/4	Help Ian with PCB Schematic and order parts	Help Ian with PCB Schematic and order parts	Finish working on PCB Schematic
Week of 10/11	Start compiling a list of online references for LED interfacing	Start compiling a list of online references for USB interfacing	Start compiling a list of online references for RPI interfacing
Week of 10/18	Begin software implementation of LED lights	Begin software implementation of USB interface	Begin soldering parts to PCB board
Week of 10/25	Finish LED light implementation and help with RPI implementation	Finish USB implementation and help with RPI implementation	Begin software implementation of RPI
Week of 11/1	Finish software implementation of RPI	Finish software implementation of RPI	Finish software implementation of RPI
Week of 11/8	Testing for mock demo with prototype	Testing for mock demo with prototype	Testing for mock demo with prototype
Week of 11/15	Mock Demo	Mock Demo	Mock Demo
Week of 11/22	Fall Break	Fall Break	Fall Break
Week of 11/29	Demo and begin work on Final Paper	Demo and begin work on Presentation	Demo and begin work on Presentation
Week of 12/6	Presentation and finish final paper	Presentation and finish final paper	Presentation and finish final paper

Table 2: Schedule for rest of semester breaking down work for team

4. Ethics and Safety

4.1 Ethics:

Since we are creating an educational device to be used in a public building for anyone to use, we want to make sure that our device can be operated correctly so that everyone who uses our device will learn about Quantum Entanglement in a fun, safe way. It is important that we follow the 7.8 IEEE Code of Ethics [5], specifically in code I.1 which states that our project must “hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment”, and I.2 which states that our project must “improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies”. We will be inspecting our device frequently, mainly the keyboard and monitor, to make sure they are well maintained. This project will be open to all individuals who have a curious mind and wish to see a simple display which shows a much more complex element. We will make sure that these ethics are upheld before, during, and after the construction of this device so that there is no one that will feel unsafe or uncomfortable using it.

4.2 Safety:

With our project being open to the public, we need to make sure that we have the proper safety warnings so that there are no instances of public endangerment. We will be using proper insulation and grounding everything using electricity so that there is no danger of anyone being on the end of any electric shocks. In addition, there can be some sharp edges on the copper tape used, so we will be covering any sharp edges with clear tape so that they cannot harm anyone. Due to the ongoing pandemic, we also plan on having a cleaning station available to all those who wish to disinfect the display after each use to stop the spread of germs.

5. References

[1] F. Wilczek and substantive Quanta Magazine moderates comments to facilitate an informed, “Entanglement made simple,” *Quanta Magazine*, 23-May-2019. [Online]. Available: https://www.quantamagazine.org/entanglement-made-simple-20160428/. [Accessed: 19-Oct-2021].

[2] “1.3 introduction to Capacitive Touch Sensors,” *Fieldscale*. [Online]. Available: https://fieldscale.com/learn-capacitive-sensing/intro-to-capacitive-touch-sensors/. [Accessed: 11-Sep-2021].

[3] *Drafting for electronics--block diagrams*. [Online]. Available: http://www.industrial-electronics.com/drafting-for-electronics-12.html. [Accessed: 11-Sep-2021].

[4] *Keyboard Scan Rate Tool*. [Online]. Available: https://blog.seethis.link/scan-rate-estimator/. [Accessed: 30-Sep-2021].

[5] “IEEE code of Ethics,” *IEEE*. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html [Accessed: 13-Sep-2021].