

OPTICAL BASED MULTI-TOUCH TABLE TOP

NOVEMBER 12, 2011

THE UNTOUCHABLES

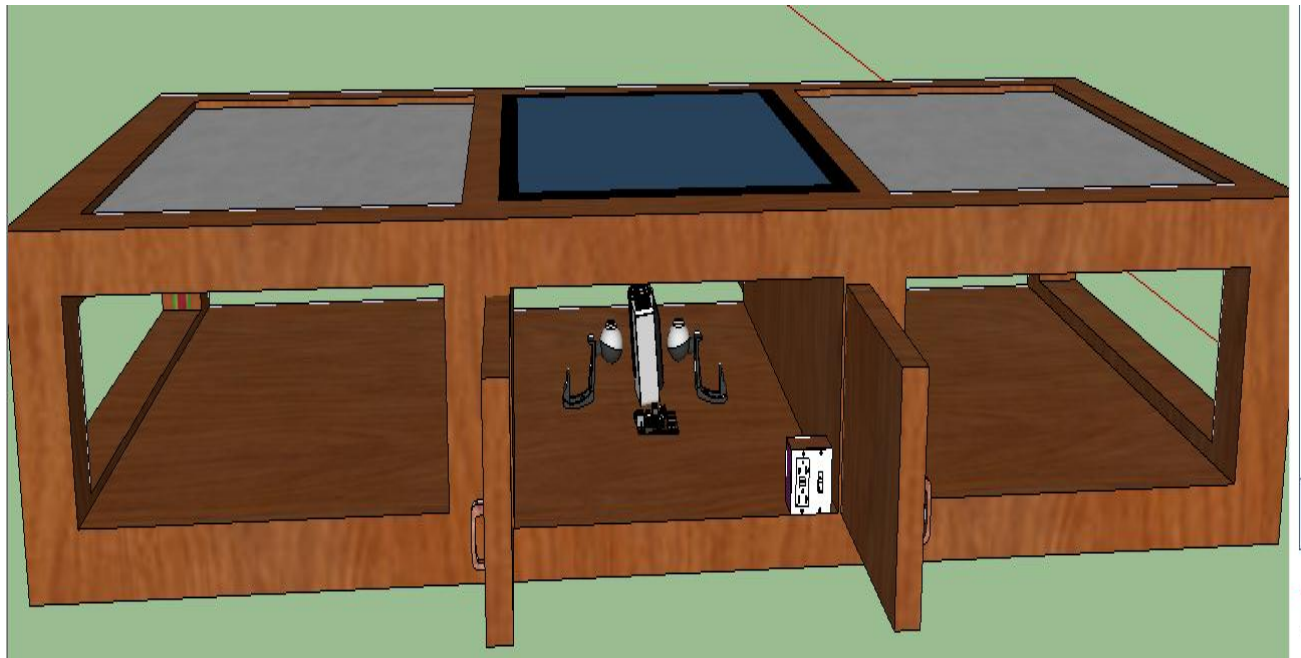
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Executive Summary

For engineering senior design class, *The Untouchables* team of electrical and computer engineering seniors will create a computer built into a two-by-four foot coffee table with a touch-screen interface, with usability similar to an iPad and the functionality of a desktop computer. The technology used for sensing touches is called frustrated total internal reflection (FTIR), where infrared light-emitting diodes (LEDs) send infrared light waves through a Plexiglas screen which reflect back and forth within it by total internal reflection, until a small amount of pressure is applied to the surface and frustrates it, allowing light to escape out the bottom. These waves are picked up by an infrared camera at 60 frames per second, and, using various image processing algorithms, they get interpreted as touch gestures. People can use this input to control the computer as a keyboard and mouse, or programs written specifically for this system can choose to use the camera's input in a more advanced way, such as to allow people to manipulate the screen from multiple locations at once.

The underlying computer system will be structured around a single-board computer such as a Beagle Board, which will contain a processor and other computer peripherals. The prototype's power will be within the range of a low-end PC in terms of memory and processor speed. It will also have USB ports available for additional input. The target market for this product is younger technology-inclined people with disposable income to spend on luxury items for their living rooms, so it will run on a standard North American power outlet. The prototype will cost approximately \$600 in materials; a mass-produced version would cost less for the materials in bulk, but it's likely that higher-quality parts would be used. The retail price external stores would sell it to is about \$1,100 to \$1,200; we would sell it to them at \$1,000, a profit margin which would allow us to break even within 3 years and about 1,600,000 units sold.

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1 INTRODUCTION

1.1 ENGINEERING 339 – SENIOR DESIGN

In this class we will learn the complete design process for a product. We will build and test a prototype of our coffee table touch-screen computer while also learning how to act in the engineering workplace effectively and ethically. This semester is focused more on planning and feasibility, but it does include a lot of time to work on the project itself. By the end of the semester we hope to have the parts ordered and put together so the second semester can be focused on adding features to the table.

1.2 TEAM BIOGRAPHY

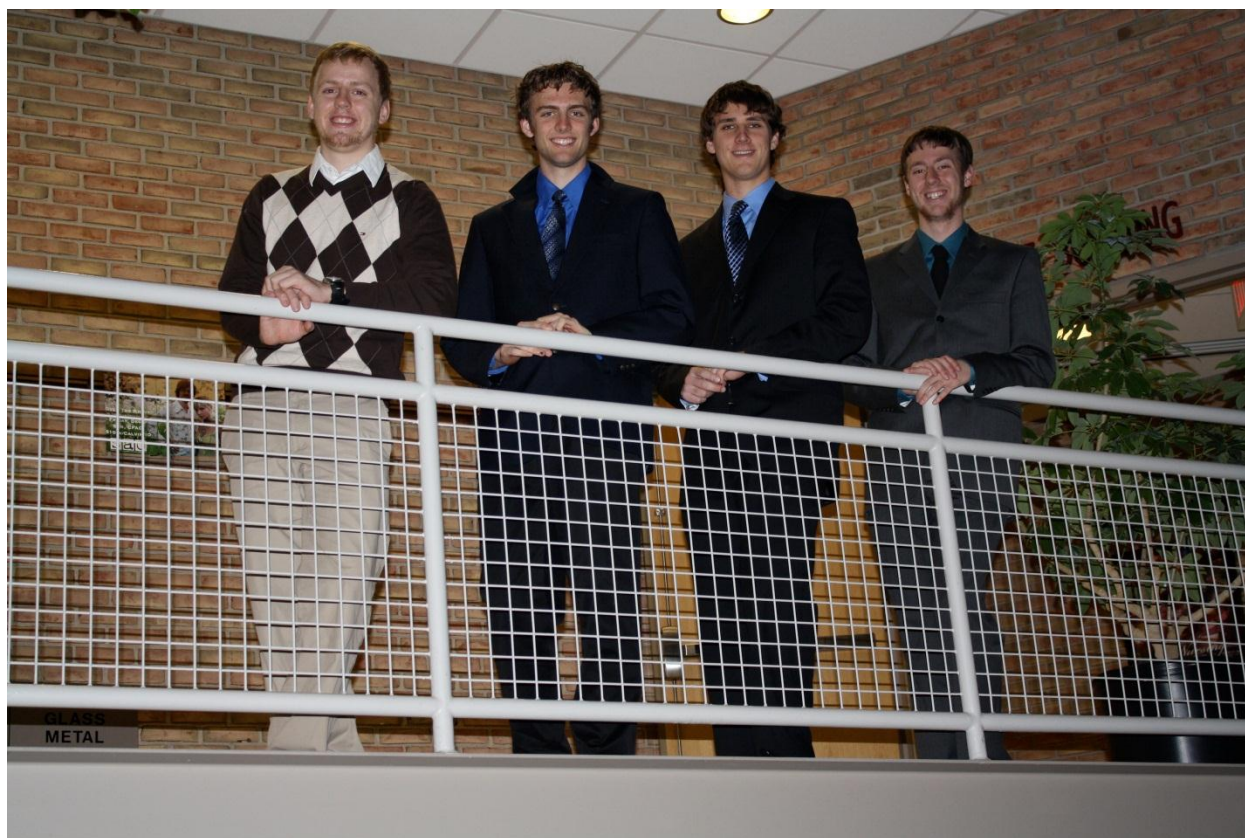


Figure 1: Left to Right: Michael Williams, Ed Smilde, Ben Lubbers, Nick Truer

1.2.1 BEN LUBBERS

I am a senior electrical and computer engineering student at Calvin College and am a member of the Untouchables design team. I have had two previous internships that have given me tools that I can use in creating and designing this project. I have interned at D.C. Cook Nuclear Power Plant and TRW Automotive the last two summers. At Cook Nuclear I worked on a modification project to the plant that required the powering of a crane from a nearby power source. It gave me good insight into what needs to be considered when powering certain tools and components. Some of these are breakers, wire mapping, and phase coordination. At TRW Automotive I did testing of software and learned how to locate and debug failures and unexpected results. I hope to use both of these experiences in helping me create this

project. My role reflects my previous experience by allowing me to be in charge of powering the entire system and help others by testing their components.

1.2.2 ED SMILDE

I am a senior engineering major with an electrical and computer concentration at Calvin College and member of the Untouchables design team. I am most interested in object-oriented programming and applied mathematics, the main experiences I will bring to the team. My role in the making of the touch table will be handling the image processing, which will involve algorithms using some numerical analysis of differential equations programmed in C++. I will be focused on the software on the machine, such as the operating system and drivers for the cameras and touch screen, and writing some useful libraries and demo applications to help showcase the power and usability of the device.

1.2.3 NICK TRUER

I am a senior engineering student with an electrical and computer concentration at Calvin College and a member of The Untouchables. I hope to bring my experience interning at both Twistthink and DornerWorks to help manage and lead our team through the project. At DornerWorks I was responsible for my own tasks on a project and I had customers that expected results by a certain timeframe and so I have experience working with a schedule and can make sure that The Untouchables will stay on task. I will be doing a lot of the overall concept design and work to schedule tasks and divide them up amongst the team.

My current role in the project is defining the optical design requirements and how we will meet these as a team. I began by researching various alternatives that can be used to produce our touch screen and then selected the appropriate one for our project. I will be continuing with the optical design through building and testing our touch screen and optics.

1.2.4 MICHAEL WILLIAMS

I am a senior engineering student with a concentration in electrical and computer engineering, and as a member of the Untouchables I would bring to the table interest and enthusiasm for designing the hardware of our touch table. My role in the team is to develop the core hardware system that will be running the touch system apparatus. After having built a computer as a hobby, developing this system will provide me with a plethora of learning opportunities to further understand the computing infrastructure.

1.3 PROJECT SELECTION – HOME ENTERTAINMENT

1.3.1 PROBLEM

The Untouchables team project is to build a multi-touch screen device to fit inside a coffee table. Functionally, it is similar to an iPad resting atop a table, but with a few more unique characteristics: anything applying pressure to the table can be read as a touch, so any combination of regions can be recognized as being “touched” at any point, which allows for a variety of inputs. The screen size will be 22” by 16”, and it will run everything you’d find on a personal computer. The need we’re hoping to fill is people looking for good home entertainment for their living rooms, a large target audience perhaps being young tech-savvy couples. For now this would still be a luxury item, but in the future, furniture with this kind of interactive technology built-in could be much more common. We are breaking into that potential market early, advancing interactive technology integration.

1.3.2 APPROACH

The touch screen built-in to the coffee table uses “Frustrated Total Internal Reflection” (FTIR). Pressure on different regions of the screen cause the infrared waves, which are bouncing around inside the screen (due to total internal reflection) to diffuse, escaping the screen out toward the camera. The image data from the camera is read at 30-60 frames per second (FPS) and processed to interpret the input, which can involve any complex set of regions on the touch screen. These are often interpreted as common keyboard and mouse movements, but they can be more advanced, such as a game of air hockey, where multiple different “cursors” need to be controlled. The visual output comes from a rear-projector which projects from underneath onto the screen.

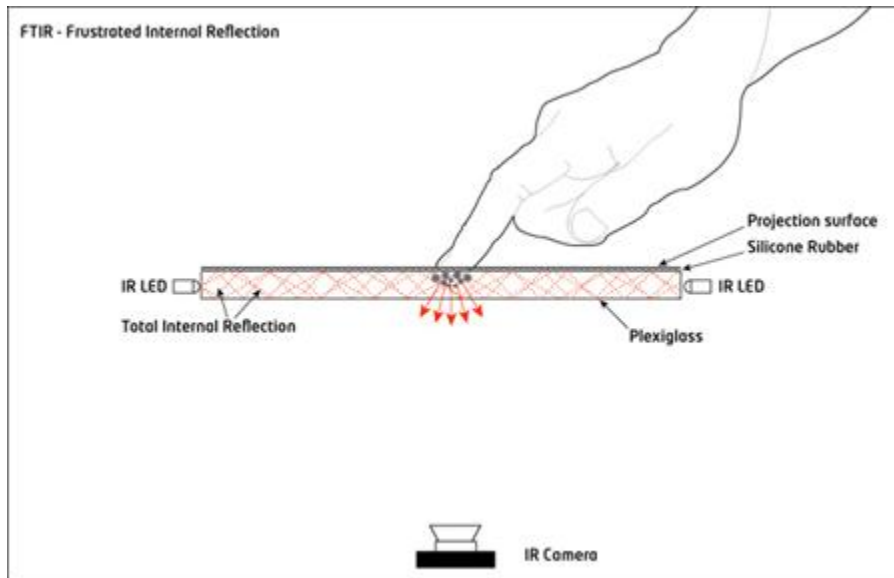


Figure 2: Frustrated Total Internal Reflection concept diagram



Figure 3: Concept drawing of our optical and hardware system

2 SYSTEM ARCHITECTURE

The Table of Content will be divided into three main sections: touch technology and optics, hardware, and software. These three sections will be aesthetically integrated together to create a computer platform that can be used for entertainment and development and is completely incorporated into a coffee table. Each section will be created, tested, and modified to keep cost-low, throughput high, and failures to a minimum. In Figure 4 below you can see our top level block diagram describing how the parts are defined and connected. Each component will need to be mechanically connected to the coffee table so that the optical system does not need to be recalibrated. We will not be in charge of the manufacturing of the coffee table but will work with a company to install our systems properly.

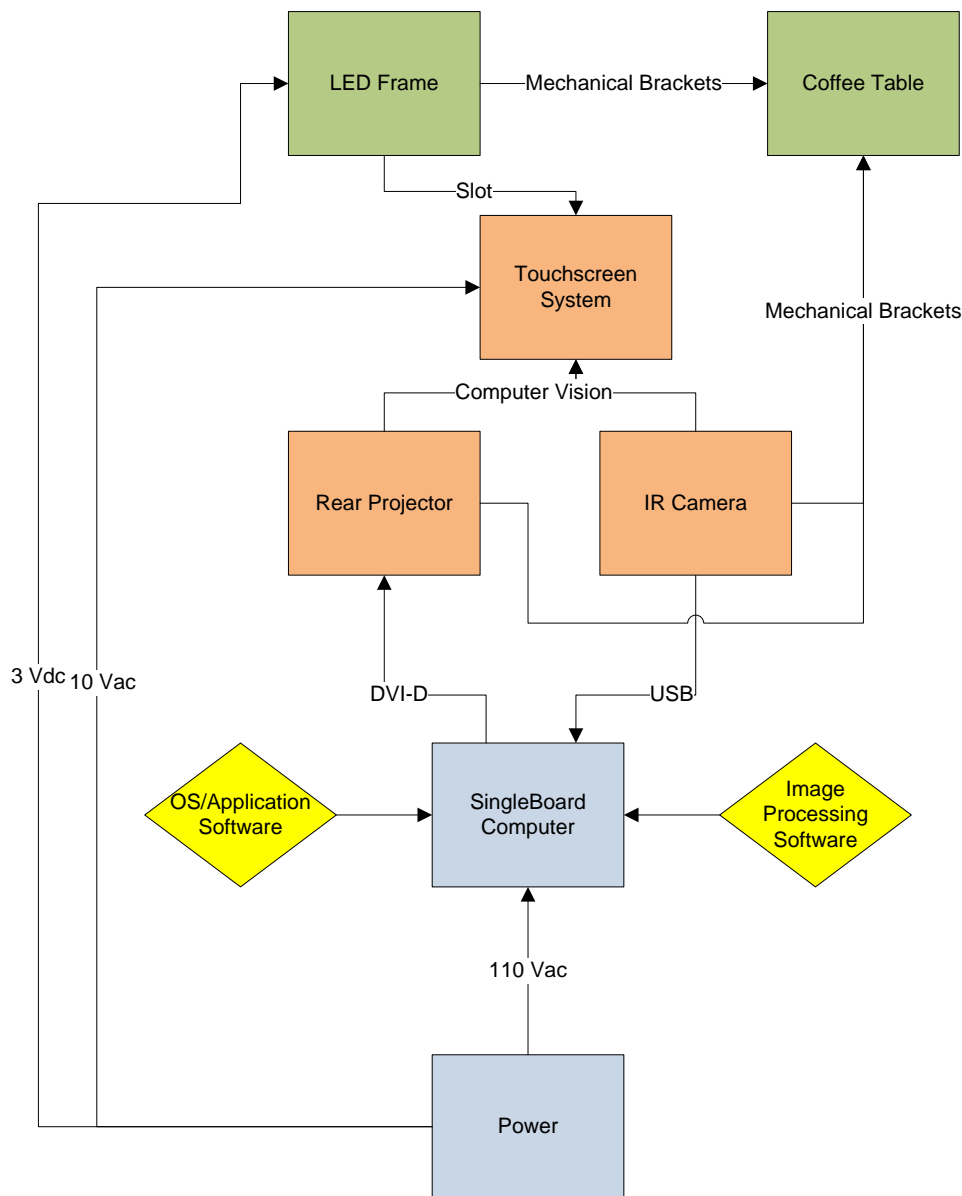


Figure 4: Top level block diagram showing integration of the three subsections and their interfaces.

2.1 TOUCH TECHNOLOGY

The optical system is important because it is the first thing clients will see, and the part they will interact with the most. The touch screen will have many layers constructed properly in order to create the correct effect for recognizing touches. Along with the layers the screen will also require a LED frame to provide the infra-red light that will be reflected and seen by the cameras.

IR cameras are the next part of the optical system. The camera will need to be able to take a picture of infra-red light when it is reflected in order to be sent over DVI-D to the video processing where it can be turned into coordinates. The last part of the operating system is the projector, which will receive data from the single board computer (SBC) by USB, will project an image on to the screen. It will need to project onto the entire screen so it may require mirrors and optical techniques to create the optimal screen size. The screen will have to be flush with the normal surface of the table with the LED frame positioned correctly. Underneath the screen the cameras and projectors must be positioned correctly to do their functions. These components must fit within the casing of the coffee table itself.

2.2 HARDWARE

The hardware components will also have to fit within the coffee table and will be in the form of a single board computer. It will provide the processing power for both the applications and the video processing. The operating system and memory will be part of the hardware system and supports the software running our platform. Hardware provided the backbone upon which the optical and software portions of our project run.

2.3 SOFTWARE

Software will be written in order to perform the desired functions for our prototype. The video processing software will take the video output from the cameras in the optical system and interpret them. The output will be coordinates of where the finger touch is. The video processing software will also be able to tell what a finger at that point on the screen means in the function of the program being written. Multiple touches at any given time will need to be tracked and deciphered. Software drivers will play a large part in the functionality of our product in that it will allow certain external peripherals to be used intuitively. As a computing platform we will also allow the customers to create their own software programs able to be run on our system.

2.4 EXTERNAL PERIPHERALS

Another goal of our team is to integrate external peripherals into our system for testing and convenience. A keyboard and a mouse are standard input devices for computers with our system they will not be the standard. Allowing these inputs opens our system up to a wider range of functions. It will also be an easier tool for testing specific functions of our system. Other important networking devices that we are looking to include in our possible input device list are Wi-Fi and blue-tooth. These would add to the luxury of our product giving the customer what they want and supplying them with so many more options of uses. Our single board computer will need to be able to connect to an internet card and other wireless communication receivers.

3 REQUIREMENTS

3.1 MECHANICAL SYSTEM

3.1.1 WEIGHT, SIZE, AND SHAPE

3.1.1.1 WEIGHT

Under the assumption that our average user can lift about 50 pounds, and that there will be two people to lift the product, we want our product to have a maximum weight of 100 pounds.

Since most of the lifting should be done with the legs (a much stronger muscle system when compared to lifting with the arms) this should be a reasonable weight for lifting.

3.1.1.2 SIZE

For our prototype the maximum dimensions of the screen are 22 inches by sixteen inches. After looking at the standard sizes of coffee tables available we have about 2 feet by 4 feet of surface area with 1.5 feet of height to work with. The entire system should fit within these confines of the coffee table, without having pieces of the system protruding. The table should be a natural fit in replacement of a similar usage coffee table.

3.1.1.3 SHAPE

We want to eliminate the chance of a user's hand running into a sharp edge while interacting with the table, minimizing the possible injury from our table. The surface of the coffee table should be completely smooth, without ridges or bumps where the touch screen joins the coffee table supporting structure, and the touch screen should function as a normal coffee table top would. We want the entire touch table to look like a coffee table, so that it can seamlessly take the place of a coffee table within the users home.

The touch surface will be flush with the surrounding coffee table surface. The shape of the coffee table will follow the standard convention of 4 legs, a lower shelf, and the table top above. The shelf will be where we set up the apparatus used for or multi-touch system.

3.1.2 TEMPERATURE RANGE

Any part that runs at a high enough temperature to present a danger to the user should be enclosed, ensuring no accidental contact will occur. As long as proper air flow is maintained the system heat buildup will be comparable to an average personal computer running.

The assumed normal ambient operating temperature for our system will be around 68° F, room temperature, with a running temperature that factors in heat created by the system. The acceptable temperature range for the running system will be from 32° up to 140° F (based on the range of temperatures limiting a typical single board computer¹).

3.1.3 DURABILITY

For load bearing our touch screen should be able to withstand the weight of coffee mugs, books, vases or a multitude of other commonplace items that could be placed onto a coffee table. The touch surface should be able to support someone propping their feet on the touch surface, but would not be expected to

¹ <http://www.ibase.com.tw/ib882.htm>

support the full weight of a person's body, should they choose to sit on the surface. While exposed to acceptable ranges of loads the touch screen should not start to permanently deform. Similar to these forces we should expect items being dropped onto our table, and, considering this fact, the surface should be resilient to these forces as well.

The load bearing capabilities of the touch screen will be sufficient for weights up to about 30 pounds; the touch table would not be accountable for any weights substantially over this. Also, items of 5 pounds or less dropped from heights up to 5 feet above the surface will not break the surface (with break defined as a shear crack going entirely through the surface from top to bottom).

Another condition that tests our table's durability will be the potential of spilled liquids. Drinks and vessels containing liquid will be set upon the table, and, inevitably, an accident will spill liquid upon the touch surface. Protecting the circuitry from the spill will be the first priority to ensure that the system will still function.

The hardware for the system will be encased in a water resistant casing, preventing liquids spilled from above the system from falling directly on the circuit board, projector, and camera. Additionally the touch screen and accompanying LED frame will provide a seal that will provide a first line of defense to stop the liquid from spreading systems critical for operation.

3.2 HARDWARE

3.2.1 POWER CONSUMPTION

While plugged into the outlet our system should maintain a sustainable current, realizing that the average breaker will only allow so many amps to be used at any one point and that our systems power usage will be added onto other appliances running at the same time. Our system should avoid using excessive amounts of power to limit the amount of current required to run.

Power for the system can be drawn from the average household 120 volt outlet. In order to maintain good stewardship of the current share available our system would have about 10 to 15 total amps available, and we would use no more than 1/5 of that amount for our system (with a conservative maximum of 2 amps for our system and an absolute maximum of 3 amps).

3.2.2 VOLTAGE RANGE

The intake voltage for the touch table will be 120 volts at 60 Hz, the standard available from traditional US household sockets. Internally voltages are reduced to the correct levels for running the hardware systems.

3.2.3 STATIC PROTECTION

In order to protect the system from static the board for our system should be grounded to some source capable of dissipating the charge. The housing for the hardware should provide sufficient shielding to ground any accidental static that the user might discharge on the system.

3.3 SOFTWARE

3.3.1 USER INTERFACE

A readily understandable operating system should encapsulate the entire software experience for the touch table. This will allow the user to manage and organize applications simply through the use of touches and gestures.

Touch recognition software will be able to recognize all of the following touches and gestures that could be used within the operating system: one-finger touch, two-finger touch, two-finger drag, two-finger pinch, and the two-finger flip (later defined in pointer controlling section of chapter 7: Image Processing Software).

3.3.2 TOUCH RESOLUTION

To avoid an undesirable user experience the touch resolution for the screen should be fine enough to distinguish individual fingers, even two fingers that are separated by a small gap that would seem comfortable to the user. Finger touch pattern size will vary from person to person, but a range for expectable touch sizes would be from 1/4 of an inch diameter (for children) to 3/4 inch diameter (adult). Smaller touch areas could be achieved by using writing instruments that would make a smaller imprint.

The system will be able to split the screen into 1/8 inch square sections. Contact patterns that exceed these bounds will be reduced to a point within these 1/8 inch bounds.

3.3.3 LATENCY

In order to create a fluid user experience our system will seek to minimize the response time between an action and the system processing that action. Poor response time will cause the. With applications like games response time becomes critical to the users experience. Keeping the response time unperceivable will allow the user to fully enjoy their experience.

The touch system will be able to respond with a maximum latency of 16ms. The human eye can perceive 60 frames per second. Converting this number to the amount of time a frame can be displayed gives us the 16ms of time, any longer and the human eye will notice the delay.

4 PROJECT MANAGEMENT

To manage the project we will be looking to create an organized structure, the foundation we will work within. Three key areas to define are: team organization, schedule, and milestones. Team organization will give each person a role. Team organization will give each role a timeline. The milestones will focus the timeline towards tangible results. With these structures in order we will have productive way to efficiently use time.

4.1 TEAM ORGANIZATION

Individual interests and group democratic procedures develop which roles individual group members are assigned. Team members volunteer for tasks that they are comfortable with and certain activities that fall outside of the group's interest are split up, trying to give each member a similar time commitment. Team Roles

4.1.1.1 HARDWARE

Michael spearheads the hardware section, overseeing the hardware selection. On items such as camera and projector Michael will work with Nick and Ben on picking the projector and camera for the system. Key to this category will be the interaction between all the parts of the system between processor, camera, and projector, ideally creating a system with minimal latency and maximum frames per second. Power for the hardware will be handled by Ben, accounting for the intake from the outlet to supplying the entire system with the proper power required.

4.1.1.2 SOFTWARE

Ed will be the primary developer for software. He will handle finding drivers, developing an operating system and pattern recognition software, for identifying touches. Both Nick and Ed will then oversee the creation of applications that will show the functionality of our table, accentuating the potential of multi-touch systems.

4.1.1.3 OPTICAL

Nick will be the lead for the optical portion of the system. He will formulate the approach for generating and receiving touch for the system. Along with Ben he will be involved in the construction of the screen, along with the LED framework that will encase the screen. Nick's role entails adjustments needed for the focal length of the system and any modification needed on the projector and camera, along with incorporating any mirrors or lenses needed for the system.

4.1.2 OUTSIDE ROLES AND HELP

4.1.2.1 DORNERWORKS

On October 5th we met with DornerWorks, where Nick interned for the summer, to discuss aspects of our project with engineers who worked on a similar optical touch project. By meeting with DornerWorks our team intended to better define the tasks that ahead of us. DornerWorks sought to give advice concerning design decisions we faced, and advise on tasks that might bottleneck our design process.

4.1.2.2 INDUSTRIAL CONSULTANT

We met with Tim Theriault for the industry consulting portion of our senior design class, on Thursday November 10th. During the meeting Mr. Theriault helped us clarify what type of scope our project would

have, and how to manage our resources efficiently in order to remain on schedule. His industrial experience shed light on how we should proceed with defining our project.

4.1.2.3 FACULTY

Steve VanderLeest advises our team, as a part of the senior design course. He concerns himself with the progress of our team, and helps us stay on task by requiring weekly status reports. As an advisor professor VanderLeest can be used as a resource for technical problems that may arise throughout the project. Professor VanderLeest provides an important role by giving feedback on the performance of the group as we progress through designing and constructing our project.

For help with selecting and ordering parts Bob DeKraker and Chuck Holwerda can be contacted for advice. Bob DeKracker directly oversees parts order forms, and Chuck Holwerda also has extensive technical knowledge on part specifications. These two can be referenced for help in hardware.

For the mechanical aspect of our project Phil Jasperse can be consulted to subsidize our lack of mechanical experience. For the physical arrangement and anchoring of the system his advice and knowledge of tooling procedure will prove valuable for improving our system.

4.2 SCHEDULE

Using organizational structures, such as a work breakdown schedule and Status reports, the team focuses on working toward meeting deadlines. By providing a timeline and scope for our project, the schedule enables a more efficient use of time.

4.2.1 WORK BREAKDOWN SCHEDULE

In order to organize our efforts on the project our team came up with a work breakdown schedule to schedule the time commitment required for individual aspects of the project. We broke down the task into four major sections: optical design, hardware design, System design and software design.

Optical design is further broken down into camera, projector, Touchscreen, and LED frame. Hardware Design is broken down into CPU, memory, video card, and system connection. Software Design is broken down into tasks relating to image processing, and programming. Then System design is broken down into tasks involving the integration and combination of the previous three systems (optical, hardware, and software). These major sections and their subsections then have the research, design, and construction components associated with them scheduled into expected time slots. Within this framework certain tasks are linked together as reliant, or performed in parallel when possible.

Along with tasks solely focused on the design work of the system we had additional sections for documentation and the business plan. These tasks were scheduled around due dates of events such as status reports (due every week) and presentations for our senior design class. This helped us realize deadlines that occurred along with the designing.

A copy of the work breakdown schedule document can be found on the status section of the team website: <http://www.calvin.edu/academic/engineering/2011-12-team4/?page=status>.

4.2.2 STATUS REPORT

For the duration of the project we will be giving weekly updates to our senior design team supervisor, professor VanderLeest. In order to keep track and record each weeks report, the team has set up a Google document to keep an ongoing documentation of weekly goals and progress. At this point in time the team has logged a total of 136 hour (as of 11/11), and will continue to keep track of hours spent on the project. To help facilitate the writing of the status report our team meets weekly to discuss the future direction for the upcoming week. Other than that each team member is expected to apply themselves each week toward the goals set out for the upcoming week, and is held responsible for having accomplished past goals set for the previous week.

4.3 MILESTONES

The end focus for our project will be to have completed the entire touch table system. Along the way we will be breaking down the components of the system into miniature systems that are testable as standalone parts. These milestones will provide components of the overall system, cataloging the overall progress.

4.3.1 OPTICAL

The first step toward producing the optical portion of the touch screen will be to construct the screen and then project an image onto the screen. This can be done outside the confines of our table dimensions at first; if the focal length turns out to be outside the foot of space we have available in the coffee table. The screen does not have to have infrared light running though the surface at this point, and no other electrical system needs to be running besides the projector.

For the first step in integrating the camera into our system, we must modify (if necessary) the filter for the camera to enable infrared light to be picked up. Once the camera can identify the frequency of infrared light the LEDs for the project emit, then the focal length of the camera must be found, to ensure the cleanest picture possible. At this point the screen should be used with the LED frame in place.

Once we establish that the screen can properly display and view the picture we will then begin adjusting the position of the projector and camera, via lenses or mirrors, so that the optical system will fit within the defined confines of our coffee table. Any alterations to the physical layout of the coffee table should be made at this time, and will provide future boundaries as to where hardware can be placed.

4.3.2 HARDWARE

For hardware the first step will be to start communication from a computer to the single board computer. Once we are able to communicate between the computer and single board computer, the next step will be to create or find (if the Linux operating system being developed by us is not yet operational) an operating system to run. Once running we can begin to connect the other peripherals to the board and begin interfacing. It is at this point that hardware and software will merge to complete the system, and making the software work on the hardware will be the primary goal.

4.3.3 SOFTWARE

Initial programs should start to identify patterns within images, and then map the coordinates of the. Starting off the images do not need to be representations of what images from the camera would be, but once infrared images from the camera are available to test the programming should focus on interpreting those images. Image tests should include images that simulate interference (desired finger touch patterns mixed with unwanted patterns, and faded touch images), which will more appropriately represent actual

image conditions coming from the camera. Future benchmarks will be to make the adapted Linux operating system, and drivers for the camera.

5 TOUCH TECHNOLOGY

The touch technology will affect the quality of the system, the cost of the system and many other aspects of our project. Therefore, we created a decision matrix that allowed us to rate each technology based on a series of qualities that were important to our specific project and also our product. This decision matrix led us to the technology that would best integrate itself into our project and our schedule.

We now have to decide how we will implement this technology and what material alternatives will be used. In order to integrate the touch screen into our product design without any issues there will be extensive testing performed using controlled scenarios. The testing of the optical portion of the design can be performed independently of the rest of the design. Therefore, we will validate the feasibility as well as effectiveness of the chosen technology for our project and also for our product.

This section will review which touch technology will be used for our design. It will go into details about the alternatives that were considered along with our criteria for deciding on a specific technology. After this it will go into more detail on how this decision was made and how we plan on using the chosen technology for our project.

5.1 DESIGN ALTERNATIVES

5.1.1 CAPACITIVE TOUCH

Capacitive touch is a technology being used in many different touch devices that are currently in production. For example, capacitive touch screens are used in many MP3 players, smart phones, tablet computing platforms, and even cars such as the new Ford Edge have a capacitive touch center console. Capacitive touch surfaces work well in small to medium sized applications like the ones listed above but begin to be much more demanding as the size of the touch surface increases. For this reason it is unlikely to see a capacitive touch surface in a cost effective multi-touch table system.

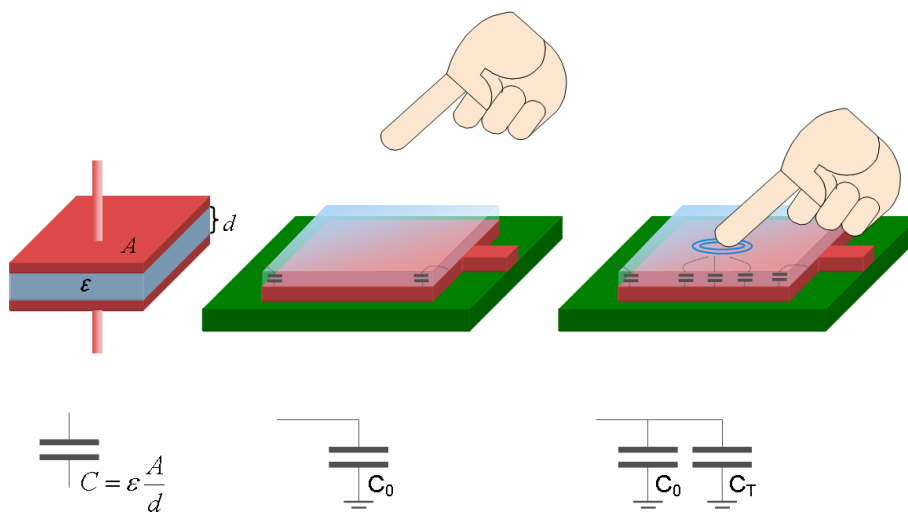


Figure 5: Functional diagram of a capacitive touch surface²

² <http://www.fujitsu.com/downloads/MICRO/fme/articles/fujitsu-whitepaper-capacitive-touch-sensors.pdf>

Figure 5 shows that capacitive touch screens operate by using the electrical properties of a person's hand. By placing your fingertip or hand on the screen you will change the overall capacitance as seen by an observing sensor. In order to do this there has to be a transparent conductor layer such as indium tin oxide on an LCD screen which will sense the electrical properties of human contact. An indium tin oxide surface produces a specific electrostatic field that is disrupted by the electrical conductivity of the human body.³

5.1.2 RESISTIVE TOUCH

Resistive touchscreens are another method of producing a multi-touch interface. Resistive touch surfaces consist of two resistive surfaces which are separated by an air gap created by microdots. Microdots are spacers that are attached to one of the resistive surfaces in order to prevent conduction when no touch is present. When pressure is made between two of the separate microdots there is a conductive connection between the two which creates a voltage drop. Using the principles of a resistive voltage divider it is possible to calculate both the X and Y coordinate of the touch location. Figure 6 shows how this resistive concept is created as a physical screen and how touching it interfaces with it.⁴

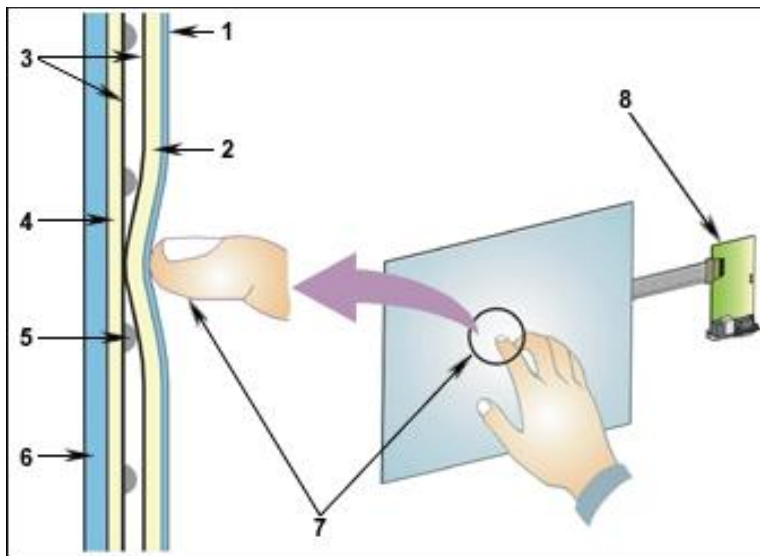


Figure 6: Functional diagram of a resistive touch screen⁵

Resistive touchscreens are actuated by small amounts of pressure creating a connection between the two resistive surfaces and for this reason it is possible to use objects besides a fingertip to interface with the screen. It is also possible to measure the resistances of multiple touch inputs however with a larger screen there is going to be a higher amount of resistance and it becomes difficult to calculate the exact location. Due to the density required of resistive surfaces it is also expensive to implement large scale screens. The resistive material required for this type of touch screen will negatively impact the picture quality by creating a darker image with less contrast.

5.1.3 REAR DIFFUSED ILLUMINATION

³ <http://electronicdesign.com/article/components/please-touch-explore-the-evolving-world-of-touchsc.aspx>

⁴ http://courses.engr.illinois.edu/ece317/presentations/Touch_Screen_Pres.pdf

⁵ <http://freddywal.tripod.com/touch-screen-resistive-tech2.jpg>

It is also possible to use an optical based system in order to interpret touches on the screen itself. Rear Diffused Illumination (Rear DI) is an optical based touch system that relies on infrared light along with an infrared sensitive camera in order to pick up various touches. Rear DI is a common choice among the New User Interface (NUI) community when building your own touchscreen. This is due to the simplicity of building the physical screen required for picking up touches.

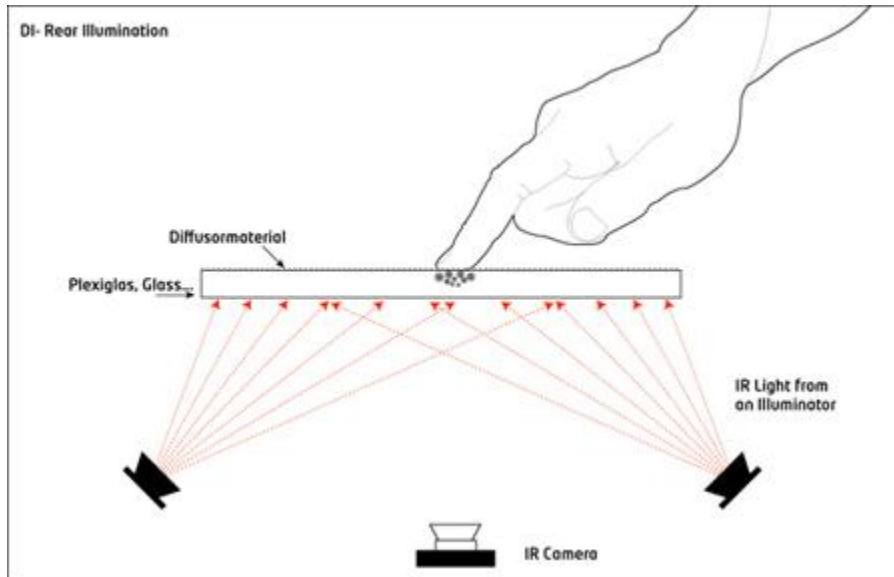


Figure 7: Functional diagram of rear diffused illumination⁶

A rear DI system uses an acrylic surface as its primary medium for touching. There needs to be a source of infrared light on the back side of the touchscreen that can then be reflected back at the infrared camera in order to identify touches. Since all of the infrared light is passing through the acrylic surface, both the diffusing surface and background will be partially reflected back to the infrared camera. When something touches the surface there will be more infrared light reflected back than the surrounding background, which can be identified as a touch. However, due to the fact that you can reflect light from anything on the opposing side of the touchscreen it is possible to set up a system that can identify hands hovering slightly above the surface. However, this versatility has a drawback in the contrast of the touch events or hovering actions because some infrared light is reflected by the background as well.⁷

⁶ <http://wiki.nuigroup.com/images/a/a0/Rearditouch.jpg>

⁷ http://wiki.nuigroup.com/Diffused_Illumination



Figure 8: Typical Rear DI infrared image⁸

5.1.4 FRUSTRATED TOTAL INTERNAL REFLECTION

Frustrated Total Internal Reflection (FTIR) is another optical-based multi-touch technology. Using an infrared sensitive camera it is possible to sense the light that is being reflected out of the bottom of the surface. An FTIR based touch system relies on the optical properties of both the screen and also as a method of identifying touches from the surface. This requires an optical system design to be in place that allows the camera and projector to view the entire touchscreen. Frustrated total internal reflection is a common technology in larger touchscreen devices such as multi-touch tables.

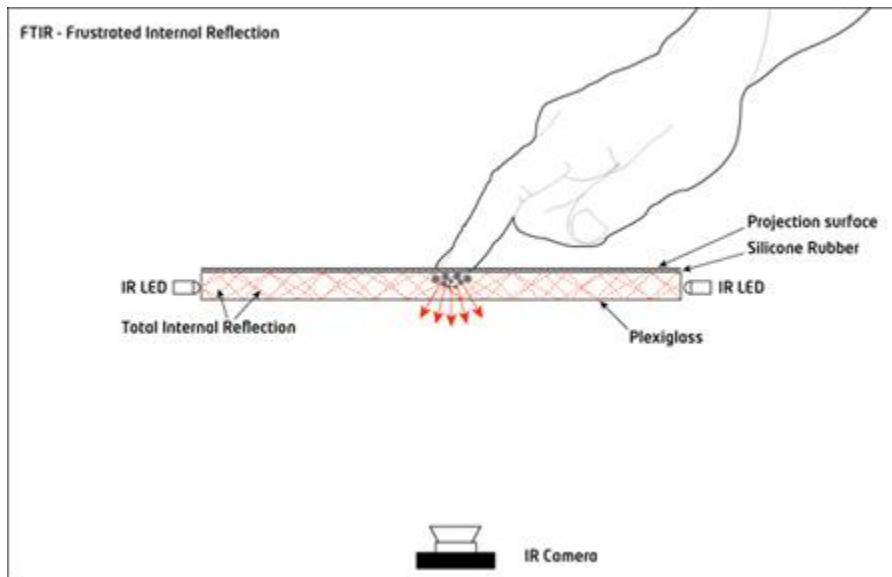


Figure 9: Functional diagram of an FTIR touch screen⁹

⁸ <http://wiki.nuigroup.com/images/3/3c/Reardigraphic.jpg>

⁹ <http://wiki.nuigroup.com/images/f/f7/Ftir.jpg>

Figure 9 shows the makeup of the screen as a whole and how this specific composition allows us to use this screen as an environment for producing touch events. The first layer of the screen is the acrylic and this layer is essential for any FTIR based touch screen. The FTIR screen relies heavily on the properties of light reflecting or refracting on a glass surface. Due to the boundary between the glass edge and the air around it any light that hits the glass at an angle larger than its critical angle will be 100% reflected and none will pass through. Using this optical principle it is possible to shine infrared LEDs into the sides of an acrylic and produce a system of total internal reflection and essentially flood the acrylic with infrared light waiting to be used.¹⁰

The next layer that is shown in Figure 9 is the silicon rubber layer which is also known as the compliant surface. The purpose of the compliant surface is to frustrate or interfere with the total internal reflection. By applying any pressure to the touchscreen the compliant surface will change the boundary between the acrylic and air causing refraction to occur and allow the light to exit the bottom of the acrylic surface. Once the infrared light is frustrated and allowed to exit through the bottom of the acrylic it is possible to use the infrared camera to identify finger touches, or other touches. Due to the compliant surface and principle of total internal reflection the FTIR system produces precise and bright touches that are easy to identify.

The final layer that is required for an FTIR system is some sort of projection surface or diffuser. The projection diffuser is any type of material that diffuses the light and does not allow it to completely pass through it. Many drafting papers, vellums, or clear plastics such as mylar can be used as a projection diffuser. The projection diffuser is the portion of the touchscreen that receives the image from a rear-projector and allows the user to see it and interact with it.

5.2 TOUCHSCREEN DESIGN CRITERIA

This purpose of this section is to discuss our chosen design criteria that will be applied to the discussed touchscreen technologies. These design criteria are meant to represent what is important to our specific project in terms of the touch technology. In the following sub-sections we will discuss what each criteria means in terms of the touch technologies considered.

5.2.1 PRACTICALITY

Practicality is defined as the applicability of the touch technology to our project and our purposes. In deciding between the major touch technologies this is the highest priority criteria. The reason that this is of high priority is because if a touch technology recognizes touches quickly and cost effectively but interferes with the desired user experience of our system then it should not be considered.

Front diffused illumination is an example of this. Although front DI is competitive in many respects to the other technologies it is not practical to put infrared LEDs over the top of the touch surface and use shadows to identify touches because the technology itself is in the way of the interface.

5.2.2 ROBUSTNESS

When defining robustness in terms of the differing touch technologies it has to do with the capability of picking up varying touches. A more robust system will be able to pick up touches with varying pressure,

¹⁰ <http://wiki.nuigroup.com/FTIR>

size, and contact material. The most robust systems can also pick up hovering objects that are not even touching the surface.

Frustrated total internal reflection is able to pick up touches of varying pressures, sizes, and also materials. Capacitive touch surfaces require a conductive point of contact (i.e. human fingertips) and will not work through contact with an electrically insulated point of contact (i.e. thick gloves). Optical based systems are able to respond to pressure on the screen regardless of the material making them a more robust system.

5.2.3 COST

Cost is an important criterion when deciding which touch technology to use in our prototype and product. When designing the multi-touch table the cost of the overall system has to be considered for two main reasons. The first reason being that there is an inherent market value on every product and consumers will not pay any more than this value. The second reason is that we have a limited budget that drives how much we can spend on each sub-system.

5.2.4 CONTRAST

Contrast is another driving criterion when choosing a touch technology because contrast directly relates to the complexity of identifying touches. For optical based systems contrast is defined in the same way that it is defined for a picture or image. Contrast is a measure of the difference between light and dark, or white and black. The higher the contrast is the easier it is to identify the difference between an actual touch location and a light spot from a source of disturbance or interference.

For the two passive technologies that respond electrically to contact with the surface from an outside source contrast would be defined as the difference in touching one location and an adjacent location. This directly affects the complexity of the software required to decode a touch and is how we can apply a “contrast” amount to both optical and passive technologies.

5.2.5 ACCURACY

Accuracy of a touch technology is defined by how close the identified touch is with the actual touch. Most of this can be accomplished through the software that identifies the touch and it is possible to use more computing power to improve the accuracy of the system. However, things like blurred or partially reflected images could be misinterpreted as a touch. For this reason a system could produce a false touch and become harder to interact with. Systems with the infrared LEDs external to the screen will produce more difficult images to process and therefore a less accurate system.

5.2.6 PERFORMANCE

Performance in terms of the touch technology is derived from both the frame-rate that is possible through each system and also the latency of the system. Frame-rate is the number of full image frames that can be processed and output to the screen per second. Latency is defined as the time from when the user touches the screen to when the system responds visually.

Although the system as a whole is governing the performance, it is possible for certain touch technologies to limit this performance. With the optical technologies it is important to use a camera that is able to provide a high Frames per Second (FPS) and then the system must keep up. It is possible to optimize performance by ensuring simple and fast image processing software.

5.2.7 SIMPLICITY

When rating the touch technologies on their simplicity we had decided to focus on the physical simplicity of the screen and system as opposed to the touch identification software. The complexity of the software required to decode a touch event is already considered through the contrast and performance criteria. When considering the simplicity of the touch technology we looked at what was required for creating the screen and what hardware was required for the system.

For example, the FTIR system requires a more complicated screen composition in order to identify touches from a surface flooded with infrared light. The rear and front DI systems require less in terms of screen composition and therefore are easier to implement. For capacitive and resistive touch screens there is an extra layer to a typical LCD screen which would require special hardware to connect with.

5.2.8 PICTURE QUALITY

The picture quality of our system is directly related to the resolution of the image being presented to the consumer. However, all considered technologies can provide varying picture qualities. With the passive touch technologies you can improve the resolution of your LCD and with the optical technologies you can improve the resolution of your projector. For comparing touch technologies we looked at any ways that the specific technology would limit or prevent the picture quality from improving.

5.3 DESIGN DECISION

Table 1: Decision matrix of the various touch technologies available

Touch Screen Technology Decision Matrix	Priority	Optical Technologies			Passive Technologies	
		FTIR	Rear DI	Front DI	Capacitive Touch	Resistive Touch
Practicality	8	6	4	1	7	6
Robustness	7	6	7	4	5	5
Cost	6	8	8	8	2	3
Contrast	6	9	5	4	8	8
Accuracy	5	7	5	3	8	7
Performance	4	6	4	4	7	8
Simplicity	3	4	6	6	4	4
Picture Quality	3	7	7	6	10	6
Total		284	239	175	261	246

Table 1 shows a decision matrix that was used in order to reinforce our research and decision with which touch technology to use. The decision matrix points to us using an FTIR based touch system which is one of the optical technologies. FTIR is a strong choice for our project because it consistently scores well with the criteria we used to compare technologies.

Based on our criteria we can see major drawbacks in many of the technologies that were considered for our project. Front DI scored very poorly in practicality because it would require LEDs to be placed above the screen. This would interfere with actually using the screen itself.

Rear DI was also considered as an option for our touch technology. However, Table 1 shows that for the purpose of our project Rear DI was less applicable than FTIR. The main advantage of using a Rear DI touch technology is that it can be considered more robust than FTIR because contact with the actual surface is not required to create IR reflection. However, the scope of our project is to identify contact with the surface itself and for this FTIR is more finely tuned. It provides better contrast, accuracy, and therefore performance.

Resistive touch falls under a similar category as Rear DI. Although it was considered for our project it research has shown that a resistive touch screen is very similar to a capacitive touch screen. Resistive touch screens are slightly cheaper than capacitive making it more applicable to our project; however, large high density resistive screens are still expensive when comparing with the other technologies.

5.3.1 FTIR COMPARED WITH CAPACITIVE

Capacitive touchscreens scored the next highest in our decision matrix. A major drawback when creating a system based on capacitive touchscreens is the cost associated with the screen. In smaller products, 3.5-9.7 inch diagonal, it is more feasible to implement a capacitive screen due to lower cost. For these devices it is also impossible to fit the required optical system in the device itself which limits the possibilities for producing the screen.

However, for our project we found that it is possible to fit an optical-based touchscreen into our system. This allows us to save money on the screen itself allowing for more to be spent on other portions of the project while still remaining within our budget. Through research we also found that an FTIR system can perform competitively with a capacitive touch system because of its high touch contrast. This high contrast makes the image processing software required less complex.

This allows us to focus on providing good latency from the user input to the system response. With careful consideration for the components used with the FTIR system we are able to limit the latency between user inputs and system response. This can provide similar results to a capacitive touchscreen while limiting the cost required. For these reasons we chose to use an FTIR touchscreen rather than a capacitive touchscreen.

5.3.2 MATERIAL ALTERNATIVES

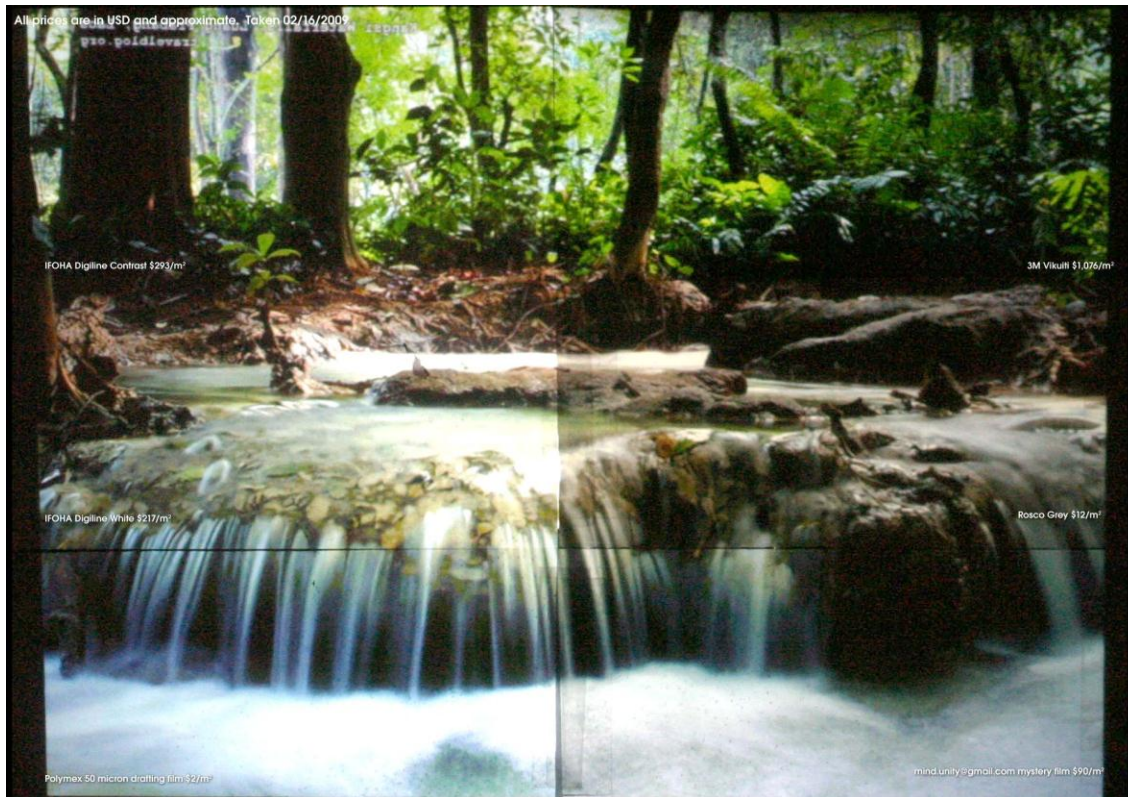


Figure 10: Comparison of various Projection Diffusers¹¹

The market currently offers alternatives for projection diffusers that can affect the picture quality of our system. Figure 10 shows six different projection diffusers that can be used to produce the FTIR touchscreen. For The Untouchables and our prototype it is important to look at the cost associated for each material. The prices ranged from \$2 - \$1076 per square meter. We considered projection diffusers that are less than \$50 per square meter. This left only the Drafting Film and Rosco Grey materials. Figure 10 shows that the brightness and contrast of the Rosco Grey is worse than that of the Drafting Film while also costing more.

¹¹ http://nuiigroup.com/?ACT=28&fid=37&aid=2596_pgcBjhy3fB20pWodYSv4

5.4 BUILDING THE SCREEN

This section will discuss the different portions of construction the physical touchscreen that we will be constructing for our prototype. The two categories of construction are the screen and the LED frame. It will also analyze the cost of implementing the touch technology component of our project for use in the prototype budget.

5.4.1 SCREEN CONSTRUCTION

The Untouchables decided to save in parts and prototype cost by building our own FTIR touchscreen. The method that was settled on for this is called the Tinkerman method and the most important part is how you apply the compliant surface (silicon rubber) to the acrylic in a way that effectively actuates the IR touches. The way that Tinkerman decided to do this is by mixing the silicon with xylol, paint thinner, to form a liquid substance that could easily be spread using a paint roller. After thirty minutes to an hour the Xylol will cure out of the liquid leaving a thin layer of silicon rubber that allows for touches. This silicon and Xylol mixture is typically applied to the projection diffuser in order to preserve the quality of the rubber.¹²

5.4.2 LED FRAME CONSTRUCTION

Constructing the LED frame that is required for creating introducing the infrared light into our system will require two different designs. We will have to design the mechanical design of the frame and how this will connect with our touchscreen and also with our coffee table. We will also have to consider the electrical circuit design and soldering required for creating this circuit.

5.4.2.1 MECHANICAL CONSTRUCTION

The mechanical construction of the LED frame will be made out of either wood or metal. We will be constructing a frame with holes in it to hold the LEDs in which the acrylic sheet will slide into. We will decide on an optimum LED distance from the acrylic sheet and position the sheet accordingly. This LED frame will be fastened to the coffee table from the bottom to ensure a steady connection.

The recommended distance between LEDs for sufficient IR light is one LED per inch of acrylic. However, since we are shining IR light from all four sides of the acrylic we will be placing an LED every two inches with opposite sides offset by one inch. Our acrylic will be 22" by 16" and therefore require 11 LEDs on two sides and 8 on the other two. This will be the nominal LED density to be tested.

5.4.2.2 ELECTRICAL CONSTRUCTION

The electrical circuit will be wired together based on the schematic shown in Figure 11. We are choosing to wire up the LEDs in parallel in order to prevent all of them from dying if one LED is burnt out. By wiring up the LEDs in parallel it will also require a lower voltage in order to turn on all of the LEDs in order to limit our power consumption.

¹² <http://nuigroup.com/forums/viewthread/2383/>

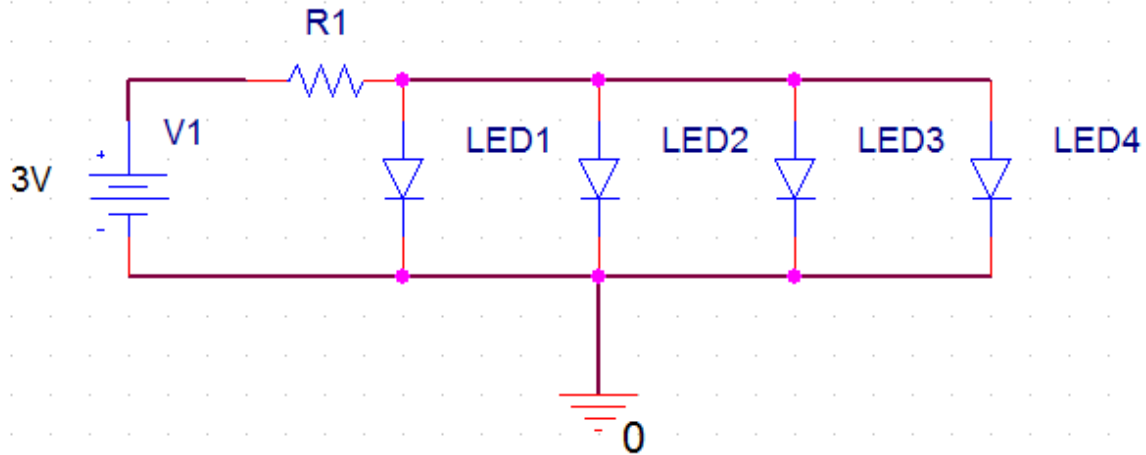


Figure 11: Electrical schematic of our LED circuit

5.4.3 COST ANALYSIS

Table 2: Cost of the Touch Screen

Item	Quantity	Unit Cost	Total Cost
Acrylic/Plexiglass	1	\$48.00	\$48.00
Infrared LEDs	38	\$0.35	\$13.30
Frame Material	1	\$10.00	\$10.00
Silicon Rubber	1	\$6.31	\$6.31
Xylol (Solvent)	1	\$5.07	\$5.07
Projector Diffuser	1	\$5.00	\$5.00
Total for Touch Screen	1	\$84.18	\$87.68

After selecting the appropriate materials for building our touchscreen it was necessary to identify vendors and suppliers of these materials for the budget. The touchscreen itself is roughly one sixth of our entire prototype budget and for this reason it was important to identify the best cost for performance materials to use in constructing the screen. In order to potentially save some money we decided to construct our own screen out of the various materials and layers that are used instead of buying one from a company that potentially already makes touchscreens as they would charge extra for their time and effort. Using a bit of our own effort we are able to save some money to use elsewhere.

The majority of the cost of the touch screen comes from the acrylic layer and so a lot of time was spent comparing prices from various vendors to find the cheapest sheet. For the size we wanted, prices would range from as low as \$48 to as high as \$70. The difference in the cost of the acrylic is due to the durability of the individual sheets and since the acrylic being used in our project will not be subject to any sort of harsh weather it is possible to buy a less expensive sheet and save money that way. Most other

components going into the screen are pretty set in price by the market that they are part of and so there was less flexibility in those areas.

5.5 INTEGRATING THE SCREEN

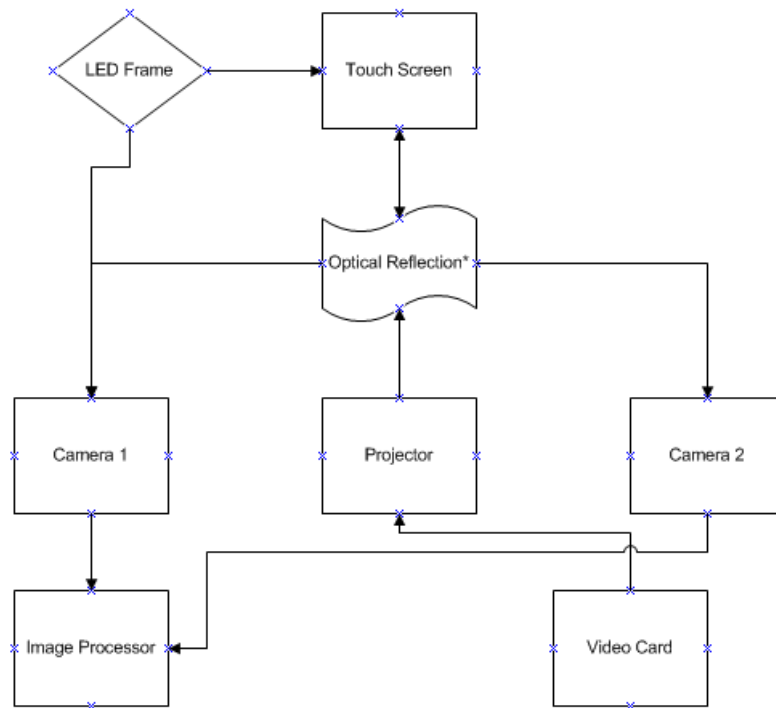


Figure 12: Block diagram of the optical system

Figure 12 shows how the optical system will be tied in with the multi-touch table system. The block diagram shows that there will be an image processor and a video card to communicate with the optical system. We are considering using a single board computer as our hardware platform which will include video output and input peripherals.

5.5.1 CAMERA TYPE

When we were choosing the type of camera to use for identifying our infrared touches there were a few driving factors that aided us. We looked at the cost and connection type. Due to the budget available for our prototype we have to be good stewards with our money. Typical infrared cameras can cost anywhere from \$84 to \$2000 which far exceeds our budget. These are also analog cameras that will output video in the NTSC or a related format which can be hard to interface with our hardware platform.

Our research showed that you can modify a cheap USB webcam to become IR sensitive while filtering out the visible light spectrum. With the USB webcam we are able to stay within budget and make use of the USB peripheral ports available on the hardware platform. The specific webcam that we choose will be

based on how easily we can modify the IR filter and also if it is supported by the Linux operating system. This will ensure software compatibility along with hardware connection.

5.5.2 PROJECTOR TYPE

The projector must also connect with our hardware platform. In order to do this we are considering both projectors and hardware platforms that use either S-Video or DVI-D. By defining the interface requirement of our system we will be able to ensure that they will connect without any custom design work being necessary. Although we have identified the system connection requirement for both the hardware platform and projector to be used we have not selected a specific projector yet. This decision will be based on the video input, focal length, the cost, and resolution.

5.6 TOUCH TECHNOLOGY TEST PLANS

Through testing and data acquisition we hope to get a better idea of how well the screen is working in order to better integrate it into our system. This will also give us an idea of how the touchscreen and optical technology will affect the overall performance of our system. The following sections will detail how we will test the touchscreen itself and also the optical system as a whole.

5.6.1 LED TEST PLAN

Through the test plan that is laid out in Table 3 we hope to optimize our screen design and construction. This will allow us to produce the brightest touches based on the highest brightness of each test. By combining the optimization of each individual LED variable we can create a system that performs the best.

Table 3: Preliminary Screen LED Test Plan

Proposed Test	Purpose of Test	Method of Testing
Density Test	To measure the brightness of touches as a function of the density of LEDs per inch of screen length	Start with a low LED density and increase the density while measuring the improvements on touch brightness
LED Angle Test	To measure the brightness of the touches as a function of the angle that the LED is placed with respect to the acrylic edge	Vary the angle of the LEDs placement with respect to the acrylic edge and measure the brightness of the touches
Distance Test	To measure the brightness of touches as a function of the distance that the LEDs are from the acrylic surface	Place the LEDs close to the acrylic edge and increase the distance plotting the brightness of the touch
Acrylic Angle Test	To test the brightness of touches as a function of the angle at which the acrylic surface is cut	Create a test piece of acrylic that has four different angles on each side and place a strip of LEDs on each side respectively and measure the brightness of the touches

5.6.2 SCREEN TEST PLAN

The testing that is shown in Table 4 will be largely used in defining values for our image processing software development. Essentially we will get an operating range of the touchscreen and therefore a list of limits required for brightness, size, and number of touches that our software system has to recognize. It will also allow us to use software to potentially normalize the background brightness to improve touch recognition in potentially bright areas. Figure 13 shows an image produce by an infrared camera looking at an FTIR touch system. These are the kinds of images that will hopefully be produced by our screen as well.

Table 4: Preliminary Screen Test Plan

Proposed Test	Purpose of Test	Method of Testing
Contrast Test	To compare the brightness difference between the touches (average pressure) with the brightness of the background	Create an image of hand placement and create illumination measurements for touches and background
Brightness Test	To measure the brightness of a touch based on the pressure applied	Measure the pressure applied on the screen and the brightness of the touch and produce plots of results
Size Test	To measure the effect of increasing the pressure on the size of the respective touch using finger touches	Apply touches measuring the pressure and the diameter of the respective touches produced. Base this on the actual width of the respective finger
Lighting Test	To measure the effect of varying ambient lighting conditions on our system	Take images of the screen in a controlled lighting environment where we can then measure the brightness of the background
Touch Interference Test	To place a quantitative value on the effect of having interfering touches near each other	Create patterns of touches that could potentially interfere with the light reflection and measure the brightness of a “test” touch to verify multi-touch quality
Multi-touch Test	To quantify the effect of having an increasing number of touches near each other	Measure the brightness of touches as you increase the number of touches in close proximity



Figure 13: Example of finger touches on an FTIR screen¹³

5.6.3 OPTICAL SYSTEM TEST PLAN

Table 5: Preliminary Optical System Test Plan

Proposed Test	Purpose of Test	Method of Testing
Camera Frame-rate Test	To verify the frame-rate of the camera in order to identify the number of images we will have to process per second	Set up a live feed of our camera and write a set of software to measure the frame-rate of the camera
Camera Latency Test	To verify the latency that our camera alone will add to our overall system responsiveness	We use an outside video camera to record an LED turning on and also a live stream of our camera viewing the LED turning on. Using this we can calculate the time it took for the camera feed to react

Table 5 shows the preliminary test plan for our optical system. The purpose of these tests is to create a working set of data to use with our software development. The camera frame-rate will determine the maximum rate at which we can track touches for our system. The camera latency will determine the effect that our camera will have on the latency of our system as a whole. We hope to identify these statistics in order to determine how fast our software will have to process the images as well as what the latency allowed will be. Our overall system latency requirement is defined as 16 milli-seconds.

¹³ <http://wiki.nuigroup.com/images/f/f5/Ftirtouch.jpg>

6 HARDWARE

6.1 DESIGN CRITERIA

Design criteria are used to determine the overall value of a particular design alternative. The final design choice will be based on each criterion and how the particular alternative scores in that category. Our criteria reflect the ability of hardware to fit in to the entire system design, and what types of qualities the hardware should exhibit.

There are two major spectrums that we seek to balance when it comes to design criteria. With cost and performance we face direct tradeoffs between the two. With more money spent on hardware we are able to purchase hardware that will perform above and beyond our system requirements. The opposing option would be to find a system that costs less and can handle our system requirements, but with less than ideal performance, e.g. increased latency and a lower frame rate. For our prototype we will find that price becomes the dominating factor due to budget constraints.

The second spectrum combines tradeoffs between scope and education. While focusing primarily on educational purposes, we could conceive a project that seeks to build the product from the ground up, tailoring each individual piece with what we want for the system. This approach would provide an understanding of each individual component, and how it fits into the overall system architecture. The cost of all this learning would be the amount of time needed to complete the project; therefore, we must balance scope and education to find a reasonable balance. The limiting factor between these two is scope, and we will lean toward finding a design that will be achievable within the time constraints of the project.

6.1.1 SCOPE

One factor that heavily influences what type of hardware design we choose has to do with how much time we have available. In order to achieve our overall system goals we need to be conscious that we do not spend copious amounts of time on any one aspect of the system, while leaving the other parts to diminish in quality. Each option will have a general time commitment associated with it, and options with a shorter completion time score better within the realm of scope.

6.1.2 COST

We are limited in the amount of money we can budget toward hardware. Our overall system has a budget of around \$500, and only a portion can be allocated for the hardware. For hardware we have a relatively simple correlation of amount spent to the capabilities of the system. With more money components such as the CPU and RAM could be upgraded.

6.1.3 PERFORMANCE

With the system we have in mind performance will be a determining factor as to if our quality goals can be met. Our CPU will have to handle running image processing software, taking in input from a camera, displaying an image through a projector, and running an operating system with applications open. The processes that need to be supported with hardware are not simple in nature, and require a system with adequate RAM and processing speed to iterate through software with minimal latency. With too much latency the end user experience will be lacking.

6.1.4 CONNECTIVITY

In order to connect all of the necessary pieces of our system the hardware system needs sufficient input/output ports of the correct variety in order to communicate with peripherals. Either the option has the required I/O ports, or it does not, and any option without appropriate connectivity will not be considered. Once the presence of the proper I/O ports has been established, the criteria has been met, and other deciding factors should then be used to indicate which option wins out. Some additional value will be added to options that have additional connectivity options. Each option will then be weighed more upon the addition connection options, such as WiFi or BlueTooth, which would not be crucial connections for our system, but could be used for further improvements.

6.1.5 EDUCATION

We make plans for developing our design as an end product, but we still consider the process of developing our prototype as important. The learning involved while developing our system can be considered an additional resource gained from our design. While not as palpable as more concrete criteria (such as cost or performance) we intend to weigh each alternative by the amount of potential experience that each offers. More difficult options will provide more learning opportunities, but also cause the project to take a longer time.

6.1.6 EXPERT OPINION

While meeting with Dornerworks we were able to speak with engineers, who had worked on a project dealing with touch screens, about what type of equipment they used. These professionals used a BeagleBoard on their project, and this meeting also introduced us to the idea of using single board computers. Talking with engineers, who designed and constructed a working system using a single board computer, we have feasibility from a firsthand source.

6.2 GENERAL SYSTEM DESIGN ALTERNATIVES

6.2.1 PC

The primary appeal to a PC (personal computer) comes from the ability to mix and match off the shelf components that will then connect to a motherboard. This gives the user the ability to easily pick and choose what type of system specifications he or she may want, and have a company give them a product that contains the appropriate components to meet desired specifications, or construct their own system with purchased components. Besides knowing about what making sure that each part fits on the motherboard, constructing a PC requires little knowledge about the hardware that goes into the system. A PC is then able to perform a plethora of general tasks that the user might need. The problem with using a PC for our design would be that there is not much learning to be achieved when constructing the system. Though easy to find parts that are capable of handling the hardware needs of our project, the cost of making a quality PC that would be able to handle our requirements would be quite expensive.

6.2.2 EMBEDDED SYSTEM

The opposite end of the spectrum from the PC is the embedded system. Systems that use embedded systems are specifically tailored to the task that the hardware is supposed to handle. This process requires a greater amount of knowledge and research about each individual part to properly interface the whole system. Generally the processors used are low power options specifically designed for use in embedded system (for example processors like ARM, or the Intel atom).

In order to implement an embedded system we would want to use a field programmable gate array (FPGA) to achieve the pattern recognition that we are currently doing in hardware. Using hardware to do this would provide a faster system, but takes a much greater amount of design work and, therefore, time. Another option, once the design for the FPGA is cemented, would be to design an application specific integrated circuit. Unlike the FPGA it would not be reprogrammable, but would be a more cost effective alternative for production.

6.2.3 SINGLE BOARD COMPUTER

Between a fully embedded system and PC comes the single board computer (SBC). Unlike the PC a SBC comes fully assembled, and does not require additional daughter boards to function. That being said there are additional backplanes available to interface multiple single board computers. The PC gives the option of expanding the number and variety of ports available to use, but the SBC comes with a fixed set of ports to use, making it more tailored to specific areas of use.

Unlike an embedded system the SBC does not require a large amount of design work and can be used as a general purpose board for different applications. The SBC comes as a completed product, while the process of designing an embedded system implies long hours of development. Through designing an embedded system the final product will only have the desired ports and parts desired, without unused resources. The SBC, on the other hand, provides a spread of possible ports and parts to be utilized or not as the user sees fit.

6.2.4 DEVELOPMENT BOARD

A development board has similar qualities to a SBC. They both provide the user with a fully assembled package for designing a system. Both are intended to be used as the basis for constructing a whole system, while giving the user sufficient infrastructure (ports and peripherals) to design the system he or she desires.

The main difference between a development board and a SBC comes from the final usage of the two in industry. Using a SBC for development usually means that the SBC will then be used in production, while a development board comes with the assumption that the system will be designed with the development board, but produced using a different board.¹⁴

For prototyping purposes our team does not make that particular distinction between the two categories. Our final product we work toward will be using the board we select now as the hardware component. Also, since the future product design will likely use a custom tailored embedded system, neither type of board will be considered for the final production line, further trivializing the difference between a development board and SBC for us.

¹⁴ http://www.efymagonline.com/pdf/single-board-computers_aug10.pdf

6.3 GENERAL SYSTEM DECISION

Each of the above general system options will be weighted based on the design criteria outlined above. By compiling the score of each system based on their performance in each criteria category, a unbiased measurement for the ability of each category can be formed.

6.3.1 DECISION MATRIX

Table 6: General System Decision Matrix

General system Decision Matrix	Priority	Personal Computer	Embedded system	Single board computer
Scope	6	9	1	7
Cost	8	1	9	7
Performance	5	8	4	6
Connectivity	3	5	2	2
Education	6	2	10	6
Expert Opinion	5	3	0	5
Total		144	164	195

Based on a weighted score for each design criteria we were able to determine that the use of a single board computer would be the most beneficial system for our purposes. The SBC scored better due in part to its ability to make a decent compromise between the opposing criteria of scope versus education and cost versus performance. Additionally professional opinion helped boost the score of single board computer, differentiating it from the other potential systems.

6.4 SBC DESIGN ALTERNATIVES

6.4.1 BEAGLEBOARD XM¹⁵

¹⁵ <http://beagleboard.org/>

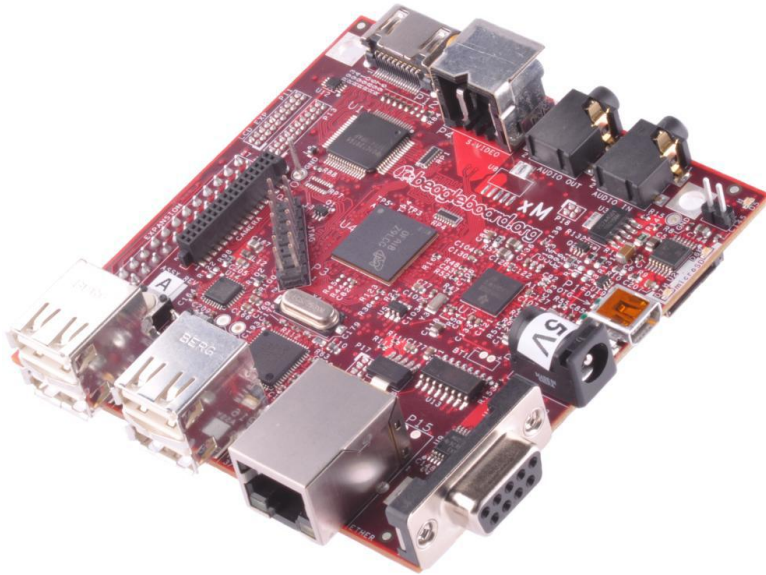


Figure 14: BeagleBoard

\$149

One SBC option is the BeagleBoard, a product first developed by Texas Instruments, now branched off into its own third party product. The total cost for this board is \$150, making it an affordable all-in-one package. At the heart of the BeagleBoard lies an ARM Cortex A8, a single core processor that runs between 600MHz – 1GHz.¹⁶

This SBC comes with a C64+ DSP (digital signal processor) Core, providing some potential speed up. The DSP deals with the time consuming process of handling continual streams of images, like the ones we will be receiving from our camera, within hardware. The speed up in the system will come from reduced latency, due to the DSP handling image processing.

For memory the BeagleBoard has 512MB of LPDDR (Low Power Double Data Rate) RAM available to use, along with a slot for a microSD (Secure Data) card (a non-volatile memory card, which acts as the hard drive for the system). Though the RAM for the system remains static at 512MB, the memory available from the microSD card can range from 2-32GB, with speeds varying from 2-10 MB/s.

The ports that we are likely to use are the DVI-D (Digital Visual Interface) for transmitting images, USB (Universal Serial Bus) for camera input, and possibly the audio input and output for any audio system that might be included. For debugging the system we have the RS232 port to communicate with the board available.

6.4.2 PANDABOARD¹⁷

¹⁶ <http://www.arm.com/products/processors/cortex-a/cortex-a8.php>

¹⁷ <http://pandaboard.org/>

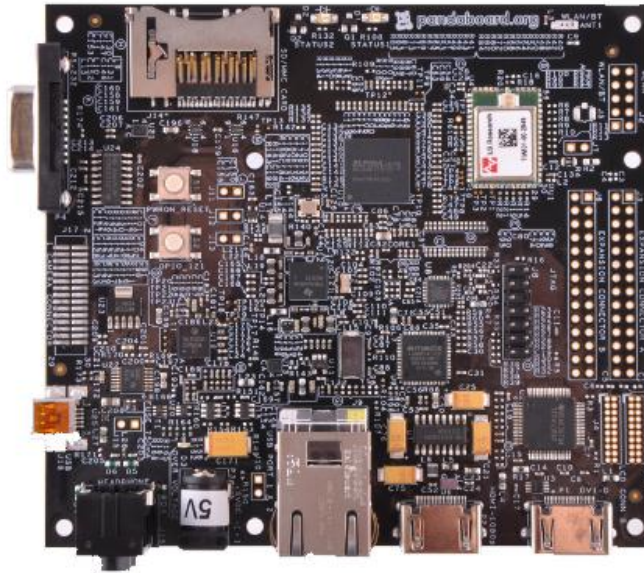


Figure 15: PandaBoard layout

\$174

The PandaBoard builds itself around a dual-core ARM Cortex A9. Similar to the BeagleBoard the PandaBoard uses Texas Instruments OMAP (Open Multimedia Application Platform) structure, which includes a DSP for faster processing of images coming into the board. Unlike the BeagleBoard, which uses OMAP3, the PandaBoard uses the next generation of OMAP associated with the ARM A9 processor. This means that the PandaBoard is more suited to handle higher end graphics such as 1080p HD and 3-D graphics acceleration.

For memory the PandaBoard has 1 GB LPDDR2 RAM, and a larger cage, capable of supporting high-speed and high-capacity SD cards. The higher speed SD card allows for memory access speeds up to 60MB/s (six times the high end speed of the microSD cards used with the BeagleBoard).

Ports that will likely be used on the PandaBoard for our project include the HDMI (High-Definition Multimedia Interface) for the video out, and the USB ports for taking in the camera images. Again we have a RS232 port for debugging our system.

6.4.3 SBC8530 BY EMBEST¹⁸

¹⁸ <http://www.armkits.com/Product/sbc8530.asp>



Figure 16: SBC8530

\$199(for just the board) \$249(board plus peripherals such as antenna power adapter)

The SBC8530 comes with an ARM Cortex-A8 processor. The SBC8530 comes with a TI DM3730 DaVinci digital media processor. The purpose of the digital media processor is to provide “best in class ARM and graphics performance while delivering low power consumption”¹⁹. This system combines two digital media processors (DM3730 and DM3725) in order to create a capable media processing system. While still trying to provide quality computing ability the system seeks to provide the power savings necessary for embedded systems, allowing the board to consume 0.31A at 5 V.

The SBC8530 includes 512MB of DDR SDRAM, and 512MB NAND flash memory. This board comes with a TF card slot (another name for an SD card slot) for additional memory capacity.

For video I/O the SBC8530 incorporates a DVI port, and has a camera interface, supporting a CDD or CMOS camera. Other communication ports included are: two USB 2.0 ports, an Ethernet interface, and a WiFi/Bluetooth module.

6.4.4 TCS-001-01849 BY TCS (TOTAL CONTROL SOLUTIONS)²⁰

¹⁹ <http://www.ti.com/product/dm3730>

²⁰ <http://www.totalcontrolsolutions.com/single-board-computer/TCS-001-01849>



Figure 17: TCS-001-01849

Approximately \$200-250 (guess)

The TCS-001-01849 comes with an Intel Atom D525, a dual core processor running at 1.8GHz. For graphics processing a GMA (Graphics Media Accelerator) 3150 chipset is used. To replace the need for an additional graphics card Intel incorporated a GMA's for their Atom processors. This allows embedded systems to make use of the multimedia capabilities of the chipset, without having to look for another board to add to the system. The particular version in the TCS-001-01849 was developed primarily for mobile devices, such as netbooks.

For memory the TCS-001-01849 has 1GB of on board DDR3 SDRAM. With two SATA slots this particular board has the option of adding in full size hard drives, giving the user a multitude of options based on how much they are willing to spend. There will be additional infrastructure required to power this type of main memory.

For video I/O a DVI port can be utilized. There are 8 USB 2.0 ports, and 2 SATA (one extra port if the hard drive uses one connection) connections that can be utilized. Overall the system uses 1.7A, requiring a CPU fan to dissipate heat.

6.4.5 CAPA110 BY AXIOMTEK²¹

²¹ <http://axiomtek.com/products/ViewProduct.asp?view=917>



Figure 18: CAPA110

Approximately \$200-250 (guess)

The CAPA110 has a dual core AMD G-Series APU (Advanced Processing Unit) dual core T56N, clocking at 1.65 GHz. This particular CPU specializes at running high end graphics applications, with AMD's Radeon 6320 controller.

The CAPA110 has a DDR3 slot to support up to 4GB of Ram, and two SATA ports to support hard drives for main memory. The board includes a DVI video I/O, along with multiple USB ports.

6.5 SBC DECISION

There are multiple SBCs that cater to multimedia applications, which could qualify for use in our project. A final decision will be made during interim. We still need to finalize our overall budget, and, with cameras and projectors still undecided on, the amount available for purchasing our SBC has yet to be determined. Also the additional research into possible educational discounts needs to be explored before pricing can be finalized. Extra attention needs to be focused on pricing, because price per performance will be the primary factor for determining which board will be chosen.

7 IMAGE PROCESSING SOFTWARE

7.1 DATA SOURCE

The camera will write data to a location in memory, ideally at 60 frames per second. It will be in full-frame AVI format, which is uncompressed. Although it's infrared, it will still have 3 channels (like visible red, green, and blue, but at lower frequencies), which will help contrast light from the in-screen LEDs to ambient infrared light, which will likely have a different "hue." Using proper drivers, a program within the operating system will read this data. The goal will be to eventually translate this data into the equivalent of various mouse gestures.

7.2 OPENCV

To avoid "reinventing the wheel," a couple computer vision libraries were considered, including MT4J and OpenCV. MT4J is only available for Java, which is a language not built for speed and therefore not used. OpenCV wrappers are available for C, C++, Python, Ruby, and Java; C++ was chosen in this case as it's only marginally slower than C and faster than the other languages, and it can be developed in fewer lines than C to reduce coding time. OpenCV, which stands for "Open (Source) Computer Vision," has many desirable capabilities, including reading various image formats and lots of basic image processing functions.²² The most important factor in our case is speed, though, as all image processing needs to be done fast enough to keep up with 60 frames per second (about 16 milliseconds). Due to this, and the fact that one DornerWorks employee we met with suggested it and had some experience with it, OpenCV was chosen.

7.3 MAIN FUNCTIONS

7.3.1 POINTER CONTROLLING

The important result of "processing" the images is to interpret correct "gestures" which will be read by other programs on the operating system as input. Specifically, the gestures that need to be implemented are:

- Single, one-finger touch down interpreted as a single (left) mouse click down, and a release interpreted as a click release; this means that dragging is done with only one smooth touch, rather than two as on most laptop track pads



Figure 19: One-finger touch gesture

²² Bradski and Kaehler, *Learning OpenCV*, 2008

- Two-finger quick touch interpreted as a single alternate (right) mouse click



Figure 20: Two-finger touch gesture

- Two-finger drag interpreted as a scroll wheel in any direction (left, right, up, down)



Figure 21: Two-finger drag gesture; any direction will work

- Two-finger pinch or reverse-pinch interpreted as zoom-in or zoom-out (equivalent to Ctrl + Scroll Wheel on some operating systems)



Figure 22: Two-finger "pinch" gesture; outward direction also interpreted

- Two-finger counter-clockwise “flip” used to bring up the on-screen keyboard, and clockwise to close it (*if time permits*)



Figure 23: Two-finger "flip" gesture; reverse direction also interpreted

To do this, the image processing program must be able to detect different regions of high-luminous infrared light within the range of the webcam and determine the location on the screen they inhabit. It would also have to track similar regions from frame to frame to see which direction a region is moving in addition to its location.

7.3.2 ON-SCREEN KEYBOARD

External keyboard and mice can be used, but a keyboard still needs to be made available on-screen. The 'built-in' keyboard will be displayed on-screen, also via the image processing software. The keyboard will be semi-transparent, adjustable, and moveable. Here is an example of how an on-screen keyboard may look to the user:



Figure 24: Example on-screen keyboard²³

However, the standard keyboard that comes with the operating system (or any pre-written keyboard program) will not suffice, because it expects normal mouse input and therefore there is no way to press multiple buttons at once. This would be an unnecessary inconvenience for the user, so a new on-screen keyboard application will have to be written which can take advantage of multiple, simultaneous touches, making it easier to perform keystrokes such as "Ctrl+C."

7.3.3 ADDITIONAL FUNCTIONS

The main touch gestures are enough to replace a mouse on a typical computer. More complex input is capable with the touch table, and this will be made available so other software can take advantage of it. For example, a paint program may want to know the coordinates of *every* location on the board currently being touched at all times, or all the regions being touched and their relative "sizes" or "weights." A C++

²³ Image taken from <http://www.filetransit.com/screenshot.php?id=62121>

library will be made available for developers to use and adopt a more “raw” version of the input for programs written specifically for this touch table.

7.4 IMAGE PROCESSING SOFTWARE DESIGN

7.4.1 APPROACH

The image processing software can be described in pseudo code as:

Loop:

```

    Grab next frame

        Take the discrete Hessian of frame (a discrete
approximation of the Hessian operator)

        Find 'trackable' items by Hessian values above threshold

        If more than 2 'trackable' items

            Take only top 2

            If a trackable item is within a certain threshold of a
trackable item in the previous iteration's set of trackable items

                It is assumed to be the same item, moved slightly

                If there is only one current trackable item

                    If currently already clicking down

                        Continue clicking down (do nothing)

                    Else

                        Begin click down

                Else, if there are two trackable items

                    If previous iteration had 2 trackable items,

                        Take dot-product of velocities of trackable
items

                        If dot-product is positive, above certain
threshold

                            Two trackable items are moving in
approximately the same direction, so interpret as a scroll wheel
movement

```

Else if dot product is negative, below a certain threshold

Two trackable items are moving in opposite direction, so **interpret as showing keyboard**

Else

Interpret as right-click

Else (no trackable items)

Release click

Save two trackable items for use in next iteration

Save image in shared memory location (for use by programs which chose to use image input differently)

Next loop iteration, until there are no new frames to grab

Actions noted in bold are actions in which control the pointer; since the table will be based on Ubuntu Linux, the kernel provides some services to do this.²⁴ To demonstrate what is meant by “trackable items,” here is an example image with the “corners” highlighted:



Figure 25: Example webcam image with 100 most “trackable” items marked with black circles

²⁴ “Writing Linux Mouse Drivers,” *Linux Magazine*, <http://www.linux-mag.com/id/330/>

The OpenCV library calls these points “corners” because they’re based on locations with rapid changes in color which are nearby smooth locations with little change in color. This is based on the Hessian operator, which is based on the difference in second derivatives in the x and y directions. Finding corners is only one step; to determine which trackable items are actual touches, the brightness and frequency of the area within a circular range of the corners will be compared to the LEDs’ frequency. To be considered a touch, a section of this circular region must be within a certain (constant) range of the LEDs’ frequency. Then, of those eligible regions, only those above a certain threshold brightness will be considered touches. If there are still more than two eligible regions, only the top two (by brightness) will be used, because no mouse gesture uses more than two regions. The corners, therefore, are only used to track these “trackable items,” i.e. touch regions, from one frame to the next. The aforementioned constant thresholds of frequency range and brightness will be determined through experiment; a program can be written for the touch screen that will calculate these “touch regions” and highlight them on the screen, so that we can practice touching the screen and examining whether the touch regions appear where we want them to.

For an example of some OpenCV library functions, the program that generated Figure 25 (and will continue to generate pictures like it, live, with whatever the webcam sees), Figure 26 below is the source code, compiled with the OpenCV framework:

```

#include <OpenCV/cv.h>
#include <OpenCV/cxcore.h>
#include <OpenCV/highgui.h>

int main(int argc, char** argv) {
    cvNamedWindow("Beijing", CV_WINDOW_AUTOSIZE);
    CvCapture* capture = cvCreateCameraCapture(CV_CAP_ANY);
    IplImage* frame;
    CvScalar black = cvScalar(0, 0, 0, 0);
    while(1) {
        frame = cvQueryFrame(capture);
        //if (!frame) break;
        CvSize myImgSize = cvGetSize(frame);

        //int myWinSize = 10;
        CvArr* myGrayscale = cvCreateImage(myImgSize, frame->depth, 1);
        cvCvtColor(frame,myGrayscale,CV_BGR2GRAY);

        CvArr* myEigImage = cvCreateImage(myImgSize, IPL_DEPTH_32F, 1);
        CvArr* myTempImage = cvCreateImage(myImgSize, IPL_DEPTH_32F, 1);
        CvPoint2D32f* myCorners = new CvPoint2D32f[100];
        int myCornerCount = 100;
        double myQuality_level = .01;
        double myMin_distance = 5.0;

        cvGoodFeaturesToTrack(myGrayscale, myEigImage, myTempImage, myCorners,
&myCornerCount, myQuality_level, myMin_distance, NULL, 3, 0, 0.4);

        for (int i = 0; i < myCornerCount && i < 100; i++) {
            cvCircle(myGrayscale, cvPointFrom32f(myCorners[i]), 5, black, 1, 8);
        }

        cvShowImage("Beijing", myGrayscale);
        char c = cvWaitKey(30);
        if (27 == c) break;
    }
}

```

Figure 26: Example C++ source code using OpenCV to take webcam input and draw circles around "corners"

7.4.2 IMPLEMENTATION CHALLENGES

Every image must be loaded, completely processed, and the input sent back within the frame rate (10-30 milliseconds). A test procedure for this would be:

1. Write a preliminary image processing program.
2. Approximate its by running it on a personal computer. The execution time can be computed using the "time" command on the OS X terminal followed by the program (or, better yet, a bash script that runs the program 1,000 or so times).

3. Estimate amount of time used for memory storing and loading by walking through the source code and looking up the appropriate memory speed of the personal computer it's being tested on (taking into account good spatial locality in the program).
4. Subtract the time computed in exercise 3 and assume the rest of the time is processor computation.
5. Look up the memory and processor speed of the Table of Content, once its specifications are chosen, and make the necessary conversions to determine the equivalent time on our target processor.

If the result of step 5 is a time much greater than 10 milliseconds, necessary steps will need to be taken to speed up image processing, and then this test process will be repeated. Since there is less range of choice in the processor specifications (for example, it will likely be close to 1 GHz), the processor specifications will be chosen *before* the program is written. In other words, if the image processing software doesn't run fast enough, it will be solved by writing a program that runs faster, not by getting a faster processor. To make the program run faster, the number of "corners" calculated and the resolution of the pixels being checked can be reduced, with the tradeoff of interpreting the touches in a less accurate way.

7.4.3 LOCATION

The image processing software will be written and run on the same processor as the operating system as opposed to running on its own field-programmable gate array. Using drivers to read data (detailed in section 10), it will take data from the camera and analyze it. The image data will be processed and interpreted as one of many gestures – a click, a scroll, a zoom, etc.

7.5 APPLICATION PROGRAMMING INTERFACE

7.5.1 USE OF API

A C++ API will be published for any developer to take full advantage of the touch screen input for things such as advanced games with multiple touches at once. The API will give developers direct access to the image data from the camera if they choose, but it will also contain useful functions to:

- Automatically determine "touch regions," much like the ones described in section 7.4, except with an unlimited number
- Return the entire input pixel grid, each pixel being "on" or "off," representing whether it's touched or not, based on whether the pixels' properties fall in a certain constant range (using the same constants as determined in section 7.4.3)

7.5.2 EXAMPLE APPLICATIONS

7.5.2.1 MULTIPLE TOUCH REGIONS

One demonstration app that will be written that will take advantage of multiple "touch regions" is an air hockey game. Air hockey is controlled by two independent people on opposite sides of the screen, something which would be impossible with just one mouse.

7.5.2.2 PIXEL GRID SENSING

An example of another demonstration app which will be written to show utilization of the entire pixel grid is a paint program. Any touch anywhere would be reflected on the paint canvas. Thus, if someone was

painting in black on a white canvas and stuck his or her hand on the screen, the entire solid shape of a hand would turn black on the canvas.

8 INTEGRATION AND TESTING

Upon completion of our system we will begin testing the performance of the system. Determining the bounds of our system in a variety of categories provides information on the system vital to determining the performance of the system.

Proposed Test	Purpose of Test	Method of Testing
System running temperature	Finding the upper limit of operating temperature	Continuous use of the system under expected conditions
Touch Resolution	Find the ability of the system to recognize closely spaced touches as unique	Using an increasing number of touch points, constantly move touches closer together
Power Consumption	Find how much power our system consumes	Run the system under a variety of workloads in order to determine an average amount of power consumed
Screen Durability	Confirm or deny the ability of the screen to withstand the application of various weights	Increment an applied weight until a certain deformation, bend, is achieved, and base the strength of the screen on this, extrapolating to find the maximum weight limit
Frames Per Second	Determine how fast images can be shown on the touch screen	Measure the number of frames per second using software
Latency	Determine the elapsed time between an interaction with the system and the systems recognition of that action	Develop tracking software then videotape a user's interactions

8.1 SYSTEM REQUIREMENTS TESTING

Once complete, our prototype can then be tested to determine performance. By testing the system we can then continue on to try and improve any categories that are not up to standard. The general system tests listed above indicate how close to our proposed requirements we have come.

8.1.1 TEMPERATURE

In order to determine the running temperature of the system we will run the system within a normal setting under an exaggerated work load. The normal setting will be an open space with some air flow, trying to simulate conditions present in an average living room. The ambient temperature will be the standard value of 68°. A continually running program, ideally running the processor at 80 to 100% of its potential, simulates the exaggerated work load. Running the system for 6 hours and graphing the temperature of the system versus time shows the system temperature limits.

8.1.2 TOUCH RESOLUTION

To start testing the resolution of the touch recognition of our system, two touch points, cylinders with 1/8 inch diameter, will be brought close together. As the touch points are brought together incrementally where the system maps the touch will be mapped. Once the border between when the system recognizes the two touches and when the two touches merge into one is determined we can determine our resolution

8.1.3 POWER CONSUMPTION

To ensure that we remain under the expected power consumption of the system we need to measure the power consumption of our device. We can test the power consumption of the system while we do the tests for temperature.

8.1.4 SCREEN DURABILITY

Testing our screen durability poses some problems when dealing with the prototype. We need a test that can give a relatively accurate prediction of the maximum weight capabilities, without testing until failure. Incrementing the weight placed on the screen until a certain amount deflection occurs in the screen. Studying the already measured rigidity of our Plexiglas can then help us determine when the screen will be permanently deformed or break.

8.1.5 FRAMES PER SECOND (FPS)

Frames per second can be measured with software. Using already existing software we can measure how well our system outputs images to the screen. Ideally we want the frame rate to run around 60 FPS (the maximum frame rate the human eye can perceive), but 30 FPS results fulfill our prototype expectations.

8.1.6 LATENCY

Determining the latency measures the capability of the system. To measure latency a tracking program for showing where a touch occurs must first be developed. A video camera can then be used to record a person using the tracking software. Analyzing the recording will show the time it takes for the tracking software to catch up to the user's finger, and this elapsed time will be the latency of the entire system.

9 BUSINESS PLAN

9.1 EXISTING PRODUCTS

One product already available is the MT55 Platform multi-touch table. This table runs the Intel i7 processor, has 8GB of ram, a 256GB solid state drive, and displays on a 55 inch touch screen. All of this power and size can be purchased for \$17,950.²⁵

Two products from the same company are the TT45²⁶ system and the TT84²⁷ system developed by TouchTable. Both of these are table meant to be used standing up in business environments. The company focuses on creating a virtual space usable by multiple users, primarily on geographical projects for oil and gas companies.

9.2 MARKETING STUDY

Our market and primary product lines will be divided into two categories. We will be looking into both the home market and the business market. The difference in these product lines will be through the need that we are hoping to satisfy with both markets. For the home market we are hoping to provide an entertainment system that can fit within a typical coffee table. This will provide screen dimensions roughly 2 feet by 1 foot. For the business market we are looking to provide interactive conference tables. Typically these are larger than a household coffee table and will therefore require new system requirements.

9.2.1 HOME MARKET ANALYSIS

Prior to launching any sort of marketing campaign it is important to know who you are marketing to and how you can reach those people. It is also important that you create a device or system that is desired or necessary by that particular market. The Untouchables has a two-fold strategy for developing an in depth market analysis for our multi-touch table.

The first method we used to analyze our target market and provide initial revenue estimates was a simple interest survey. We described what the final product would be and then requested a level of interest and also the amount that they would be willing to pay for such a product.

Overall, people in our target market appeared interested in owning such a device due to its expansive application set. The average price that people were willing to pay for our table was around \$1100 which was higher than our original selling price. However, this was a fairly limited survey with only 7 responses that were not an extensive representation of our market.

The second market analysis strategy that we are hoping to perform will be research into methods of advertising and getting the news of our device to our target market. This will require an analysis of what our target market reads, what they watch, and what sort of events that they participate in. Once we identify how to reach our target market it will be easier to produce advertisements that they will see and convince them that they desire our product. The last method of reaching them would be through

²⁵ http://www.ideum.com/products/multitouch/platform/ga/?gclid=CIm79q_EtKwCFQ1x5Qod9nf-Fw

²⁶ http://www.touchtable.com/docs/datasheet_tt45.pdf

²⁷ http://www.touchtable.com/docs/datasheet_tt84.pdf

technology trade shows that show off all of the years newest products as that would be a good way of producing news about our product.

9.2.2 BUSINESS MARKET ANALYSIS

Another option for financial growth is by finding a way to satisfy a businesses need. To capture these important business clients we would have to adapt our product into one that competes with their existing way of addressing an issue. The issue that we will try to revolutionize is one of presenting and reviewing information with clients or during in-company meetings. By providing an interactive platform to view presentation material would hope to replace the necessity of having projectors in every meeting room.

Our aim in making our product adaptable for the business market is to make many of our critical components upgradeable in order to present a faster, higher quality product to businesses. Another difference in our home market product and business market product will be the screen size. The size will be larger in order to be seen clearly by more users. A large part of our plan that may be changed by this upgrade is the optical system layout. A larger screen may require two cameras in order to capture the reflected light from the touches from a larger area. This may require a small adjustment in our software but definitely easily covered by the extra revenue produced by the business product. Another change in the optical system will be because of the added height under the touch surface. This will cut down on the price of the cameras and projector because of no longer having the short distance requirements. It certainly will remove any need for mirrors or optical reflection techniques.

In order to get a general idea of interest from businesses we will need to do a survey. From that survey we could desire for our product and what attributes are most important. After gathering information on the market we would need to reach them with our product proposal. We would likely advertise our product in similar places as projectors and office furniture. These could include catalogs, business magazine ads, local television, conventions, and having a sales staff do demonstrations for potential clients. The ease of use and adaptability will be selling points to clients who may have a very wide variety of how to use it.

9.3 BUDGET ANALYSIS

9.3.1 PROTOTYPE COST ANALYSIS

Table 7: Prototype Cost Estimate

Item	Quantity	Unit Cost	Total Cost	Total System Cost
Touch Screen	1	\$84.18	\$84.18	\$234.18
Acrylic/Plexiglass	1	\$48	\$48	
Infrared LEDs	28	\$0.35	\$9.80	
Frame Material	1	\$10	\$10	
Silicon Rubber	1	\$6.31	\$6.31	
Xylol (Solvent)	1	\$5.07	\$5.07	
Projector				
Diffuser	1	\$5	\$5	
BeagleBoard (or devBoard)	1	\$150	\$150	

SD Card	1	\$20	\$20	\$254.18
Camera	2	\$50	\$100	\$354.18
Projector	1	\$200	\$200	\$554.18
Coffee Table	1	\$10	\$10	\$564.18
External Hard drive	1	\$25	\$25	\$589.18

The Untouchables used a combination of existing multi-touch technologies and parts research to identify cost estimates for the major components of our design. The touchscreen section and its comprising parts have been identified and chosen and are actual market parts that we plan on purchasing. For the rest of the budget we looked at various options of the part and chose the high end cost that could potentially ensue on our budget. The budget in Table 7 accounts for the highest cost estimates for all major components and should therefore limit the risk associated with parts costs.

9.3.2 PRODUCTION COST ESTIMATES

9.3.2.1 VARIABLE COST

Table 8: variable cost for one production touch table

Item	Additional Specifics	Total Amount Needed	Reference	Total Cost
FPGA	Arria GX	1000000	http://search.digikey.com/us/en/products/EP1AGX20CF484C6N/544-2395-ND/1641003	\$85,000,000.00
Processor	AMD Phenom II	1000000	http://www.newegg.com/Product/Product.aspx?Item=N82E16819103727	\$65,000,000.00
Board		2000000	http://www.ourpcb.com/pcb-price.htm	\$116,570,000.00
Camera		1000000	(from prototype budget)	\$25,000,000.00
Projector		1000000	(from prototype budget)	\$100,000,000.00
Coffee Table		1000000		\$50,000,000.00
Hard drive		1000000	http://www.newegg.com/Product/Product.aspx?Item=N82E16822148789	\$37,500,000.00
RAM		1000000	http://www.newegg.com/Product/Product.aspx?Item=N82E16820233145	\$35,000,000.00
Acrylic/Plexiglass		1000000	(from prototype budget)	\$24,000,000.00
Infrared LEDs		28000000	(from prototype budget)	\$175,000.00
Frame Material		1000000	(from prototype budget)	\$5,000,000.00
Silicon Rubber		1000000	(from prototype budget)	\$3,155,000.00
Xylol (Solvent)		1000000	(from prototype budget)	\$2,535,000.00
Projector Diffuser		1000000	(from prototype budget)	\$2,500,000.00
Packaging	7000 square inches of cardboard, 20000 cubic inches of styrofoam, plastic wraps around parts and maual	1000000	(further research needed)	\$5,000,000.00
Paper user manual		1000000	(further research needed)	\$500,000.00
Nuts + screws to hold camera and SBC		9000000	(further research needed)	\$750,000.00
Replacements	(for warranty program)	1000000	(5% of total cost)	\$27,884,250.00
<i>Grand total</i>		<i>1000000</i>		<i>\$585,569,250.00</i>

The single-board computer includes a built-in power supply, which can also be used to supply the camera and LEDs. The production cost includes an FPGA that would be used to implement the touch recognition system, implemented with software in our prototype, and board fabrication. These are two aspects of production that fell outside of the scope for our prototype, but would be implemented for our final

product. One assumption made for the cost estimate in Table 8 was that buying in bulk would generally cut the cost in half for items (if research was not readily available for such large quantities to provide a more concrete number). The board used for estimation was 10cm by 10cm and had 4 layers. We assumed that two were needed for the general Processor board, and another to cover the FPGA video processing. The cost for the board also assumes that populating the board is included in the price.

Some additional research on precise costs for supplies in bulk (count of one million plus) will be refined later, as well as choice of how to package the product. Numbers given are based on prices of single parts and on trends of price rates falling with increasing volume.

9.3.2.2 FIXED COST

Table 9: Cost of design

Design					Total	**Includes design of prototype, and design for production. See WBS for details.
# of Engineers	\$/hour	hours/ engineer**				
4	\$100.00			170	\$68,000.00	

Pricing for the design of the project was based on our team of four doing all of the design work for the project. It also included additional work for making the product ready for production. Assuming that an average worker works for about 2000 hours a year (at eight hours a day, five days a week, 50 paid weeks per year) this project is proposed to be completed within a quarter of a year by a team of 4 (including a manager for the four engineers, that cost will be covered later). The estimate of total hours is based on our work breakdown schedule, which estimates that our current 210 hours has us approximately 35% done.

Table 10: Cost of Advertising

Advertising	(price of one)	(per year amounts)	(total)	
Online Video Promotion	\$45.00	182500	\$8,212,500.00	http://www.quora.com/How-much-do-Hulu-ads-cost
National Commercials	\$100,000.00	200	\$20,000,000.00	http://www.gaebler.com/Television-Advertising-Costs.htm
Local Commercials	\$1,000.00	1000	\$1,000,000.00	
Commercial Development	\$150,000.00		\$150,000.00	
Staffing	\$50,000.00	4	\$200,000.00	
Total			\$29,562,500.00	

Table 10 shows our expected cost of advertising our product in a variety of markets. We expect to primarily advertise through television and internet sources, though a portion of Table 11 sales includes a cost for participating in conferences, which will also be another place to advertise our product.

Table 11: Cost of sales

Sales	(price of one)	(amount)	(total)	
Business interactions	\$100,000.00		10.	\$1,000,000.00 for meetings, travel expenses)
Staffing for quarter-year	\$50,000.00		4.	\$200,000.00
Total				1200000

For sales we have allocated funds to cover attending up to ten large tech conferences, along with funds for business meetings and travel expenses to attend these. We will employ four full-time staff each at \$50,000 per year. Though a much smaller budget than advertising, we are assuming that sales primarily deals with current customers and retail stores, that will need less monetary commitment to persuade and interact with.

Table 12: Cost of burden

Burden	(one year salary)
Management CEO and upper level management	\$150,000.00 \$400,000.00
Total	\$550,000.00

For our burden section we include the upper level management personnel that would not be directly involved with designing or constructing the product, but would have influence over product development and company direction. Only one year is taken into account for salary assuming that the overall company will have other product lines to bear the subsequent salary cost.

Table 13: Cost of Production

Production	
Office and Factory Rent	\$1,000,000.00
Utilities	\$100,000.00
Labor	\$150,000,000.00 (5 hours at \$30/hour)
Logistics	\$500,000.00 (shipping and getting the product out to the customer)
Total	\$151,600,000.00

The cost of labor is another branch of research that will be further refined. To estimate labor costs of producing, we took a base salary of about \$20 per hour, which we believe is a good living wage, close to what countries like Sweden and Denmark pay for manual labor, the highest in the world. Then we estimated additional benefits would increase the cost to us to about \$30 an hour. While we could find labor cheaper, we believe it is more important to provide jobs which can support a family in today's economy, and having workers who are higher-paid than most other places will give us an advantage to recruit the best workers, who will in turn have better impressions of the company. The utilities cost calculated in Table 13 is based on a common estimate of 10% of our expected rent for office and factory space.

9.3.2.3 UNIT COST

Table 14: Summary of total cost and expected profit

Projected # sold:	1600000
Product lifetime (years):	3
Desired profit margin (%):	15
Cost of fabrication (per unit):	\$585.57
Yearly cost:	\$548,941,500.00
Fixed per unit:	\$343.09
Total cost per unit:	\$928.66
Sell price:	\$1,000.00
before tax profit:	\$71.34
after tax profit:***	\$46.37
Total profit:	\$74,196,005.00

*** with a assumed tax rate of 35%

For unit cost we take in the total variable and fixed cost calculated above, and summarized here in Table 14. This is another area which will require more research next semester, but for the time being we estimated a total amount sold of 1,200,000 over a lifetime of 3 years, thus the yearly costs are multiplied by 3. The selling price (to retail stores) will be set to \$1,000, who will turn around and sell it for a retail price of \$1,100 to \$1,300.

9.3.2.4 BREAK-EVEN ANALYSIS

Table 15: Pro-forma income statement for first 3 years

	The Untouchables		
	Pro-Forma Statement of Income		
	Year 1	Year 2	Year 3
	200000	400000	600000
Sales revenue	200,000,000	400,000,000	600,000,000
Variable Cost of Goods Sold	120,000,000	240,000,000	360,000,000
Fixed Cost of Goods Sold	33,000,000	43,000,000	50,000,000
Depreciation	714,500	1,367,400	1,119,400
Gross Margin	46,285,500	115,632,600	188,880,600
Variable Operating Costs	10,000,000	20,000,000	30,000,000
Fixed Operating Costs	30,000,000	65,000,000	80,000,000
Operating Income	6,285,500	30,632,600	78,880,600
Interest Expense	250,000	400,000	150,000
Income Before Tax	6,035,500	30,232,600	78,730,600
Income tax (40%)	2,414,200	12,093,040	31,492,240
Net Income After Tax	3,621,300	18,139,560	47,238,360

Table 15 shows our estimated income for the first three years of operation at our estimated production volumes. Preliminary surveying of our target market showed an interest in our product with a willingness to pay within the range of \$1100-\$1300. This allows us to sell our table to retailers at \$1000 and allow a retailer mark up. The 2009 census statistics show that there are 117 million households in America. Roughly 20% of these households have an annual income of \$100,000 which is enough to purchase our product. There are 23.5 million households that are able to afford our multi-touch coffee table and could potentially be within our target demographic.²⁸

²⁸ <http://www.census.gov/compendia/statab/2012/tables/12s0690.pdf>

Table 16: Break even volumes for first 3 years

	Year 1	Year 2	Year 3
Total Fixed Costs	63,964,500	109,767,400	131,269,400
Contribution Margin %	35%	35%	35%
Break Even Sales Volume	<u>182,755,714</u>	<u>313,621,143</u>	<u>375,055,429</u>
Break Even Products Sold	182,755.71	313,621.14	375,055

Table 16 shows our break even sales volume in both dollars and units sold. Although more detailed research will be done on this, over the product's three-year lifetime we expect the sales to increase at the rate shown. Our preliminary market research shows that our goal in the first three years is to reach roughly 5% of the available market for our product.

10 CONCLUSION

10.1 PROJECT FEASIBILITY

Creating a multi touch computer platform has varying degrees of difficulty depending on the extent of detail, quality, and compactness of the product. The project will provide engineering design tasks as well as research and construction in optical, hardware, software, and power systems. Many parts of our project are achievable through skills we have been taught and acquired during our Calvin education and job experience. A benefit of our project is that potential improvements, added features, and expanded goals can all be added if time and funding are available. The possibility of expanding our project will ensure that we get the best experience out of the design class. Through design decisions, choices have been made to give us the best technologies for our budget and capabilities.

Our preliminary budget is approximately \$590 for all the components of our prototype. That includes parts to make the screen, a BeagleBoard, an external hard drive, IR cameras, projector, the coffee table, and a SD card. Certain parts, such as the cameras and projector could change in price depending on quality of product. This will allow for some financial maneuvering to stay under the amount of money we will be given to spend on the project. Each part is essential to our finished product and has been selected as the best part for that function based on functionality and cost. We incorporated some of these prices into our business plan in order to get an accurate product cost.

The feasibility of our group having enough time to complete our project on time is reasonable. After the first semester we will have approximately 220 hours put into our project and will have our project about 35% complete according to our work breakdown schedule. If our percent completion to hours worked ratio were to stay constant that would mean we would have approximately 410 hours remaining. With interim and a more concentrated effort on this project in the second semester we are confident that we will put in this amount of work hours. As a team we will spend more time once we are in the building phase and can start to see results of our work.

10.2 CURRENT PROGRESS

The major parts of the project we have completed already are the design decisions. Our first large decision was on which touch technology we should use. We decided on FTIR and were able to have a basic project overview and budget constructed. We have created a work breakdown schedule in order to keep us on track of constructing the prototype. We have started the process of acquiring parts that will be needed to create the screen and have some software written that can be tested on camera output when we get our screen technology working. Hardware decisions are also very important in making a good and affordable product. We have decided on many hardware components that will allow us the functionality of the product that we want.

As we discussed in the feasibility section we have completed approximately 35% of our project in 220 hours. Most of the tasks that were completed on our work breakdown schedule were research and design decisions. Preliminary design is important in order to not have to redo large parts of our prototype once we start construction. The calculated 410 hours needed to complete the project will most likely increase but with the solid plans that we have created in this first semester we should be on our way to a

successful project. Below in Table 17, we can see our estimated completion of each large section of our project.

Table 17: Percent Completion

Optical	44%
Hardware	38%
Power	35%
Software	23%
System	1%
Documentation	65%
Total	35%

10.3 SMALL-SCALE PROTOTYPING

We plan on creating our prototype in stages so that we can guarantee that each parts works independently of the whole system. This way we can easier debug problems and show progress in our prototype construction. The first small scale prototype will be our touch screen using the FTIR technology. Hardware and some software components will be able to be tested independent of the optics before being connected. We will also test power consumption of each part individually to get a good idea of what our overall power consumption will be and which parts are the main contributors. Our goal through small scale prototyping is to eliminate a finished product that has complications and having to try and debug the product has a whole instead of directing our attention on the specific component that needs debugging.

10.4 FUTURE RISKS AND PLANS

It is difficult to predict which part of the project will cause the most issues and delay the finish. However, there are certain things we are going to look out for specifically. One is the camera and how it picks up touches by the infrared light versus sources of ambient light. Other risks we will be watching out for are the limited space we have for the optical requirements, limited processing power for both image processing and applications, and systems engineering. We also have frame rate and latency goals that our hardware choices may influence negatively because of staying within our budget.

11 ACKNOWLEDGEMENTS

11.1 PROFESSOR STEVE VANDERLEEST

Professor Steve VanderLeest is our current advisor for our Senior Design project and class. He has contributed heavily in keeping us on schedule with our project and reaching goals for the first semester. In the coming semester we expect Professor VanderLeest to aid us heavily in the validation of our project along with goal projection.

11.2 CLASS ADVISORS

Along with Professor VanderLeest there are three other Senior Design class advisors. These are Professor Ned Nielsen, David Wunder, and Wayne Wentzheimer. All three of these professors along with Professor VanderLeest will provide us with informative lectures to help us prepare for the different aspects of our project along with our migration into the engineering workforce.

11.3 DORNERWORKS – TODD BURGHGRAEF, AARON CORNELIUS, CURT STIENSTRA

In the first semester we engaged DornerWorks in preliminary conversation about our project as an industrial support for our team. DornerWorks was willing to meet with us and discuss the early definition stage of our project and advise us on possible goals to strive for and work to accomplish. In the coming semester we hope to communicate with DornerWorks while constructing our prototype for help with project direction and debugging.

11.4 INDUSTRIAL CONSULTANT - TIM THERIAULT

We met with our industrial consultant, Tim Theriault, during first semester to discuss our project. Tim was willing to provide feedback on our current progress as well as potential risk areas to consider when going forward with our project. We will meet with Time again in second semester with the hope of providing more details on our project and having him guide us more in the design work.

11.5 PROFESSOR RANDALL BROUWER

Professor Brouwer is an Electrical Engineering professor at Calvin College. We have all had classes with Professor Brouwer and will use him as a resource for any issues we may run into with our project. Professor Brouwer has helped prepare us for this project through the information that he has taught us in the previous years.