

Multi-Touch Table: A Natural User Interface Using a Projector and Infrared Tracking

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Add a projector in a box to infrared tracking of gestures using frustrated total internal reflection, get a multi-touch table.

Abstract

A multi-touch screen is a natural and intuitive way to interact with computers, and have many applications – from interactive exhibits, assistance or computer use for people who are disabled, to collaboratively working on a computer. This project is a multi-touch display built into a table structure. Using infrared LEDs and a makeshift infrared camera, touch events are captured using digital signal processing, and the gesture data is used to control software and applications on a computer. The project is complete, with two software and two hardware versions. The first hardware version utilizes the Altera DE2 board to complete the image processing, with the board, a USB webcam, and the projector connected to the computer (the board is connected via Ethernet), and runs with approximately a four second lag. The second hardware version has all processing running on the computer, with little noticeable lag. The two software versions, both simple paint applications, are a multi-user option (up to ten touches, each touch is drawn with a different colour), and a single-user option (one person can draw, with gestures to change colour and drawing size).

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Functional Requirements

A multi-touch table is an interactive touchscreen which supports multiple touches to allow natural manipulation and interaction. The central functional requirement of the table is to track multiple touches on the screen, and use the touches to control a software application. From the user's perspective, there is a flat table with a touchscreen that they can control using touches. A projector provides the image of the software that the user interacts with, and a camera and the hardware processes the touch events.

The first main section of the central functional requirement is tracking multiple touches. This consists of a mechanism to produce touch events, which is done using infrared light and a camera outfitted with a filter to capture the light. These touches are captured, and the images of infrared light "blob" touches are processed to give multiple touch points. The movement of the touches is used to control the application running on the computer.

The second section is a software application, running on a main computer and displayed on the multi-touch screen, controlled by the touches and gestures.

Finally, the table is required to have a calibration mode to calibrate the spatial location of the touches on screen, such that the output of the projector is calibrated to the touches of the user.

Our final design largely achieved the above functional requirements. A working multi-touch table, with limited gesture support, was created. The mechanisms used to create the infrared touch events worked well.

A paint application was created to show the usage of the table, which used some gestures to switch colours, size of paintbrush, and to clear the image. In a multi-user paint application, each separate touch was tracked using a specific colour. Calibration was created and used at the beginning each time the application was run.

Two versions of the hardware of the multi-touch table were created. Both had the USB webcam and projector connected to a computer, rather than the Altera DE2 board. The first version connected the DE2 board to the computer via Ethernet (rather than USB), and ran all processing on the board, which resulted in around a four second lag. The second version ran all processing on the computer, with little lag.

Design and Description of Operation

Overall Operation

Essentially, the multi-touch table enables control of software applications using multiple touches. There are three main pieces to the hardware design: the hardware and equipment to produce gestures that can be tracked, the drivers and image processing to track the gestures, and a main application and operating system.

Two different hardware set-ups were made and used. The first set-up utilized the Altera DE2 board to complete the image processing. The webcam was connected to the computer via USB, the projector connected via DVI, and the DE2 board connected via Ethernet. The computer received the images from the webcam, sent them over Ethernet to the DE2 board which completed the image processing and sent the touch points back to the computer over Ethernet. This resulted in approximately a four second lag. The second hardware version had the webcam and the projector connected similarly, but all image processing ran on the computer instead of the DE2 board. There was little noticeable lag.

The two hardware block diagrams below (Figure 1) show the overall operation of the multi-touch table using the two hardware set-ups. The touch events that are processed by the hardware are produced using infrared LEDs and a technique called Frustrated Total Internal Reflection (FTIR), and the touch events are captured by the camera. The projector simply provides the image of the software onto the touch interface.

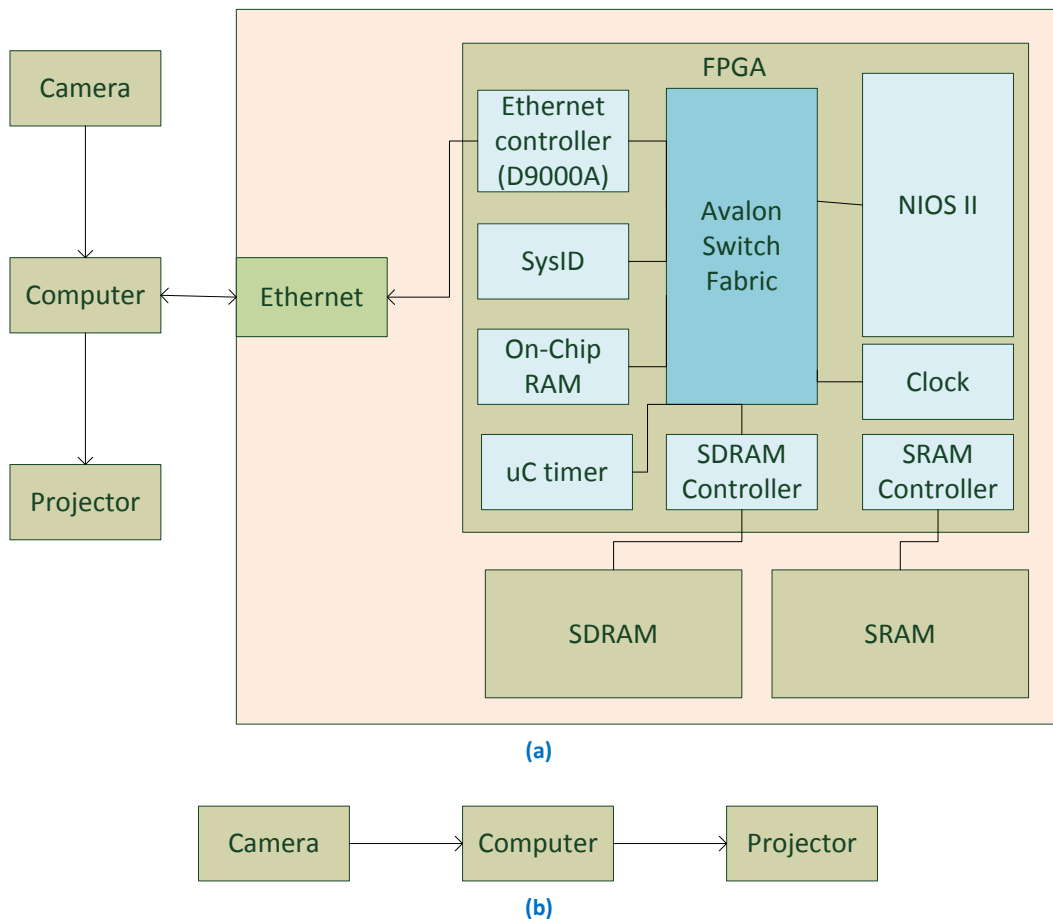


Figure 1: Hardware diagram of the multi-touch table. (a) shows the version of the multi-touch table utilizing the Altera DE2 board for image processing, and (b) shows the version with the image processing on the computer.

Infrared and Frustrated Total Internal Reflection

The multi-touch screen has three essential layers: an acrylic sheet, a compliant layer, and a projection surface (from bottom to top).

The acrylic sheet enables the touch events to occur. It is surrounded by a rim of infrared LEDs (with wavelength of 850nm) directed into the acrylic sheet, with one LED per inch. This enables a technique called Frustrated Total Internal Reflection (FTIR) to occur. First, the infrared light is trapped within the acrylic surface, as the critical angle of the infrared light is such that is reflected by the top and bottom of the acrylic surface and cannot escape (this is the “total internal reflection”).

When a touch event occurs (that is, the total internal reflection is “frustrated”), infrared light reflects downwards from the touch event due to the changed critical angle. A webcam with a filter to only pass infrared light is directly below the multi-touch screen, and captures images of infrared light containing the touch events.

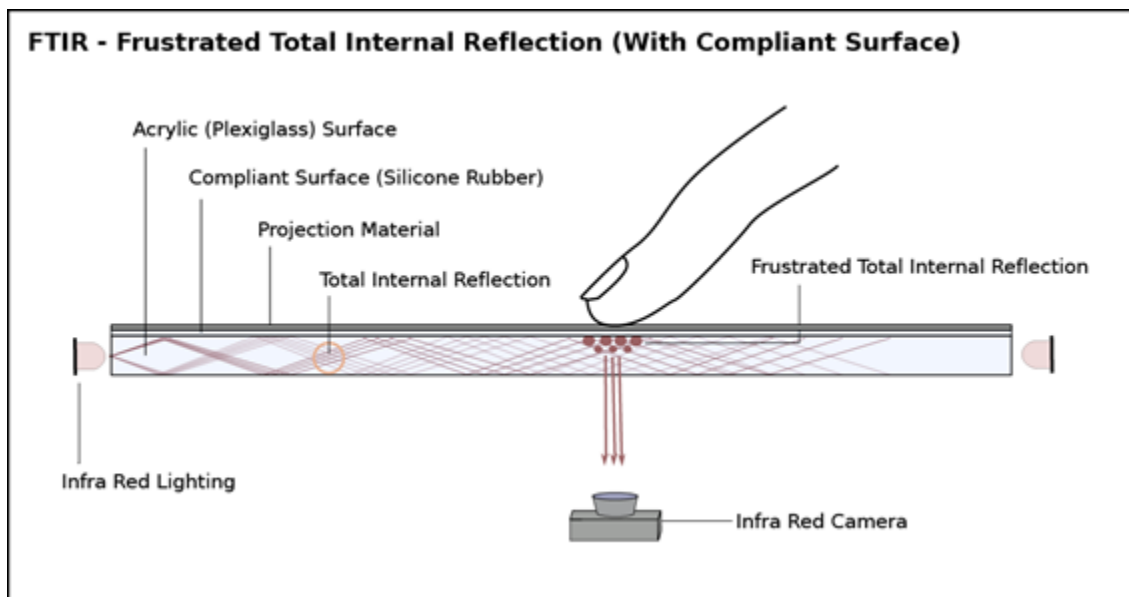


Figure 2: Frustrated Total Internal Reflection [1]

Total internal reflection is obtainable due to Snell's Law [2]:

$$n_1 \sin \theta_i = n_2 \sin \theta_t$$

Find θ_i when $\theta_t = 90^\circ$ and thus $\sin \theta_t = 1$. The resulting value of θ_i is equal to the critical angle.

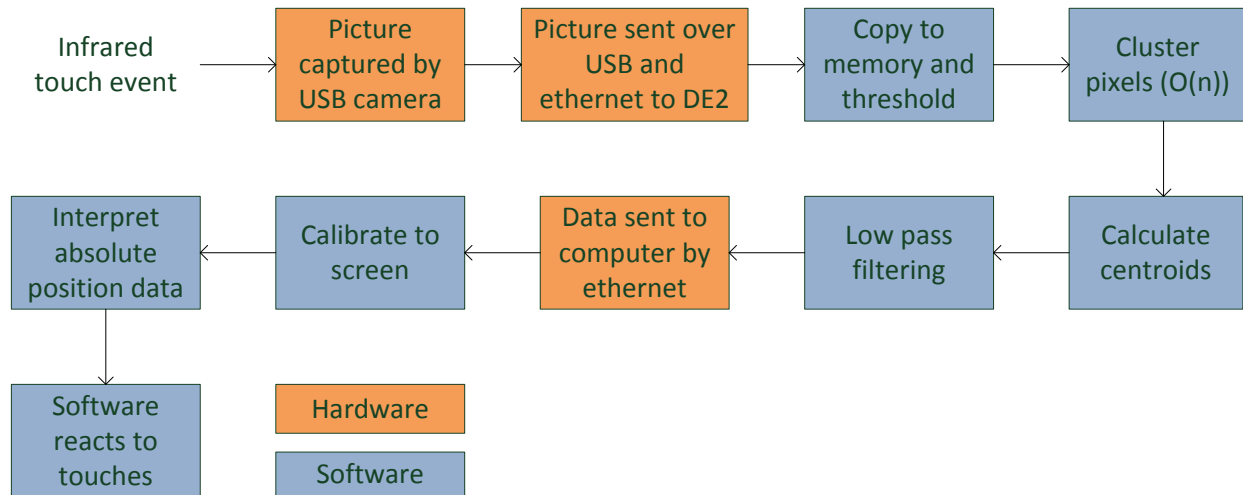
With a wavelength of 850 nm for the infrared light [3], the refractive index for acrylic is 1.485 [4]. The corresponding refractive index of air is roughly 1. When these two values are used, we get a critical

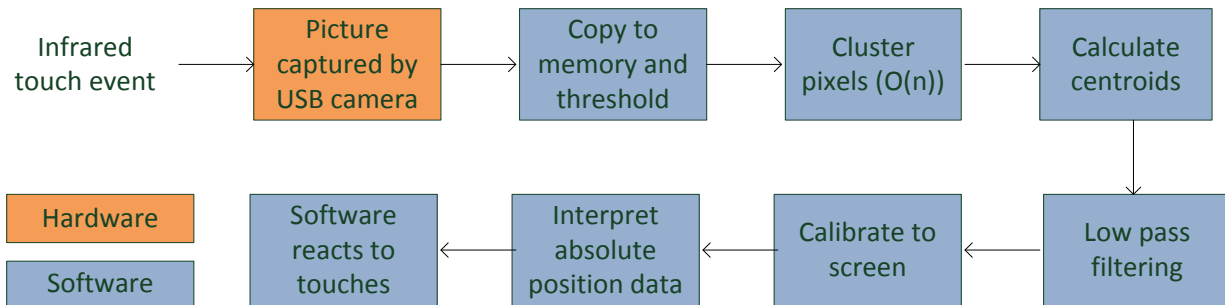
angle of 42.33° . This means that the infrared light that is shone into the acrylic must have most of it approach the internal border of the acrylic at this angle or greater in order for it to be reflected within the acrylic. In order to break the light out of the acrylic, we must make it so that the critical angle within the acrylic does not exist, such that n_2/n_1 is greater than 1. This can be achieved by replacing the air with another, high refractive index material, like silicone. When this occurs any light that touches the new border will have a different reflected angle, and much of it will exit the opposite side of the acrylic. This is how the “blobs” are generated.

The next two layers – a compliant layer and the projection surface – are required for correct operation of the table. As acrylic is too clear to be projected on to, a projection surface (vellum) is used. A compliant surface (silicone rolled on to the vellum, such that the silicone layer is between the vellum and the acrylic) is used to enable better images of the touches. Without a compliant surface, it is difficult to perceive moving touches (as it depends on properties of the finger – how oily, etc.). The silicone creates microblobs, which, when pressure is applied to the vellum, temporarily bond with the acrylic and frustrates the total internal reflection. This technique works well even with moving touches and does not depend on the properties of the finger.

Tracking of Gestures

The data flow to process the touch events is shown in Figure 3, with two different data flow diagrams for the corresponding hardware set-up (see Figure 1)





(b)

Figure 3: Data flow to process touch events. (a) shows the version of the multi-touch table utilizing the Altera DE2 board for image processing, and (B) shows the version with the image processing on the computer.

First, the images are captured by the USB camera using raw Bayer format [5], and sent to the computer, where they are either sent over Ethernet to the Altera DE2 board for processing, or processed on the computer. The infrared touch events appear as white “blobs” in the picture. The software (either on the board or on the computer) processes the images pixel-by-pixel. First, it thresholds each pixel (a pixel with an intensity above a certain amount is considered to be “1” and contain part of a touch, else that pixel is considered to be “0” and not be part of a touch). Next, it clusters groups of “1”s together into groups, separating each area of the image that contains a distinct touch event. Centroids are calculated of each separate thresholded area of the image, which is the point taken as the touch point. A low-pass filter is used to smooth the touch point as compared to the last picture frame, resulting in a smoother path of the gesture over time. This data, if on the board, is sent to the computer over Ethernet. The data is then calibrated to the size of the screen, from which the absolute position data is found. This position data enables control of the software (a paint application).

Computer and Paint Application

The main computer runs the operating system used, drives the projector image through the DVI, runs the paint application, and in one version, runs the image processing.

There are two different paint applications. The first is a multi-user application, which will track each touch, and draw in a different colour for each touch (the software picks the colours sequentially from a colour palette defined in the application). If a touch is continuous (that is, the centroids are close enough each frame), then it is considered to be one touch, and is drawn continuously in one colour.

The second application is a single-user application, where a single user can paint using one finger, but can select the colour and size that they are drawing with. To select the colour (from the limited colour palette defined in the application), the user presses using two fingers until they have selected the colour that they want. The options rotate through the entire palette. To select the size, the user presses three fingers.

In both applications, the screen can be erased using one large touch – such as a palm – pressing down. The software detects a large centroid, and completely refreshes the screen, erasing the painting.

Hardware Requirements

There are two different hardware requirements for the two different hardware set-ups. The first set-up, using the Altera DE2 board for the image processing, has all requirements detailed below. The second set-up, using a computer for the image processing, has interface requirements with the webcam and the projector.

The webcam's nominal frame rate is 24fps, but, measured at a data transfer rate of approximately 0.7MB/s, which is approximately 7fps. The frame rate for the projector is 80MHz [6]. The projector will interface to the computer using a DVI connection, and the webcam will interface to the DE2 board using a USB connection.

Interfaces

The interface between the webcam and the computer is USB, with a measured data transfer rate of 0.7MB/s. Ethernet is used between the computer and the DE2 board, if the DE2 board is used. The interface between the computer and the projector is a standard DVI interface, though VGA is easily substitutable.

Input/Output Rates

Output to Projector

Video bandwidth for projector is 80MHz, with 3 bytes per pixel.

$$80 \text{ MHz} * 3\text{B} = 240 \text{ MB/s}$$

A generalized video output from the DE2 to the projector requires too much data. Therefore, the main application runs on a computer and is output to the projector from the computer.

Webcam to Board

The rate of data from the webcam to a computer was tested to be 0.7MB/s, which includes all data for the pictures. Although the webcam has a nominal frame rate of 24fps, the tested rate of 0.7MB/s works out to approximately 7fps. This rate is reasonable for a USB 1.0 interface (which has a maximum rate of USB full-speed, 12Mbit/s, or 1.5MB/s), and easily managed by a USB 2.0 interface.

Board to Computer

For each frame sent by the webcam, data for ten touch points is sent to the computer. Each touch point contains three integers: an x location, a y location, and the size of the touch point. Therefore, the data rate is:

$$24\text{Hz} * (3*10*4\text{Bytes} + 4\text{Byte header}) = 2976\text{B/s}$$

This rate is reasonable for Ethernet.

Processor Performance

For the image processing, the number of calculations per second is:

Copy and threshold	1 comparison per pixel
Cluster pixels	5 comparisons per pixel for first pass 2 comparisons per pixel for second pass
Calculate centroids	Four multiplications and two additions for each of up to 10 clusters
Low-pass filter	Two multiplication and two additions for each of 10 points
Calibrate	Two multiplications for each of 10 points

This is a total of approximately 8×101376 pixels + 40 = 811048 (comparison, addition, subtraction) operations and 80 multiplications per frame. For 24Hz, there are 19,465,152 (comparison, addition, subtraction) calculations per second, and 1920 multiplications per second.

The NIOSII/f can run at 0.8DMIPS/MHz, or 80DMIPS at 50MHz. This speed is adequate for the above processing, and the processing of each image was virtually instantaneous when tested.

Required Capacities

To buffer one frame in the SRAM, which is the only memory requirement, 101kB is required (the size of one frame from the webcam), far below the capacity of 512kB. There are 5617 FPGA logic gates used.

Bill of Materials

Part	Specifications	Supplier	Datasheet	Cost
Projector: NEC MT1065	3400 Lumens output 2.46-68.9' projection distance 25-500" diagonal image size 4:3 image ratio VGA input 100-120VAC at 4A or 200-240VAC at 2A 390W power consumption 80MHz video bandwidth	University-supplied (AICT)	http://www.projectorcentral.com/NEC-MT1065.htm	\$0
Logitech Quickcam Express		Group member	http://logitech-en-amr.custhelp.com/app/answers/detail/a_id/3606	\$0
Infrared LED: HIR7393C	850nm 1.45V, 100mA forward DC 50° viewing angle	Digikey (manufacturer is Everlight Electronics Co Ltd)	http://www.digikey.ca/product-detail/en/HIR7393C/1080-1033-ND/2675524	\$33.73 for 100

Clear acrylic sheet	18"x24" Polished edges 3/8" thick	ECE machine shop		\$43.20 (\$0.10 per square inch)
Vellum	18"x24"	Colours Art Store		\$2.45
Silicone		Home Depot		\$4.99
Xylene		Group member	http://www.sciencelab.com/msds.php?msdsId=9927646	\$0
Construction materials		Home Depot and group member		\$15
Ethernet cross-over cable		Staples		\$17.95
Altera Terasic DE2 Development Board		Lab kit	http://www.altera.com/education/univ/materials/boards/de2/unv-de2-board.html	\$517.72
VGA cable		Lab kit		\$20.00

Total: \$640.04

Reusable Design Units

Open Source Software

LibUSB

LibUSB [10] contains a C library for USB interfacing for multiple operating systems. The full library is approximately 45kB, but the full library is not necessary. The full source code is available from <http://www.libusb.org/>. The code to interface to the webcam over USB is approximately 100kB.

Calibration Software

Simple calibration software [11] implements calculations necessary to obtain calibration factors for a touch screen that suffers from multiple distortion effects. This code is suitable to run our calibration program, and is 18kB. It is available from <http://www.embedded.com/design/system-integration/4023968/How-To-Calibrate-Touch-Screens>.

Device Drivers

Linux Driver for Logitech Quickcam Express

The Linux Driver for Logitech Quickcam Express [12] includes the protocol for the webcam used, allowing the resolution for 352*288 pixels. The sensors in the camera are controlled via an I2C bus. The compiled size is approximately 100kB and is available from <http://www.lrr.in.tum.de/~acher/quickcam/>.

USB Application Notes

The USB application notes [13] include a USB driver, for use with the ISP 1362 USB chip on the Altera DE2 board with the ISP 1362 controller. It is available from https://www.ualberta.ca/~delliott/local/ece492/appnotes/2013w/USB_ISP1362/, and compiles to a size of 109kB. These drivers are modified to work with a different hardware controller.

Datasheet

Processing on Altera DE2 Board

The user-perspective block diagram can be found below. Of note this that all components must be connected to appropriate power supplies, and the projector and webcam must be positioned directly beneath the touchscreen surface. The computer and Altera DE2 board are connected using a crossover Ethernet cable, the projector and computer are connected using a DVI cable (a VGA cable may also be used), and the webcam and computer are connected using a USB cable.

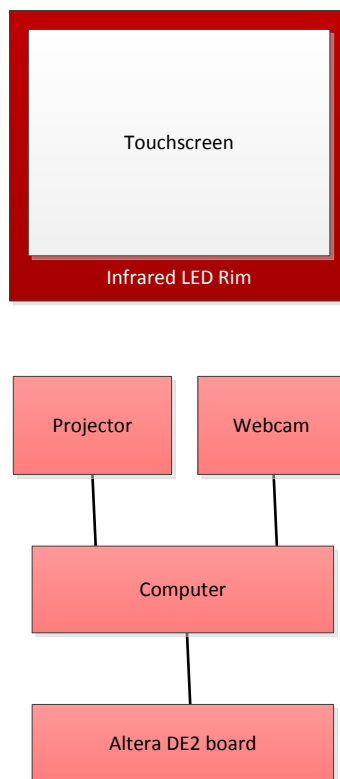


Figure 4: User perspective block diagram of the multi-touch table.

In this set-up, there is approximately a four second lag between the actual touch and the response in software.

Signal	Details	FPGA to Board	Off-board to other boards/chips	Off-board electronics to world
Computer to projector	5V VGA, supplied from computer		X	
Webcam to computer	5V USB, supplied from computer		X	
DE2 board to computer	2.5V crossover Ethernet, supplied from computer		X	
Ethernet controller to Ethernet		X		
Infrared light from touches to webcam				X

Component	Details	FPGA to Board	Off-board to other boards/chips	Off-board electronics to world
Power for LEDs	Peak voltage: 12V Current: 1.4A (0.1A for each branch of circuit) Maximum current: 0.200A for each LED [3] Measured as LED circuit was on.			X
Power for DE2	9V AC wall power Peak voltage: 9.00V Peak current: 0.61A Measured as DE2 was operating.			X
Power for computer	Voltage: 19.5V Current: 3.34A From datasheet for computer [14].			X
Power for projector	Voltage/current: 100-120VAC at 4A or 200-240VAC at 2A. From datasheet [6].			X

In active mode, the power for each device is:

Projector: 400W
LED circuit: 16.8W
Altera DE2: 5.49W
Computer: 65.13W
Total: 487.42W

There is no idle mode.

In sleep mode, the power for each device is:

Projector: 0W
LED circuit: 16.8W
Altera DE2: 5.49W
Computer: 0W
Total power: 22.29W

Processing on Computer

The user-perspective block diagram can be found below. Of note this that all components must be connected to appropriate power supplies, and the projector and webcam must be positioned directly beneath the touchscreen surface. The projector and computer are connected using a DVI cable (a VGA cable may also be used), and the webcam and computer are connected using a USB cable.

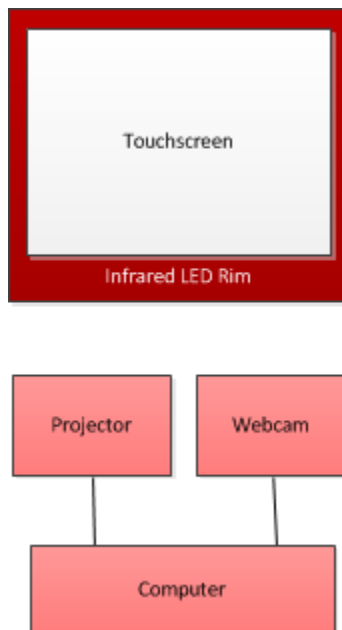


Figure 5: User perspective block diagram of the multi-touch table.

In this set-up, there is little noticeable lag between the actual touch and the response in software.

Signal	Details	FPGA to Board	Off-board to other boards/chips	Off-board electronics to world
Computer to projector	5V VGA, supplied from computer		X	
Webcam to computer	5V USB, supplied from computer		X	
Infrared light from touches to webcam				X

Component	Details	FPGA to Board	Off-board to other boards/chips	Off-board electronics to world
Power for LEDs	Peak voltage: 12V Current: 1.4A (0.1A for each branch of circuit) Maximum current: 0.200A for each LED [3] Measured as LED circuit was on.			X
Power for computer	Voltage: 19.5V Current: 3.34A From datasheet for computer [14].			X
Power for projector	Voltage/current: 100-120VAC at 4A or 200-240VAC at 2A. From datasheet [6].			X

In active mode, the power for each device is:

Projector: 400W
LED circuit: 16.8W
Computer: 65.13W
Total: 481.93W

There is no idle mode.

In sleep mode, the power for each device is:

Projector: 0W
LED circuit: 16.8W
Computer: 0W
Total power: 16.8

Background Reading

Low-Cost Multi-Touch Sensing Through Frustrated Total Internal Reflection

This paper [15] goes through the history of FTIR applications and the method that we are using for our project. The paper also explores possible reasons for certain choices (Compliant surfaces to create sharper images) and potential unique applications to be explored in the future. These unique applications will not be explored by our group due to the amount of research that would be required for them to be complete.

USB 2.0 Specification

The USB 2.0 specification [16] details the USB 2.0 interface and defines the industry-standard USB. It “describes the bus attributes, the protocol definition, types of transactions, bus management, and the programming interface” to build systems that are compliant. This specification was particularly relevant to earlier versions of the multi-touch table, which connected the USB webcam to the Altera DE2 board, and was useful while working on the USB controller for the DE2.

Digital Image Processing

In this text [17], methods of digital image processing are detailed, including discussion of concepts and algorithms, as well as examples and ready-to-use implementations. While most concepts of the digital image processing used in the multi-touch table are from knowledge from courses taken (ECE 440), this serves as a useful supplement and source of examples.

Software Design

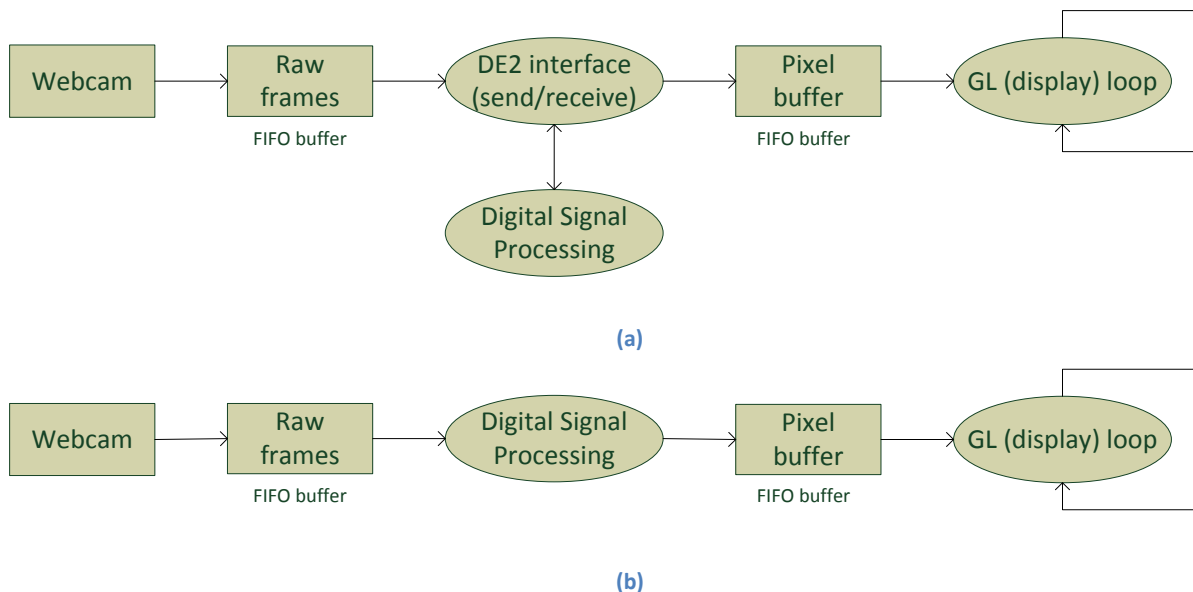


Figure 6: Software process diagram. In (a), the digital signal processing is done on the DE2, while in (b), the processing is completed on the computer.

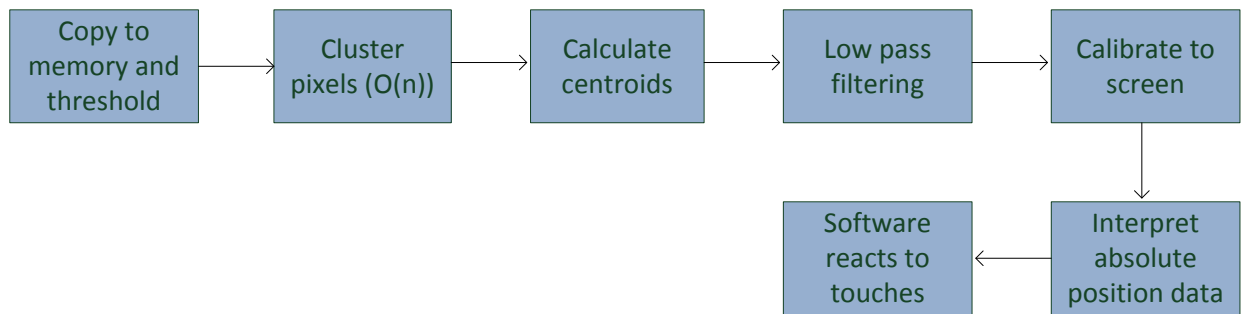


Figure 7: Software data flow to process touch events.

From the webcam, we receive images such as the one below. This image will be reduced to a binary image by thresholding each pixel. If the thresholding picks up some of the noise pixels, low-pass filtering may be used to smooth the image before the thresholding. Post thresholding, the image is binary (pixels are 1 or 0). With this binary image, pixels are clustered, with groups of '1's clustered into groups.

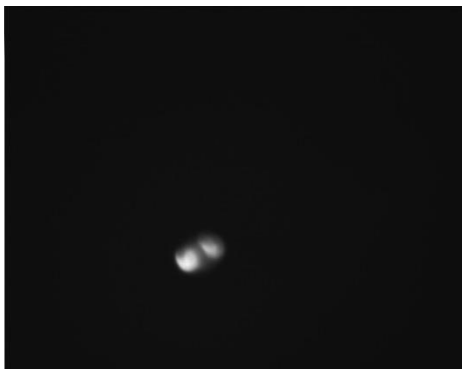


Figure 8: Infrared picture

Clusters that have sub-par pixel count, determined by a constant, are removed, and the remaining clusters represent fingers. The centroid of each cluster that represents a finger, as well as the size of the cluster, is calculated and used to represent the single instantaneous point of the touch. Afterwards, another temporal low-pass filter is used to smooth jitter in the finger position. Previous finger data is also useful in splitting one large cluster that is formed from multiple touches.

Once touch points are distinguished, they are run through a gesture detector which takes finger data as inputs and outputs computer actions to the computer. The software (a simple paint application) reacts to those touches. There are two different paint applications: a single user and a multiple user application. In the multiple user application, up to ten touch points are found from each frame. Each touch is assigned a colour from a selected palette, and that touch then draws in that colour. In the single user application, one touch is used to draw, two touches is used to switch the colour, and three touches is used to change the size of the paintbrush.

If a touch point has not moved much, and has a continuous line through time, then that line is considered to be one touch. Several simple gestures are found for the single-user application: if two touches are detected, then the colour switches between colours in the selected colour palette, and if three touches are detected, then the size increases (up to the maximum size, and then circles back to the smallest size). Finally, for both applications, if a cluster of a significant size is detected, then the display is erased – for example, placing a palm on the touchscreen will erase the screen.

Before running the application, initialization includes filtering of noise and calibration. The initial frame from the webcam is used to filter out all noise – the byte values of each pixel in this frame is subtracted from each frame afterwards, which filters out everything but touches (including a spot from the projector, as well as any spots from the infrared LEDs).

Calibration is run at the start of the application, which consists of having the user touch each of three asymmetrically placed points. The user touches the surface and then lifts their finger, and the application considers the last touch point found (that is, when the user lifts their finger), to be the physical place where the point was displayed. Using the points that the webcam detects (the “physical” points), and the point on the screen where that point was displayed, a calibration matrix is created. This calibration matrix is multiplied against every touch point detected in the program to determine where to display that point on the screen.

Test Plan

Software Test Plan

To test the software, first functionality was tested using unit tests and integration tests to ensure that the software processes worked correctly, particularly testing each individual step of the digital signal processing. Test image frames (both generated and real from the camera) were used, and the software process was tested on the computer, printing out the data after each step.

Gestures, as detailed in the software design section, were also tested – two touches to change colour, three touches to change size, and one large touch to erase the display. The ability to draw, and have one moving touch tracked as one touch (and drawn using one colour) was tested.

Hardware Test Plan

Each section of hardware was be unit tested, and the integration and overall functionality was be tested.

Webcam Infrared Tracking

Using the acrylic sheet surrounded with infrared LEDs with the webcam placed beneath looking up, the acrylic screen was touched, registering touch events in the webcam. The webcam was attached to a computer with the provided driver, and the ability to visually track the touches and the contrast of the touches was tested. Three types of touches were tested: multiple moving touches (upper bound), normal usage with two-three touches, a single non-moving touch, and no touches (lower bound).

USB controller and driver

The USB controller and driver was tested using simple uC/C programs that test the basic functionality. The USB was first tested by reading registers from the ISP 1362 chip, including the chip ID and registers that contain information on devices plugged in. The USB was tested by using a simple device to send single bytes of data to the board.

Ethernet controller and driver

The Ethernet controller and driver was tested using simple uC/C programs that tested connection between the Altera DE2 board and the computer.

Integration

First, simple tests were performed after integration – sending data from the computer to the board, calculating centroids on the board, and sending those centroids back to the computer, ensuring that those centroids were correct.

Final functional testing will include testing the strict functionality of the multi-touch table: that the software responds to multiple touches. This will be done by testing multiple moving touches (upper bound), normal usage with two-three touches, a single non-moving touch, and no touches (lower bound), and test that functionality is correct for each. Gestures were also tested – two touches, three touches, a large touch to erase, and moving continuous touches.

Performance and characterization included testing response time (that is, the time between a touch on the screen and the response of the screen projection), the pressure of the touch required and if there is any noise (that is, touches recorded by software but not actually performed), and recognition of gestures (that is, how precise a gesture needs to be before it is recognized).

A calibration procedure was also tested: calibrating the spatial location of touches on the screen (by having the user touch three specific points on the screen).

Results of experiments and characterization

All of the different units have been tested: the ability of the webcam to capture infrared light and touches to the acrylic, the digital signal processing of infrared light from the webcam, the communication over Ethernet, the functionality of the USB, and the usage of gestures.

Integrated testing has also been completed.

Webcam and USB Communication

The ability and rate of communication over USB between the webcam and a computer were tested, using the webcam driver and a short program designed to test the rate of communication. The communication over USB was successful (the webcam has been initialized with starting messages over

the USB from the computer using C code), and was found to have a rate of 0.7MB/s, below the maximum full speed USB data rate of 1.5MB/s.

The USB controller was able to read the ISP1362 chip ID. The ability to send and receive interrupts via USB was also tested, using a SONY playstation 2 controller, which sends consistent data over USB. Using the USB controller with the USB webcam, the ability to change control registers in the webcam over USB was tested and functional. The USB controller was not able to correctly receive isochronous data packets from the webcam.

Webcam and Infrared Light

The webcam, outfitted with the filter to pass infrared light, has done adequately. Two pictures of the testing are below; the first is a picture looking directly at an infrared LED. It is clear that the wavelength of the infrared light (850nm) is clearly picked up and results in a clear image. The second picture shows finger touches on the acrylic, which results in a picture with visible finger touches.



Figure 9: Directly looking at infrared LED

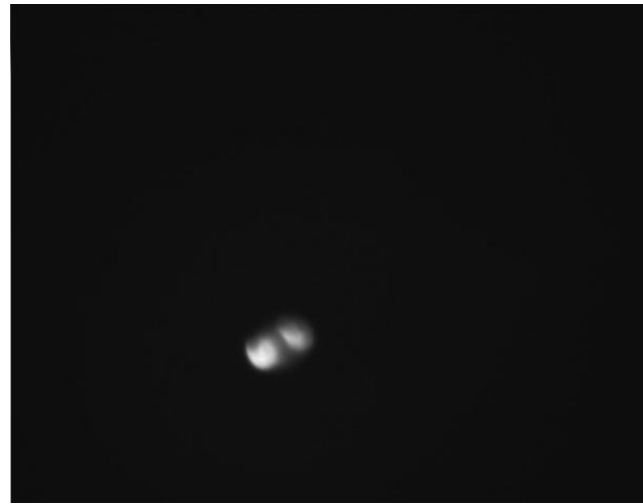


Figure 10: Touch event on acrylic

Digital Signal Processing

The ability of the digital signal processing was tested: each step of the digital signal processing was tested as it was created. The calculation of centroids have also been unit tested to ensure that the centroids are mathematically accurate. The final ability of the digital signal processing to process infrared light touch events (“blobs”) and calculate a single point (the centroid of the infrared touch event) is shown in the figure below.

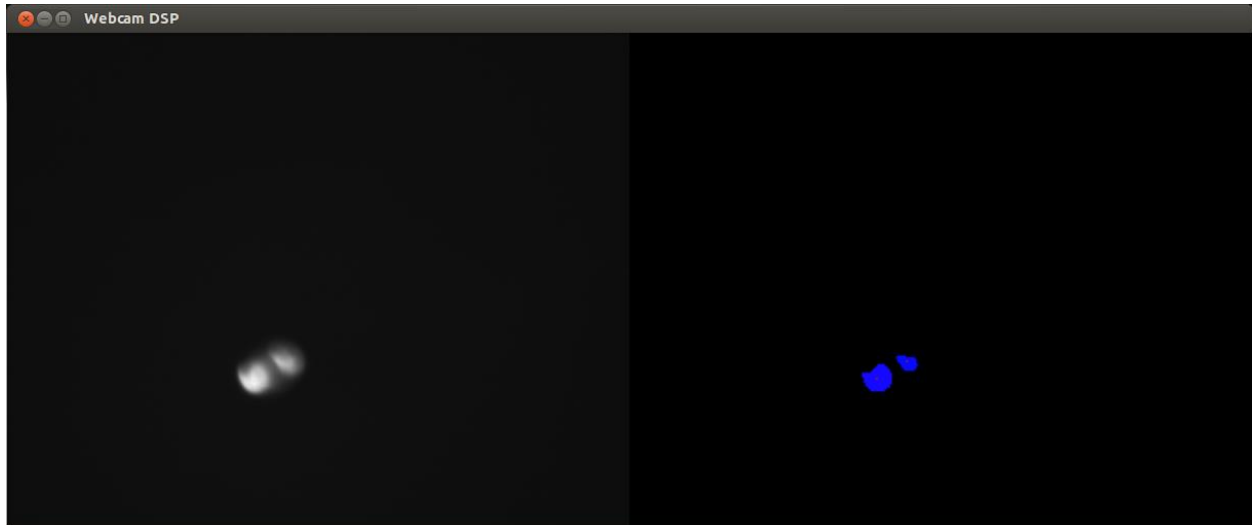


Figure 11: On the left is the infrared touch event, on the right is the same image post-digital signal processing (centroid points are small red dots).

A higher density LED rim will result in more clear touch events, as there will be a higher intensity of infrared light trapped within the acrylic. However, there is a trade-off here between adequate operation and cost, time, and effort to solder the LED circuit. We have decided to use one LED per inch around the circumference.

Integration Testing

Using the Altera DE2 board to complete the image processing, touches were detected. Images were sent from the computer to the Altera DE2, and the centroids calculated on the Altera DE2 were returned to the computer. Initially, this process took approximately 40 seconds. Using a faster processor and optimizing the code, this process took approximately 4 seconds. However, the image sent over Ethernet was skewed slightly, so, while touch points were calculated, calibration did not work.

Using the computer to complete the image processing, touches were detected, correct centroids were found, and the image was drawn on the display properly calibrated. The multi-user version drew multiple touches, and tracked moving touches. The single-user version used the gestures to change colour and size appropriately. There was little noticeable lag, even with many touches.

A medium amount of pressure was required in both cases to register touches.

Safety

There are no major safety risks posed by this project, but there are two minor safety risks.

The first risk is during production of the table: xylene is mixed with silicone. The xylene [7] can cause severe eye irritation, is an irritant and harmful if absorbed through the skin, is dangerous if inhaled or swallowed. First aid measures in case of contact to the substance are flushing with water for eyes and skin, removing from exposure and oxygen if breathing is difficult in case in inhalation, and water and

medical aid in case of ingestion. Preventative measures include adequate ventilation to keep airborne concentrations below exposure limits in addition to personal protective equipment (safety goggles, protective clothing to prevent skin contact). To safely make the compliant surface, one group member underwent the appropriate training (laboratory safety training, MSDS), and used the mixture in an appropriate organics fume hood using the appropriate personal protective equipment, under the supervision of an experienced lab member with the permission of the laboratory technician.

There is slight possible safety risk posed by the infrared LED, as our eyes are unable to “warn” about too much or too intense light, and heat is damaging to eyes. However, the LEDs have a low radiant intensity and are directed into the acrylic, away from humans. According to [14], for exposure time greater than 1000 seconds, the below (where E_e is irradiance and I_e is radiant intensity, found from [3]) must be true:

$$E_e = \frac{I_e}{d^2} \leq 100$$
$$d \geq \sqrt{\frac{I_e}{100}} = \sqrt{\frac{50mW}{100 \frac{sr}{100}}} = 0.0224m$$

Therefore, any distance greater than 2.24cm away from the LEDs is safe for any working condition. As a precaution, the rim of the table was covered, covering the edges of the LEDs and ensuring that the infrared light is directed solely into the acrylic and that the LEDs are not looked at directly.

For the infrared LEDs, the maximum input voltage is 12V (total for circuit), with 150mW power for each LED and -40-+85°C operating temperature. The projector has a maximum input voltage of 240V, an operating temperature of 0-35°C, and power consumption of 390W. The Altera DE2 has an input voltage of 9V and power consumption of 13.5W. Finally, the laptop has 19.5V input voltage with 65.13W power consumption.

There is no stored energy except for the laptop, and the multi-touch table is not moving.

Environmental Impact

The multi-touch table is not RoHS (Restriction of Hazardous Substances) compliant, due to the webcam. The webcam was first released in 1999, before RoHS standards were implemented in 2006, and so cannot be guaranteed to be RoHS compliant. The infrared LEDs are RoHS compliant, and silver solder is used. The computer used and the Altera DE2 board are also RoHS compliant.

To ensure that future versions of a multi-touch table were RoHS compliant, the only modification required would be to use a RoHS compliant webcam.

Sustainability

Using the DE2, in active mode, the power for each device is:

Projector: 400W
LED circuit: 16.8W
Altera DE2: 5.49W
Computer: 65.13W
Total: 487.42W

There is no idle mode.

In sleep mode, the power for each device is:

Projector: 0W
LED circuit: 16.8W
Altera DE2: 5.49W
Computer: 0W
Total power: 22.29W

The active mode has a duty cycle of 33% and the sleep mode has a duty cycle of 67%. This results in an average power of 175.78W. Similarly, if the DE2 board is not used, the average power is 170.29W.

In a year, this is: $175.78W * 24 \text{ hours/day} * 365.25 \text{ days/year} = 1540.89\text{kWh/year}$

The cost of providing this electricity is: $1540.89\text{kWh} * 8.7\text{c/kWh} = \$134.06/\text{year}$

Without using the Altera DE2, electricity consumption is 1492.76kWh for a year, which costs \$129.87 per year.

The amount of CO₂ released from this electricity consumption is: $1540.89\text{kWh/year} * 0.989\text{kg CO}_2 = 1524 \text{ kg CO}_2/\text{year}$ (1476kg without using the DE2).

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Appendices

Quick Start Manual

- 1) Download OpenGL (GLFW3), and have gcc installed.
- 2) Plug in projector, and turn on.
- 3) Plug in LEDs, taking care to wire it correctly (white is power, red is ground). They should be powered at 12VDC with around 1.0A. Current may be increased slightly to increase the intensity of the touches.
- 4) Attach webcam to computer using USB.
- 5) Attach projector to computer appropriately, using either VGA or DVI.

If using the board:

- 1) Restore the archived Quartus project and unzip the software in the folder named "software".
- 2) Generate the Qsys system.
- 3) Compile the hardware.
- 4) Program the board using `niosII_microc_v5_0_nonvol.pof`.
- 5) Program the board using `niosII_microc_v5_0_nonvol.sof`.
- 6) The software project used is `socket_server` (with `socket_server_bsp`).
- 7) In `bsp_editor`, make sure that `dhcp` is unchecked.
- 8) Generate the `bsp`.
- 9) Clean and build `socket_server`.
- 10) Run software on NiosII hardware.
- 11) Flash software using the `flash` flash file.
- 12) Attach board to computer using cross-over Ethernet cable.
- 13) Change computer to static IP 192.168.1.2.
- 14) Build software on computer: in the folder `plan_b`, run `make`, and then run `./dsp`.
- 15) If green LED is on, then the socket server is ready for a connection. Once the green LED turns off, the connection has been made. On the computer, a welcome message from the DE2 will be displayed.
- 16) Move window to projection.
- 17) Touch calibration points as they appear (three of them).
- 18) Draw!
- 19) Press your palm (or other large surface) to erase the display.

If using only the computer:

- 1) Build software on computer: in the main project folder, run `make`, and then run `./dsp`.
- 2) Move window to projection.
- 3) Touch calibration points as they appear (three of them).
- 4) Draw! Use two touches to change colour and three touches to change size.
- 5) Press your palm (or other large surface) to erase the display.

Future Work

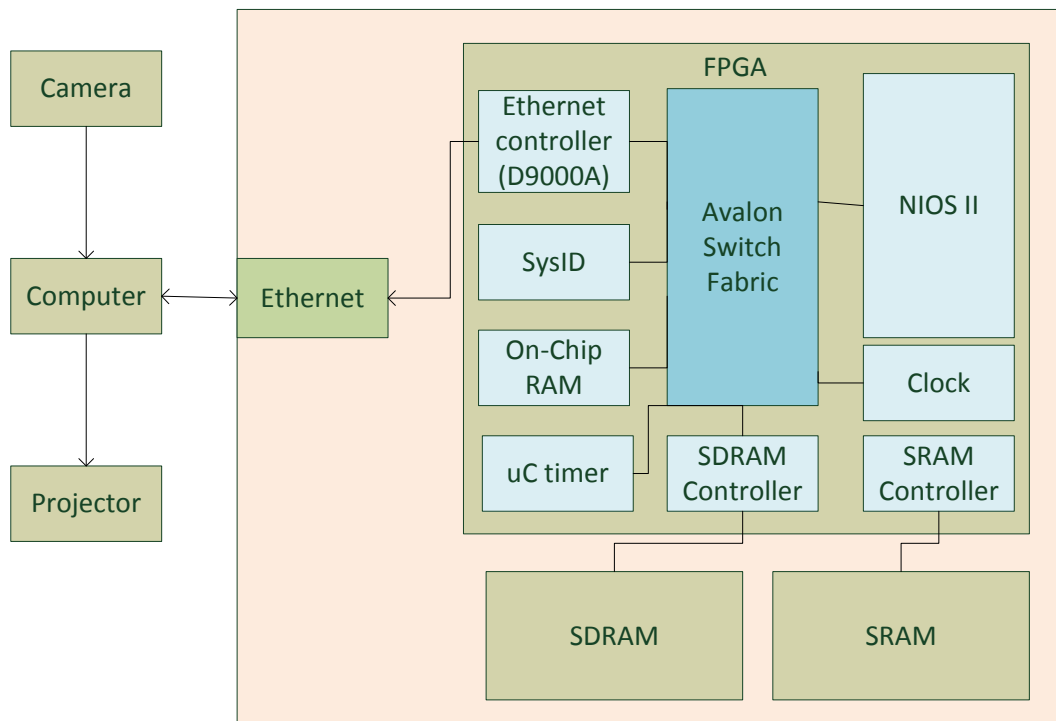
Modifications include only tracking a single touch, or completing a single action based on the average of all touches to the screen. Gesture tracking may be dropped, and only touches may be recognized. An optical filter made for infrared light at the correct wavelength may be used.

There are far more extensions. The first extension is simply hardware – completing the USB driver on the Altera DE2 board, and interfacing the USB webcam to the DE2 board instead of to the computer. In this version, all processing would be completed on the Altera DE2 board. A further extension of this would be to interface the Altera DE2 board to the computer using USB instead of using Ethernet.

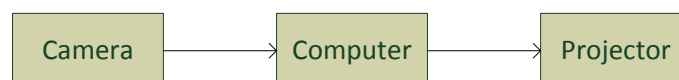
More complex digital image processing could be complete – adding in more gestures, as well as allowing the user to control their computer and other applications using touch and gestures. More complex actions, including features such as hand angle calculation, could be included and used to interface with the software.

A more complex application could be created, and applications specific to uses of a multi-touch table (eg. rehabilitation) could be created. A further extension is an application running solely on the Altera DE2 board, in which case a VGA controller and driver would have to be created for the DE2.

Hardware Documentation



(a)



(b)

Figure 12: Hardware diagram of the multi-touch table. (a) shows the version of the multi-touch table utilizing the Altera DE2 board for image processing, and (B) shows the version with the image processing on the computer.

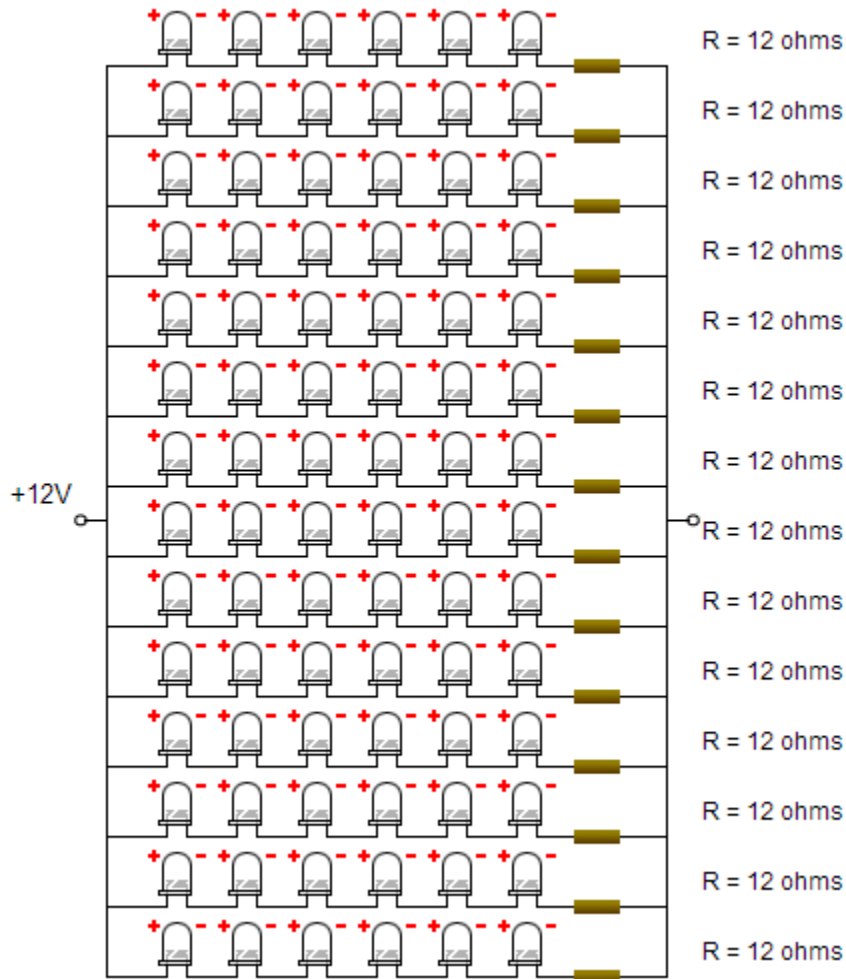


Figure 13: Infrared LED circuit

Source Code

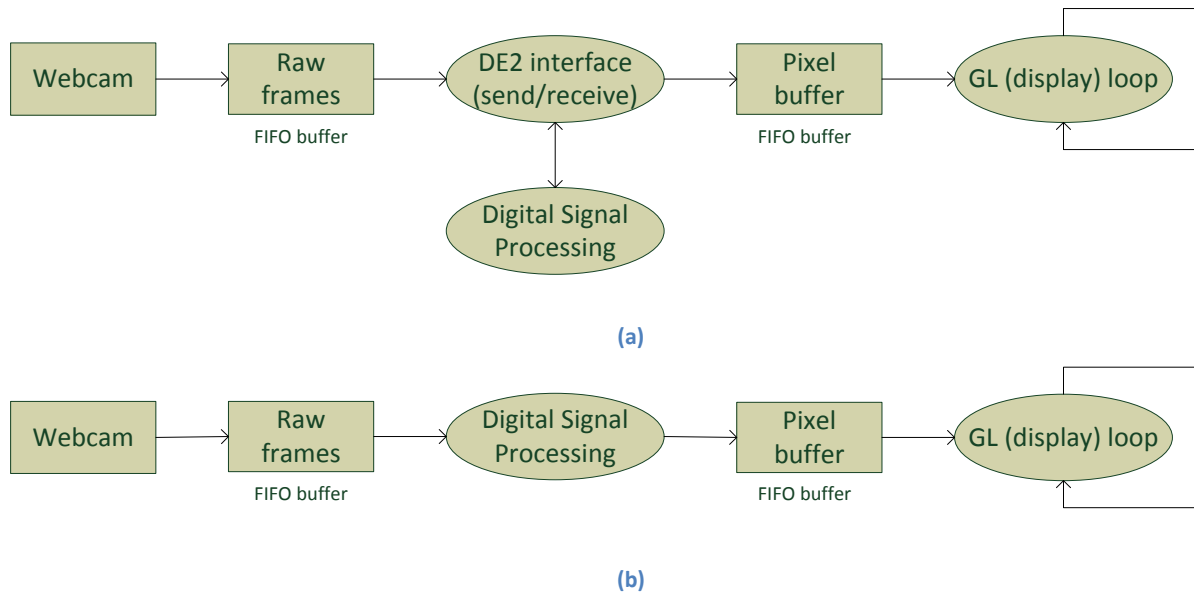
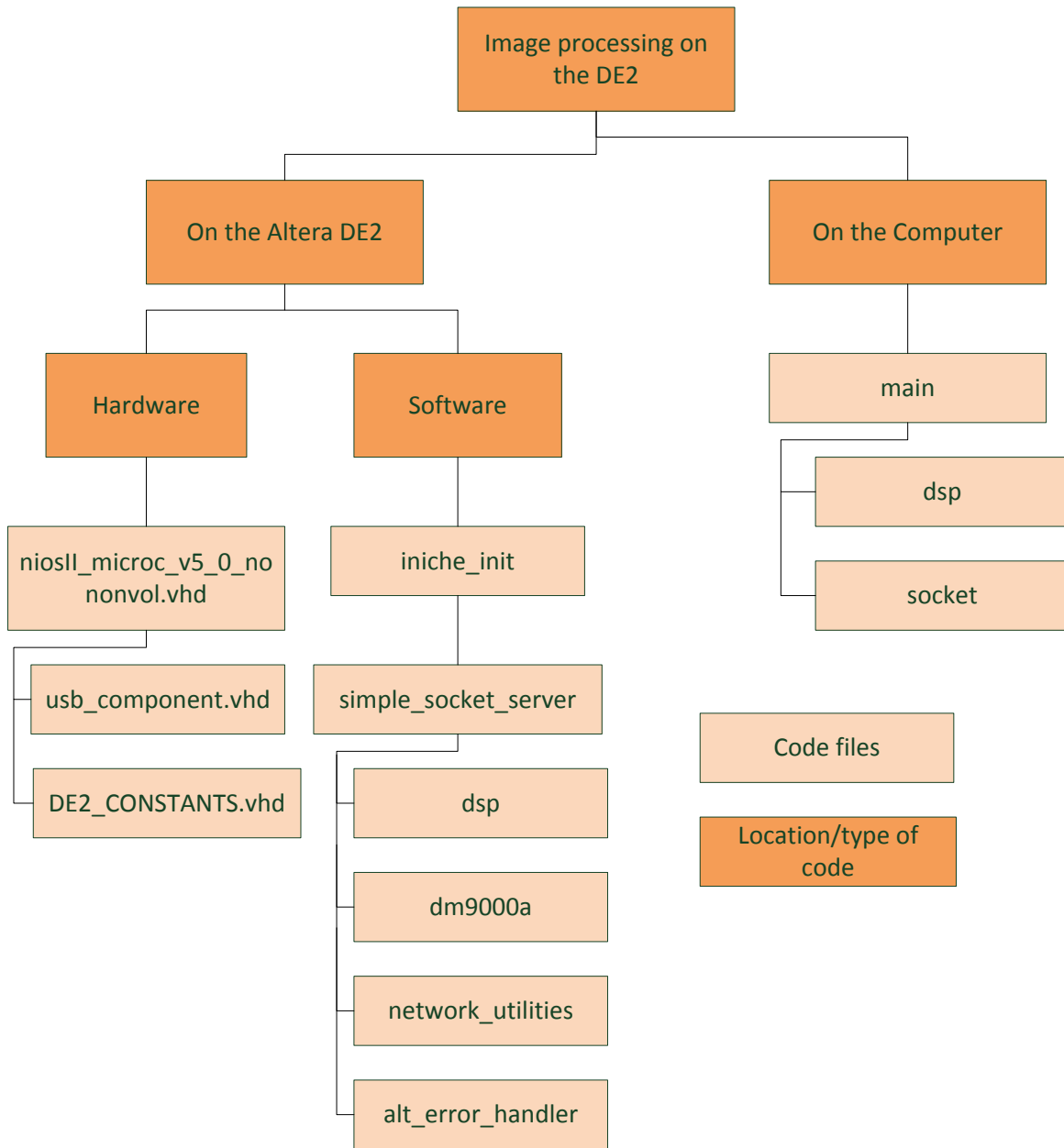


Figure 14: Software process diagram. In (a), the digital signal processing is done on the DE2, while in (b), the processing is completed on the computer.

Source code is provided in attached zipfile.

Index to Source Code



(a)

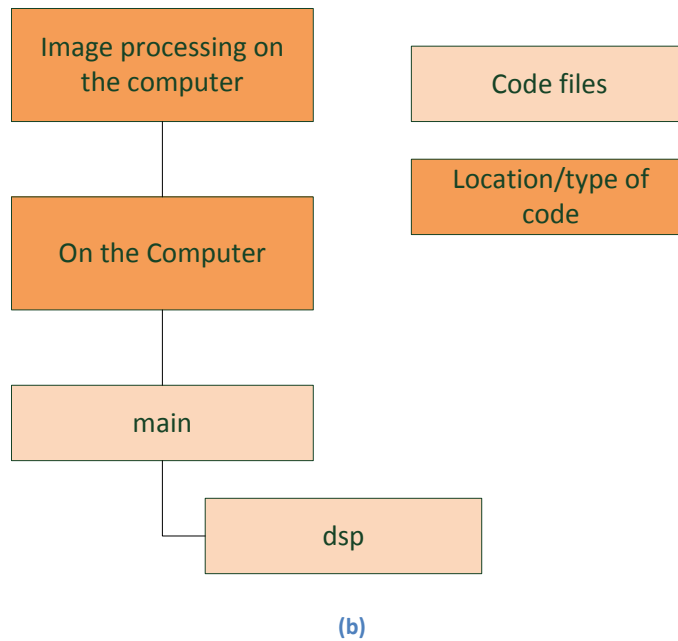


Figure 15: Code hierarchy. In (a), the image processing is done on the DE2. In (b), the image processing is done on the computer.

Image Processing on Altera DE2

Code on Altera DE2:

Name	Description	Status
usb_component.vhd	VHDL component for USB controller.	T
niosII_microc_v5_0_nonvol.vhd	VHDL toplevel for Altera DE2 hardware.	T
DE2_CONSTANTS.vhd	Constants used in the USB controller and toplevel file.	T
alt_error_handler.c	Error handler for socket server, provided by Altera.	T
alt_error_handler.c		
dm9000a.c	Ethernet driver, provided from application note.	T
dm9000a.h		
dm9000a_regs.h		
dsp.c	Digital image processing and calculation of touch points.	T
dsp.h		
iniche_init.c	Start point for socket server (includes main() function for software running on DE2)	T
network_utilities.c	Utility functions for the Ethernet connection. Provided by Altera.	T
network_utilities.h		
simple_socket_server.c	Manages the socket server, running on DE2. Provided by Altera.	T
simple_socket_server.h		

Code on Computer (all in plan_b folder):

Name	Description	Status
main.c	Main function: receives frames from webcam, uses functions from dsp.c to perform digital signal processing, and outputs display to projector.	E
makefile	Use make to build the software.	T
dsp.c	Functions for use in digital signal (image) processing.	T
dsp.h		
socket.c	Functions for use in sending and reading to the Altera DE2 over the Ethernet connection.	E
socket.h		
tests/makefile	Use make to make the unit tests.	E
tests/unit_tests	Unit tests to test the digital image processing.	T

Image Processing on Computer

Name	Description	Status
main.c	Main function: receives frames from webcam, uses functions from dsp.c to perform digital signal processing, and outputs display to projector.	T
makefile	Use make to build the software.	T
dsp.c	Functions for use in digital signal (image) processing.	T
dsp.h		
tests/makefile	Use make to make the unit tests.	T
tests/unit_tests	Unit tests to test the digital image processing.	T

Mouse Control

Name	Description	Status
macro.c	Gets information from a playstation controller and converts it to control the mouse. Can be modified to use with touch points.	E
macro.h		
makefile	Use make to build the software.	E