FPGA Virtual Air Hockey

A Design Project Report

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by

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Abstract

Master of Electrical and Computer Engineering

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Design Project Report

Project Title: FPGA Virtual Air Hockey

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Abstract: A virtual air hockey game was designed that blends together many aspects of embedded systems design in electrical and computer engineering to create an interactive game that is sophisticated yet intuitive to play. The video game is implemented on the DE2 FPGA educational development board made by Terasic for Altera's Cyclone II processor. The FPGA is used in combination with a CCD camera for video input as well as a monitor and speakers for game output. The camera tracks movements of LED paddles through image processing techniques and the players move the paddles to strike a virtual puck which is displayed on the monitor along with the on-screen paddles. In addition to synthesizing basic hardware on the DE2, a general purpose CPU, called the Nios II, is also instantiated on the board, which runs high-level C code. The dynamics of the game is coded in C. The result is a fully interactive game in which the users' movements of LEDs register as movements of paddles in the virtual air hockey game, accompanied by sound.

Report Approved by

Project Advisor:____Date:______________

Executive Summary

This design project was inspired by my interest in games and gaming console design. With the current generation of gaming consoles incorporating cameras, microphones, and motion sensors as inputs to the games, it was decided that a similar approach would be used. It takes a simple game like air hockey and incorporates image processing to mimic actual hand-controlled motion of the on-screen paddle. The image processing accurately captures the velocities of the users' movements to realistically affect the dynamics of the game.

The game utilizes sophisticated dynamics for controlling the puck movements, as well as many low-level hardware modules including video output, audio Digital to Analog Conversion, and image processing. Since the VGA only has whole numbered pixel resolution, 32-bit fixed point arithmetic allowed quick conversions of puck position between integer values and mixed fractional values. A high-resolution camera for the system used in conjunction with various digital image processing techniques such as dilating and eroding allowed accurate position detection for the paddles.

Originally, I had envisioned implementing the game on a traditional microcontroller. However, the idea of using reconfigurable hardware was appealing in that future firmware upgrades could also potentially change the features of the hardware and add or reduce functionality where needed. This last point is certainly relevant considering the existing game consoles on the market today already support firmware updates through internet connections. The entire project was done on the DE2 FPGA development board and TRDB_DC2 1.3 Megapixel camera, both made by Terasic Technologies, a speaker, a VGA monitor, and two LED-mounted paddles. The hardware was programmed in Verilog and the Nios II CPU was programmed in embedded C.

The project was a great success, and the game play is both natural and fun. I am extremely satisfied with the results and found the entire process very rewarding.

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INTRODUCTION

Upon starting my Masters of Engineering design project, my goal was to create an embedded systems project that would utilize both knowledge of hardware organization and software development. To achieve this goal, the idea to create a video game that was both interactive and intuitive to play was born. The idea of physical movements controlling the game was influenced by the present state of the gaming industry, and provides an added fun-factor for the user who feels more involved in the game play. Even a seemingly simple game such as air hockey involves a great deal of electrical and computer engineering knowledge. By organizing the hardware on the FPGA for fast response as well as programming a general purpose CPU instantiated on the FPGA to run high-level logic, I was able to create the game environment I aimed for. Through use of the system, one can immediately see that it is highly responsive to the user's movements, and the dynamics of the game emulates the real experience very well.

DESIGN REQUIREMENTS

There were three main requirements for this video game which ultimately shaped the resulting product. The most important design requirement was the responsiveness of the system. For the most part, this meant that the image capturing and outputting needed to be fast and therefore implemented in hardware which required no additional software logic. The game dynamics could take a little longer since the game needed to be slow enough for humans to play, and was accordingly implemented in software running on the Nios II CPU. Other requirements were that the video game run smoothly with no lags or glitches in the game play and simply that it should feel like a real game of air hockey. This last requirement is a bit subjective and required adjustments made by iterative trial and errors.

The requirements of this project are summarized as the following:

- Good responsiveness, the actions feel like an extension of the user’s body
- Precise and accurate game dynamics
- Overall experience like playing real air hockey

BACKGROUND

Interactive Gaming-

With the recent burst of interactive video game consoles hitting the market, it is clear that there is much consumer interest in interactive gaming. The accelerometer/gyroscope technologies combined with infrared position triangulating in the Nintendo® Wii allow users to aim a gun or slash a sword, while the SIXAXIS tilt sensitive controller for the Sony Playstation® 3 allows players to guide a flying object with the tilt their hands instead of the motion of their thumbs. Other forms of interactive games also exist, such as stepping on pressure-sensitive pads or playing musical instruments along with a specific rhythm. While the packaging and forms may be different, the goals of these systems are all the same: provide control input to the game through the user's physical motion or sounds instead of key presses. The game input devices can be either digital, in the case of games like Guitar Hero, or analog like in Karaoke Revolution.

Air Hockey-

The game of air hockey adheres to fairly straightforward rules that can be modeled by a physics engine quite nicely. The game can be represented on a two dimensional space from a bird's-eye perspective which is also ideal for displaying relatively simple graphics. The energy input to the system are typically all impulses which translates to a sudden change in the puck's acceleration, or jerk, and small amounts of friction and energy dissipation due to inelastic collisions will remove kinetic energy from the puck and slow it down. The physics differ from elastic collisions like many billiard ball simulators. One reason is that the mass of the paddle is considerably larger than the mass of the puck because the user holds onto the paddle. In other words, the conservation of momentum ($p = m * v$) is trickier to express, assuming an extremely large mass of the paddle with a non-completely elastic collision. However, aside from paddle/puck collision math, the overall behavior of the system like position and velocity can be modeled nicely in a 2-dimensional coordinate system.

RANGE OF SOLUTIONS

To create a realistic game experience, many possible implementations and ideas were considered. Much cost-benefit analysis had to be taken into account and the following were things that were considered in ultimately coming up with the project solution.

Game Input

Upon coming up with the idea of the air hockey game, the first possibility for game input was to use accelerometers in conjunction with a camera so that I could measure actual acceleration, and therefore determine the force at the time of "contact". The accuracy of the collision force made this option fairly attractive. However, in researching wireless radio transmissions, it was determined that the overhead of both cost and time did not warrant that level of precision measuring. Instead, simply using the change in position from the imaging would have to provide sufficient data for the dynamics of the system.

The next idea was to use just a camera to determine the position of the paddles. The Sony PlayStation® 2 EyeToy camera uses edge detection and various signal processing techniques to determine the user's movements against the background. Conveniently, Terasic Technologies makes a CCD camera for the FPGA board that was ultimately used for this project. My idea was to draw upon principles similar to the EyeToy but to make the processing easier by detecting distinct colors, for example. The camera has a fairly high resolution that is capable of 1.3 Mega pixels which is more than enough for my desired application.

To ensure that the game can be played in all types of lighting, I decided to use colored LEDs as inputs for the game. Unfortunately the sensitivity of photo capture is different from human eyes and the colors of LEDs are not easily distinguishable as recorded through the camera. The following figure is an example of what a blue and yellow LED look likes through the camera, with the blue LED on the left and yellow on the right.

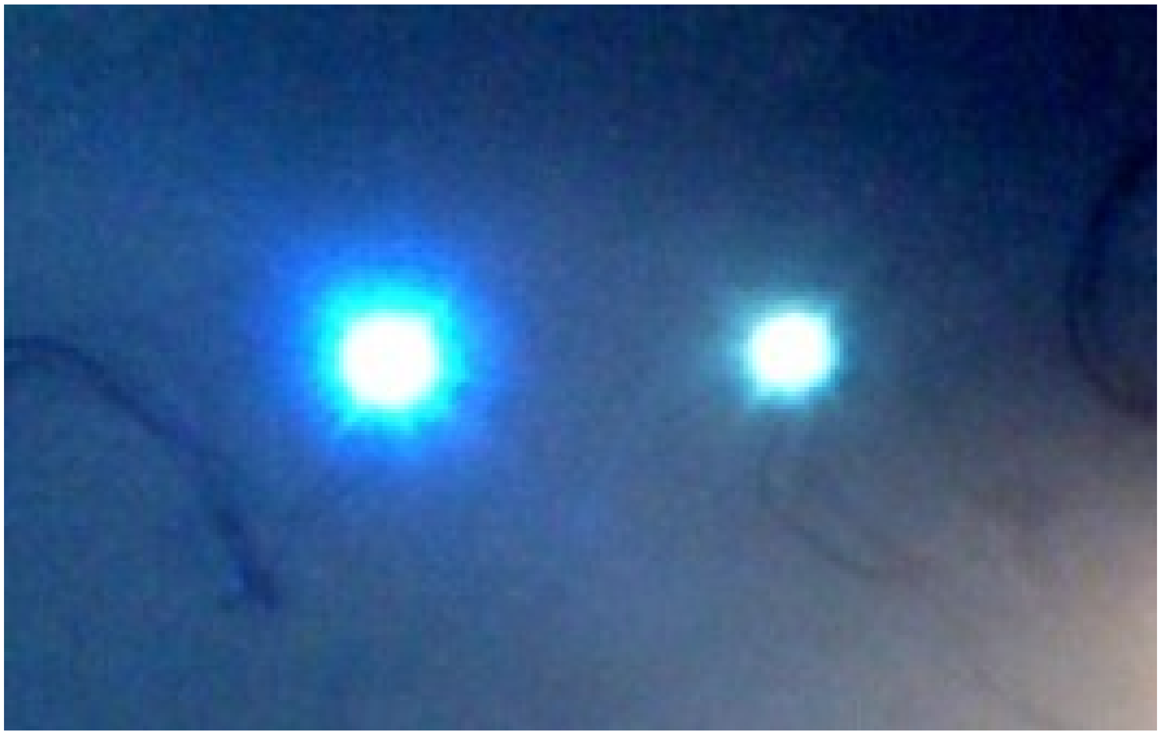


Figure 1

Notice that the blue LED, while having some blue in the fringes, is almost completely white. The yellow LED looks completely white, and differentiating the two in a reliable manner could prove to be complex. Instead of color, the next choice for detection was to simply use light intensity, tracking a certain level of whiteness (an intense mixture of red, green, and blue light), and splitting the playing space among the two players so that player 1 cannot move into player 2's space on screen.. Figure 2 is an example of what the light intensity of an LED looks like up close, with a value of zero being the lowest intensity (black) and five being the highest (white):

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	1	1	2	2	2	1	1	0	0	0	0
0	0	0	1	1	2	3	3	3	2	1	0	0	0	0
0	0	0	1	2	3	5	4	4	2	2	1	0	0	0
0	0	1	1	2	3	5	5	4	3	2	1	0	0	0
0	0	0	1	2	3	4	4	3	2	1	0	0	0	0
0	0	0	1	1	2	3	3	2	1	0	0	0	0	0
0	0	0	0	1	1	2	2	1	0	0	0	0	0	0
0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 2

One limitation of this approach is that dispersed light sources in the same camera space would need some sort of mechanism to decide which pixel would represent the paddle. In other words, how do we process the peak values (i.e., 5) in Figure 2 in an orderly and systematic fashion? The solution for this will be discussed in the DESIGN AND IMPLEMENTATION section.

Video Output

The idea is to play this game on a large display. For that reason, considerable time was spent considering the form of the video output. Digital outputs like HDMI or DVI are fairly standard in new televisions and monitors. HDMI and DVI have the ability to output tremendously high-resolution video of 1920 x 1080 and 1920 x 1200 pixels respectively. In addition to the digital video formats, there is also NTSC video used in standard television coaxial cables, and VGA for computer monitors. After considering the multitude of video output formats, a VGA interface was chosen for several reasons. First, the high definition digital formats are completely excessive for the type of video this system expects to output, which are simple geometric shapes with solid colors. The digital formats are also strictly specified so the time put into implementing and debugging the video output to conform to the strict standards would not be worth the benefits (which this project will be unable to make use of, anyway).

The VGA specifications are very similar to the NTSC protocol used for standard analog television sets, with two differences. One difference is that there are separate analog lines for each of color: red, green, and blue. The other major difference is that there are separate lines for horizontal and vertical sync pulses.

The basic premise of VGA is that the output device will send a repeating series of horizontal and vertical sync pulses to the monitor, which specifies the exact pixel to brighten or darken. Each horizontal sync pulse indicates to the monitor to shift its focus to the next pixel on the same line, while each vertical sync pulse tells the monitor to move on to the next line. Each pixel can be set to a specific red, green, and blue value depending on the voltage level of the respective color input, with a higher voltage level corresponding to a brighter color. Figure 3 is an example of what a sample VGA video signal may look like for the green color with respect to the sync pulses:

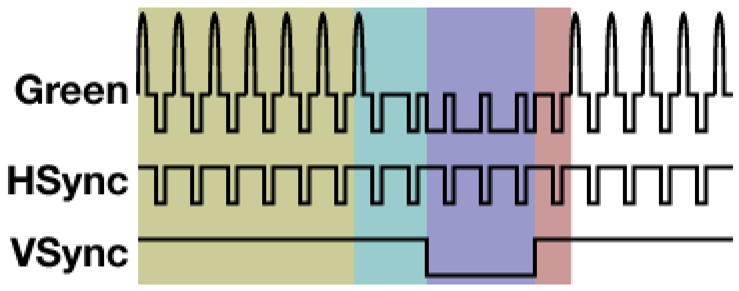


Figure 3

Sound Output

The aim for this project is to create a rich gaming experience, and no game would be complete without sound effects. There are many viable techniques for generating sounds, and the one chosen for this project is direct digital syntheses (DDS). The general functionality of DDS is explained as follows: a calculated constant number called a phase increment is added to an n-bit register every N clock cycles, causing the n-bit register to overflow at some constant rate. At the same time, the top x-bits (where $x < n$) of that register are used as index values for a table with y elements ($2^x \geq y$). This table is the digital values of a single sine wave spread out evenly over y elements. These digital values are sent to the DAC and an analog since wave is generated. To change frequencies, simply change the constant value that is added to the n-bit register. Mathematically expressed, the formula is:

$$\phi_{increment} = \frac{freq_{\sin e} * 2^n * N}{clk}$$

By correctly choosing the phase increment based on your known clock and N values, a sine wave with the desired frequency can be created. Notice that as you increase the sine frequency by using higher increment values, the time resolution of the sine wave gets worse and worse.

Final Project Definition

The final project is summarized as follows:

- Game input of detecting LED movements through a digital camera
- Game dynamics engine based solely on LED positions
- Video output via VGA interface
- Sound generation through Direct Digital Synthesis

DESIGN AND IMPLEMENTATION

This section details the video input hardware, paddle control hardware, video output hardware, sound output hardware, and other miscellaneous hardware, as well as the game dynamics software. The block diagram of the virtual air hockey system is show below:

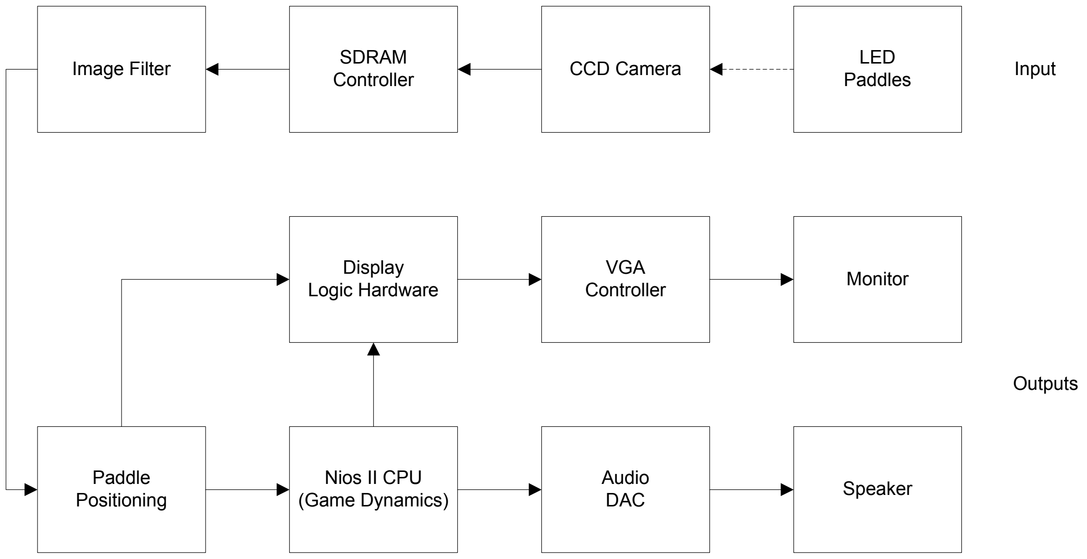


Figure 4

Video Input Hardware

The CCD camera uses a 25 MHz clock that is derived from the internal 50 MHz clock divided by two. The module takes control inputs to start, stop, and reset the camera, and outputs 10-bits of raw data on the mCCD_DATA bus. That bus is an input to the module RAW2RGB, which then separates the raw camera information into red, green, and blue values in for each pixel position. Note that the CCD camera code is provided by Terasic with no changes made. More design details of the code can be found from Terasic at http://www.terasic.com.tw/cgi-bin/page/archive.pl?Language=English&No=50.

The CCD camera's information is stored in on board the SDRAM memory. The SDRAM contains 307,200 pixels of information per frame (640 x 480) but less than 60 percent of those pixels are used because the video that is generated is a 600 x 300. It would have been desirable to have the camera skip the unused video space so that each frame took only 58.6 percent of the time it actually takes. However, after thorough research and analysis, it was determined that the TRDB CCD camera cannot be hacked to display less information, and using anther camera was not a realistic option. As a result, the data path of the camera's information and identifying the source was a source of performance constraint. As I found out later in the project, this was actually the largest constraint in the project, and this will be discussed further in the RESULTS section of the report.

Another constraint on the system is that the camera will pick up light reflection from the paddle LED. In order to avoid false position calculations, the system needs to be used in an environment free of reflective objects in the camera's field of view. This includes the actual playing surface, and during development and testing a large non-smooth black piece of paper was used under the playing area.

Paddle Control Hardware

The paddle detection hardware is one of the more complex sections of this project with many steps in the process. First the red, green, and blue data for each pixel in the SDRAM is processed by image filtering hardware to even out extraneous data. That filtered data set is used to determine the center locations of the two paddles, and finally when each pixel is output on the VGA, it's proximity to the center of the paddles are checked and the right action is taken in drawing the pixel.

To perform the image filtering on the red, green, and blue values of each pixel in SDRAM, there are three special shift-registers called taps that shift in the information every clock cycle. The taps are unique because as their name suggests, they allow the hardware to tap each position of the shift-register to access its bits. The taps were created using the MegaWizard Plug-In Manager in the Quartus II IDE. For more information on how these work see: http://www.altera.com/literature/ug/ug_alt_shift_taps.pdf. The taps are used to perform two morphological image processing techniques called erode and dilate which fade away the edge of the foreground and background respectively. The information is then used to compare against the next state of the shift-register and if it can detect whether "change" (motion) has occurred or not. If no motion has been detected, the VGA output address going to the Nios II retains the value from the previous position.

Next, a finite state machine was utilized in determining the location and drawing of the two paddles for many reasons. One of the reasons is that a scheme is necessary to manipulate the video memory only while the sync signals are asserted so that no video artifacts show. Another reason is that the FSM provides a systematic way to detect motion in which the playing space which has been divided into two regions, one for each paddle. Use the figure below as a guide in following the FSM description. While there are only a few number of states in the state machine, the last state is fairly complex with a lot of parallel hardware so please review the following carefully.

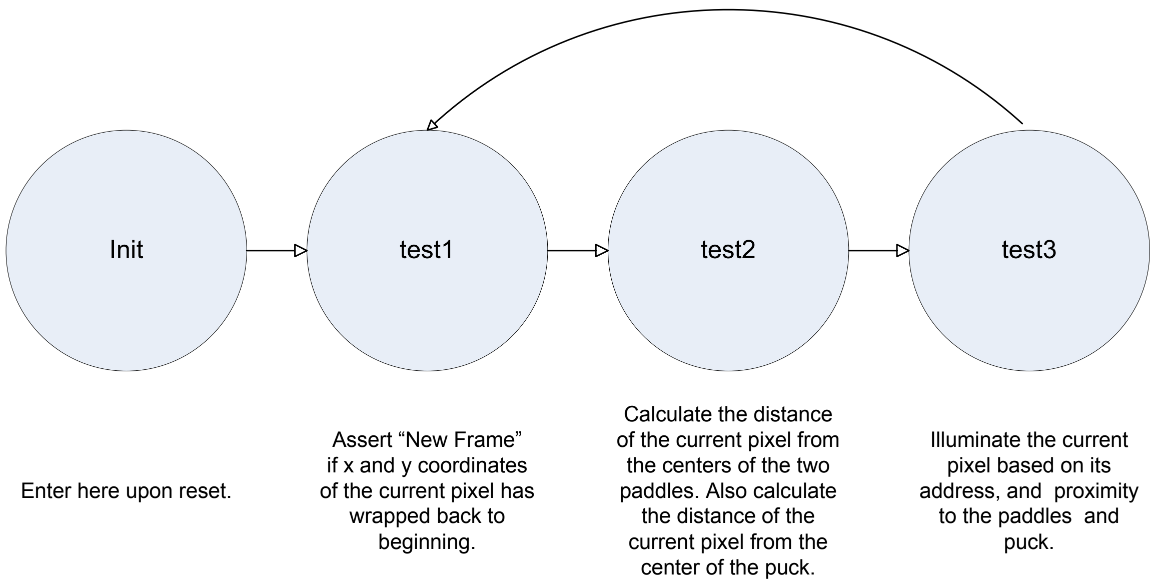

Init
test1
test2
test3
Enter here upon reset.
Assert "New Frame" if x and y coordinates of the current pixel has wrapped back to beginning.
Calculate the distance of the current pixel from the centers of the two paddles. Also calculate the distance of the current pixel from the center of the puck.
Illuminate the current pixel based on its address, and proximity to the paddles and puck.

Figure 5

The state machine is clocked by the rising edge of 50 MHz clock and begins in the "init" state. If at any time KEY[0] s pressed, the state machine returns to the "init" state. No action is taken in the init state except to set the state variable to "test1".

In the state "test1", the goal is to record the most recently known location of the LEDs in each playing space. Each cycle of the 50 MHz clock also increments the mVGA_X and mVGA_Y variables which have red, green, and blue values of mVGA_R, mVGA_G, and mVGA_B. Using this, the values in mVGA_R, mVGA_G, and mVGA_B are checked against the filtering threshold to determine the center of the LED. Undoubtedly, there will be multiple pixels who satisfy this condition, and to avoid having a moving virtual paddle for a static LED, a first-satisfied scheme is utilized where one a fresh frame has started and a "LED center" has been detected, the state machine does not attempt to update the paddle center addresses until a new frame begins, which is defined by mVGA_X == 20 and mVGA_Y == 20. For example in Figure 2, the algorithm would always identify the top-left most pixel labeled 5 as the center of the paddle. If no LED center is found the previous paddle locations are kept. Such a case would be possible only if the LED leaves the camera view, or is turned off. Once these steps are completed, the state variable is updated to “test2”.

State “test2”, is used to determine the surrounding pixels of the paddle centers, which were recorded in state “test1”. To do this, the paddle center’s x and y addresses have mVGA_X and mVGA_Y subtracted, and that difference is stored in registers DIFF_X_1, DIFF_Y_1, DIFF_X_2, and DIFF_Y_2. Unlike programming in sequential languages like C and Java, Verilog cannot perform the calculations in states “test1” and “test2” in the same cycle because “instructions” are actually dedicated hardware on the DE2 board and happen concurrently at the clock-edge with no knowledge of data dependencies. In addition, the puck’s x and y addresses are also subtracted from the VGA x and y address and recorded. The state variable is then set to “test3”.

In state “test3” the actual drawing of borders, paddles, and puck occur. The borders are drawn by using absolute addresses of mVGA_X and mVGA_Y, where the border is a rectangle defined by the points (20,100), (620,100), (20, 400), and (620,400). Please note that in the VGA coordinate system the Cartesian coordinate system has been reflected over the y-axis, or in other words, the positive direction of y is down. In drawing the paddles, the previously calculated difference values are used to determine how far away from the center of the paddle the current pixel is. If the current pixel is a within a defined radius of the center, that pixel is illuminated according to the corresponding paddle color. And lastly, the illumination of the puck is done in the same way as the paddles, with a slight difference in that the x and y coordinates of the puck’s center are passed from the NIOS II CPU via a bus instead of being detected by the camera. When this is all done, the state variable is set back to “test1” and the process begins anew.

Users should note that there are limitations on the camera and its refresh rate. It is possible for the user to move the LED faster than the camera’s refresh rate which results in a huge jump in the paddle’s position. This is because the time between the previous position and the new position detected by the camera is so long. This was exactly the problem that was described in the Video Input Hardware and really has no solution in hardware. While it is possible to detect the huge jump in software and extrapolate some trajectory (a straight line, for example), this was not done because of the additional complexity that such a scheme would introduce.

Video Output Hardware

The VGA_Controller is clocked at 25 MHz and provides the monitor with the information to be displayed on the screen. The outputs of the module are on five lines, VGA_Red, VGA_Green, VGA_Blue, VGA_HSYNCH, and VGA_VSYNCH. The VGA_Controller module keeps track of incrementing and resetting the horizontal and vertical synch values so that it outputs the correct sequence of horizontal and vertical sync pulses. The inputs to the module are the red, green, and blue information we wish to output based on the red, green, and blue values stored at the x and y coordinate in SDRAM. The red, green, and blue values we wish to output are set by the state machine discussed earlier and use a blue value for the air hockey table border, white for the goals, blue for player 1's paddle, white for player 2's paddle, yellow for the puck, and black everywhere else. There are also two white boxes that are necessary to satisfy the "start game" condition which will be covered further in the *Starting, Scoring, & Ending Rules* section of the report. Again, these pixel values are only altered while the VGA_HSYNCH and VGA_VSYNCH lines are asserted.

Sound Output Hardware

A phased-locked loop (PLL) is used to take one of the FPGA's internal clocks of frequency 27 MHz and output a 18.4 MHz clock which is subsequently used as the audio control clock. A Quartus II IDE wizard, which generates PLL modules with a few high-level design inputs, was utilized to create the PLL. The three other inputs into the audio module are a reset delay line, an on/off signal, and a source select signal. The reset delay signal is asserted by the Reset_Delay module when KEY[0], or the system reset button, is pressed. The delay is to provide enough time for all components of the system to reach a known steady state before continuing. The on/off signal is asserted for example when a sound effect is needed. In the AUDIO_DAC module, a DDS system is used to generate sine waves of different frequencies based on a phase increments which is depend on the source select. The foundation of the code was used from Teraic's TRDB camera's motion detection example, and more design details can be found at http://www.terasic.com.tw/cgi-bin/page/archive.pl?Language=English&No=50. In extending the code, multiple sounds for different circumstances with various frequencies were added. This was accomplished by adding a source select bus to the AUDIO_DAC module which controlled the phase increment. Each source can play for different time intervals by having separate control lines for the on/off signal. For example, when the puck reflects off of a border, ten cycles of 10 KHz sine wave is generated, but when the puck enters a goal, a chime with increasing frequencies is played. The duration of the tone was controlled by the on/off signal which can be controlled precisely by using a 24 bit counter. Because the sound generation hardware that is an input to the AUDIO_DAC is clocked at 50 MHz, asserting the on/off signal for 50 million counts generates a one second tone. In the case of the chime that is played when a player scores a goal, four different thresholds were used for the 24-bit counter and during each threshold, a different source select value was used, causing the AUDIO_DAC to use phase increments corresponding to each of the different source selects. The result is a chime that increases in frequency three times every 63 ms for a total 252 ms, and it sounds quite good. For a waveform of the output signals, please see the RESULTS section.

In hindsight, if I were to do the project again, I would write the AUDIO_DAC module from scratch rather than start with Terasic's code as a foundation. The main reason is that the lookup table only has 48 elements because the original hardware only output a 1 KHz sine wave. The sound output is very good when simply multiplying the frequency, but in trying to create musical notes, i.e. frequencies less than 1 KHz, the DDS was limited by the number of A/D values it had in the table and the output suffered as a result.

Miscellaneous Hardware

The DE2's on-board 7-segment displays were used to indicate each player's current numerical score. To do this, a lookup table module was created which took a 4-

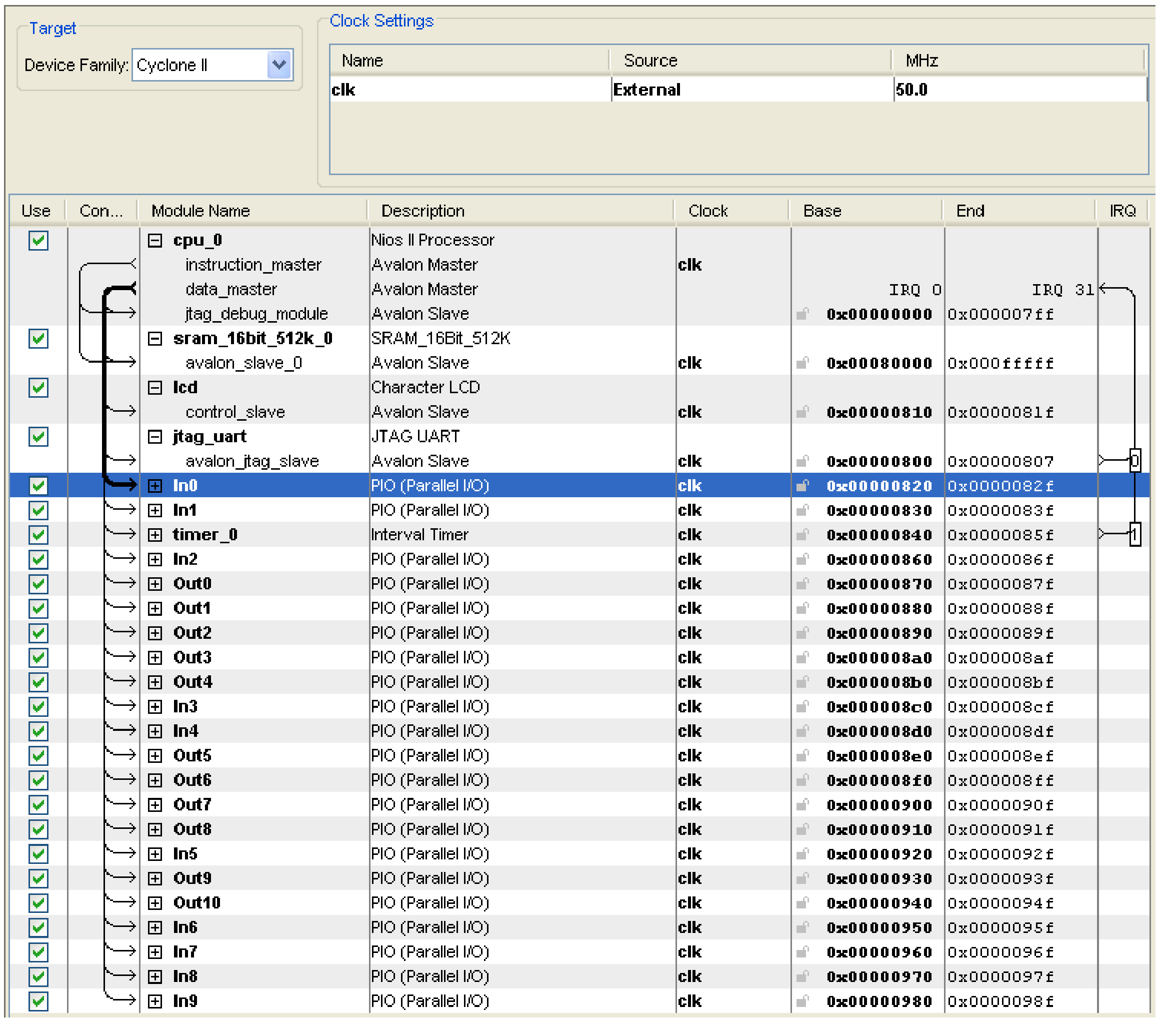
bit input and output 7-bits. The four bits represent 16 possible values ranging from 0x0 to 0xh, and a lookup table maps each of the 16 values to a corresponding 7-bit pattern that make up alphanumeric outputs on the 7-segment display.

In addition to the 7-segment displays, 18 general purpose red LEDs exist on the DE2 which were used during development to blink on and off depending on the specific need of the task. The 7-segment displays are active low, while the LEDs are active high.

As mentioned previously in the Sound Output Hardware section, there is a Reset_Delay module on the board that detects the KEY[0] button press. When this button is pressed, three different delay lines are controlled, each with its own time delay before it is asserted. The delay values used by the Sdram_Control module is approximately 41.9 ms, the delay for the CCD_Capture, RAW2RGB, and AUDIO_DAC modules are approximately 62.9 ms, and the delay for the VGA_Controller is 83.9 ms.

Game Dynamics Software

A Nios II/f core (fast) was used in implementing the game dynamics. The Quartus II IDE has a built in module called the SOPC (System On Programmable Chip) Builder which takes care of generating the general purpose CPU out of your high level design requirements. See the figure below for the specific SOPC Builder parameters.



Target

Device Family: Cyclone II

Clock Settings

Name	Source	MHz
clk	External	50.0

Use	Con...	Module Name	Description	Clock	Base	End	IRQ
✓		cpu_0	Nios II Processor				
		instruction_master	Avalon Master	clk			
		data_master	Avalon Master		IRQ 0	IRQ 31	
		jtag_debug_module	Avalon Slave		0x00000000	0x000007ff	
✓		sram_16bit_512k_0	SRAM_16Bit_512K				
		avalon_slave_0	Avalon Slave	clk	0x00080000	0x000fffff	
✓		lcd	Character LCD				
		control_slave	Avalon Slave	clk	0x00000810	0x0000081f	
✓		jtag_uart	JTAG UART				
		avalon_jtag_slave	Avalon Slave	clk	0x00000800	0x00000807	0
✓		In0	PIO (Parallel I/O)	clk	0x00000820	0x0000082f	
✓		In1	PIO (Parallel I/O)	clk	0x00000830	0x0000083f	
✓		timer_0	Interval Timer	clk	0x00000840	0x0000085f	1
✓		In2	PIO (Parallel I/O)	clk	0x00000860	0x0000086f	
✓		Out0	PIO (Parallel I/O)	clk	0x00000870	0x0000087f	
✓		Out1	PIO (Parallel I/O)	clk	0x00000880	0x0000088f	
✓		Out2	PIO (Parallel I/O)	clk	0x00000890	0x0000089f	
✓		Out3	PIO (Parallel I/O)	clk	0x000008a0	0x000008af	
✓		Out4	PIO (Parallel I/O)	clk	0x000008b0	0x000008bf	
✓		In3	PIO (Parallel I/O)	clk	0x000008c0	0x000008cf	
✓		In4	PIO (Parallel I/O)	clk	0x000008d0	0x000008df	
✓		Out5	PIO (Parallel I/O)	clk	0x000008e0	0x000008ef	
✓		Out6	PIO (Parallel I/O)	clk	0x000008f0	0x000008ff	
✓		Out7	PIO (Parallel I/O)	clk	0x00000900	0x0000090f	
✓		Out8	PIO (Parallel I/O)	clk	0x00000910	0x0000091f	
✓		In5	PIO (Parallel I/O)	clk	0x00000920	0x0000092f	
✓		Out9	PIO (Parallel I/O)	clk	0x00000930	0x0000093f	
✓		Out10	PIO (Parallel I/O)	clk	0x00000940	0x0000094f	
✓		In6	PIO (Parallel I/O)	clk	0x00000950	0x0000095f	
✓		In7	PIO (Parallel I/O)	clk	0x00000960	0x0000096f	
✓		In8	PIO (Parallel I/O)	clk	0x00000970	0x0000097f	
✓		In9	PIO (Parallel I/O)	clk	0x00000980	0x0000098f	

Figure 6

The Nios II/f has several advantages over the Nios II/e (economy) and Nios II/s (standard) in that it has a six-stage pipeline to achieve greater throughput, or instructions per second, and also has single-cycle hardware multiply and barrel-shift operations, something that is very useful for this project.

The default memory available to the Nios II is either SDRAM or M4K memory, and the choice can be configured through the Nios II IDE project settings. Since, our project utilizes the SDRAM to store the CCD camera's data and M4K blocks are not sufficiently large enough to contain this code space. Instead, the Nios II instantiated for this project utilizes a 512k block of SRAM whose implementation was made available by Terasic in the module SRAM_16bit-512k.

Fixed-Point Arithmetic

Fixed-point arithmetic was used to represent non-integer values. In the Nios II architecture, int values are 32-bit values, so the top three bytes are used for the whole-number value, and the lower byte is used for fractional values. The virtual decimal point was located between the first and second low-order bytes and values to the right of the decimal represented one divided by two raised to the position's value (see figure 7).

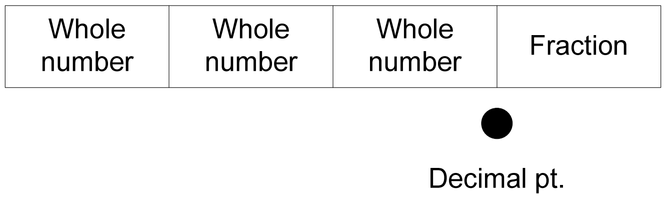


Figure 7

For example, a hex value of 0x00000040 is ¼ because there is no whole-number value and the fraction value is 1 divided by two squared. Conversion back to a rounded whole number (basically a floor function) is to shift the fixed-point variable to the right 8-bits. Conversion from integer would be to shift the value to the left 8-bits, and conversion from a floating point value is to multiply the value by 256.0 (same as shifting left by 8 but keeps the correct data type) and to cast the result as an int to keep the 32-bits. Therefore, when displaying video of a puck whose address is (450.25,300.5) will result in the puck being at location (450,300).

Puck Velocity Integration & Position Calculation

In each iteration of the Nios II main loop, a simple integral is performed to determine the new position of the puck. In performing this integral, it is assumed that the main loop runs at a regular interval so that the time between each position update is constant. To validate this assumption, a simple exercise was conducted where the Nios II toggled a GPIO on the DE2 board each iteration of the main while-loop. The CPU's tight-loop takes at 40 µs with slight variance at times. The worst observed variance was 48 µs. However, the frequency of the variances was very low, about 4 out of every 100 iterations. With the worst possible variance being 20% but only occurring 4% of the time, one can see that the variance is fairly insignificant. With such low margins of error, it was determined that this method of calculating integrals was acceptable.

Having established that a mostly constant time interval exists between position updates, the integration is performed by simply adding the current velocity to the current position. Of course, collisions with the boundaries of the air hockey table as well as paddles and the goal conditions are checked prior to moving the puck so that impossible conditions are avoided when possible. However, it is possible that the puck's velocity is such that in one time-step, it moves from near an object (wall or paddle), to overlapping the object, and this is not checked prior to moving the puck. This usually happens for only a single frame and is virtually undetectable by the human eye at game speeds. The code will reflect the object in the appropriate direction assuming the point of collision to be where it should have been, rather than where it currently is. See APPENDIX E for implementation details. There are rare instances where the puck can move completely through a paddle in one cycle of the main loop. While it is possible for this to happen, the occurrences are rare because the speed of the puck needs to be near the maximum allowed value and the user must be moving the paddle in the opposite direction at a high speed as well. I decided that the complexity of detecting this corner case is not worth the payoff in the context of this project, especially since there is no protection against the user moving the LED too fast for the camera, and having the paddle jump discontinuously. Future work may include exploring the many possible solutions for corner cases.

Physics Modeling

The physics involved in air hockey is modeled in this game by keeping track of the puck's x and y-velocities as well as calculating the paddles' x and y-velocities in real-time. The puck's movements are straight with very little friction, just like real air hockey. The velocity vector changes directions with some speed loss upon colliding with static objects on the table, with the energy being transferred from kinetic energy to friction heat and sound energy. This is done in software reducing the absolute value of the velocities upon a collision and asserting an output line to the AUDIO_DAC module to create a sound. For simplicity, the speed of the puck was not taken into account and a constant energy loss was implemented, although future implementations could certainly improve upon this by making the energy loss more accurate to the physical world. Energy input is achieved by striking the puck with the paddle, with more energy transferred to the puck when the paddle is moving faster. This is good in that there is never any constant acceleration (we ignore force of friction because this is virtual air hockey, after all). The tricky part is that the paddle has a much larger mass compared to the puck and the paddle's velocity remains unchanged after the collision. Therefore the concept of conservation of momentum where the momentum of the entire system (consisting of n objects with mass m and velocity v defined below)

$$\sum_{i=0}^{n} m_i * v_i$$

before the collision is equal to the momentum of the entire system after the collision is computationally hard because there is no known mass of the paddle. There was some leeway in designing the non-completely elastic collision, because the precise amount of energy lost to sound and friction depend on many factors in the real world. In adding energy to the puck, my design based the speed increase on the current speed of the puck and the speed of the paddle at the time of collision, with a saturation point near the maximum allowed puck speed defined by the constant MAX_SPEED. For exact implementation details, please refer to APPENDIX E.

Even though the code is quite lengthy, the actual logic for changing directions and speeds based on collisions with walls and paddles is fairly straightforward. The wall collisions require simply detecting the x or y address of the puck to be greater than or less than the boundary depending on the wall in question. For the paddles, the design broke down the different scenarios in which collisions could occur. Based on the code prior to the dynamics calculations, a flag is set based on the distance between the paddle and puck being greater or less-than-or-equal-to twice the radius of the puck and paddle (they share the same radius lengths). Figure 8 is an accompanying partial flow chart meant to facilitate the understanding of the collision logic and is not representative of the entire code. It was determined that the logic would first determine which direction the puck was traveling (positive x & positive y, positive x & negative y, negative x and positive y, or negative x and negative y). In each of these scenarios, the collision with the puck is then categorized again. This time, we are interested in which area of the paddle makes contact with the puck. If you think of the puck being at the origin of a two-dimensional graph, then the x and y-axis' divide the paddle into 4 quadrants. Similar to the Cartesian coordinate system, the design refers to the top right as quadrant I, bottom right as quadrant II and so on. Once these two parameters of the collision scenario are known, the appropriate reflecting direction is determined. In referring to the figure below, please remember that it is not a complete representation of the dynamics engine.

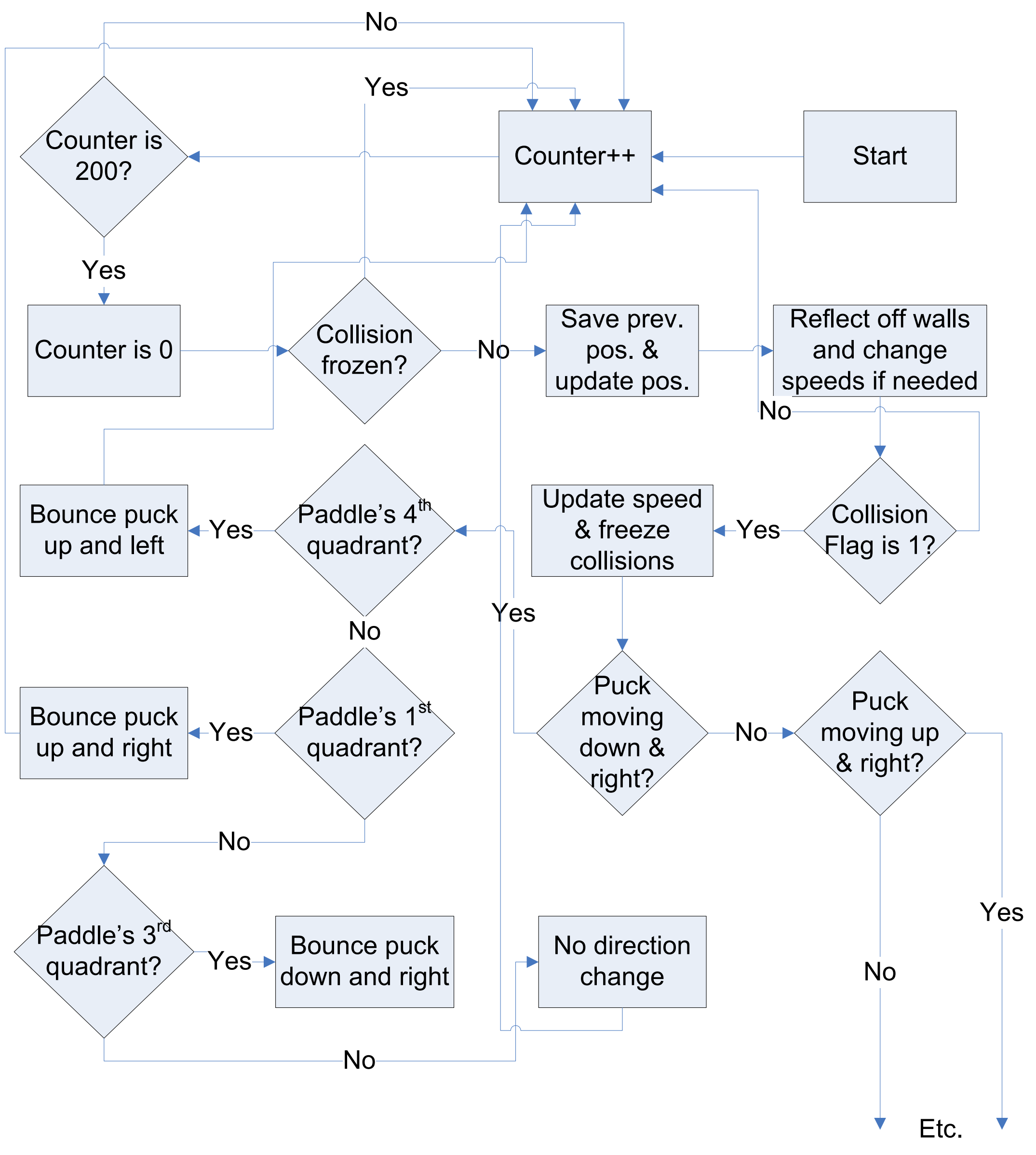


Figure 8

Lastly, the speed of the puck resulting from a paddle collision occurs as a function of the paddle speed. A conscious decision was made to transfer energy from the paddle to the puck non-linearly so that at low speeds the resolution of speed differentiation is large but as the paddle moves faster the speed increases in larger step intervals. This is to provide precise control at low speeds when users want to control the puck using finesse, but can also take hard shots at high speeds. The calibration for this was done over many trials and was largely subjective to what I felt was a good level of game control. There was one design problem that surfaced during the testing – the sampling rate of the paddle positions is so fast that the difference in the LED positions from the user's movements were registered as zero for a majority of the movement duration. See Figure 9 below for one example of the perceived X position differences when moving the LED at a constant low speed.

Original X Position Delta

Sample	Calculated X Delta	Sample	Calculated X Delta
1	0	26	0
2	0	27	0
3	76	28	64
4	0	29	0
5	0	30	0
6	0	31	0
7	46	32	0
8	0	33	83
9	0	34	0
10	21	35	0
11	0	36	47
12	0	37	0
13	0	38	48
14	0	39	0
15	57	40	0
16	0	41	23
17	64	42	0
18	0	43	0
19	0	44	0
20	23	45	45
21	0	46	0
22	0	47	0
23	0	48	49
24	45	49	0
25	0	50	0

Figure 9

The problem was remedied by inserting logic to detect a lengthy period of zero movement before registering the speed as zero, in this case 15 consecutive zeros. This is not unreasonable since calculations are separated by about 40 µs so 0.6 ms after user has stopped moving, the game will register that the paddle is static, which is virtually unnoticeable to the human player. The results of applying the algorithm on the data in Figure 9 are shown below in Figure 10.

Adjusted X Position Delta

Sample	Calculated X Delta	Sample	Calculated X Delta
1	0	26	45
2	0	27	45
3	76	28	64
4	76	29	64
5	76	30	64
6	76	31	64
7	46	32	64
8	46	33	83
9	46	34	83
10	21	35	83
11	21	36	47
12	21	37	47
13	21	38	48
14	21	39	48
15	57	40	48
16	57	41	23
17	64	42	23
18	64	43	23
19	64	44	23
20	23	45	45
21	23	46	45
22	23	47	45
23	23	48	49
24	45	49	49
25	45	50	49

Figure 10

Starting, Scoring, & Ending Rules

In order to start a game, both players must be ready. To indicate this, a start condition must be satisfied before the Nios II will populate the puck. The starting condition is met by each player placing his or her paddle within a specified area on the screen. This area is highlighted by the display logic hardware and will remove the box when a signal from the Nios II indicates that the game has begun. After asserting this logic line, the Nios II will populate the puck in the middle of the table in the reach of both players. In the course of play, if the puck hits the goal (white) region on the east/west walls, the scoring condition is met and a point is awarded to the player opposite of the goal that was scored upon. Afterwards, the puck is re-populated on the side of the player that was scored upon.

Debugging

The debugging process was a conducted by utilizing the hardware's LED's and print statements, as well subjective methods for the "look and feel" aspects. The 18 red LEDs on the DE2 helped show the state of certain variables in real time and were a low-cost method of debugging without introducing extra delays because it is completely done in hardware. For more complex tasks that required more details, print statements were used through the JTAG UART on the DE2. The print statements were extremely useful, but they introduced some delay into the calculations that depend on constant time so they were avoided when possible. Additionally, I used my own judgment in determining what a realistic reaction to collisions was. This included decisions like how much to increase the puck's speed based on how "hard" (velocity) you hit the puck. This was fairly arbitrary because there is no known mass of the two objects and no good way to determine just how the energy is conserved.

Some interesting bugs were observed in the course of this project. In my first try at VGA video through the FPGA, I encountered problems where the pixel changes were not where I expected them to be. This was a result of executing two calculations that needed to be done sequentially in the same state in the FSM. That meant that while I wanted the code to be run one after the other, they were actually being run simultaneously in hardware. Another bug was seen which eventually led to the addition of the Freeze_Collision flag. The symptoms were erratic puck/paddle collisions upon a moderately fast collision. The reason for this was that the updating of the puck's position at high speeds would draw the puck overlapped with the paddle. This of course is a collision scenario and the puck's direction and speeds are updated. In the very next update, the puck is still somewhere overlapping the paddle, and another direction and speed update occurs. This problem of multiple collisions detected as a result on one collision was compounded by the fact that the user is moving the paddle, usually further towards the center of the puck. The solution was to set the aforementioned flag and to not allow another collision to occur until that flag is de-asserted through counting down a variable.

Finally, there were some obscure problems as a result of using the two integrated development environments (IDEs). First, the Quartus II IDE's SOPC builder's naming convention caused one problem where the orders of the Parallel Input/Out (PIO) busses ended up in the wrong order. The reason for this was that the naming convention used for this project was numbering all inputs and outputs sequentially. This worked fine for Out0 through Out9, but as soon as Out10 was added, everything stopped working. Digging into the generated Verilog file, bigNios.v, it was later revealed that the order used by the SOPC builder was Out0, Out1, Out10, Out2, etc. which is in alphanumerical order. Once the bus ordering in the high level Verilog code was switched, the code worked flawlessly. The problem encountered with the Nios II IDE was also non-intuitive, and the problem occurred when I made a copy of my source code and placed the copy in the same directory as the original source file. This was done because I was about to make dramatic changes to the code and I wanted to retain a copy of the working code. Subsequent changes to the original source code made no differences in the behavior of the program, which was extremely puzzling. The reason for this turned out to be that the copy of the original was being compiled and run on the board instead of the original source file because the name of the copy file came before the name of the original file, and the builder took the first main function it saw. In this scenario, I would have at least expected the code to not run or throw some warnings during compilation, but it did neither of those.

RESULTS

The overall results were very positive. The video output of the puck movement showed no artifacts when the game speed was increased during testing. The puck lost video continuity when the puck began traveling at about 13 pixels per frame which makes sense since the radius of the puck is also about 13 pixels. Generally during the course of play, the puck velocity never reached 1.3 pixels per frame (10% of 13 pixels per frame) which is a fairly conservative measure of video continuity. Furthermore, fear of discontinuity is not even an issue in this application since a puck traveling that fast is not conducive to a realistic gaming environment.

The paddle detection was very precise with LED position detection resolution of approximately 1 cm when played from 2 feet away from the camera. This was far better than my expectation. In contrast, the speeds at which the user could move the LED and have the movement registered in a continuous manner were somewhat disappointing. This was the result of the CCD camera taking so long to capture one frame of information and moving onto the next frame. This result forced the game dynamics to be more exaggerated at medium speeds, so that users can still perform hard shots while not losing their paddle on the screen. In general, users became accustomed to the limits of the camera very quickly and controlled the paddle expertly. I was also satisfied by the overall ease of use of the system. New users required virtually no instructions and learned the system through using.

The sound generation hardware worked quite well for the range of sine waves which was 1, 2, 3, 4, 5, and 8 K Hz. As shown in Figures 11 and 12 below the 1 KHz signal had plenty of samples and a solid time resolution to define a clean sine wave.

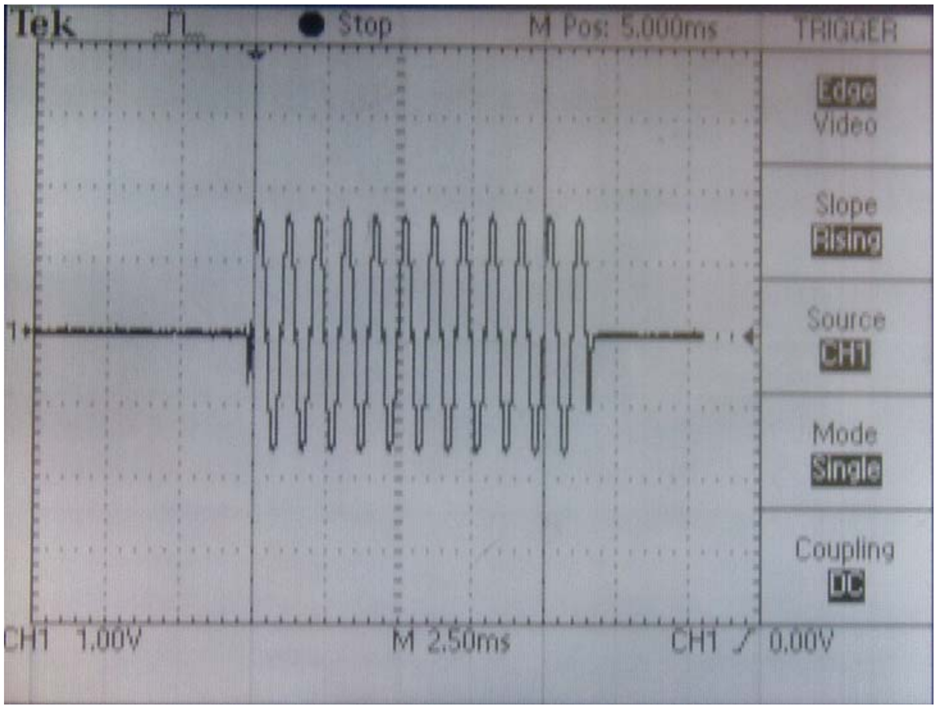


Figure 11

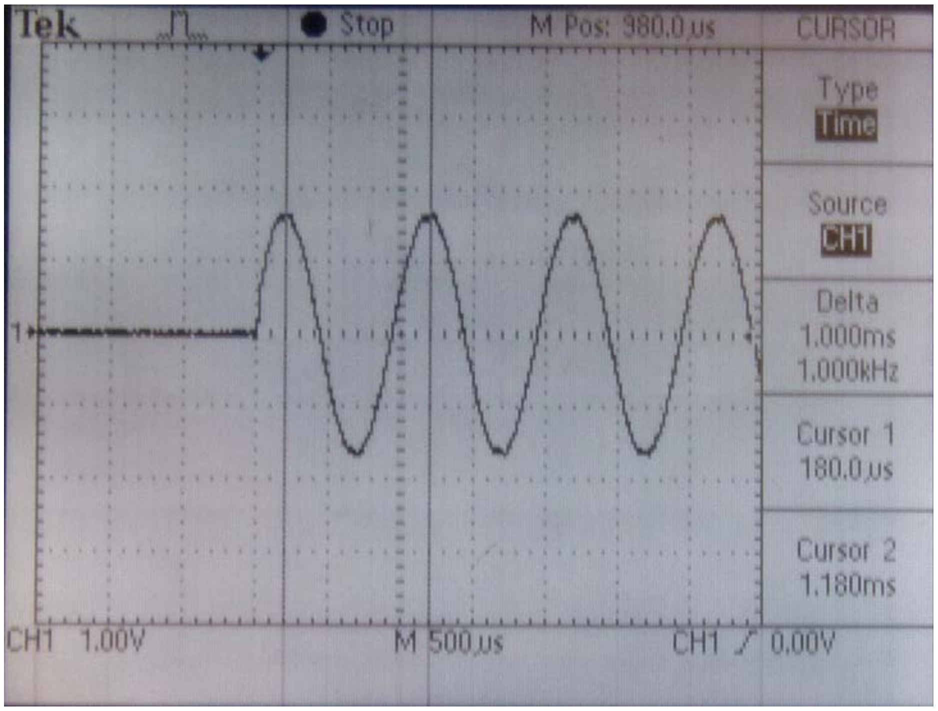


Figure 12

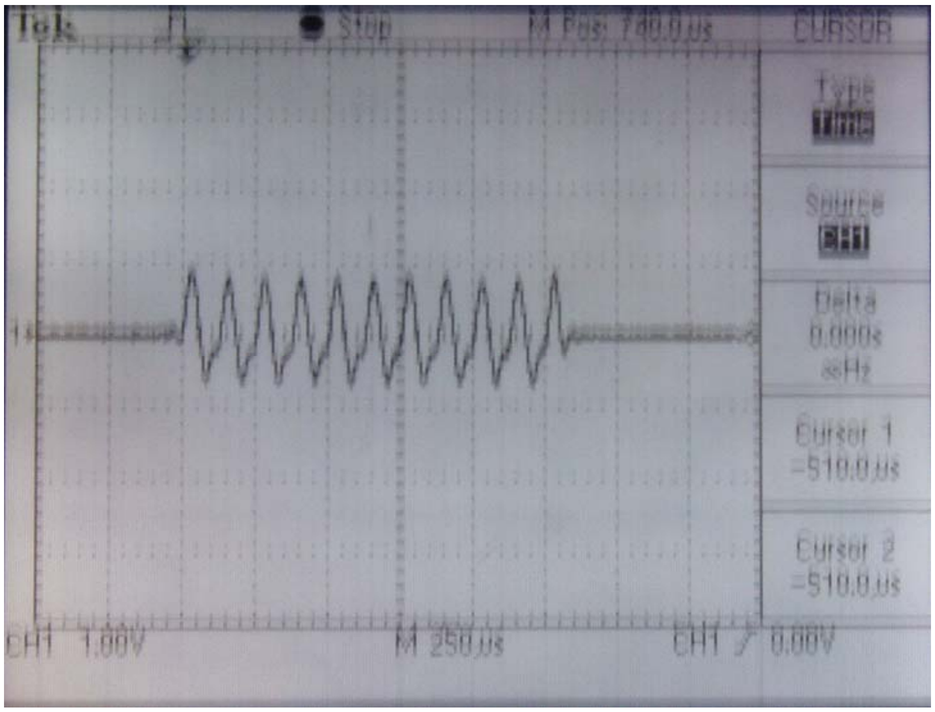


Figure 13

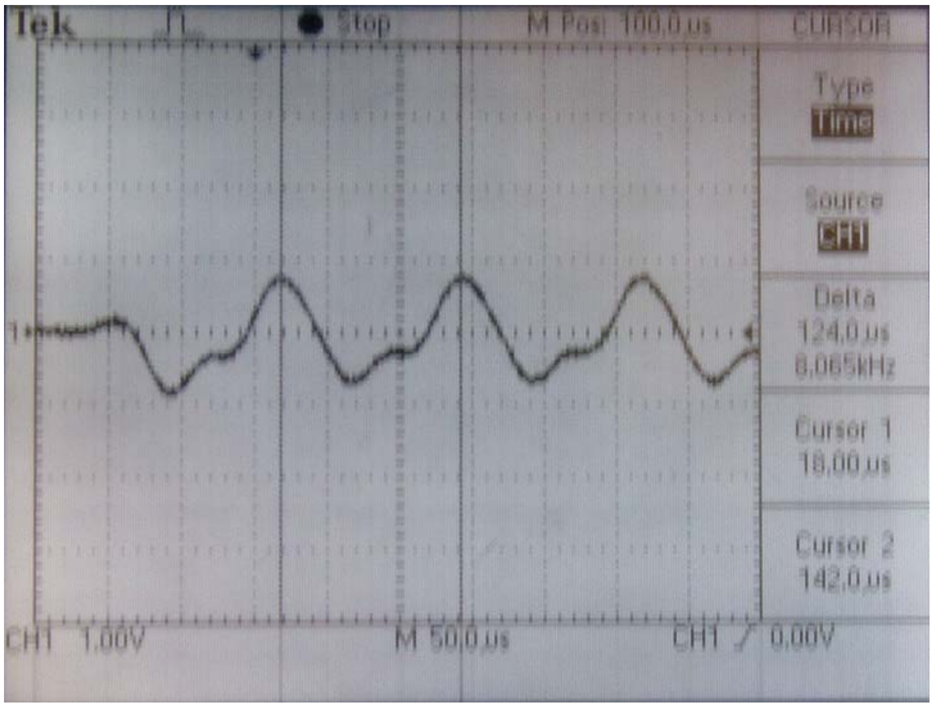


Figure 14

In Figure 13 and 14, the 8 KHz signal begins to show some distortions in the waveforms. However, this worked perfectly as the 8 KHz sound was used to create a harsh, sharp noise of the puck reflecting off of the border.

The goal to play this game in most conditions was also met, as testing in different lighting conditions showed no artifacts. Of course, the testing was carried out with the black paper below the camera and no other reflective objects in the view screen of the camera.

The game dynamics felt very natural, even though some calibrations were purely subjective. The approximations made for reflection angles were convincing for the players while not introducing too much complexity into the physics engine. When the puck is traveling at high speeds, there is an element of unpredictability in the reflection when striking the puck with the paddle which provides an experience just like in real air hockey. There were conscious design decisions to not address certain corner cases such as paddles disappearing at one coordinate and reappearing at another or a puck traveling at high speeds going through a paddle. These cases were ignored in an interest to keep the code relatively straightforward, but some possible solutions were considered and discussed in the DESIGN AND IMPLEMENTATION section of the report.

The lack of accelerometers was somewhat noticeable as sometimes there were variances in the resulting puck speeds after collisions of seemingly similar speeds. However, the variances were on the order of ± 3 speed increments, or 1.5 pixels per position update which is noticeable but certainly acceptable.

FUTURE WORKS

This project has developed the foundation for a simple yet robust video game. With some modifications, one can imagine implementing many other games which feature similar physics. For example, games like virtual Pong are possible using the same image tracking concept to control paddle movements. Some changes to implement elastic collision physics would enable a game like billiards where the players control the pool cues via image tracking. Collaborative games like curling where one player throws the rock and another player sweeps the ice with the broom is extremely conducive of the image tracking technology as well as the distance calculating hardware already in existence from this project.

While requiring slightly more work, it is also conceivable to take advantage of the DE2's Fast Ethernet Network Controller to implement a cross-board game where each player has their own DE2, TRDC camera, and monitor. As an example, if the air hockey game is used, each player may only see their half of the table, their own paddles and the puck when it is in their playing space. With so many features available on this hardware, the gaming possibilities are quite extensive.

In addition to other possible games, I believe that this project or parts of it would be useful as laboratory teaching material for academic purposes, as this project incorporates many aspects of DE2 programming like state machines, video generation, CPU synthesis, and high level C code.

CONCLUSIONS

The results from the air hockey game were overall very positive. Taking into consideration all of the unforeseen bugs and problems I ran into, the end product has met the high expectations set at the beginning of the project.

The paddle control is very precise and smooth at moderate speeds which are sufficient for the game play, and the video output is very stable with no flickering or breaking whatsoever. The sound output is also very neat and adds significant depth to the game play. The system is robust enough to play in different light settings, although care needs to be taken to ensure there are no reflective objects within the range of the camera.

In addition to the positive performance of the system, I have learned a great deal about game and gaming console design. Having previous experience in designing a simple video game on an 8-bit microcontroller, the Nios II was a much more pleasant experience. With its pipelined architecture, the faster throughput for computing was instrumental in creating a rich gaming experience that required many calculations per frame of video. In addition to the power of the CPU, creating dedicated audio and video generation hardware was also a powerful tool. This hardware had a simple interface with wires or busses to and from the CPU creating instant audio and video results with no additional time spent by the CPU.

I feel that I was able to achieve the intuitive factor which I set out to accomplish from the beginning. Much like the Wii, users were able to pick up a paddle and play the game with a very small learning curve.

I am extremely pleased to have undertaken this project, as I was able to turn my interests in gaming into an academic endeavor which was both enlightening and educational.

ACKNOWLEDGEMENTS

There are some individuals to whom I am grateful in completing this project. First, I owe many thanks to Dr. Bruce Land whose inputs and suggestions were vital to my progress. I would like to thank Elissa Chin for all her support and for putting up with my lack of communication during the long hours of solitude spent in lab. And lastly, the facilities crew responsible for the maintenance of Phillips 238 digital lab has done a tremendous job in making my second home an enjoyable place.

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<http://www.altera.com/products/ip/processors/nios2/ni2-index.html>

APPENDIX A – Glossary of Terms Used

Dynamics/Physics engine

- computer logic to simulate Newtonian physics models using variables like mass, velocity, friction, and acceleration.

Cartesian coordinate system

- a two dimensional coordinate system consisting of an abscissa (x-coordinate) and an ordinate (y-coordinate) where two points can uniquely identify every point in the plane.
- also known as the rectangular coordinate system.

Elastic collision

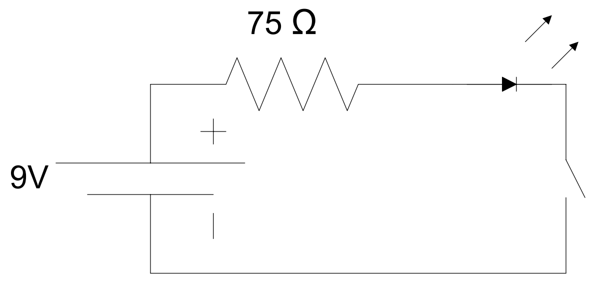
- a physical collision where the total kinetic energy of the system is the same before and after the collision.

Inelastic collision

- a physical collision where the total kinetic energy of the system is not the same before and after the collision.
- the kinetic energy that is not conserved is transferred to other forms of energy such as heat and sound.

APPENDIX B – Hardware Schematics and Diagrams

Paddle Circuit Schematic



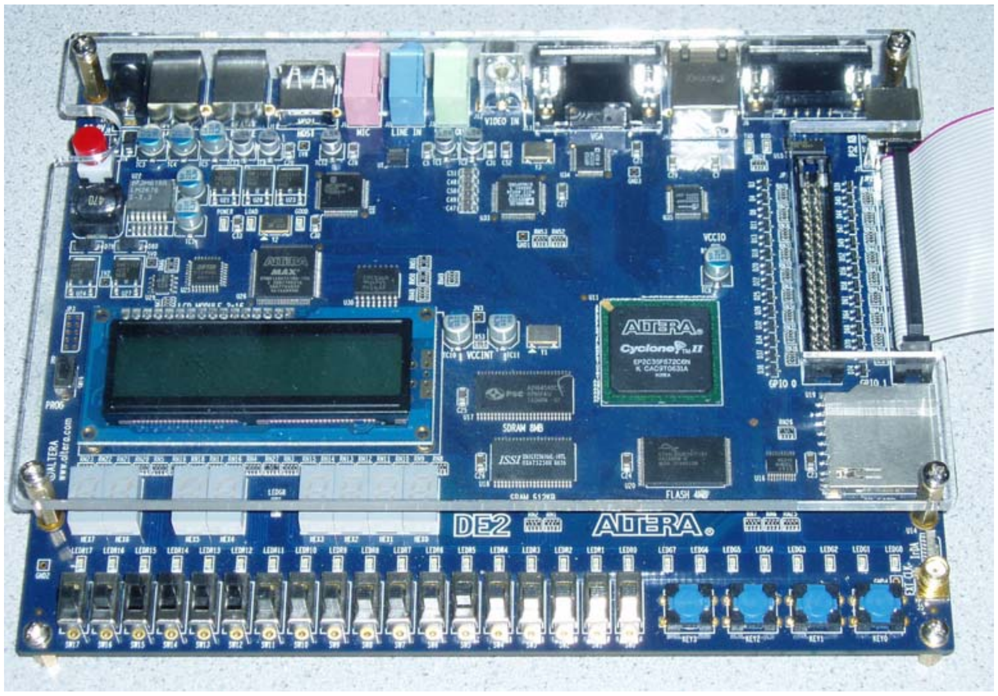
System Diagram

See Figure 4

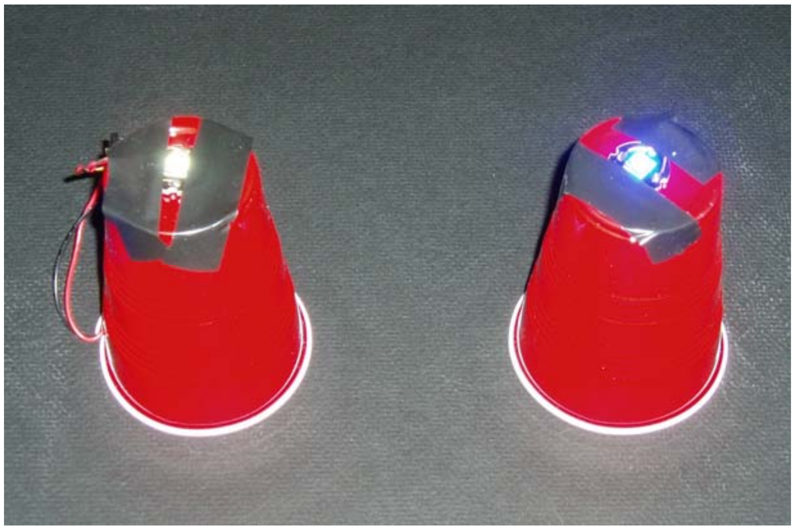
APPENDIX C – Virtual Air Hockey Photos

TRDB_DC2 1.3 Megapixel CCD Camera

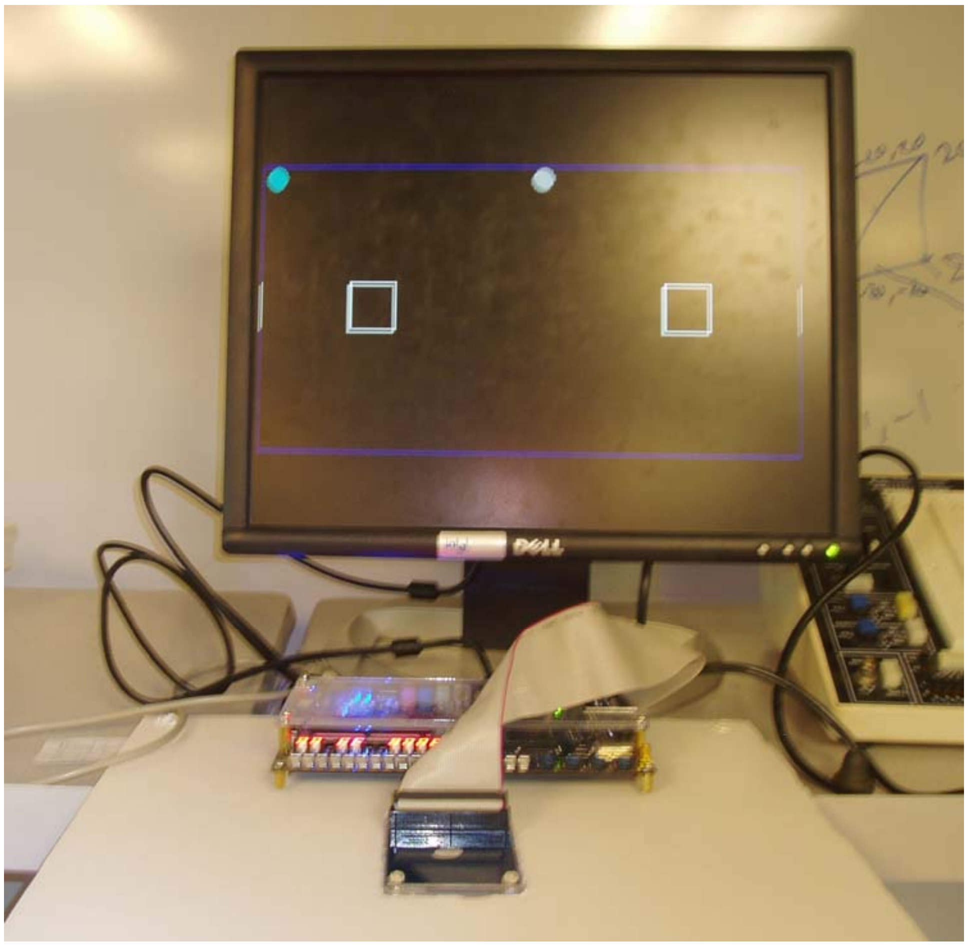
DE2 Development and Educational Board



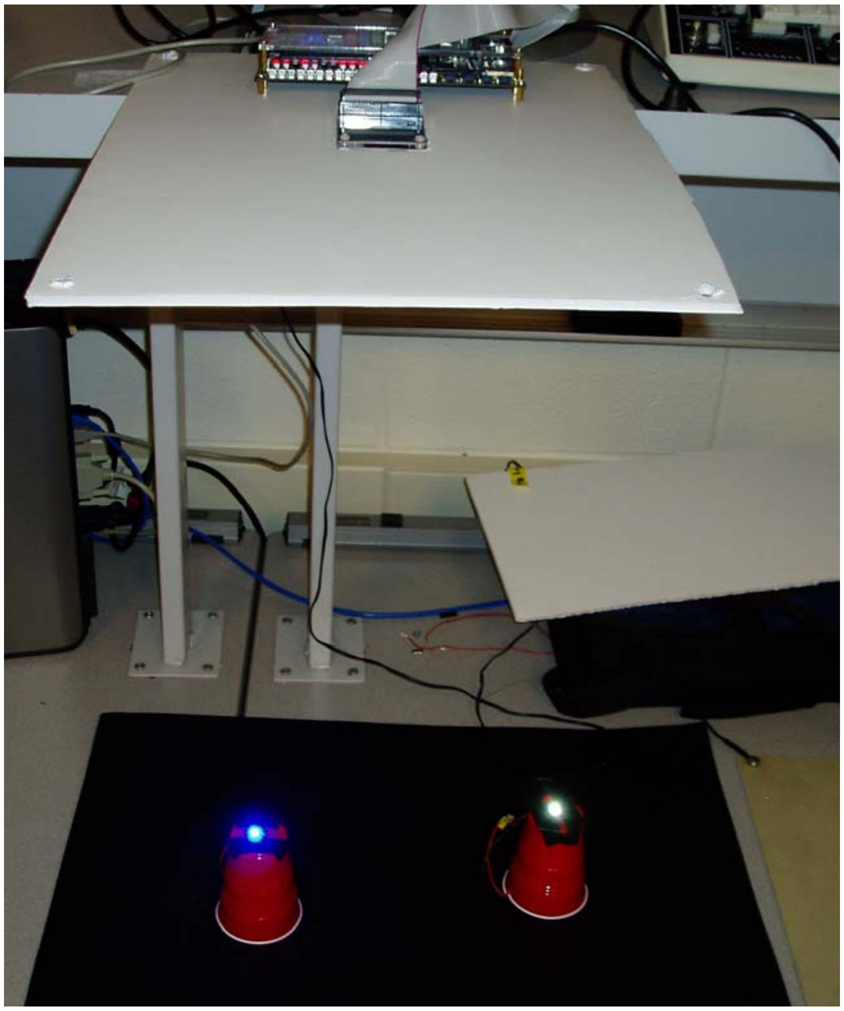
Homemade Paddles



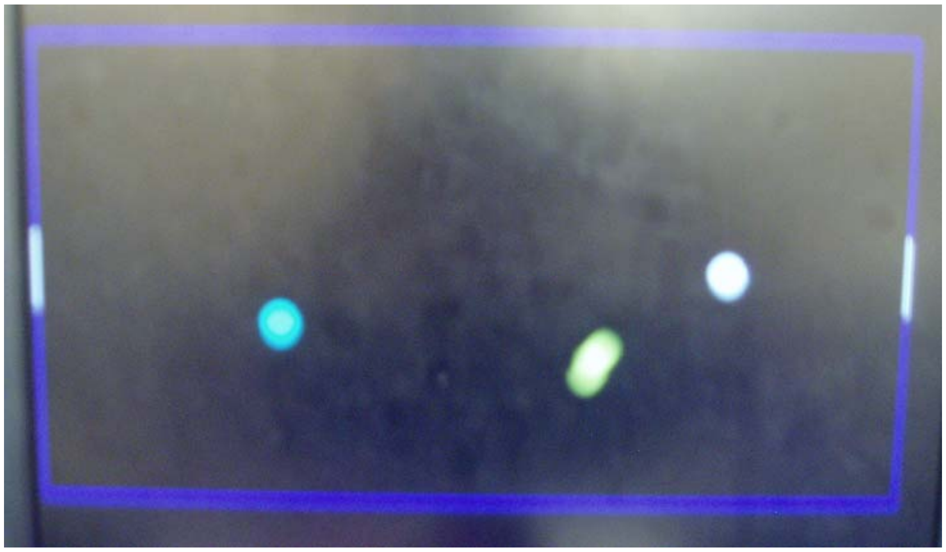
System Setup Pt. 1 – Top



System Setup Pt. 2 – Bottom



Game Screen Shot



APPENDIX D – User’s Manual

1. Select a surface that is non-reflective.
2. Remove DE2 board and TRDB camera from packaging. Note: You must handle the boards only on the ESD mat.
3. Connect the camera and the FPGA via the ribbon cable to the GPIO 1 expansion slot on the DE2 board.
4. Fit the camera into slot in the middle of stand with the lens in the center and the FPGA resting on the stand.
5. Connect the monitor’s VGA cable to the VGA port on the DE2.
6. Connect the speakers to the green port labeled “LINE OUT”.
7. Connect the PC to the DE2 using the USB cable to the port labeled “BLASTER”.
8. Connect the power cable.
9. Turn on the power supply with the red switch on the DE2 board.
10. Open the “DE2_CCD_Detect” project file using the Quartus II IDE on the PC.
11. Program the board by clicking on the third icon from the top right labeled “Programmer” and click “Start”. Note: Make sure the device is on “USB Blaster”.
12. Press the pushbutton labeled “KEY3” on the DE2 to start the camera.
13. Open the Nios II IDE and select the workspace to be “\DE2_CCD_detect_noos\software”.
14. In the “Run” menu at the top of the window, click on “Run…” and click on “Run” in the bottom right of the new window.
15. When ready to play, each player must move their paddle into their respective white boxes on the air hockey table.
16. First player to 10 goals wins.

APPENDIX E – Code

Verilog Code

Instantiated Nios II module

```
//============================ Nios II ============================//

      bigNios nios2(CLOCK_50, KEY[0],
            // parallel i/o
            current_dram_addr_x,  //In0
            addr_valid,           //In1
            current_dram_addr_y,  //In2
            current_dram_addr_x_2,//In3
            current_dram_addr_y_2,//In4
            start_game,  // In5
            DIFF_X_1_IN, // In6
            DIFF_Y_1_IN, // In7
            DIFF_X_2_IN, // In8
            DIFF_Y_2_IN, // In9
            GPIO_0[0],   // Out0
            LED_RED,     // Out1
            chime_sound, // Out10 - stupid naming convention
            SPEED,       // Out2 - Actually, left player's score
            X_ADDRESS,   // Out3 - Actually, right player's score
            Y_ADDRESS,   // Out4
            PUCK_CENTER_X, // Out5
            PUCK_CENTER_Y, // Out6
            sound_signal,  // Out7
            collision_sound,// Out8
            suppress_boxes, // Out9 1 bit Suppress-Boxes signal
            // lcd
            LCD_EN, LCD_RS, LCD_RW, LCD_DATA,
          // the_sram_16bit_512k_0
          SRAM_ADDR,
          SRAM_CE_N,
            SRAM_DQ,
          SRAM_LB_N,
          SRAM_OE_N,
          SRAM_UB_N,
          SRAM_WE_N);
//========================== End Nios II ==========================//
```

Paddle Detection & Video Generation

```
//=================== Paddle Detection & Drawing ===================//

always@(posedge CLOCK_50)
begin
if (mVGA_X == 20 && mVGA_Y == 20)
begin
      NEW_FRAME_1 <= 1'b1;
      NEW_FRAME_2 <= 1'b1;
end
if (!KEY[3])
```

```
begin
      reset_pressed = 1'b1;
end

if (reset)        //synch reset assumes KEY0 is held down 1/60 second
begin
      //initialize variables
      CENTER_X_1 <= 20;
      CENTER_Y_1 <= 20;
      CENTER_X_2 <= 620;
      CENTER_Y_2 <= 20;
      state <= init;    //first state in regular state machine
end
else if (VGA_VS | VGA_HS) //modify display during sync
begin
      case(state)
      init:
      begin
            state <= test1 ;
      end

      test1: //locate center
      begin
            if (mVGA_R >= 10'b1011000000 ||
                  mVGA_G >= 10'b1011000000 ||
                  mVGA_B >= 10'b1011000000 )
            begin
                  if (NEW_FRAME_1 == 1 &&
                      mVGA_X >= 32     && // avoid left border
                      mVGA_X < 305     && // to avoid being cut
                      mVGA_Y >= 112    && // avoid top border
                      mVGA_Y < 388)       // avoid bottom border
                  begin
                        CENTER_X_1 <= mVGA_X;
                        CENTER_Y_1 <= mVGA_Y;
                        NEW_FRAME_1 <= 1'b0;
                  end
                  if (NEW_FRAME_2 == 1  &&
                      mVGA_X >= 335     && // to avoid being cut
                      mVGA_X <  608     && // avoid right border
                      mVGA_Y >= 112     && // avoid top border
                      mVGA_Y <  388)       // avoid bottom border
                  begin
                        CENTER_X_2 <= mVGA_X;
                        CENTER_Y_2 <= mVGA_Y;
                        NEW_FRAME_2 <= 1'b0;
                  end
            end
            state <= test2 ;
      end
      test2: //calculate diff
      begin
            DIFF_X_1 <= mVGA_X - CENTER_X_1;
            DIFF_Y_1 <= mVGA_Y - CENTER_Y_1;
            DIFF_X_2 <= mVGA_X - CENTER_X_2;
            DIFF_Y_2 <= mVGA_Y - CENTER_Y_2;
            DIFF_CENTER_X <= mVGA_X - PUCK_CENTER_X;
```

```
        DIFF_CENTER_Y <= mVGA_Y - PUCK_CENTER_Y;
        state <= test3 ;
end
test3: // draw paddles
begin
        // draw puck
        if ((PUCK_CENTER_X != 0 && PUCK_CENTER_Y != 0) &&
           (( DIFF_CENTER_X <= 8  && // the square
              DIFF_CENTER_X >= -8 &&
              DIFF_CENTER_Y <= 8  &&
              DIFF_CENTER_Y >= -8)
            ||
            ( DIFF_CENTER_X == 9  && // the right arc
              DIFF_CENTER_Y <= 6  &&
              DIFF_CENTER_Y >= -6)
            ||
            ( DIFF_CENTER_X == 10 &&
              DIFF_CENTER_Y <= 5  &&
              DIFF_CENTER_Y >= -5)
            ||
            ( DIFF_CENTER_X == 11 &&
              DIFF_CENTER_Y <= 3  &&
              DIFF_CENTER_Y >= -3)
            ||
            ( DIFF_CENTER_X == 12 &&
              DIFF_CENTER_Y == 0 )
            ||
            ( DIFF_CENTER_X == -9 && // the left arc
              DIFF_CENTER_Y <= 6  &&
              DIFF_CENTER_Y >= -6)
            ||
            ( DIFF_CENTER_X == -10 &&
              DIFF_CENTER_Y <= 5   &&
              DIFF_CENTER_Y >= -5)
            ||
            ( DIFF_CENTER_X == -11 &&
              DIFF_CENTER_Y <= 3   &&
              DIFF_CENTER_Y >= -3)
            ||
            ( DIFF_CENTER_X == -12 &&
              DIFF_CENTER_Y == 0 )
            ||
            ( DIFF_CENTER_Y == 9 && // the top arc
              DIFF_CENTER_X <= 6 &&
              DIFF_CENTER_X >= -6)
            ||
            ( DIFF_CENTER_Y == 10 &&
              DIFF_CENTER_X <= 5  &&
              DIFF_CENTER_X >= -5)
            ||
            ( DIFF_CENTER_Y == 11 &&
              DIFF_CENTER_X <= 3  &&
              DIFF_CENTER_X >= -3)
            ||
            ( DIFF_CENTER_Y == 12 &&
              DIFF_CENTER_X == 0 )
            ||
    ( DIFF_CENTER_Y == -9 && // the bottom arc
      DIFF_CENTER_X <= 6  &&
      DIFF_CENTER_X >= -6)
    ||
    ( DIFF_CENTER_Y == -10 &&
      DIFF_CENTER_X <= 5   &&
      DIFF_CENTER_X >= -5)
    ||
    ( DIFF_CENTER_Y == -11 &&
      DIFF_CENTER_X <= 3   &&
      DIFF_CENTER_X >= -3)
    ||
    ( DIFF_CENTER_Y == -12 &&
      DIFF_CENTER_X == 0 ))
)
begin
      green <=    10'b1010100000;
      red   <=    10'b1010100000;
      blue  <=    10'b0000000000;
end
else
begin
      if ((CENTER_X_1 != 0 && CENTER_Y_1 != 00) &&
      (( DIFF_X_1 <= 8  && // the square
      DIFF_X_1 >= -8 &&
      DIFF_Y_1 <= 8  &&
      DIFF_Y_1 >= -8)
    ||
    ( DIFF_X_1 == 9  && // the right arc
      DIFF_Y_1 <= 6  &&
      DIFF_Y_1 >= -6)
    ||
    ( DIFF_X_1 == 10 &&
      DIFF_Y_1 <= 5  &&
      DIFF_Y_1 >= -5)
    ||
    ( DIFF_X_1 == 11 &&
      DIFF_Y_1 <= 3  &&
      DIFF_Y_1 >= -3)
    ||
    ( DIFF_X_1 == 12 &&
      DIFF_Y_1 == 0 )
    ||
    ( DIFF_X_1 == -9 && // the left arc
      DIFF_Y_1 <= 6  &&
      DIFF_Y_1 >= -6)
    ||
    ( DIFF_X_1 == -10 &&
      DIFF_Y_1 <= 5   &&
      DIFF_Y_1 >= -5)
    ||
    ( DIFF_X_1 == -11 &&
      DIFF_Y_1 <= 3   &&
      DIFF_Y_1 >= -3)
    ||
    ( DIFF_X_1 == -12 &&
      DIFF_Y_1 == 0 )
    ||
    ( DIFF_Y_1 == 9 && // the top arc
      DIFF_X_1 <= 6 &&
      DIFF_X_1 >= -6)
    ||
    ( DIFF_Y_1 == 10 &&
      DIFF_X_1 <= 5  &&
      DIFF_X_1 >= -5)
    ||
    ( DIFF_Y_1 == 11 &&
      DIFF_X_1 <= 3  &&
      DIFF_X_1 >= -3)
    ||
    ( DIFF_Y_1 == 12 &&
      DIFF_X_1 == 0 )
    ||
    ( DIFF_Y_1 == -9 && // the bottom arc
      DIFF_X_1 <= 6  &&
      DIFF_X_1 >= -6)
    ||
    ( DIFF_Y_1 == -10 &&
      DIFF_X_1 <= 5   &&
      DIFF_X_1 >= -5)
    ||
    ( DIFF_Y_1 == -11 &&
      DIFF_X_1 <= 3   &&
      DIFF_X_1 >= -3)
    ||
    ( DIFF_Y_1 == -12 &&
      DIFF_X_1 == 0 )))
begin // blue paddle
      green <=    10'b1010100000;
      red   <=    10'b0000000000;
      blue  <=    10'b1010100000;
end
// draw left start box
else if ((suppress_boxes == 0) &&
      (mVGA_X == 120 || mVGA_X == 119)   &&
      (mVGA_Y >= 224 && mVGA_Y < 276))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
else if ((suppress_boxes == 0) &&
      (mVGA_X == 170 || mVGA_X == 169)   &&
      (mVGA_Y >= 225 && mVGA_Y < 275))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
else if ((suppress_boxes == 0) &&
      (mVGA_X > 120 && mVGA_X <= 170)   &&
      (mVGA_Y == 225 || mVGA_Y == 224))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end

else if ((suppress_boxes == 0) &&
      (mVGA_X > 120 && mVGA_X <= 170)   &&
      (mVGA_Y == 274 || mVGA_Y == 275))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
// draw left top border
else if ((mVGA_X == 19 || mVGA_X == 18)   &&
       (mVGA_Y >= 98 && mVGA_Y < 225))
begin
      green <=    10'b0000000000;
      red   <=    10'b0000000000;
      blue  <=    10'b1010100000;
end
// draw left goal
else if ((mVGA_X == 19 || mVGA_X == 18)   &&
             (mVGA_Y >= 225 && mVGA_Y < 275))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
// draw left bottom border
else if ((mVGA_X == 19 || mVGA_X == 18)   &&
             (mVGA_Y >= 275 && mVGA_Y < 403))
begin
      green <=    10'b0000000000;
      red   <=    10'b0000000000;
      blue  <=    10'b1010100000;
end
// draw top left border
else if ((mVGA_X >= 19 && mVGA_X < 320)   &&
             (mVGA_Y == 98 || mVGA_Y == 99))
begin
      green <=    10'b0000000000;
      red   <=    10'b0000000000;
      blue  <=    10'b1010100000;
end
// draw bottom left border
else if ((mVGA_X >= 19 && mVGA_X < 320)   &&
             (mVGA_Y == 401 || mVGA_Y == 402))
begin
      green <=    10'b0000000000;
      red   <=    10'b0000000000;
      blue  <=    10'b1010100000;
end
// blacken all else on left side
else if (mVGA_X >= 20 &&
         mVGA_X < 320)
begin
      red   <=    10'b0000000000;
      blue  <=    10'b0000000000;
      green <=    10'b0000000000;
end
// 2nd paddle
if ((CENTER_X_2 != 0 && CENTER_Y_2 != 0)&&
      (( DIFF_X_2 <= 8  && // the square
      DIFF_X_2 >= -8 &&
      DIFF_Y_2 <= 8  &&
      DIFF_Y_2 >= -8)
    ||
    ( DIFF_X_2 == 9  && // the right arc
      DIFF_Y_2 <= 6  &&
      DIFF_Y_2 >= -6)
    ||
    ( DIFF_X_2 == 10 &&
      DIFF_Y_2 <= 5  &&
      DIFF_Y_2 >= -5)
    ||
    ( DIFF_X_2 == 11 &&
      DIFF_Y_2 <= 3  &&
      DIFF_Y_2 >= -3)
    ||
    ( DIFF_X_2 == 12 &&
      DIFF_Y_2 == 0 )
    ||
    ( DIFF_X_2 == -9 && // the left arc
      DIFF_Y_2 <= 6  &&
      DIFF_Y_2 >= -6)
    ||
    ( DIFF_X_2 == -10 &&
      DIFF_Y_2 <= 5   &&
      DIFF_Y_2 >= -5)
    ||
    ( DIFF_X_2 == -11 &&
      DIFF_Y_2 <= 3   &&
      DIFF_Y_2 >= -3)
    ||
    ( DIFF_X_2 == -12 &&
      DIFF_Y_2 == 0 )
    ||
    ( DIFF_Y_2 == 9 && // the top arc
      DIFF_X_2 <= 6 &&
      DIFF_X_2 >= -6)
    ||
    ( DIFF_Y_2 == 10 &&
      DIFF_X_2 <= 5  &&
      DIFF_X_2 >= -5)
    ||
    ( DIFF_Y_2 == 11 &&
      DIFF_X_2 <= 3  &&
      DIFF_X_2 >= -3)
    ||
    ( DIFF_Y_2 == 12 &&
      DIFF_X_2 == 0 )
    ||
    ( DIFF_Y_2 == -9 && // the bottom arc
      DIFF_X_2 <= 6  &&
      DIFF_X_2 >= -6)
    ||
    ( DIFF_Y_2 == -10 &&
      DIFF_X_2 <= 5   &&
      DIFF_X_2 >= -5)
    ||
    ( DIFF_Y_2 == -11 &&
      DIFF_X_2 <= 3   &&
      DIFF_X_2 >= -3)
    ||
    ( DIFF_Y_2 == -12 &&
      DIFF_X_2 == 0 )))
begin // white paddle
      red   <=    10'b1010100000;
      blue  <=    10'b1010100000;
      green <=    10'b1010100000;
end
// draw right start box
else if ((suppress_boxes == 0) &&
      (mVGA_X == 471 || mVGA_X == 470)   &&
       (mVGA_Y >= 224 && mVGA_Y < 276))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
else if ((suppress_boxes == 0) &&
      (mVGA_X == 520 || mVGA_X == 521)   &&
      (mVGA_Y >= 224 && mVGA_Y < 276))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
else if ((suppress_boxes == 0) &&
      (mVGA_X > 470 && mVGA_X <= 520)   &&
      (mVGA_Y == 225 || mVGA_Y == 224))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
else if ((suppress_boxes == 0) &&
      (mVGA_X > 470 && mVGA_X <= 520)   &&
      (mVGA_Y == 274 || mVGA_Y == 275))
begin
      green <=    10'b1111100000;
      red   <=    10'b1111100000;
      blue  <=    10'b1111100000;
end
// draw right top border
else if ((mVGA_X == 621 || mVGA_X == 622)   &&
              (mVGA_Y >= 98 && mVGA_Y < 225))
begin
      green <=    10'b0000000000;
      red   <=    10'b0000000000;
      blue  <=    10'b1010100000;
```

```
            end
            // draw right goal
            else if ((mVGA_X == 621 || mVGA_X == 622)   &&
                         (mVGA_Y >= 225 && mVGA_Y < 275))
            begin
                  green <=    10'b1111100000;
                  red   <=    10'b1111100000;
                  blue  <=    10'b1111100000;
            end
            // draw right bottom border
            else if ((mVGA_X == 621 || mVGA_X == 622)   &&
                         (mVGA_Y >= 275 && mVGA_Y < 403))
            begin
                  green <=    10'b0000000000;
                  red   <=    10'b0000000000;
                  blue  <=    10'b1010100000;
            end
            // draw top right border
            else if ((mVGA_X >= 320 && mVGA_X < 621)   &&
                         (mVGA_Y == 98 || mVGA_Y == 99))
            begin
                  green <=    10'b0000000000;
                  red   <=    10'b0000000000;
                  blue  <=    10'b1010100000;
            end
            // draw bottom right border
            else if ((mVGA_X >= 320 && mVGA_X < 621)   &&
                         (mVGA_Y == 401 || mVGA_Y == 402))
            begin
                  green <=    10'b0000000000;
                  red   <=    10'b0000000000;
                  blue  <=    10'b1010100000;
            end
            // blacken all else on left side
            else if (mVGA_X >= 320 &&
                     mVGA_X < 640)
            begin
                  red   <=    10'b0000000000;
                  blue  <=    10'b0000000000;
                  green <=    10'b0000000000;
            end
            end
            state <= test1 ;
            end
      endcase
end

// Apply black thresholding
if (Read_DATA1[14:10] > 5'b10110 ||
    Read_DATA1[9:5]   > 5'b10110 ||
    Read_DATA1[4:0]   > 5'b10110
)
begin
      Temp_Read_DATA1 <= 15'b111111111111111;
end
else
begin
```

```
      Temp_Read_DATA1 <= 15'b000000000000000;
end

end
//================ End Paddle Detection & Drawing ==================//
```

Audio DAC module

```
//========================= AUDIO_DAC module =======================//
AUDIO_DAC u9 (//  Audio Side
                  .oAUD_BCK(AUD_BCLK),
                  .oAUD_DATA(AUD_DACDAT),
                  .oAUD_LRCK(AUD_DACLRCK),
                  //    Control Signals
                  .iSrc_Select(~(SP|SP2|SP3)),
                  .iCLK_18_4(AUD_CTRL_CLK),
                  .iRST_N(DLY_RST_1),
                  .iSound_Select(Sound_Select)  );
//====================== End AUDIO_DAC module ======================//
```

Sound Generation Hardware

```
//========================= Speaker Control ========================//
reg   SP;
reg   [23:0] DLY_cont;
reg   SP2;
reg   [2:0]  Sound_Select;
reg   [23:0] DLY_cont2;
reg   SP3;
reg   [23:0] DLY_cont3;

always@(posedge CLOCK_50)
begin
      if (sound_signal) // if datected => turn on speaker
      begin
            DLY_cont    <=    0;
      end
      else
      begin
            if(DLY_cont<24'h00ffff) // play for 65535 cycles @ 50MHz
            begin
                  DLY_cont <= DLY_cont+1;
                  SP <= 1;
                  Sound_Select<=  0;
            end
            else
            begin
                  SP <= 0;
            end
      end


      if (collision_sound) // if datected => turn on speaker
      begin
            DLY_cont2 <= 0;
      end
      else
      begin
            if(DLY_cont2<24'h08ffff) // play for 589823 cycles @ 50MHz
            begin
                  DLY_cont2 <= DLY_cont2+1;
                  SP2 <= 1;
                  Sound_Select<= 2'h01;
            end
            else
            begin
                  SP2 <= 0;
            end
      end


      if (chime_sound) // if datected => turn on speaker
      begin
            DLY_cont3 <= 0;
      end
      else
      begin
            if(DLY_cont3<24'h300000) // play for 3145728 cycles @ 50MHz
            begin
                  DLY_cont3 <= DLY_cont3+1;
                  SP3 <= 1;
                  Sound_Select <= 2;
            end
            else if(DLY_cont3<24'h600000) // play for another 3145728
            begin
                  DLY_cont3 <= DLY_cont3+1;
                  SP3 <= 1;
                  Sound_Select <= 3;
            end
            else if(DLY_cont3<24'h900000) // play for another 3145728
            begin
                  DLY_cont3 <= DLY_cont3+1;
                  SP3 <= 1;
                  Sound_Select <= 4;
            end
            else if(DLY_cont3<24'hc00000) // play for another 3145728
            begin
                  DLY_cont3 <= DLY_cont3+1;
                  SP3 <= 1;
                  if (DLY_cont3 % 1 == 0) Sound_Select<=  5;
                  else Sound_Select<=6;
            end
            else
            begin
                  SP3 <= 0;
            end
      end
end
//====================== End Speaker Control ========================//
```

C Code

Game Dynamics

```
//======================== C Main Program =========================//
#define begin {
#define end }
#define position_delta 0
#define CIR_BUFFER_SIZE 10
#define RADIUS  13
#define LEFT_WALL   (8  + RADIUS)
#define RIGHT_WALL  (620 - RADIUS)
#define TOP_WALL    (100 + RADIUS)
#define BOTTOM_WALL (400 - RADIUS)
#define MAX_SPEED 6
#define MIN_SPEED 0x0080
#define FREEZE_CONST 12

#define INCREASE_1  0x0000
#define INCREASE_2  0x0010
#define INCREASE_3  0x0020
#define INCREASE_4  0x0040
#define INCREASE_5  0x0080
#define INCREASE_6  0x0100
#define INCREASE_7  0x0140
#define INCREASE_8  0x0180
#define INCREASE_9  0x0200
#define INCREASE_10 0x0280
#define INCREASE_11 0x0300
#define INCREASE_12 0x0380
#define INCREASE_13 0x0400
#define INCREASE_14 0x0480
#define INCREASE_15 0x0500
#define INCREASE_16 0x0580
#define INCREASE_17 0x0600
#define INCREASE_18 0x0600

#define float2fix(a) (int)( (a) * 256.0)
#define mfix(a,b) ((int)((((long)(a))*((long)(b)))>>8))

int main(void)
begin
  int address_x, valid, address_y;
  int address_x_2, address_y_2;
  int x_position1, y_position1;
  int x_position2, y_position2, no_change;
  int sw, key, notecount;
  int left_half = 1;
  int x_diff, y_diff; // diff in x and y centers of puck & paddle
  int speed_memory_1, speed_memory_2;
  int x_speed_increase, y_speed_increase;
  int friction_distance;
  char collision_flag;
  char speed_x_positive_flag = 1;
  char speed_y_positive_flag = 1;
  unsigned char LEFT_PLAYER_SCORED = 0;
  unsigned char RIGHT_PLAYER_SCORED = 0;
  unsigned char LEFT_SCORE = 0;
  unsigned char RIGHT_SCORE = 0;

  int speed_x = 0;
  int speed_y = 0;
  int speed_x_2 = 0;
  int speed_y_2 = 0;
  int speed_x_relevant, speed_y_relevant;

  int speed;
  char game_began = 0;

  int collision_count = 0;
  unsigned int delay_counter = 0;
  int dummy = 0;

  unsigned int notes[9]={262, 294, 330, 349, 392, 440, 494, 523, 0};
  unsigned int msg = 0;
  unsigned int freq = 0;
  unsigned int x_position_history[CIR_BUFFER_SIZE];
  unsigned int y_position_history[CIR_BUFFER_SIZE];
  unsigned int head, tail;

  // Fit the entire puck within border
  unsigned int x_position = 0x1400 + (RADIUS<<8);
  unsigned int y_position = 0x6400 + (RADIUS<<8);
  int x_speed = 0x00000000;
  int y_speed = 0x00000700;

  int freeze_collision = 0;

  // jtag_uart variables
  FILE *uart_file;
  int freq_val;
  int wave_val;

  notecount = 0;
  no_change = 1;

  head = 0;
  tail = 0;

  //open the lcd --- device name from system.h
  lcd_fd = fopen("/dev/lcd", "w");
  if(lcd_fd == NULL) printf("Unable to open lcd display\n");

  while (1)
  begin

    if (game_began == 0)
    {
      x_speed = 0x00000000;
      y_speed = 0x00000400;
      x_position = 0x00013100  + (RADIUS<<8);
      y_position = 0x00006400 + (RADIUS<<8);
      IOWR_ALTERA_AVALON_PIO_DATA(OUT9_BASE, 0);
      // Paddle 1 position in int
      address_x = IORD_ALTERA_AVALON_PIO_DATA(IN0_BASE);
      address_y = IORD_ALTERA_AVALON_PIO_DATA(IN2_BASE);

      // Paddle 2 position in int
      address_x_2 = IORD_ALTERA_AVALON_PIO_DATA(IN3_BASE);
      address_y_2 = IORD_ALTERA_AVALON_PIO_DATA(IN4_BASE);

      if (address_x >= 135 && address_x <= 155)
      {
        if (address_y >= 240 && address_y <= 260)
        {
          if (address_x_2 >= 485 && address_x_2 <= 505)
          {
            if (address_y_2 >= 240 && address_y_2 <= 260)
            {
              game_began = 1;
              RIGHT_SCORE = 0;
              LEFT_SCORE = 0;
            }
          }
        }
      }
    }

    if (game_began == 1)
    begin
      IOWR_ALTERA_AVALON_PIO_DATA(OUT9_BASE, 1);

      if (msg == 0) msg = 1;
      else msg = 0;
      if (LEFT_PLAYER_SCORED)
      begin
        IOWR_ALTERA_AVALON_PIO_DATA(OUT10_BASE, 0);
        delay_counter = 0;
        while (delay_counter < 1500000)
        {
          delay_counter++;
          dummy = delay_counter;
        }
        delay_counter = 0;
        // Fit the entire puck within border
        x_position = 0x01D600  + (RADIUS<<8);
        y_position = 0x6400 + (RADIUS<<8);
        x_speed = 0x0000;
        y_speed = 0x0300;
        LEFT_PLAYER_SCORED = 0;
      end
      else if (RIGHT_PLAYER_SCORED)
      begin
        IOWR_ALTERA_AVALON_PIO_DATA(OUT10_BASE, 0);
        delay_counter = 0;
        while (delay_counter < 1500000)
        {
          delay_counter++;
          dummy = delay_counter;
        }
    delay_counter = 0;
    // Fit the entire puck within border
    x_position = 0xAA00  + (RADIUS<<8);
    y_position = 0x6400 + (RADIUS<<8);
    x_speed = 0x0000;
    y_speed = 0x0300;
    RIGHT_PLAYER_SCORED = 0;
  end


  IOWR_ALTERA_AVALON_PIO_DATA(OUT0_BASE, msg);
  IOWR_ALTERA_AVALON_PIO_DATA(OUT7_BASE, 0);
  IOWR_ALTERA_AVALON_PIO_DATA(OUT8_BASE, 0);


  // Check the validity of the data
  //valid = IORD_ALTERA_AVALON_PIO_DATA(IN1_BASE);

  x_position_history[0] = x_position1;  // Prev left paddle x pos
  y_position_history[0] = y_position1;  // Prev left paddle y pos
  x_position_history[1] = x_position2;  // Prev right paddle x pos
  y_position_history[1] = y_position2;  // Prev right paddle y pos

  // Paddle 1 position in int
  address_x = IORD_ALTERA_AVALON_PIO_DATA(IN0_BASE);
  address_y = IORD_ALTERA_AVALON_PIO_DATA(IN2_BASE);

  address_x = address_x << 8; // Paddle 1 x position in fixed point
  address_y = address_y << 8; // Paddle 1 y position in fixed point

  // Paddle 2 position in int
  address_x_2 = IORD_ALTERA_AVALON_PIO_DATA(IN3_BASE);
  address_y_2 = IORD_ALTERA_AVALON_PIO_DATA(IN4_BASE);

  address_x_2 = address_x_2 << 8;  // Paddle 2 x pos in fixed point
  address_y_2 = address_y_2 << 8;  // Paddle 2 y pos in fixed point

  x_position1 = address_x;
  y_position1 = address_y;

  x_position2 = address_x_2;
  y_position2 = address_y_2;

  no_change = 0;

  speed = sqrt((double)(
           abs(x_position_history[0] - x_position1) *
           abs(x_position_history[0] - x_position1) +
           abs(y_position_history[0] - y_position1) *
           abs(y_position_history[0] - y_position1)));


  if (x_position_history[0] == x_position1 &&
      y_position_history[0] == y_position1)
  begin
    if (speed_memory_1 == 0)
    begin
```

```
    speed_x = (x_position_history[0] - x_position1);
    speed_y = (y_position_history[0] - y_position1);
    speed_memory_1 = 100;
  end
  else
    speed_memory_1--;
end
else
begin
  speed_x = (x_position_history[0] - x_position1);
  speed_y = (y_position_history[0] - y_position1);
  speed_memory_1 = 3000;
end


if (x_position_history[1] == x_position2 &&
    y_position_history[1] == y_position2)
begin
  if (speed_memory_2 == 0)
  begin
    speed_x_2 = (x_position_history[1] - x_position2);
    speed_y_2 = (y_position_history[1] - y_position2);
    speed_memory_2 = 100;
  end
  else
    speed_memory_2--;
end
else
begin
  speed_x_2 = (x_position_history[1] - x_position2);
  speed_y_2 = (y_position_history[1] - y_position2);
  speed_memory_2 = 3000;
end

// commented out because printf takes a loooong time
// will use LEDR, and HEX0-7 instead
//  printf("x: %d\ny: %d\nspeed: %d\n",
//          address_x, address_y, speed);

  IOWR_ALTERA_AVALON_PIO_DATA(OUT2_BASE, LEFT_SCORE);
  IOWR_ALTERA_AVALON_PIO_DATA(OUT3_BASE, RIGHT_SCORE);

  speed_x_relevant = ((left_half == 1) ? speed_x :
                                         speed_x_2);
  speed_y_relevant = ((left_half == 1) ? speed_y :
                                         speed_y_2);

  if (abs(speed_x_relevant) < 1)          // 1 LED
  begin
    IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 1);
    x_speed_increase = INCREASE_1;
  end
  else if (abs(speed_x_relevant) < 1000)  // 2 LED
  begin
    IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 3);
    x_speed_increase = INCREASE_2;
  end
```

```
else if (abs(speed_x_relevant) < 2000)  // 3 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 7);
  x_speed_increase = INCREASE_3;
end
else if (abs(speed_x_relevant) < 3000)  // 4 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 15);
  x_speed_increase = INCREASE_4;
end
else if (abs(speed_x_relevant) < 4000)  // 5 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 31);
  x_speed_increase = INCREASE_5;
end
else if (abs(speed_x_relevant) < 5000)  // 6 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 63);
  x_speed_increase = INCREASE_6;
end
else if (abs(speed_x_relevant) < 6000)  // 7 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 127);
  x_speed_increase = INCREASE_7;
end
else if (abs(speed_x_relevant) < 7000)  // 8 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 255);
  x_speed_increase = INCREASE_8;
end
else if (abs(speed_x_relevant) < 8000)  // 9 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 511);
  x_speed_increase = INCREASE_9;
end
else if (abs(speed_x_relevant) < 9000)  // 10 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 1023);
  x_speed_increase = INCREASE_10;
end
else if (abs(speed_x_relevant) < 10000)  // 11 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 2047);
  x_speed_increase = INCREASE_11;
end
else if (abs(speed_x_relevant) < 11000)  // 12 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 4095);
  x_speed_increase = INCREASE_12;
end
else if (abs(speed_x_relevant) < 12000)  // 13 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 8191);
  x_speed_increase = INCREASE_13;
end
else if (abs(speed_x_relevant) < 13000)  // 14 LED
begin
```

```
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 16383);
  x_speed_increase = INCREASE_14;
end
else if (abs(speed_x_relevant) < 14000)  // 15 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 32767);
  x_speed_increase = INCREASE_15;
end
else if (abs(speed_x_relevant) < 15000)  // 16 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 65535);
  x_speed_increase = INCREASE_16;
end
else if (abs(speed_x_relevant) < 30000)  // 17 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 131071);
  x_speed_increase = INCREASE_17;
end
else                   // 18 LED
begin
  IOWR_ALTERA_AVALON_PIO_DATA(OUT1_BASE, 262143);
  x_speed_increase = INCREASE_18;
end

if (abs(speed_y_relevant) < 1)        // 1 LED
begin
  y_speed_increase = INCREASE_1;
end
else if (abs(speed_y_relevant) < 1000)  // 2 LED
begin
  y_speed_increase = INCREASE_2;
end
else if (abs(speed_y_relevant) < 2000)  // 3 LED
begin
  y_speed_increase = INCREASE_3;
end
else if (abs(speed_y_relevant) < 3000)  // 4 LED
begin
  y_speed_increase = INCREASE_4;
end
else if (abs(speed_y_relevant) < 4000)  // 5 LED
begin
  y_speed_increase = INCREASE_5;
end
else if (abs(speed_y_relevant) < 5000)  // 6 LED
begin
  y_speed_increase = INCREASE_6;
end
else if (abs(speed_y_relevant) < 6000)  // 7 LED
begin
  y_speed_increase = INCREASE_7;
end
else if (abs(speed_y_relevant) < 7000)  // 8 LED
begin
  y_speed_increase = INCREASE_8;
end
else if (abs(speed_y_relevant) < 8000)  // 9 LED
```

```
    begin
      y_speed_increase = INCREASE_9;
    end
    else if (abs(speed_y_relevant) < 9000)  // 10 LED
    begin
      y_speed_increase = INCREASE_10;
    end
    else if (abs(speed_y_relevant) < 10000)  // 11 LED
    begin
      y_speed_increase = INCREASE_11;
    end
    else if (abs(speed_y_relevant) < 1100)  // 12 LED
    begin
      y_speed_increase = INCREASE_12;
    end
    else if (abs(speed_y_relevant) < 12000)  // 13 LED
    begin
      y_speed_increase = INCREASE_13;
    end
    else if (abs(speed_y_relevant) < 13000)  // 14 LED
    begin
      y_speed_increase = INCREASE_14;
    end
    else if (abs(speed_y_relevant) < 14000)  // 15 LED
    begin
      y_speed_increase = INCREASE_15;
    end
    else if (abs(speed_y_relevant) < 15000)  // 16 LED
    begin
      y_speed_increase = INCREASE_16;
    end
    else if (abs(speed_y_relevant) < 30000)  // 17 LED
    begin
      y_speed_increase = INCREASE_17;
    end
    else                  // 18 LED
    begin
      y_speed_increase = INCREASE_18;
    end

if (((x_diff>>8) * (x_diff>>8) + (y_diff>>8) * (y_diff>>8)) <=
    (4 * (RADIUS - 1) * (RADIUS - 1)))
    // Radius - 1 makes collision closer
  if (!freeze_collision)
    collision_flag = 1;


// DYNAMICS
if (notecount++ == 200 )   // slowing down puck movement
begin
  if (freeze_collision > 0) freeze_collision--;

  // Previous puck x and y positions
  x_position_history[2] = x_position;
  y_position_history[2] = y_position;

  if (speed_x_positive_flag == 1)
  x_position += x_speed;  // x coordinate of puck
else
  x_position -= x_speed;  // x coordinate of puck
if (speed_y_positive_flag == 1)
  y_position += y_speed;  // y coordinate of puck
else
  y_position -= y_speed;  // y coordinate of puck

x_diff = (left_half == 1) ? (x_position - x_position1) :
                            (x_position - x_position2);
y_diff = (left_half == 1) ? (y_position - y_position1) :
                            (y_position - y_position2);
// RIGHT WALL
if ((y_position < ((225<<8)+(RADIUS<<8)) || y_position >=
    ((285<<8)-(RADIUS<<8))) &&
    (x_position >= (RIGHT_WALL<<8)))
begin
  if (speed_x_positive_flag == 1)
  begin
    if (x_speed > MIN_SPEED)
      x_speed -= 0x0040;
    speed_x_positive_flag = 0;
  end
  IOWR_ALTERA_AVALON_PIO_DATA(OUT7_BASE, 1);
end
// RIGHT GOAL
if ((y_position >= ((225<<8)+(RADIUS<<8)) && y_position <
    ((285<<8)-(RADIUS<<8))) &&
    (x_position >= ((RIGHT_WALL+RADIUS+1)<<8)))
begin
  // Generate chime
  IOWR_ALTERA_AVALON_PIO_DATA(OUT10_BASE, 1);
  LEFT_PLAYER_SCORED = 1;
  LEFT_SCORE++;
  if (LEFT_SCORE == 10)
  {
    game_began = 0;
  }
end
// LEFT WALL
if ((y_position < ((225<<8)+(RADIUS<<8)) || y_position >=
    ((285<<8)-(RADIUS<<8))) &&
    (x_position <= ((LEFT_WALL+RADIUS+1)<<8)))
begin
  if (speed_x_positive_flag == 0)
  begin
    if (x_speed > MIN_SPEED)
      x_speed -= 0x0040;
    speed_x_positive_flag = 1;
  end
  IOWR_ALTERA_AVALON_PIO_DATA(OUT7_BASE, 1);
end
// LEFT GOAL
if ((y_position >= ((225<<8)+(RADIUS<<8)) && y_position <
    ((285<<8)-(RADIUS<<8))) &&
    (x_position <= (LEFT_WALL<<8)))
begin
```

```
  // Generate chime
  IOWR_ALTERA_AVALON_PIO_DATA(OUT10_BASE, 1);
  RIGHT_PLAYER_SCORED = 1;
  RIGHT_SCORE++;
  if (RIGHT_SCORE == 10)
  {
    game_began = 0;
  }
end
// BOTTOM WALL
if (y_position >= (BOTTOM_WALL<<8))
begin
  if (speed_y_positive_flag == 1)
  begin
    if (y_speed > MIN_SPEED)
      y_speed -= 0x0040;
    speed_y_positive_flag = 0;
  end
  IOWR_ALTERA_AVALON_PIO_DATA(OUT7_BASE, 1);
end
// TOP WALL
if (y_position <= (TOP_WALL<<8))
begin
  if (speed_y_positive_flag == 0)
  begin
    if (y_speed > MIN_SPEED)
      y_speed -= 0x0040;
    speed_y_positive_flag = 1;
  end
  IOWR_ALTERA_AVALON_PIO_DATA(OUT7_BASE, 1);
end

if (collision_flag == 1)
// PADDLES
begin // to look convincing on video
  collision_count++;

  collision_flag = 0;
  // Collision sound effect
  IOWR_ALTERA_AVALON_PIO_DATA(OUT8_BASE, 1);
  // COLLISION 1
  if (speed_x_positive_flag == 1 &&
      speed_y_positive_flag == 1 && !freeze_collision)
  begin
    // bounce up & left if puck is above & left of paddle
    if (y_diff < 0 && x_diff < 0)
    begin
      speed_x_positive_flag = 0;
      speed_y_positive_flag = 0;
    end
    // bounce up & right if puck is above & right of paddle
    else if(y_diff < 0 && x_diff >= 0)
    begin
      speed_y_positive_flag = 0;
    end
    // bounce down & left if puck is below paddle
    else if(y_diff >= 0 && x_diff < 0)
    begin
      speed_x_positive_flag = 0;
    end
    else
    begin
      // same direction
    end

    freeze_collision = FREEZE_CONST;
  end
  // COLLISION 2
  if (speed_x_positive_flag == 1 &&
      speed_y_positive_flag == 0 && !freeze_collision)
  begin
    // bounce down & left if puck is below & left of paddle
    if (y_diff > 0 && x_diff < 0)
    begin
      speed_x_positive_flag = 0;
      speed_y_positive_flag = 1;
    end
    // bounce down & right if puck is above & left of paddle
    else if (y_diff > 0 && x_diff >= 0)
    begin
      speed_y_positive_flag = 1;
    end
    // bounce up & left if puck is above & left of paddle
    else if(y_diff <= 0 && x_diff < 0)
    begin
      speed_x_positive_flag = 0;
    end
    else
    begin
      // same direction
    end
    freeze_collision = FREEZE_CONST;
  end
  // COLLISION 3
  if (speed_x_positive_flag == 0 &&
      speed_y_positive_flag == 1 && !freeze_collision)
  begin

    // bounce up & right if puck is above & right of paddle
    if (y_diff < 0 && x_diff > 0)
    begin
      speed_x_positive_flag = 1;
      speed_y_positive_flag = 0;
    end
    // bounce up & left if puck is above & left of paddle
    else if (y_diff < 0 && x_diff <= 0)
    begin
      speed_y_positive_flag = 0;
    end
    // bounce down & right if puck is below & right of paddle
    else if(y_diff >= 0 && x_diff > 0)
    begin
      speed_x_positive_flag = 1;
    end
    else
    begin
      // same direction
    end
    freeze_collision = FREEZE_CONST;
  end
  // COLLISION 4
  if (speed_x_positive_flag == 0 &&
      speed_y_positive_flag == 0 && !freeze_collision)
  begin
    // bounce down & right if puck is below & right of paddle
    if (y_diff > 0 && x_diff > 0)
    begin
      speed_x_positive_flag = 1;
      speed_y_positive_flag = 1;
    end
    // bounce down & left if puck is below & left of paddle
    else if (y_diff > 0 && x_diff <= 0)
    begin
      speed_y_positive_flag = 1;
    end
    // bounce up & right if puck is above & right of paddle
    else if (y_diff <= 0 && x_diff > 0)
    begin
      speed_x_positive_flag = 1;
    end
    else
    begin
      // same direction
    end
    freeze_collision = FREEZE_CONST;
  end

  if (x_speed == 0)
  {
       if (abs(x_diff) <= 1)
      {
          // do nothing
      }
      else if (abs(x_diff) <= 4)
      {
          x_speed = MIN_SPEED;
          y_speed -= 0x0040;
      }
      else if (abs(x_diff) <= 8)
      {
          x_speed = 0x0050;
          y_speed -= 0x0050;
      }
      else
      {
          x_speed = 0x0060;
          y_speed -= 0x0060;
      }
  }
```

```
        // ALL COLLISIONS DONE, CHANGE SPEEDS
        if ((x_speed + x_speed_increase) <= (MAX_SPEED<<8))
        begin
          if (x_speed > 0x0500)
          begin
            x_speed += (x_speed_increase / 2);
          end
          else
            x_speed += x_speed_increase;
        end
        else
          x_speed = MAX_SPEED<<8;

        if ((y_speed - y_speed_increase) < (MAX_SPEED<<8))
        begin
          if (y_speed > 0x0500)
          begin
            y_speed += (y_speed_increase / 2);
          end
          else
            y_speed += y_speed_increase;
        end
        else
          y_speed = MAX_SPEED<<8;
      end

      notecount = 0;
    end

    if ((x_position>>8) < 320)
    begin
      // the puck is in the left half
      left_half = 1;
    end
    else if ((x_position>>8) >= 320)
    begin
      // the puck is in the right half
      left_half = 0;
    end

    IOWR_ALTERA_AVALON_PIO_DATA(OUT4_BASE, 0);

    IOWR_ALTERA_AVALON_PIO_DATA(OUT5_BASE, x_position>>8);
    IOWR_ALTERA_AVALON_PIO_DATA(OUT6_BASE, y_position>>8);

    end
  end
end
//======================= End C Main Program ========================//
```