Smart Desk

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***Abstract*—The theory, design, and implementation of a desk that offers conventional functionality in addition to touch capabilities is presented. The Smart Desk benefits people ranging from students to professionals and even casual users by providing a functioning computer within a desktop. The main technical exploration is obtaining touch capabilities through IR light rather than through capacitive materials or other traditional implementations. This alternative would offer both a cheap and durable solution to touch screens that allows for a versatile Smart Desk.**

I. Introduction

Have you ever tried to get work done at your desk, but it was too cluttered? Most users find it difficult to be productive in an environment where they must constantly be searching through stacks of papers and books. Our solution to this problem is eliminating the need for physical resources, from papers and books to even calculators, and replacing them with a digital alternative. Our system offers the conventional functionality of a desk, a surface where one can place items on and do work, while offering an embedded touch screen. This touchscreen will interface with an existing computer and offer all the functionality the computer offers. Instead of searching by hand for the gain equation of a common collector amplifier through a 500-page electronics textbook, one can simply search for it in the book's digital copy in seconds. This allows users to work more efficiently and reduce the space required to store these physical resources. The idea of a touch screen desk is nothing new, as architects and several other professionals already use this technology every day. What separates this solution from the others is cost. For most people, it is not feasible to spend 4-16 thousand dollars on a desk that is not critical to their ability to do their jobs. Another question one may ask is, "Why do I need a touch screen desk, why don't I just buy a touchscreen monitor?" This is a fair question, one could simply buy a large touchscreen monitor, and lay it flat on a desk surface to achieve the same goal. Once again, this solution costs one to five thousand dollars based on the size and resolution of the screen. Our solution will cost under $500 to deliver a durable and cost-effective touchscreen. Current solutions [1] can achieve a higher screen resolution due to the fact they are able to place the LCD screens directly behind a capacitive touch screen, but this is costlier. The price of the proposed solution is possible due to the availability of inexpensive LCD screens and replacing the capacitive screen with an infrared (IR) solution. The reason for substituting IR is the fact the IR surface scales better. Capacitive screens not only cost significantly more to produce, but when scaling the screen size, powering the surface and achieving the same accuracy becomes an issue. This scaling issue is not for large IR screens. The only issue is powering the number of IR LEDS necessary to fill the surface with light. The specifications for our design are listed in Table 1. The requirements analysis for the design was motivated by trying to allow the desk to maintain its functionality of a standard desk while integrating a touch screen in the surface of the desk. Regarding the touch screen, the requirements revolve around the system's ability to behave like a traditional touch screen, such as sufficient resolution, real-time responses, and high accuracy up to a fingertip. For the desk, it became clear that the main requirement would be a space limitation on the systems necessary to achieve the touch screen in order preserve a person's ability to comfortably fit their legs under the desk. At the end of the design, a person will be able to attach their current computer to our system and see their screen displayed in the surface of the desk. From there, they will be able to do any form of work they would like, from writing out calculations for a math problem to searching through articles for a research paper to simply playing games, all through the touchscreen.

TABLE I
SPECIFICATIONS

Requirement	Specification	Actual
Provide accurate touch inputs	Accuracy up to a fingertip	6.35mm
Provide increased versatility	Maintains function of conventional desk, while offering touchscreen	Adequate desk space with working touch screen
Responses in real time	<100ms	8ms
Interfaces with current computer	Interfaces with standard computer inputs	USB, VGA, HDMI
Power	Use the power of an average TV	110W

A. Overview

Our solution involves taking apart a 32" HD (720P) LCD TV [2], and embedding it into a wooden desk. A piece of EndLighten acrylic is placed on top of the screen and is lined with IR LEDs along all four sides. When a user places his or her finger on the acrylic, the IR light is reflected downward, through the screen, and captured via a camera below, as is shown in Figure 2. The cameras are connected directly to a computer, which is running two pieces of open-source software: Community Core Vision (CCV) which processes the camera for blob detection, and then Touch Injector which clicks on the

screen in the desired location..

Prior to deciding on using an LCD screen combined with IR LEDs, we had considered several alternatives. A projector would have fulfilled the same role as the LCD screen, however it would have eliminated all legroom underneath the desk. Instead of using IR LEDs, we considered using IR lasers. We chose not to use lasers, as the touch accuracy would not have been as high, since the lasers are shot out in straight lines while the LEDs diffuse in a fan-like pattern. Furthermore, the cost of the lasers and receivers would have used our entire budget, if not more.

Additionally, we considered using capacitive touch instead of IR reflection. Capacitive touch primarily comes in the form of surface capacitive touch or projected capacitive (PCAP) touch [3]. Surface capacitive touch was not a possible solution, as it does not allow for multi-touch. PCAP does allow for multi-touch. However, PCAP suffers from two flaws. PCAP does not scale well. This is a result of Indium Tin Oxide (ITO) being the most commonly used transparent conductive material. ITO has a relatively high resistivity. As the size of the touch sensor increases, the electrode length increases as well, resulting in an even higher resistance. This increase in resistance yields an increase in the RC time constant, concluding in a slower response time and poor sensor performance [3]. The second flaw for PCAP is the price of a sensor. The largest PCAP touch screen development kit that we could find was Reach Technology's 12.1" kit, which costs over $660 [4].

For those reasons, we have chosen to implement our design using the LCD Screen with IR LEDs. Figure 1 shows the block diagram of our proposed solution.

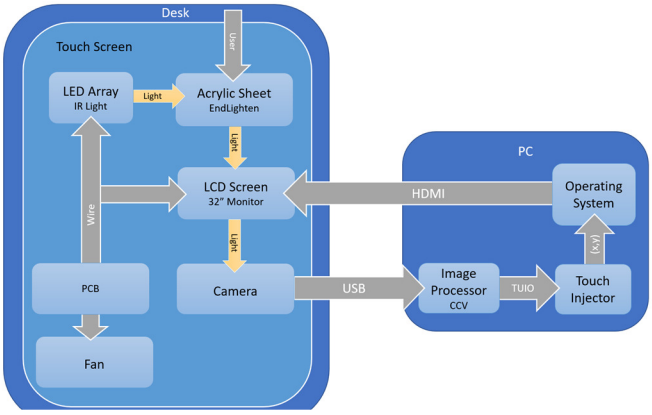

Figure 1: Block Diagram

B. Block 1: IR LEDs & EndLighten Acrylic

We reduce the cost of the touch screen by using IR light rather than a capacitive surface. IR light is used because it is invisible to the human eye [5]. Therefore, we can illuminate the entire screen of the desk without distracting the user. When the user touches their finger down on the surface of the desk, the IR light is reflected down through the screen where it is captured by the camera below.

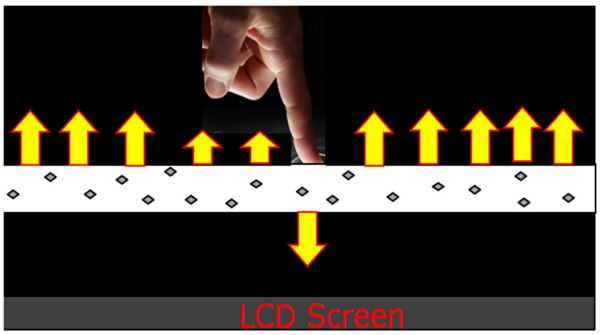

Figure 2: IR light reflected down by user's finger

To build this system we took advantage of ACRYLITE's product EndLighten acrylic [6]. This acrylic contains clear light-diffusing particles embedded inside the material which evenly emit light out of the top surface. We inject IR light into the sides of the material by using a thin IR LED strip. The injected light is evenly reflected out of the top surface of the acrylic. This process is shown in Figure 3. Also, EndLighten is a completely transparent and colorless material, making it ideal for our project.

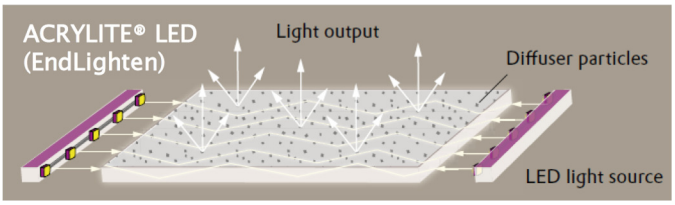

Figure 3: Light diffusion in EndLighten acrylic[6]

The IR light must reach all parts of the acrylic material to ensure the entire screen is illuminated. Otherwise, the touch screen would lose functionality in poorly illuminated areas. Looking at the EndLighten specifications [6], we chose to use the XL size sheet which is fully illuminated up to 48 inches when LED light is injected on every side of the sheet. We are using a 29" x 17" sheet of EndLighten to completely cover the LCD screen. Surrounding the acrylic on all sides with the IR LED strip also has the advantage of maximizing the screen illumination which will increase the SNR (signal-to-noise ratio) when capturing images of the IR light with our cameras.

This subsystem was implemented successfully as part of our MDR deliverables. Using an IR camera, we were able to confirm that the IR light was evenly distributed across the EndLighten material. When a finger was touched to the surface of the acrylic, IR light was reflected down towards the camera. This process was repeated for every part of the screen ensuring that the entire surface will have the ability to be converted to a touch screen.

C. Block 2: LCD Screen

The EndLighten acrylic sheet is placed on top of a modestly priced LCD screen to build the touch screen. The acrylic is transparent, so the user clearly sees the images displayed on the LCD screen. To embed the touch screen in the surface of the desk, the LCD screen must have its hardware components relocated.

We purchased the LCD screen [2] from Walmart to use in our design. The screen was housed in a plastic encasing that acts as a layer of protection and a stand. Inside this casing, there are three main hardware components: the screen controlling PCBs, LED backlighting, and a diffuser that will evenly disperse the light. These components are critical to screen functionality. The PCBs control the screen including the crystals that display the RGB colors and the volume and channel controls. The backlighting illuminates the screen, so that it can be viewed, and the brightness can be adjusted. The light diffusers evenly distribute light across the LCD screen, so the picture is undistorted.

To install the LCD screen inside the desk, we disassembled the plastic cover over the screen and carefully took out the hardware components. The PCBs controlling the screen and TV functions were attached to the screen by a ribbon cable. Due to the short length of this cable, the PCBs were moved from underneath the screen to just behind it at the back of the desk. We installed a ledge with a ground plane to house the PCBs. The PCBs are installed close enough to the LCD screen so that the ribbon cables are not stressed. The backlighting for the screen was relocated to farther underneath the screen along with the light diffuser layers. The wires connecting these components to the PCB were lengthened using wire connectors. The complete relocation of the screen components is shown in Figure 4.

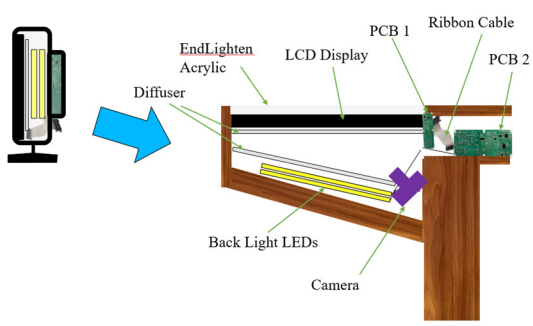

Figure 4: LCD screen hardware component relocation

This subsystem was successfully completed for our MDR deliverables. The screen was disassembled, and its parts relocated as shown in Figure 4. The screen maintained its functionality. We were able to test this by using the TV remote, sound system, and connecting the screen to a computer with an HDMI cable.

D. Block 3: Desk Structure

The technical block to be discussed in this section is the structure of the desk. Although this does not appear to be a "technical" block, it is extremely important in meeting our specifications. The primary goal of the desk is to ensure that the user will have sufficient leg room. To maintain functionality of a conventional desk, the user must be able to sit comfortably at the desk. With our proposed design, cameras must be placed below the LCD screen to capture IR-lit touch points from above. The cameras need sufficient field-of-view to cover the entirety of the screen. Using multiple cameras and concatenating their individual images prior to image processing is an option; however, concatenation is a time-costly operation which will be discussed in further detail in Section F. Consequently, our secondary goal with the design of the desk's structure is to minimize the number of cameras needed to lower the processing overhead and obtain the fastest possible response time. Our design options to be considered for the desk's structure are to have either a flat-bottomed or sloped enclosure for the cameras. Visualizations of these options can be seen in Figure 5.

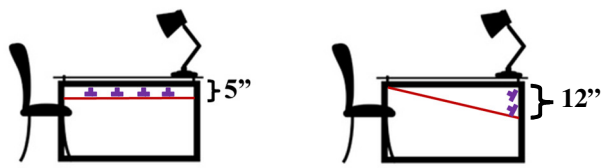

Figure 5: Flat Enclosure (Left) & Sloped Enclosure (Right)

For the flat-bottomed enclosure, we measured that it can be no more than 5 inches below the screen to maintain comfortable leg room. With this specification, we can calculate using simple trigonometry how much of the screen each camera will cover. The field-of-view of our selected camera, a PS EYE [7] with a 2.1mm wide angle lens, is 104°. Assuming the camera is about 1 inch in height, the lens of the camera is then 5" – 1" = 4" from the LCD screen. Figure 6 below clarifies the setup being considered for this calculation along with labeling specific quantities to be considered.

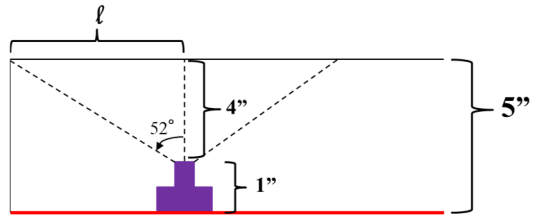

Figure 6: Diagram to determine field-of-view of one camera

The quantity labeled ℓ in Figure 6 is 5.12 inches; thus, the camera covers 10.24 inches in one direction. For simplicity of calculation, we will consider the camera having uniform coverage of 10.24" in all directions. The dimensions of the LCD screen are 28.25" length by 16.5" height; therefore, we would need 3 cameras to cover the length of the screen and 2 cameras to cover the height of the screen or a total of 6 cameras (3x2 array) for the flat-bottomed enclosure.

Next, we consider the sloped enclosure design as depicted in Figure 7. Through measurement and experimentation, we determined that the back-end of the slope can be no more than 13 inches down to maintain sufficient leg room. Knowing that the screen is 16.5" in height, we can calculate the interior angles of the slope. The setup for the subsequent calculations can be seen below in Figure 7.

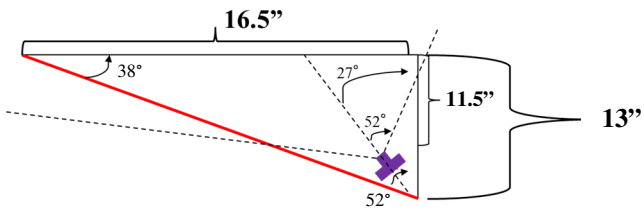

Figure 7: Diagram to determine field-of-view of one camera

If the camera sits in the slope’s angle of 52° with its normal at half of the angle, its 104° view angle will cover the entire height of the LCD screen with only one camera as shown in Figure 7. To determine how much of the length of the LCD screen that one camera will cover, we will perform a similar calculation to that completed for the flat-bottomed design. The camera now sits 11.5” down from the screen. The camera now covers 29.4” of the screen’s length. Since the screen is 28.25” in length, the one cameras will be sufficient for the sloped-enclosure. From these calculations, it appears to be an easy design decision to choose the sloped enclosure over the flat-bottomed enclosure to save both the cost of 5 cameras as well as the computational cost of extra concatenations; however, there is one more thing to be considered. With a sloped enclosure, the resolution distribution of the cameras becomes much less uniform. This will be discussed in the next section to conclude whether the sloped enclosure will function to meet our accuracy specifications.

E. Block 4: Camera Resolution

To meet the specification of fingertip accuracy, the resolution of the IR camera is critical. To reduce the number of cameras required to capture the entire space, the resolution of the cameras was affected. After researching camera resolution, it was determined that at least 2 pixels per centimeter would be required for a computer to detect and classify an object. To verify that the current design and camera configuration would meet the accuracy specification, a simulation in python was run to determine resolution distribution across the screen. The simulation was based on the set up seen in Figure 8 below, where the camera is at a distance viewing an object A.

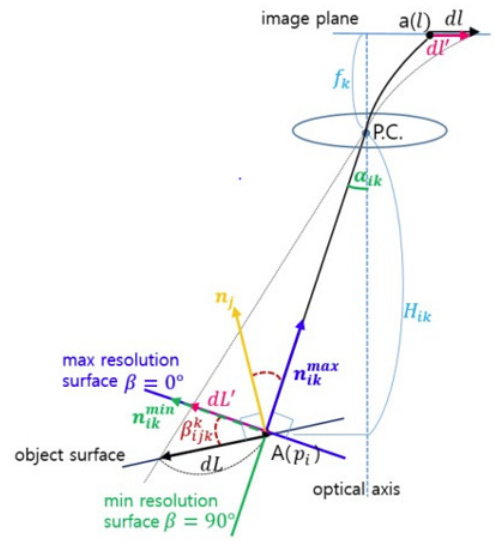

Figure 8: Configuration for Python Simulation [11]

The resolution is the ratio between the actual length of an object being viewed, dL, versus its projected length on the camera sensor plane, dl. The equation below was used in this simulation to calculate the resolution of an object being viewed at every position on the screen.

$$r = \frac{dl}{dL} = \frac{f\cos\left(\frac{\alpha}{2}\right)d\alpha\cos(\beta)}{dL\prime} = \frac{f\cos\left(\frac{\alpha}{2}\right)\cos(\beta)\cos(\alpha)}{H} \quad (1)$$

Equation (1) was derived using the arc length equation and written in terms of α, the angle between the optical axis and the object, β, the angle of the objects orientation from normal, and H, the distance of the object from the camera lens. Since the current solution uses a wide angled lens, a model for a wide camera was used, as seen in (2) where f is the focal length.

$$dl = f\cos\left(\frac{\alpha}{2}\right)d\alpha \quad (2)$$

Using Equation (1) and Equation (2), a python simulation was run to calculate the resolution at all points of the screen. After running the simulation, the areas closest to the camera have the highest resolution while the areas furthest from the camera has the lowest, as expected. The resolution distribution can be seen in Figure 9, where the camera is positioned at the back of the desk. The yellow areas represent the areas with the highest resolution, while the dark purple areas represent the areas with the lowest resolution.

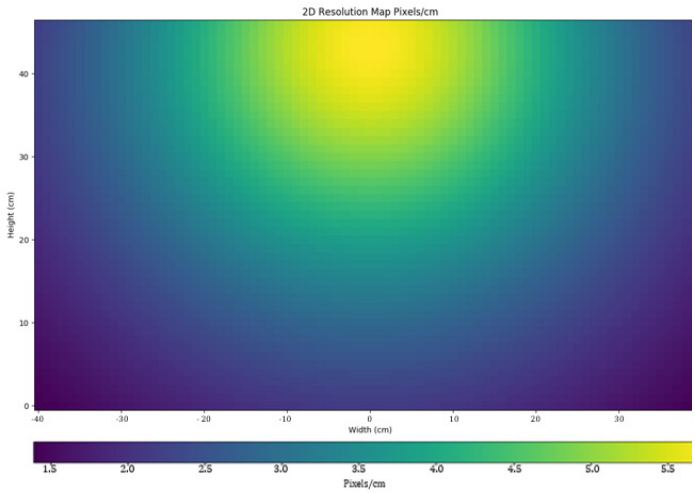

Figure 9: 2D Resolution Map

One consequence of the current configuration is the areas furthest from the user have the best resolution, whereas the areas directly in front of the user have the poorest. Since the majority of the activity, such as writing, will be done directly in front of the user, this could negatively affect the user experience. One can see, however, that this will not be an issue due to the fact that even the poorest resolution still meets the requirement of at least 2 pixels per centimeter.

F. Block 5: Image Processing

The image processing is handled on the connected computer. The camera with IR BPF is connected via USB, and the screen is connected via HDMI or VGA. We are leveraging two open-source programs: Community Core Vision (CCV) for the image processing, and Touch Injector for the mouse driver simulation [8].

When the screen is touched, a blob (or many) is visible from the camera, as shown in the bottom left of Figure 10 below. CCV passes that image through a series of filters, suchas background subtraction, smoothing filter, high pass filter, noise filter, and amplification, as shown in Figure 11. Following the amplification, each blob is assigned an ID, and the coordinates are calculated. A UDP message is then composed and sent to port 3333, where Touch Injector is listening. Touch Injector parses each message it receives at the desired port and translates it into a mouse click at the correct location. Figure 10 shows a detailed breakdown of this process.

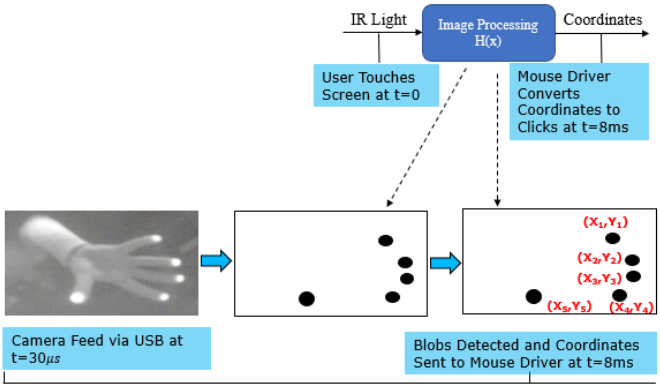

Figure 10: Breakdown of Image Processing

Community Core Vision was chosen for several reasons. The customization of filtration settings was paramount for the success of this image processing. Additionally, CCV is cross-platform, running on Mac, Windows, and Linux platforms. CCV contains a large number of parameters that are easily configured, such as minimum and maximum blob size.

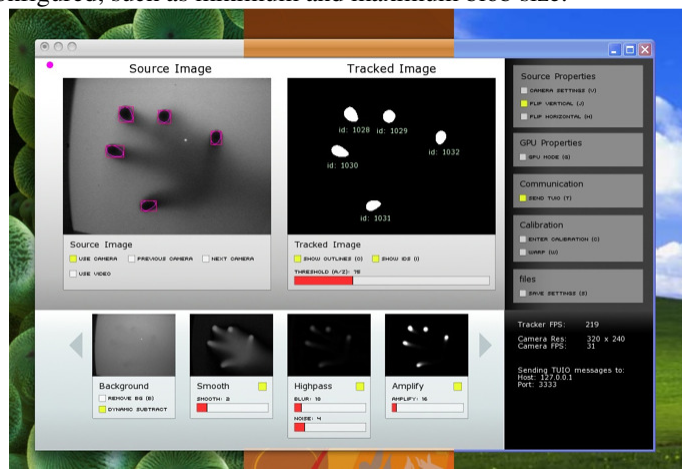

Figure 111: Community Core Vision

Furthermore, CCV's dynamic mesh calibration, shown in Figure 12 allows us to quickly create a series of calibration matrices for different users or distortions.

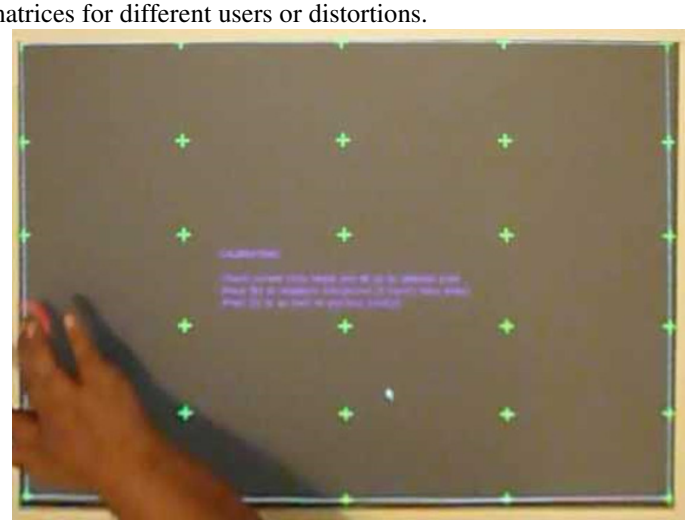

Figure 122: Dynamic Mesh Calibration of CCV

The UDP messages that CCV sends to Touch Injector are in a special Tangible User Interface Object (TUIO) format. TUIO is an open framework that defines a common protocol and API for tangible multitouch surfaces [8]. This protocol encodes control data from a tracker application (e.g. based on computer vision) and sends it to any client application that is capable of decoding the protocol. Touch Injector, shown in Figure 13, is a Windows 8/10 desktop application capable of just that. It generates Windows Touch events from incoming TUIO messages [8]. You can think of it as a virtual 'multi-touch driver', though it is technically not a driver.

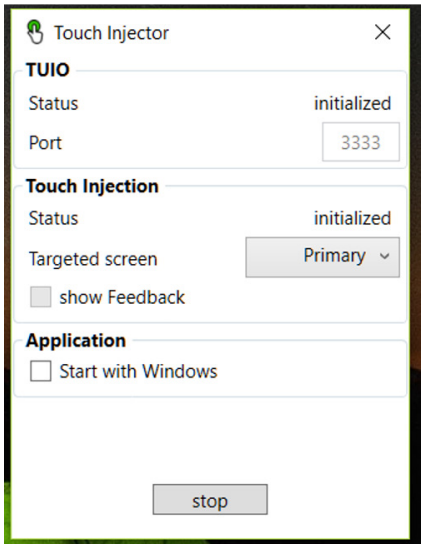

Figure 1313: Touch Injector

Our specification for responsiveness is less than 100ms. This benchmark was determined by considering the average human reaction time, which is displayed in Figure 14 below, which was created using over 55 million data samples [9].

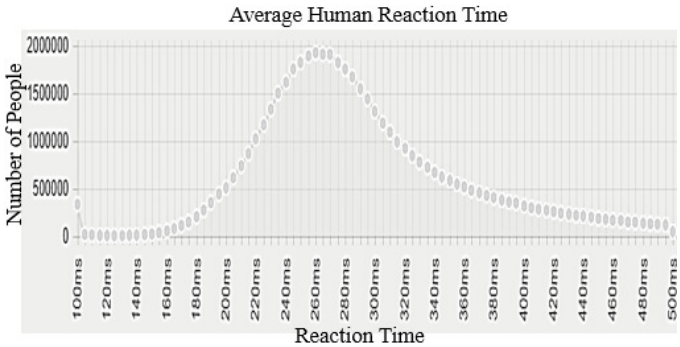

Figure 144: Average Human Reaction Time [9]

G. Block 6: Measured Response Time

To verify that the image processing from Block 5 meets the <100ms specification, thirty test points were taken. To measure the response time, a slow-motion camera recorded a video of the touch screen as a person clicked left and right on paint while also recording a stopwatch accurate up to a hundredth of a second. The start of the time interval began the moment the persons finger raised off the glass and the time interval was stopped once a dot appeared on the screen corresponding to a mouse click. Each sample was collected by reviewing the video frame by frame to determine the interval for each sample. Once the interval was established, the time from the stopwatch was used to record the latency of the image processing. Preforming this experiment thirty times, the following distribution can be seen in Figure 12.

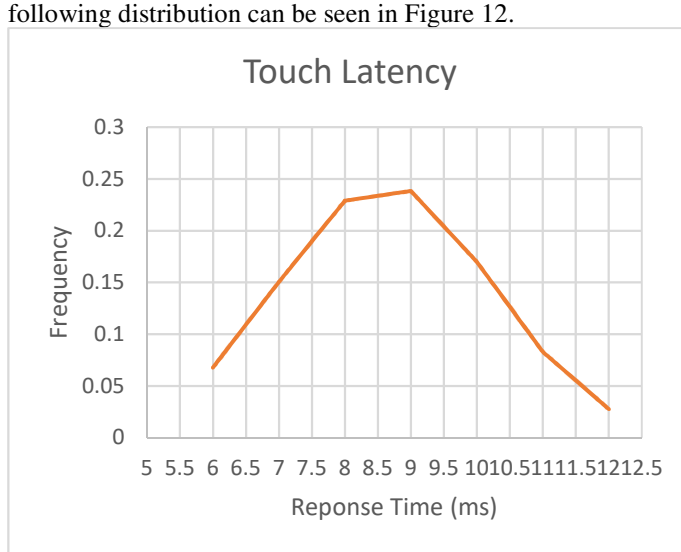

Figure 155: Touch Response Distribution

Figure 15 follows the curve of a normal distribution with an average response time of 8ms. This response time is over ten times faster than the worst case of 100ms need to meet the response time specification.

H. Block 7: Touch Accuracy Experiment

Due to the wide spread adoption of touch screens in everyday life, the average person is accustomed to pressing directly on an object on a screen and expecting the touch to be registered in that location. This is due to the majority of consumer touch screens use a thin capacitive screen that is embedded directly on top of the LCD screen. One of the drawbacks of using IR light to detect touch is the layer of glass that separates the screens surface from the LCD screen. This impacts the users experience due to the need of looking through a plane of glass to see the screen. This plane of glass also impacts the accuracy of the touch inputs. Issues arise when a user preforms the familiar action of pressing the screen directly on top of the object they would like to select. Due to the glass, the IR light does not reflect directly down from the fingers touch input, but at an angle. To cause even more augmentation of the input, a wide angled lens is used to capture the entire screen with one camera. This lens causes a fish eye effect around the edges of the desk, which adds further obstacles for image processing. Since this desk can be used from the sit down or standing position, the angle in which the light reflects varies according to several variables, such as height, position, and finger size. To test that the accuracy of a touch meets the specification of up to a fingertip, the touch inputs of several people were sampled. The experiment preformed had the test subjects choose the option to either sit or stand. Once selecting their testing position, they were asked to perform a simple grid calibration. Once the screen was calibrated for that test subject, they were asked to click on what they perceived to be the center of a target. Their click would leave a point on the target, which would be used to measure how far the point was from the center. This process was preformed ten times for each of the twenty test subjects. After all the data was collected, the

distance from the center in pixels was entered into Figure 13 below.

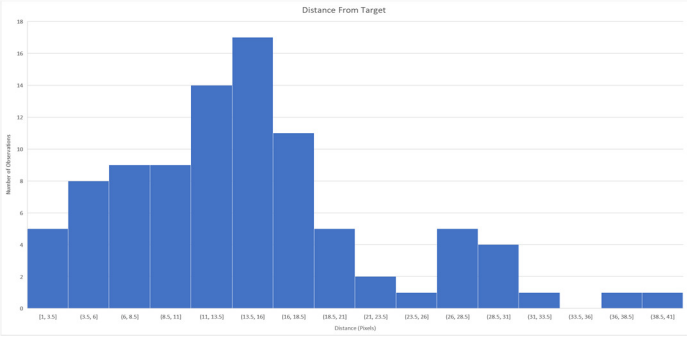

Figure 166: Touch Accuracy Experimental Results

From Figure 16, the graph can be fitted with a normal distribution with mean of 14.37 pixels and a standard deviation of 8.05 pixels. The small spikes in the graph away from the center of the curve are due to test subjects not understanding the experiment or rushing. Using this data, the average distance from the center is 14.37 pixels or 6.35 mm. This meets the specification of accuracy up to a finger tip since 6.35mm is roughly 15% the size of a fingertip.

I. Block 8: PCB for Temperature Control

Due to the electronics from the LCD screen and backlighting, heat in the vicinity of the user's legs has the potential to cause discomfort. In order to mitigate this, a temperature control system has been implemented. A temperature sensor that outputs an analog voltage proportional to the temperature is used as input to an ATMega32 microcontroller's analog to digital converter (ADC). The result of the ADC's conversion is compared to a threshold that is dynamically set to 3°F above the system temperature at boot-up. When the temperature exceeds the threshold, a high-leveled trigger is sent to an electromechanical relay which turns on a low-noise fan within the desk's enclosure. The fan stays on for a minimum of 3 minutes prior to reevaluating the temperature to ensure that cooling is sufficient. The control for this system has been integrated on a PCB and can be seen in Figure 17 below.

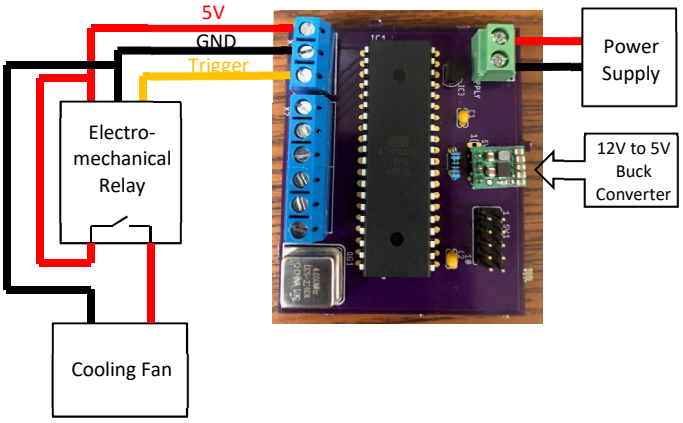

Figure 177: PCB Connections

II. Conclusion

The final SmartDesk design meets our desired specifications while also maintaining functionality as a conventional desk. The final design had high accuracy with a mean touch distance from a desired target empirically measured to be 6.35mm. The latency was well within the human reaction time and was measured to be 8ms. The unnoticeable delay between touch and response on the screen is the most impressive specification we met. Our screen has sufficient brightness and resolution. The 32" HD LCD screen is evenly and fully illuminated using multiple pairs of backlighting and diffuser layers. Our final design has a hidden cooling system with a fan that is automatically operated using a PCB and temperature sensor. With the backlighting, screen, and PCB our power consumption is a reasonable 110W, about the same as 2 incandescent bulbs. We managed to meet and exceed all our technical specifications while maintaining the durability of a standard desk. This is a result of our design using a relatively thick piece of EndLighten acrylic that is a durable and water-resistant surface.

While the final design of our project exceeded our goals and specifications, there is still room for improvement. If we were to create the SmartDesk again there are a few changes that we would make to the design. The spacing between the LCD screen and the acrylic could be reduced from ½" to ¼" or less to increase the overall accuracy. More powerful or multiple IR LED strips could be explored to increase the signal being picked up from the camera. Finally, the image processing can always be improved and worked on given time and change to the design. Even without these design improvements, SmartDesk successfully met all our technical specifications and can be used as a conventional desk to increase a user's productivity.

Acknowledgment

We thank Professor Siqueira, Professor Holcomb, and Professor Vouvakis for research advice and general technical support.

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