

# **Arcade Machine - Pong Game**

## User Guide



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## 1 Introduction

Arcade Machine is a hardware architecture designed to implement the well know game - Pong - in verilog, which will be developed to be deployed in the Digilent Basys2 board. The players make use of four buttons in a PS/2 Keyboard in order to control the position of the rackets. The game is displayed in a monitor using VGA output. Also, the score of the game is displayed in a seven segment display. Additionally, two switches are used to start the game and reset it.

For this project, the picoVersat - minimal hardware controller - will be used as a state machine. Specialized hardware will be created to handle the PS/2, the VGA and the seven segment display interfaces.

## 2 Block Diagram

In this section, a block diagram of the arcade machine's hardware is showed in Fig. 1. As mentioned previously, picoVersat is used as a state machine and four other hardware modules will be developed (which are all connected to the data bus of the picoVersat). Object Display Controller is the hardware responsible for the VGA output of the game (paddles and ball), Score Display Controller is the hardware responsible for the output of the score of the players to the seven segment displays, Paddle Controller is the hardware responsible for the acquisition of the PS/2 key presses in the keyboard and Start Game Register is responsible to register the state of the switch that command the start of the game. A deeper insight in the function of each one of the modules is given in the Section 4.

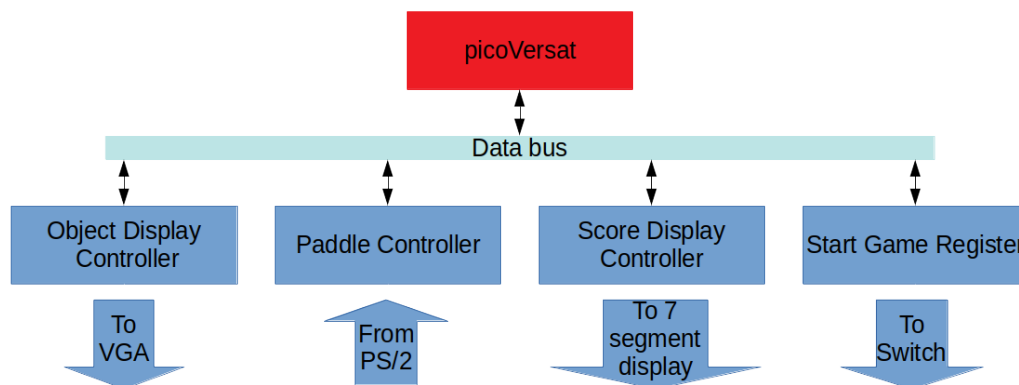


Figure 1: Block Diagram

## 3 Interface Signals

The interface signals of the Arcade machine project are described in Table 1. To implement this verilog project in a development board such as the basys2, you have to describe the connections between these signals and the correspondent IO ports.

Name	Direction	Description
clk	IN	Clock signal.
rst	IN	Reset signal.
btn	IN	When this signal is HIGH the game starts.
<b>VGA Interface</b>		
OutRed[2:0]	OUT	Intensity of red color.
OutGreen[2:0]	OUT	Intensity of green color.
OutBlue[2:0]	OUT	Intensity of blue color.
HSYNC	OUT	Horizontal sweep.
VSYNC	OUT	Vertical sweep.
<b>7 Segment Display Interface</b>		
an[3:0]	OUT	Selects the display to be light up.
seg[6:0]	OUT	Selects the segment of the display to be light up.
dp	OUT	Light up decimal point of the display selected by an
<b>PS/2 Interface</b>		
PS2D	IN	Serial data transmitted by the keyboard.
PS2C	IN	Clock driven by the keyboard.

Table 1: Interface signals.

### 3.1 VGA Interface

VGA works through sweeping screen methodology, which means each pixel is drawn one by one following a left to right and up to down pattern. The HS and VS signal transmit pulses each time the display has to change row or start a new screen correspondingly. In between pulses the red, green and blue signals are changed accordingly in order to indicate which color should be drawn.

In figure 2 there is a demonstration of the timing between the signals, where can be seen that the video signal is only valid between the HS and VS signal pulses that marks a start of a new row or screen. The displays resolution used in this project is 640 by 480 with a refresh rate of 60Hz for these specifications the signal timings are shown in figure 3.

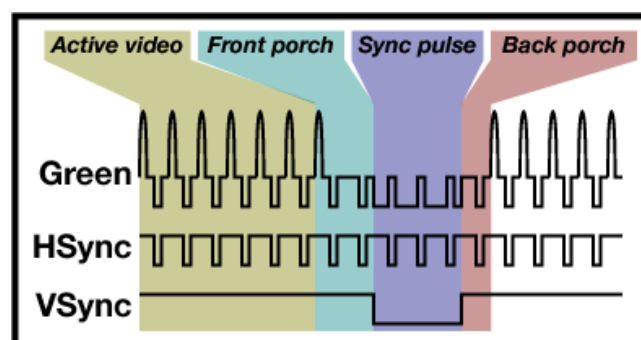


Figure 2: VGA timing diagram

### 3.2 7 Segment Display Interface

In this project it is used four 7 segment displays, two for each player score, showing a maximum of 99 points for each player. However there are only a common bus to control each one of the segments of all the displays,

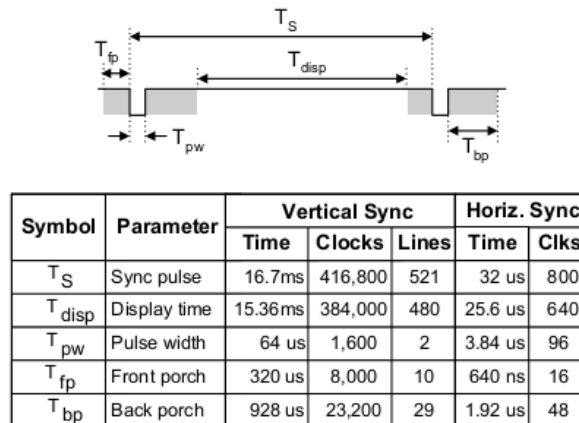


Figure 3: VGA timing specifications for a 640 by 480 display

the cathode bus, in this way to make each display to show a different number we have to make a time division multiplexing of this segment control bus signal accordingly to the enable signals of each 7 segment display. The anode bus has four signals one for each 7 segment display and it is used as a display enable since all the anodes of the segments of one display are connected to one of that four signals.

In figure 4 it is shown a timing diagram of the time division multiplexing done with the 7 segment displays.

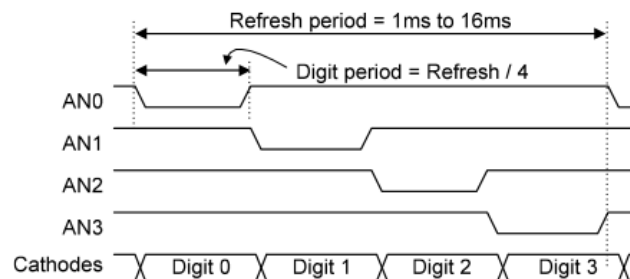


Figure 4: 7 segment display timing diagram

### 3.3 PS/2 Interface

The PS/2 interface is a typical synchronous serial bus interface, where a clock signal is driven by the transmitting device, in this case the keyboard, at the same time as the data signal, containing the binary code of the key pressed. This code is 8 bit long preceded by a start bit and followed by a stop bit. Some keys need more than a code to be identified.

In figure 5 it is shown a timing diagram of the specifications that the input signal from the keyboard has to respect in order to work with this system.

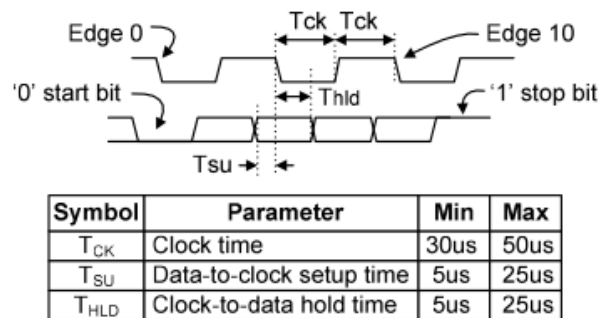


Figure 5: Timing specifications of the PS/2 input

## 4 Peripherals

In this section, a deeper insight on the architecture of each one of the modules connected to the data bus will be given. Due to the fact that the picoVersat is a third party IP, its structure will not be analysed in this document and can be seen in the following document: [picoVersat Documentation](#). Four different subsections are presented, each one relating to each one of the modules.

### 4.1 Object Display Controller

The object display controller module, represented in figure 6, is responsible to deal with the visual representation of the game, it receives as input through the data bus of the picoVersat the coordinates of the upper leftmost point of the objects to be drawn on the screen. This coordinates are stored in the object position registers and are feed to the object detection sub-modules.

The object detection modules receive a bunch of parameters as input, such as the coordinates of the upper leftmost point of an object and the width (B1,B2,etc.) and height (C1,C2,etc.) of an object. Then according to the sweep coordinates received also as input, it determines if the pixel pointed by these sweep coordinates belongs to this rectangular shaped object and outputs a HIGH signal if this condition is true.

The frame detection module works similar to the object detection modules, but it only receives the thickness of the frame as a parameter (A5), this module instead of detecting the sweep coordinates inside of a rectangular shapes, it detects if the sweep coordinates are inside the frame that is around the borders of the screen.

The output of the detection sub-modules described earlier are then encoded and used to address a color memory that is connected directly to the Red, Green and Blue buses that outputs a color to the VGA screen accordingly to the existence of an object in the pixel being drawn at that time.

The VGA controller sub-module generates both the sweep signals used to drive the VGA screen (HS and VS) and the sweep coordinates used in the detection sub-modules, in order to synchronize the color being deployed to the VGA screen with the signals VS and HS that triggers the screen sweeping.



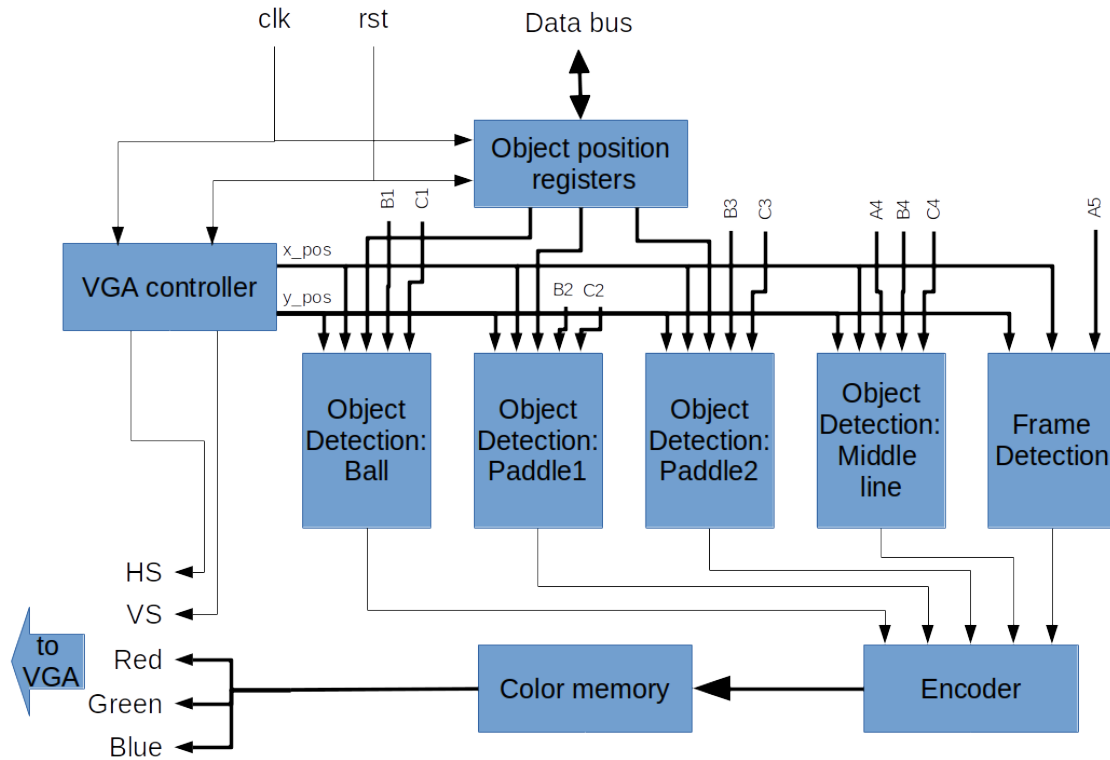


Figure 6: Object Display Controller Hardware Diagram

## 4.2 Paddle Controller

The Paddle Controller is a module responsible for getting the input from a PS/2 keyboard and register the paddles position.

The picoVersat can retrieve at any time the position of the paddles by reading the value of the paddle movement counter. The counter has an upper and lower limit, so that the paddles don't move more than the boundaries/limits of the game.

From the PS/2 input, it determines which was the key that was pressed. If the key is equal to the defined keys, it sends a signal to a bank of counters to increase/decrease the paddle position. To be able to do that, a clock divider is used to create a signal from each N clock of the FPGA clock (which is 50 MHz) to only move the paddles with a given period.

To know more about the PS/2 protocol and how it works, you can explore the following documentation: [PS/2 Protocol](#).

A simplified block diagram of the Paddle Controller can be seen in Figure 7.

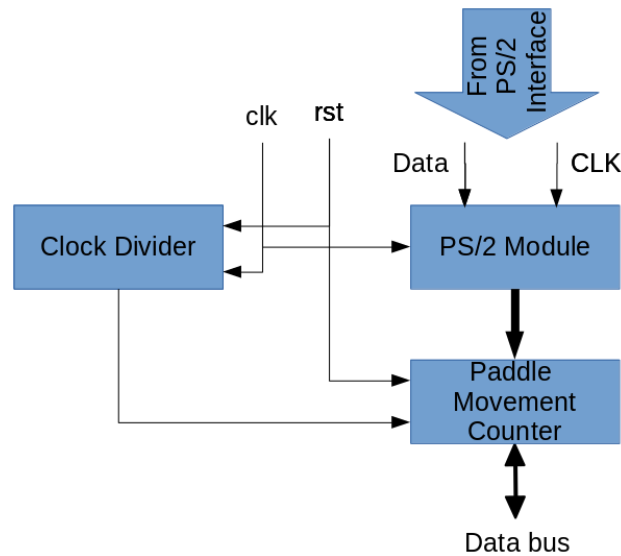


Figure 7: Paddle Controller Hardware Diagram

### 4.3 Score Display Controller

The Score Display Controller is a module responsible for the display of the score in the seven segment displays.

It receives two signals from the picoVersat from the data bus, increment score from player one and increment score from player two. This means that the registers with the scores of each player are inside this module (they are divided in four sets of registers, two sets for the tenths of the number of the score of each player and two sets for the units of the score of each player). Also, there is a memory that is used to store the conversion between number to seven segment display representation.

To show the four digits in the seven segment display (score from 0 to 99 for each player), the seven segment display needs to be refreshed every 1ms to 16ms. To be able to do that, the module has a clock divider that creates a signal from every N clock of the clock of the FPGA (which is 50 MHz). This signal selects the output for the anode signal (which is stored in a bank of registers) and the input to the memory that translates the number to the digit in the display.

As input, it also has a reset signal, which resets the score of both players to zero.

A simplified block diagram of the Score Display Controller can be seen in Figure 8.

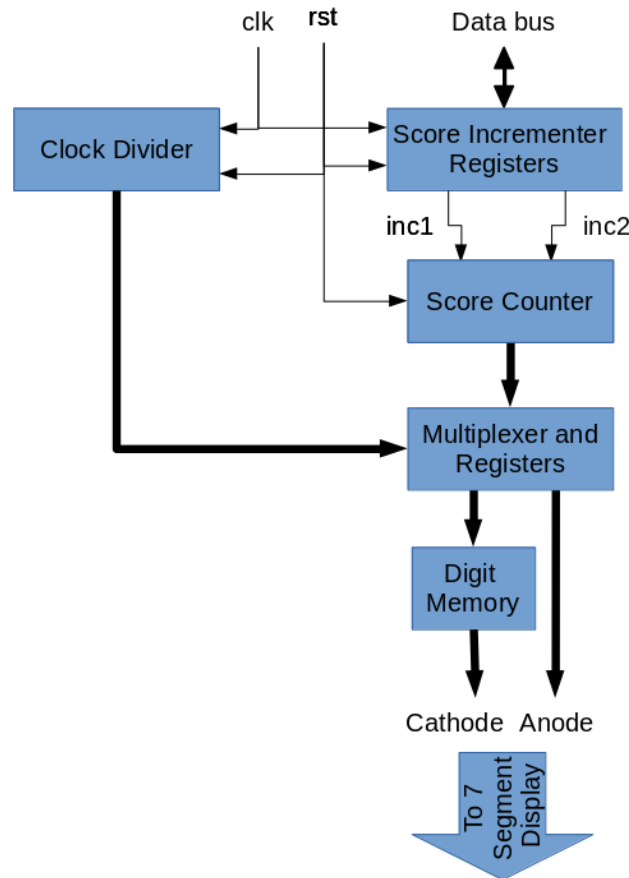


Figure 8: Score Display Controller Hardware Diagram

#### 4.4 Start Game register

The start game register is connected directly to a push button. The register can be read by the picoVersat through the data bus, in order to determine if the game can start.

## 5 Memory Map

The memory map of the system, as seen by picoVersat programs, is given in Table 2.

Mnemonic	Address	Read/Write	Read Latency	Description
MEM_BASE	0	Read+Write	1	User programs and data
REGF_BASE	1024	Read+Write	0	Register file peripheral
OBJECT_BASE	1044	Write only	NA	Object Display Controller
PADDLE_BASE	1048	Read only	0	Paddle Controller
SCORE_BASE	1050	Write only	NA	Score Display Controller
START_BASE	1052	Read only	0	Start Game Register

Table 2: Memory map base addresses

## 6 Code Analysis

In this section, the code used to program the picoVersat, in order to run the Arcade Machine, is analyzed. A simplified flowchart of the code can be seen in the Figure 9.

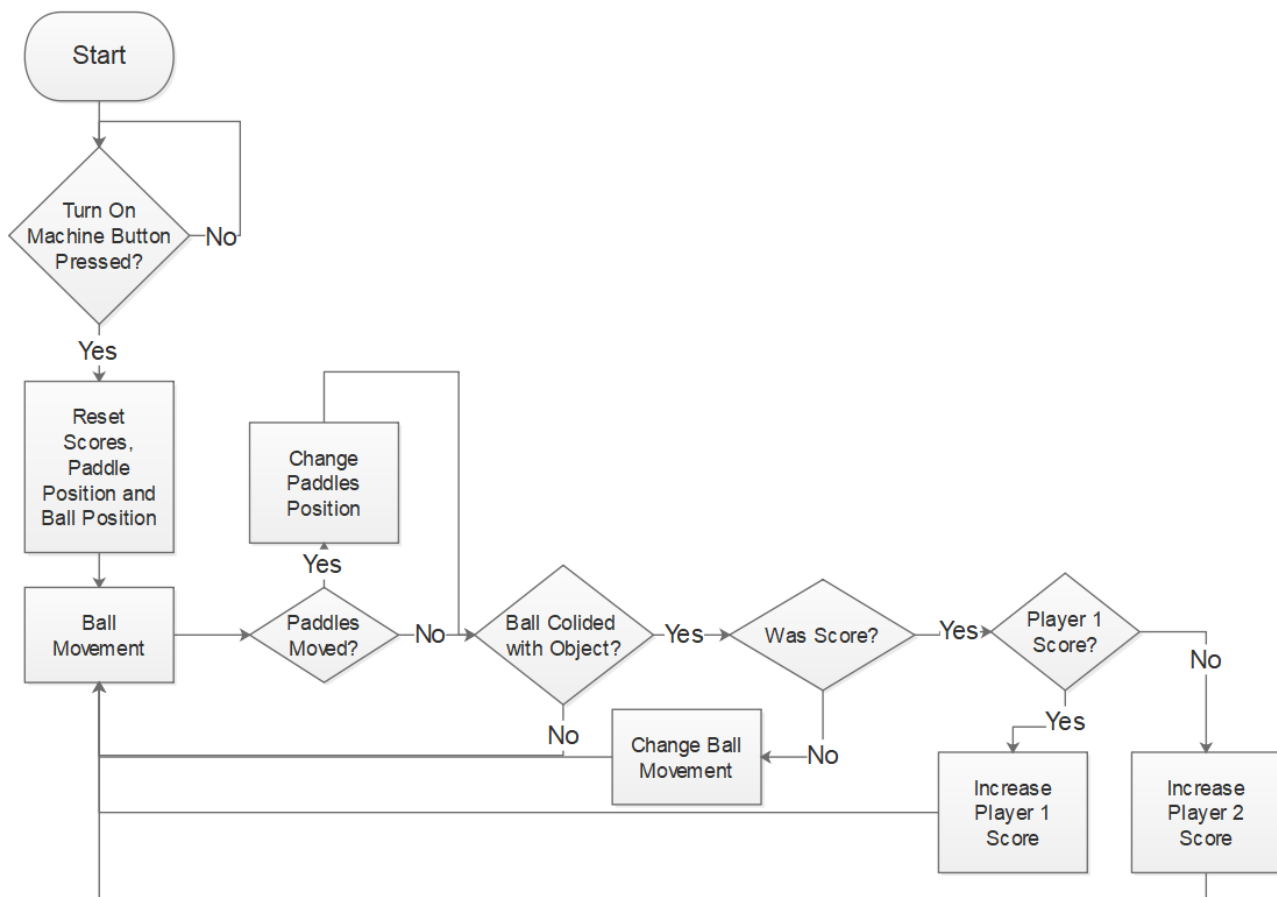


Figure 9: Paddle Controller Hardware Diagram

The arcade machine - pong game works in the following way. After the Basys 2 platform is turned on, picoVersat will start working and it will stay in a state in which it checks if the start push button is pressed. It will stay in that state until the push button is pressed, once pressed the game starts.

After starting the game, everything needs to be initialized: the scores, the paddles position and the ball position. After the initialization the ball starts moving.

If the keys which correspond to a movement of a paddle are pressed, then the paddle needs to move in the monitor (the image displayed needs to show the paddle in the new position) and we need to store this value (in order to detect collisions between the ball and the paddles). If the ball hits any object without being a goal (paddles or border of the window game), the movement of the ball needs to be changed (for example, if it was moving from right to left now it needs to move from left to right). Otherwise, if it hits an object and it was a goal, then it is needed to verify who scored the goal, increasing the correspondent player score.

## 7 Implementation Results

When implemented this systems uses the keyboard pair of keys W/S and O/L to control player 1 and player 2 paddles respectively. It uses a board push button to start the game. The left side of the seven segment display is used to display player 1 score and the right side is dedicated to player 2 score. The VGA displays starts by showing the game environment with the ball stopped in the middle. When the start button is pushed the game starts and the ball starts moving in the VGA display. The gameplay is show in the following video: [https://drive.google.com/open?id=1HeaeJE78\\_7Xhp4eX0EJKMP0hSvF\\_SwxM](https://drive.google.com/open?id=1HeaeJE78_7Xhp4eX0EJKMP0hSvF_SwxM).

Once a player reaches 99 points, which is the maximum value that can be displayed by the seven segment display, the game ends, and waits for the start game signal coming from the board push button. This behaviour is shown by the following video: [https://drive.google.com/open?id=1RJiS\\_UIbxHn7yL1VT4FF28gns7YCDyTk](https://drive.google.com/open?id=1RJiS_UIbxHn7yL1VT4FF28gns7YCDyTk).

The following subsections 7.1 and 7.2 shows the resource usage and timing results using Xilinx Spartan-3E FPGA (XC3S100E) as target device.

### 7.1 Resource Usage

To meet the timing constraints, the modules hierarchy should not be kept in order to reach further optimizations. Table 3 shows the resource usage with those optimizations, however to be able to estimate the resource usage by sub-module implementation, the Arcade Machine was also implemented keeping the hierarchy even though it doesn't meet the timing constraints. Table 4 shows estimations of the resource usage by sub-module.

	Used	Available	Utilization
<b>Slice Flip-flops</b>	332	1920	17%
<b>4-Input LUT</b>	1211	1920	63%
<b>4-Input LUT without route-through</b>	1095	1920	57%
<b>Occupied Slices</b>	699	960	72%
<b>IOBs</b>	29	83	34%
<b>BRAM</b>	2	4	50%

Table 3: Target device resource usage by resource type

Table 3 shows this system can be successfully implemented in the target device, XC3S100E, using half the BRAMs and 63% of LUTs. Not counting with the LUTs used to route-through, the resource usage of LUTs decrease to 57%, being just a little bit above half the capacity of the target device. In this way this hardware architecture shows the ability of being implemented in cost-effective low end devices.

The BRAM usage could be reduced using a smaller program memory. The designed architecture has a default program memory with a capacity for 1024 instructions, however the pong game only needs 152 instructions. The 1024 instruction capacity gives room for different games that may be developed over this architecture.

	Slice Flip-flops (%)	4-Input LUT (%)	BRAM (%)
<b>PicoVersat</b>	23	61	100
<b>Object Display Controller</b>	37	24	0
<b>Paddle Controller</b>	30	10	0
<b>Score Display Controller</b>	10	5	0

Table 4: Resource usage profiling by sub-module implementation

Table 4 shows the resource usage percentage by sub-module relative to the total resource usage of the Arcade Machine. The PicoVersat module uses most of the resources, to further reduce the resource usage, a state machine can be used to connect all the sub-modules instead of the PicoVersat, however some of the flexibility given by the software driven PicoVersat might be lost.

The Object Display Controller does not use any BRAM because this is an object driven display controller, only object proprieties must be stored not the actual values of every pixel. This approach saves memory usage, making this hardware architecture compatible with target devices with small memory capacities.

## 7.2 Timing Results

The Arcade Machine can be implemented using a **50 MHz** clock frequency, this is a clock period of **20 ns**. With this timing constraint and making use of further optimizations by not keeping hierarchy the worst case slack is shown in table 5.

	<b>Worst Case Slack</b>
<b>Setup</b>	0.070ns
<b>Hold</b>	0.844ns

Table 5: Worst Case Slack for a clock period of 20 ns

The Setup Worst Case Slack shown in table 5 is given by an internal path of the PicoVersat module. This path source is the RAM and ends in the controller of the PicoVersat.