A Triangle Drawing Machine: The Design and Implementation of a Microcomputer, VGA Driver, Programming Language, Assembler & More…

Advanced Topics in Information Technology 6206ICT, Digital Systems

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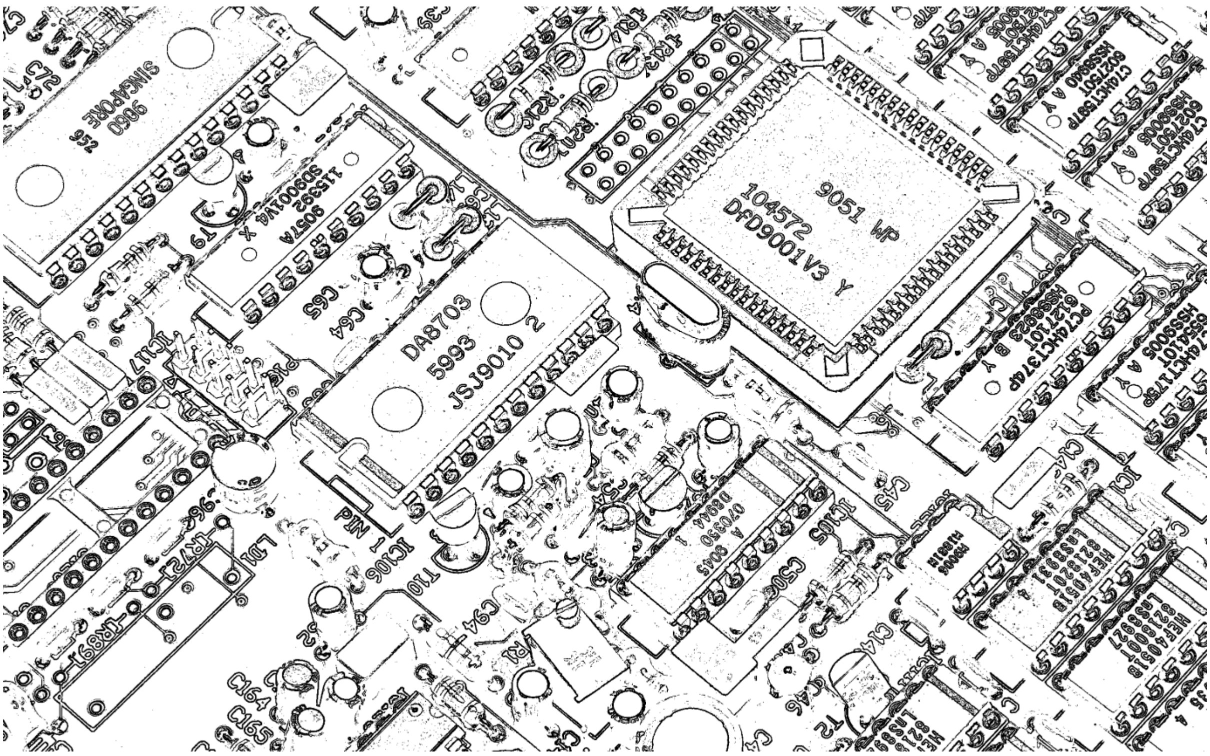

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Problem Statement

Build an electronic machine which can draw an arbitrary list of triangles to a television monitor using the Video Graphics Array (VGA) interface. This device must be implemented using a Field-programmable gate array (FPGA) using various digital techniques learned in the course.

Solution

My solution to this problem was to design my own microcomputer and assembly language. The assembly language must be simple enough for a one semester project, but must also have the robustness and completeness required to implement a triangle drawing algorithm. The microcomputer must be fully able to run the assembly language, and be able to interface with memory and output in the form of visual information. Besides the microcomputer and assembly language, a VGA driver must also be implemented, the driver must be able to transmit the image given to it by the microcomputer, and use the correct timing and protocol required by VGA input. To accomplish this, a frame buffer device was also designed and built; the system was implemented using a hardware description language and works successfully.

Digital Techniques

VGA Driver & Frame Buffer

The VGA driver generates the necessary signals to operate a television or display which honours the VGA standard. The dimensions of the input image are 640 by 480; the driver uses a sequential method to colour in each pixel. The VGA display uses 5 input signals which must be generated by the VGA driver using the exact timing requirements. A high level explanation of the VGA driver and frame buffer is shown in figure 1. The VGA driver has 14 output logic lines, one for vertical synchronization (frame complete), one for horizontal synchronization (pixel row complete), the other twelve lines contain 3 buses which of four bits each, these 3 buses correspond to the red, green and blue colour signals. The screen refreshes every 16.7 milliseconds; therefore it has a refresh frequency of around 60 Hz. The clock which synchronizes the VGA system is a 25MHz square wave oscillator. The horizontal sync signal is pulsed before each row of colour is transmitted across the communication channel, and the vertical signal is pulsed before each frame of the video is sent. Both of these signals are active low, have a specific duration and both have a buffer time both before and after the signal begins and finishes. The pre sync signal buffers are called the front porch and back porch respectively. The timing requirements are listed in figure 2. I designed a module which takes a 25Mhz clock, and outputs the vertical and horizontal sync, as well as whether the colour data should be output (a signal called data out) and the x and y position for which the corresponding input RGB signals should be sent. This module is shown in figure 3. The mod-800 counter is used for the row signal generation and the mod-521 counter uses it's RCO output as the clock input. The horizontal sync output and vertical sync output both go active high at the correct time range, the send data signal goes active high when the rgb data should be sent. The frame buffer memory is limited to a size which is less than the 640*480*4 bits which is required for a 640*480 image, therefore an image of size 160*120 is used for the frame buffer. To provide the correct indexing, the x and y coordinates are first divided by four (two right shifts) and the y coordinate is multiplied by 160 and added to the x coordinate, this is used as the address input for the frame buffer, the data is then selected to go to the output using a multiplexer. Figure 4 shows this module.

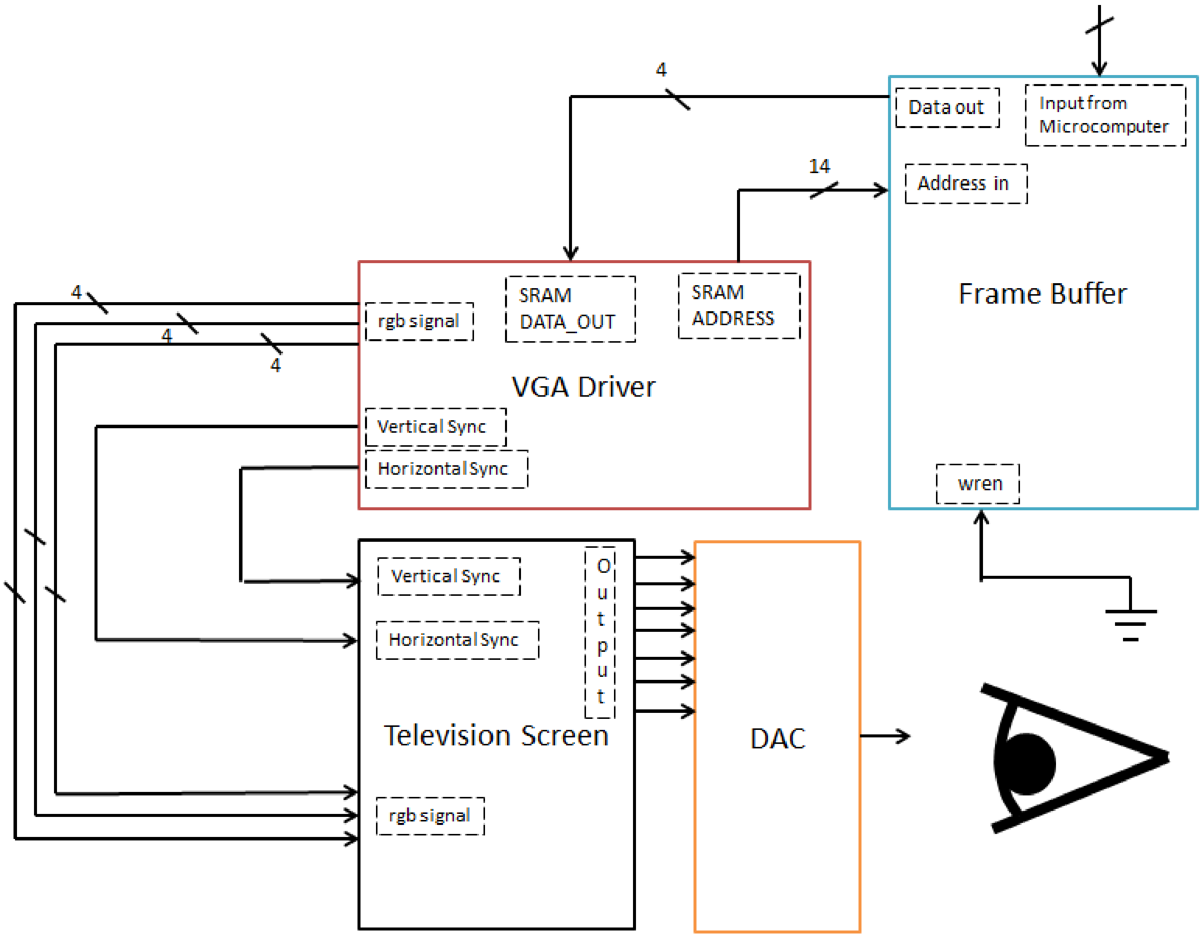

FIGURE 1 HIGH LEVEL DETAILS OF THE VGA DRIVER AND FRAME BUFFER

Symbol	Parameter	Vertical Sync			Horizontal Sync	
		Time	Clocks	Lines	Time	Clocks
T_S	Sync pulse time	16.7 ms	416,800	521	32 μs	800
T_{DISP}	Display time	15.36 ms	384,000	480	25.6 μs	640
T_{PW}	Pulse width	64 μs	1,600	2	3.84 μs	96
T_{FP}	Front porch	320 μs	8,000	10	640 ns	16
T_{BP}	Back porch	928 μs	23,200	29	1.92 μs	48

FIGURE 2 VGA SYNCHRONIZATION TIMING TABLE

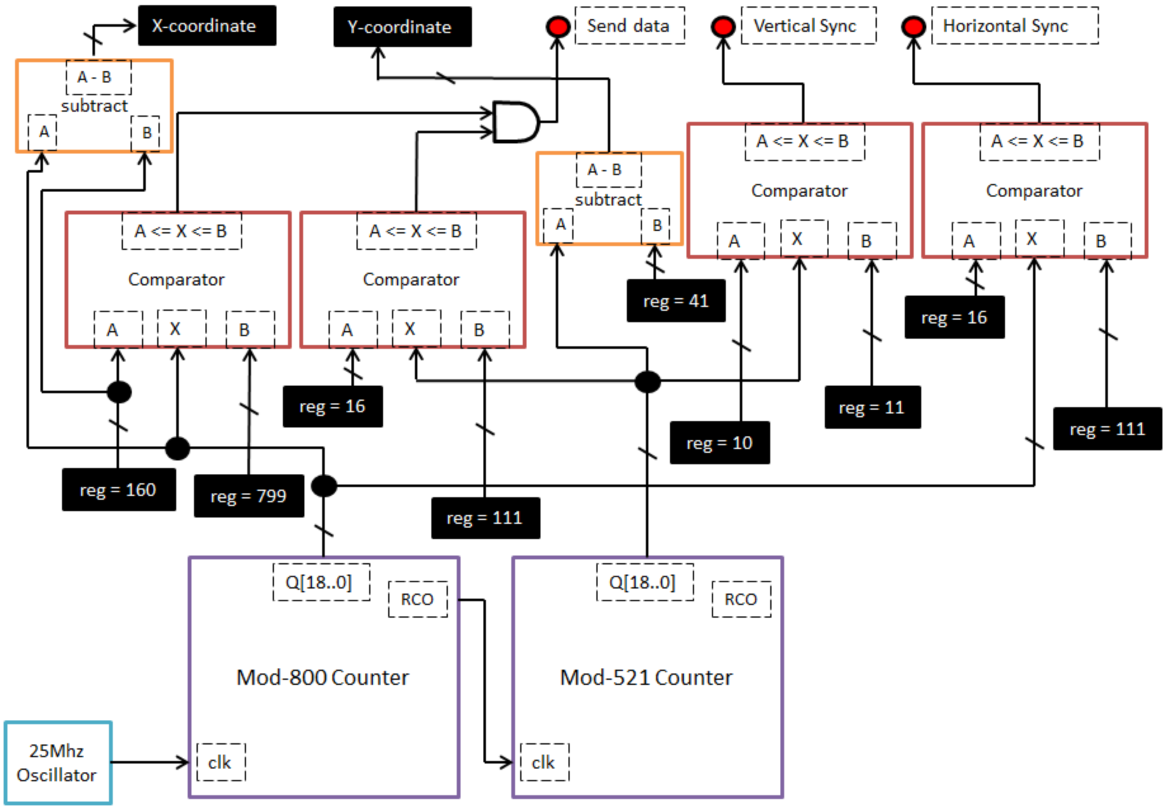

FIGURE 3 VGA DRIVER MODULE DESIGN

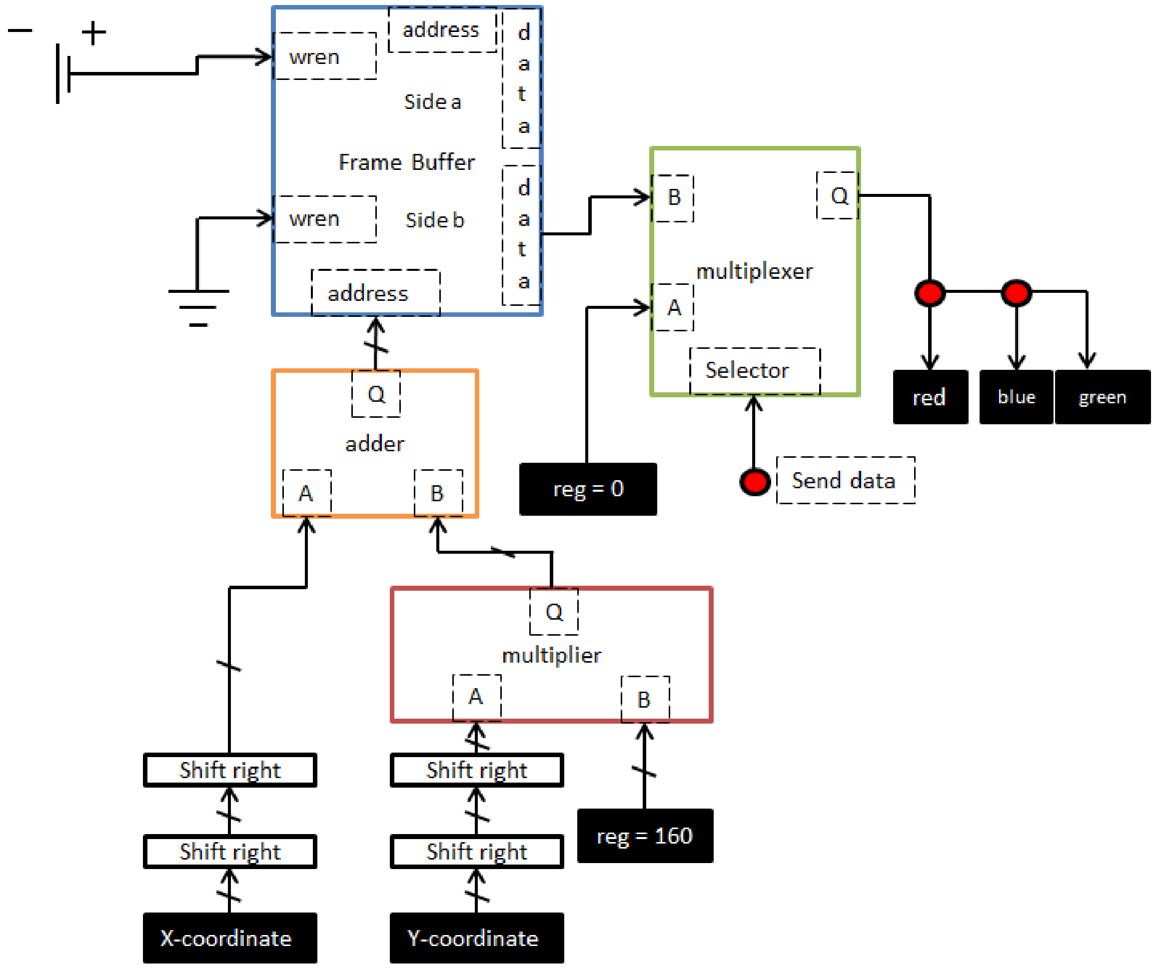

FIGURE 4 FRAME BUFFER TO DISPLAY INDEXING

MICROCOMPUTER

The microcomputer I designed includes a CPU for processing, SRAM containing 'memory contents and machine code' and a connection between the CPU and the frame buffer (for output). A diagram of the microcomputer is shown in figure 5. The program code is separated into a separate SRAM from the program memory, the CPU also controls the frame buffer. The program code has 40 bits per address, 32 bits to storage a number associated with each operation, 5-bits for the operation code and 3 bits are left blank. The CPU has several on board D-Flip Flop registers including: Accumulators A & B, the program counter PC and registers to store the current op-code and associated number. The CPU performs mathematical operations on numbers, reads and writes from memory and writes pixels to the frame buffer. There are two main sections: the ALU and the control unit. The ALU is responsible for performing mathematical operations and also modifying the program counter. The control unit controls the various signals for reading and writing to the memory units and frame buffer. Figure 6 shows a diagram of the high level operation of the proposed CPU. The registers in the CPU are processed and the output provides feedback to the new register values, the control unit receives input signals and sends output signals, the ALU processes all operations which do not require input or output. All of the operations the CPU can perform are listed in table 1. These operations are performed by either the ALU or the Control Unit, in figure 6, an encoder is used to select the correct output using a multiplexer. This provides the necessary feedback for the CPU registers. The CPU is a simple state machine, it first loads an operation then executes it, figure 7 shows this state diagram as well as the timing diagram which the CPU follows.

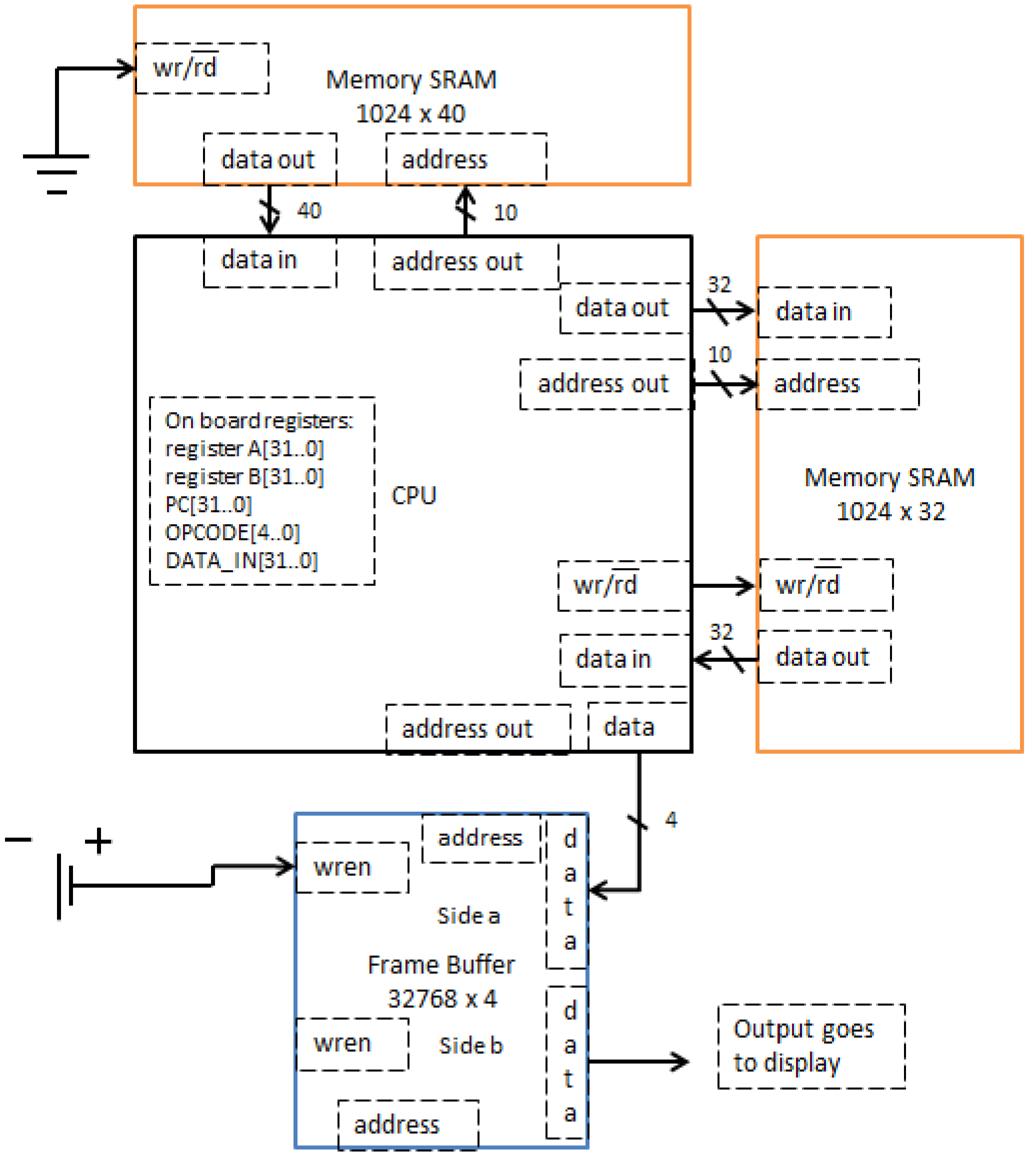

FIGURE 5 HIGH LEVEL MICROCOMPUTER DIAGRAM

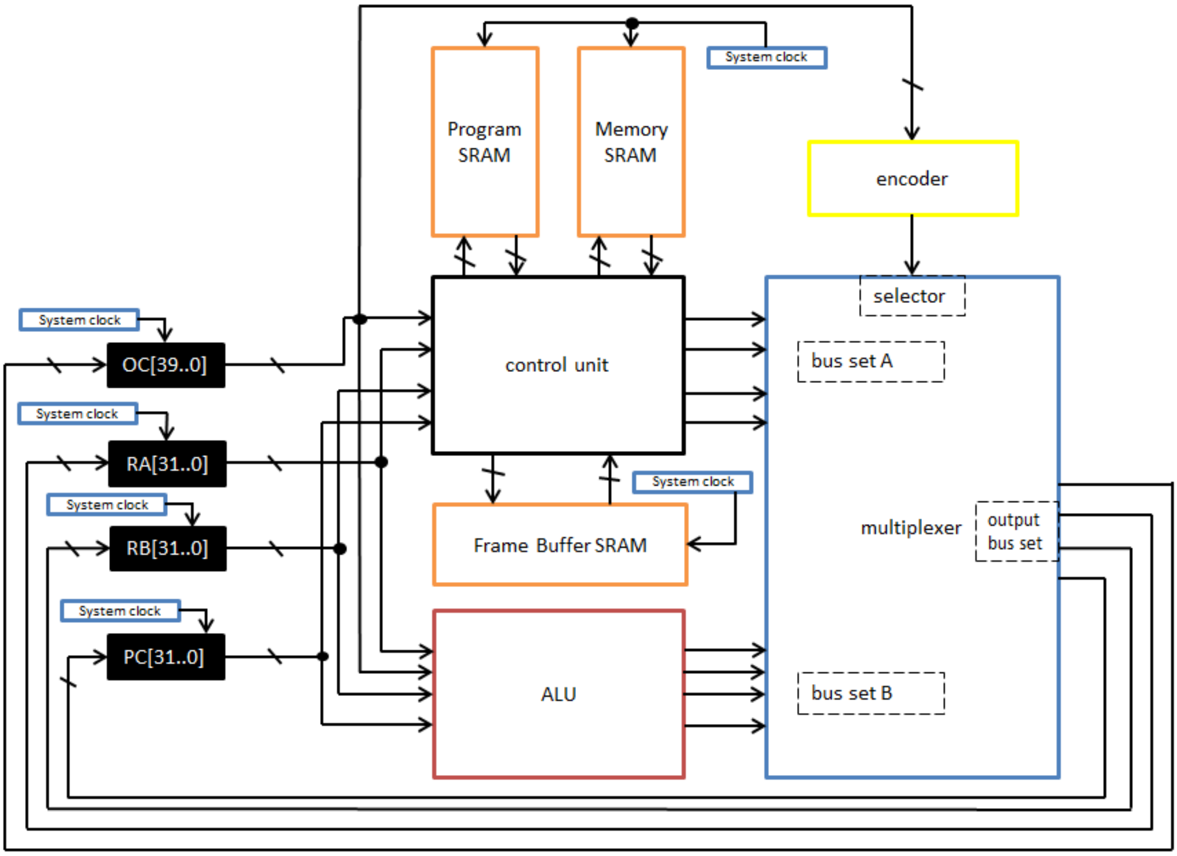

FIGURE 6 INSIDE THE CPU

TABLE 1 CPU OPERATIONS

op-code	function	type	binary oc
0	Comment	Do Nothing	00000
1	Function	Do Nothing	00001
2	lda	Control Unit	00010
3	ldb	Control Unit	00011
4	ldafb	Control Unit	00100
5	sta	Control Unit	00101
6	stb	Control Unit	00110
7	staib	Control Unit	00111
8	setim	Control Unit	01000
9	bisa	ALU	01001
10	goto	ALU	01010
11	goa	ALU	01011
12	ifa	ALU	01100
13	ifan	ALU	01101
14	altb	ALU	01110
15	aeqb	ALU	01111
16	agtb	ALU	10000
17	add	ALU	10001

18	inca	ALU	10010
19	deca	ALU	10011
20	sub	ALU	10100
21	or	ALU	10101
22	and	ALU	10110
23	xor	ALU	10111
24	not	ALU	11000
25	shla	ALU	11001
26	shra	ALU	11010
27	end	Do Nothing	11011

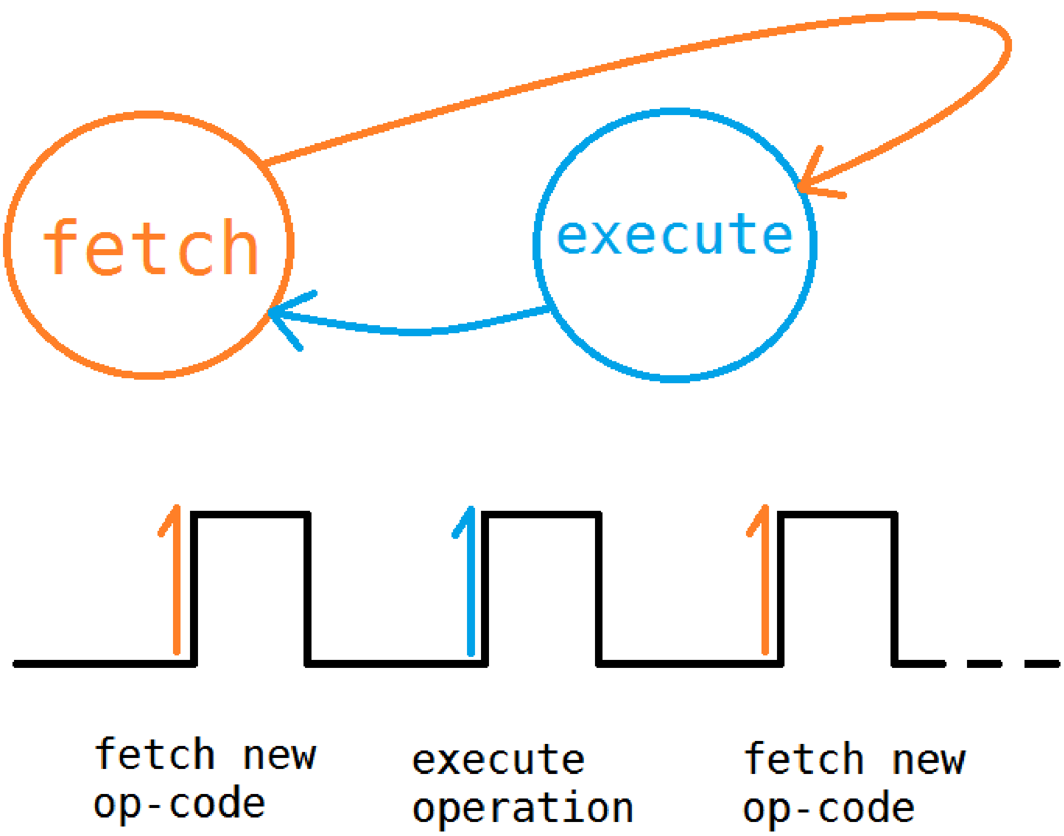

FIGURE 7 CPU STATE MACHINE AND TIMING DIAGRAM

Luke's Assembly Language 4.0 (LAL4)

LAL4 is the 4th assembly language designed for this project, it's specifications are listed in below. The name column is the assembly defined names for writing in assembly, descriptions and machine codes are provided for each code. The x symbol represents the raw address or number associated with each code, the vx allows the programmer to load a static number into a register, this is not an actual operation performed by the CPU, instead the assembler converts this to an address where the static number can be stored. When jumping to different locations in the memory, the PC must be altered, the n symbol allows the programmer to specify where the PC should be set, the func word allows the programmer to specify a location within the program, the name following this is the one used in the naming convention.

```
Lukes Assembly Language 4.0
Memory:
Flip-Flops in CPU: a, b
SRAM: X * 16 bit memory (X is user defined)

codes and operations

No. Operations : 28
OpCode: 5 bits XXXXX

Numerics 32-bits
Total CodeLen: 40 bits : [5-bit op-code | 32-bit num | 3-bit empty section]
                          (39-35)         (34-3)       (2-0)

OPCODE          Name            Usage           description
Others:
00000           #               #blah blah      comment
00001           func            func name       function naming
11011           end             end             stop execution

Control/Memory:
00010           lda             lda x           load memory[x] into a
                                lda vx          load value x into a
00011           ldb             ldb x           load memory[x] into b
                                ldb vx          load value b into b
00100           ldafb           ldafb           load memory[b] into a
00101           sta             sta x           store a in memory[x]
00110           stb             stb x           store b in memory[x]
00111           staib           staib           store a in memory[b]
01000           setim           setim           store a in image.data[b]
ALU/PC:
01001           bisa            bisa            b = a
01010           goto            goto n          set PC to n
01011           goa             goa             set PC to a
01100           ifa             ifa n           if a != 0, set PC to n
01101           ifan            ifan n          if a is 0, set PC to n
01110           altb            altb            if a < b -> a = 1, else a = 0
01111           aeqb            aeqb            if a == b -> a = 1, else a = 0
10000           agtb            agtb            if a > b -> a = 1, else a = 0
10001           add             add             a = a+b
10010           inca            inca            a = a+1
10011           deca            deca            a = a-1
10100           sub             sub             a = a-b
10101           or              or              a = a|b
10110           and             and             a = a&b
10111           xor             xor             a = a^b
11000           not             not             a = !a
11001           shla            shla x          shift a left by x bits
11010           shra            shra x          shift a right by x bits
```

THE LAL4 ASSEMBLER & INTERPRETER

The LAL4 assembler and interpreter (LAL4AI) performs several tasks, it converts any LAL4 assembly program into machine code which can be run on the my microcomputer, it also converts the static functions and variables into a memory initialization file which is loaded into the main memory on start up. The interpreter can be used to simulate LAL4 programs, and even provides an output image so the programmer can see what the television screen should look like.

The LAL4AI is written in the python programming language, the entire program is shown below. Not shown is the bitmap object which simply communicates with a C program which reads and writes images to the hard drive.

```
class Assembler:
    def __init__(self, finame):
        fi = open(finame, 'r')
        self.lines = fi.readlines()
        fi.close()
        self.programCounter = 0
        self.memory = []
        self.im = BMP()
        self.im.setupFile(160, 120)
        self.memoryAmount = 1000
        self.stackMemCount = self.memoryAmount - 1
        self.ra = 0
        self.rb = 0
        self.end = False
        for i in range(self.memoryAmount):
            self.memory.append(0)
        count = 0
        lut = [0, 1024, 512, 341, 256, 204, 170, 146, 128, 113, 102, 93, 85, 78, 73, 68, 64, 60, 56, 53, 51, 48, 46, 44, 42, 40, 39, 37, 36, 35, 34, 33, 32, 31, 30,
29, 28, 27, 26, 26, 25, 24, 24, 23, 23, 22, 22, 21, 21, 20, 20, 20, 19, 19, 18, 18, 18, 17, 17, 17, 17,  16, 16, 16, 16, 15, 15, 15, 15, 14, 14, 14, 14, 14, 13, 13, 13, 13, 13, 12, 12,
12, 12, 12, 12, 12, 11, 11, 11, 11, 11, 11, 11 , 11, 10, 10, 10, 10, 10, 10, 10, 10, 10, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7,
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1, 1, 1, 1 , 1]
        for i in range(300, 941):
            self.memory[i] = lut[count]
            count += 1
        self.setupStackMemory()
        self.functionNames = []
        self.functionLines = []
        self.setupFunctionNames()
        self.genMachineCode()
        #self.printInfo()

    def setupFunctionNames(self):
        for i in range(len(self.lines)):
            st = self.lines[i]
            codes = st.split(' ')
            if(codes[0] == 'func'):
                self.functionNames.append(codes[1])
                self.functionLines.append(int(i))
        for i in range(len(self.lines)):
            st = self.lines[i]
            codes = st.split(' ')
            if(codes[0] == 'goto' or codes[0] == 'ifa' or codes[0] == 'ifan'):
                self.lines[i] = codes[0] + ' ' + str(self.findFunctionLine(codes[1], i))
            if(codes[0] == 'lda' or codes[0] == 'ldb'):
                if(codes[1][0] == 'n'):
                    funcName = codes[1]
                    funcName = funcName[1:]
                    val = int(self.findFunctionLine(funcName, 2))
                    naddr = self.addStackMem(val)
                    self.lines[i] = str(codes[0]) + ' ' + str(naddr)
```

```
def findFunctionLine(self, name, xval):
	for i in range(len(self.functionNames)):
		if(name == self.functionNames[i]):
			return int(self.functionLines[i])
	return int(xval)
def printInfo(self):
	print self.lines
	print 'Program Counter: ', self.programCounter
	print 'functions:'
	for i in range(len(self.functionNames)):
		print self.functionNames[i], ' on line: ', self.functionLines[i]
	print 'memory:'
	#for i in range(self.memoryAmount):
	for i in range(90):
		print '\t', i, '\t', self.memory[i]
def setMem(self, addr, val):
	self.memory[addr] = int(val)
def getMemory(self, addr):
	return int(self.memory[addr])
def addStackMem(self, val):
	self.memory[self.stackMemCount] = val
	r = self.stackMemCount
	self.stackMemCount -= 1
	return r
def chomp(self, strin):
	return strin.rstrip()

def setupStackMemory(self):
	for i in range(len(self.lines)):
		st = self.chomp(self.lines[i])
		self.lines[i] = st
		codes = st.split(' ')
		if(codes[0] == 'lda' or codes[0] == 'ldb'):
			if(codes[1][0] == 'v'):
				lnch = codes[1]
				lnch = lnch[1:]
				val = int(lnch)
				naddr = self.addStackMem(val)
				self.lines[i] = str(codes[0]) + ' ' + str(naddr)
def run(self):
	while(1):
		self.iterateProgram()
		if(self.end == True):
			return

def iterateProgram(self):
	st = self.lines[self.programCounter]
	incit = True
	codes = st.split(' ')
	if(codes[0] == 'lda'):
		self.ra = self.getMemory(int(codes[1]))
	elif(codes[0] == 'ldb'):
		self.rb = self.getMemory(int(codes[1]))
	elif(codes[0] == 'ldafb'):
		self.ra = self.getMemory(int(self.rb))
	elif(codes[0] == 'bisa'):
		self.rb = int(self.ra)
	elif(codes[0] == 'sta'):
		self.setMem(int(codes[1]), self.ra)
	elif(codes[0] == 'stb'):
		self.setMem(int(codes[1]), self.rb)
	elif(codes[0] == 'staib'):
		self.setMem(self.rb, self.ra)
	elif(codes[0] == 'setim'):
		self.im.data[self.rb] = self.ra
		#self.im.saveFile('out.bmp')
	elif(codes[0] == 'goto'):
		self.programCounter = int(codes[1])
		incit = False
	elif(codes[0] == 'goa'):
		self.programCounter = int(self.ra)
		incit = False
	elif(codes[0] == 'ifa'):
		if(self.ra != 0):
			self.programCounter = int(codes[1])
			incit = False
	elif(codes[0] == 'ifan'):
		if(self.ra == 0):
			self.programCounter = int(codes[1])
			incit = False
```

```
		elif(codes[0] == 'altb'):
			if(self.ra < self.rb):
				self.ra = 1
			else:
				self.ra = 0
		elif(codes[0] == 'aeqb'):
			if(self.ra == self.rb):
				self.ra = 1
			else:
				self.ra = 0
		elif(codes[0] == 'agtb'):
			if(self.ra > self.rb):
				self.ra = 1
			else:
				self.ra = 0
		elif(codes[0] == 'add'):
			self.ra = self.ra + self.rb
		elif(codes[0] == 'inca'):
			self.ra = self.ra + 1
		elif(codes[0] == 'deca'):
			self.ra = self.ra - 1
		elif(codes[0] == 'sub'):
			self.ra = self.ra - self.rb
		elif(codes[0] == 'or'):
			self.ra = self.ra | self.rb
		elif(codes[0] == 'and'):
			self.ra = self.ra & self.rb
		elif(codes[0] == 'xor'):
			self.ra = self.ra ^ self.rb
		elif(codes[0] == 'not'):
			self.ra = ~self.ra
		elif(codes[0] == 'shla'):
			self.ra <<= int(codes[1])
		elif(codes[0] == 'shra'):
			self.ra >>= int(codes[1])
		elif(codes[0] == 'end'):
			self.end = True


		if(incit == True):
			self.programCounter += 1

	def printProgram(self):
		for i in self.lines:
			print i
	def printMC(self):
		for i in self.machineCode:
			print i
	def genMachineCode(self):
		self.machineCode = []
		for i in self.lines:
			codes = i.split(' ')
			if(codes[0][0] == '#'):
				self.machineCode.append(getBin(0, 5) + zeroStrs(35))
			elif(codes[0] == 'func'):
				self.machineCode.append(getBin(1, 5) + zeroStrs(35))
			elif(codes[0] == 'lda'):
				self.machineCode.append(getBin(2,5) + getBin(codes[1], 32) + zeroStrs(3))
			elif(codes[0] == 'ldb'):
				self.machineCode.append(getBin(3,5) + getBin(codes[1], 32) + zeroStrs(3))
			elif(codes[0] == 'ldafb'):
				self.machineCode.append(getBin(4, 5) + zeroStrs(35))
			elif(codes[0] == 'sta'):
				self.machineCode.append(getBin(5, 5) + getBin(codes[1], 32) + zeroStrs(3))
			elif(codes[0] == 'stb'):
				self.machineCode.append(getBin(6, 5) + getBin(codes[1], 32) + zeroStrs(3))
			elif(codes[0] == 'staib'):
				self.machineCode.append(getBin(7, 5) + zeroStrs(35))
			elif(codes[0] == 'setim'):
				self.machineCode.append(getBin(8, 5) + zeroStrs(35))
			elif(codes[0] == 'bisa'):
				self.machineCode.append(getBin(9, 5) + zeroStrs(35))
			elif(codes[0] == 'goto'):
				self.machineCode.append(getBin(10, 5) + getBin(codes[1], 32) + zeroStrs(3))
			elif(codes[0] == 'goa'):
				self.machineCode.append(getBin(11, 5) + zeroStrs(35))
			elif(codes[0] == 'ifa'):
				self.machineCode.append(getBin(12, 5) + getBin(codes[1], 32) + zeroStrs(3))
```

```
                elif(codes[0] == 'ifan'):
                    self.machineCode.append(getBin(13, 5) + getBin(codes[1], 32) + zeroStrs(3))
                elif(codes[0] == 'altb'):
                    self.machineCode.append(getBin(14, 5) + zeroStrs(35))
                elif(codes[0] == 'aeqb'):
                    self.machineCode.append(getBin(15, 5) + zeroStrs(35))
                elif(codes[0] == 'agtb'):
                    self.machineCode.append(getBin(16, 5) + zeroStrs(35))
                elif(codes[0] == 'add'):
                    self.machineCode.append(getBin(17, 5) + zeroStrs(35))
                elif(codes[0] == 'inca'):
                    self.machineCode.append(getBin(18, 5) + zeroStrs(35))
                elif(codes[0] == 'deca'):
                    self.machineCode.append(getBin(19, 5) + zeroStrs(35))
                elif(codes[0] == 'sub'):
                    self.machineCode.append(getBin(20, 5) + zeroStrs(35))
                elif(codes[0] == 'or'):
                    self.machineCode.append(getBin(21, 5) + zeroStrs(35))
                elif(codes[0] == 'and'):
                    self.machineCode.append(getBin(22, 5) + zeroStrs(35))
                elif(codes[0] == 'xor'):
                    self.machineCode.append(getBin(23, 5) + zeroStrs(35))
                elif(codes[0] == 'not'):
                    self.machineCode.append(getBin(24, 5) + zeroStrs(35))
                elif(codes[0] == 'shla'):
                    self.machineCode.append(getBin(25, 5) + getBin(codes[1], 32) + zeroStrs(3))
                elif(codes[0] == 'shra'):
                    self.machineCode.append(getBin(26, 5) + getBin(codes[1], 32) + zeroStrs(3))
                elif(codes[0] == 'end'):
                    self.machineCode.append(getBin(27, 5) + zeroStrs(35))
                else:
                    self.machineCode.append(getBin(0, 5) + zeroStrs(35))

    def saveMachineCode(self, fname):
        fi = open(fname + '_program.mif', 'w')
        count = 0
        fi.write('\n\nDEPTH = 1024;\n')
        fi.write('WIDTH = 40;\n')
        fi.write('ADDRESS_RADIX = HEX;\n')
        fi.write('DATA_RADIX = BIN;\n')
        fi.write('CONTENT\nBEGIN\n\n')
        for i in self.machineCode:
            fi.write(getNormalHex(count) + ' : ' + i + ';\n')
            count += 1
        fi.write('END;')
        fi.close()

    def saveProgramMemory(self, fname):
        fi = open(fname + '_memory.mif', 'w')
        count = 0
        fi.write('\n\nDEPTH = 1024;\n')
        fi.write('WIDTH = 32;\n')
        fi.write('ADDRESS_RADIX = HEX;\n')
        fi.write('DATA_RADIX = BIN;\n')
        fi.write('CONTENT\nBEGIN\n\n')
        for i in self.memory:
            fi.write(getNormalHex(count) + ' : ' + getBin(i, 32) + ';\n')
            count += 1
        fi.write('END;')
        fi.close()

assemblerA = Assembler('triangleDrawerOther')
assemblerA.saveMachineCode('lineDrawer')
assemblerA.saveProgramMemory('lineDrawer')
print 'Saved Machine Code'
print 'running program::>>'
assemblerA.run()
assemblerA.printProgram()
assemblerA.printMC()
assemblerA.printInfo()
assemblerA.im.saveFile('out.bmp')
```

The LAL4AI sets up a look up table which is used as a function generator to generate the reciprocal of a function F(x) = pow(x, -1). It also sets up all the memory locations where static numbers are required; it does this similarly to the malloc functions present in the C programming language. Both the machine code and the initial main memory are saved in a special file format called a memory initialization file. The programmer can use the interpreter to print out the entire main memory contents and step through each operation.

TRIANGLES, DRAWING, AND ASSEMBLY TECHNIQUES

Drawing triangles requires algorithms and concepts from computer graphics, the triangle has 3 points A, B and C, the algorithm which is used in this project is the most basic, it samples the points from A to B, then draws lines from these points to C. To perform these operations, the principle of functional programming is used, where functions can perform independent operations on input and provide output, the technique used by the assembler is to specify specific areas of memory for which each function can use. A total of 13 functions were generated for use in the triangle drawing program. These functions are mapped to specific areas of memory for which their input and output can be stored. Notice all functions have one common element, they all contain a variable input called nextLocation, this specifies where the PC should return to after the function is complete. The rest of the program can then collect the output values from their memory location for further processing.

```
Memory Function Mapper:

divider_Function (24,x) (25,y) (26,ans) (23,nextLocation)

getLUTVal (29,denominator) (28,output) (27,nextline)

multiplier (30,x) (31,y) (32,looper) (33,ans) (34,nextLocation)

absoluteVal (35,inp) (36,ans) (37,nextLocation)

maximumlVal (38,a) (39,b) (40,ans) (41,nextLocation)

divider_Function2 (42,x) (43,y) (44,ans) (45,nextLocation)

setPixelF (46,x) (47,y) (48,dval) (49,nextLocation)

logicalEnd (50:x) (51:xd) (52:y) (53:yd) (54:l1) (55:l2) (56:l3) (57:ans) (58:nextLocation)

lineDrawerLoopA (73:ox) (74:oy) (75:x) (76:y) (77:incx) (78:incy) (79:l1)
(80:l2) (81:l3) (82:xd) (83:yd) (84:x1) (85:y1) (86:nextLocation)

lineDrawerFunctionPart1 (59:x1) (60:y1) (61:x2) (62:y2) (63:ox) (64:oy)
(xd:65) (yd:66) (absxd:67) (absyd:68) (maxd:69) (incx:70) (incy:71)
(72:nextlocation)

screenClear (yax:87) (88:nextLocation)

DrawTriangle (89:x1) (90:y1) (91:x2) (92:y2) (93:x3) (94:y3) (95:ox) (96:oy)
(xd:97) (yd:98) (absxd:99) (absyd:100) (maxd:101) (incx:102) (incy:103)
(104:nextlocation)

DrawTriangleLoop (105:ox) (106:oy) (107:x) (108:y) (109:incx) (110:incy) (111:l1)
(112:l2) (113:l3) (114:xd) (115:yd) (116:x1) (117:y1)  (118:x3) (119:y3) (120:nextLocation)
```

The high level program is shown in below on the left, it simply sets the screen to black, then draws three triangles and begins again. The other two columns show the first half of the triangle drawing program

```
func restart
lda v0
sta 48
lda nafterTheScCLR
sta 88
goto screenClear
func afterTheScCLR
lda v255
sta 48
lda nafter2ndTriangleDrawingIsComplete
sta 104
lda v58
ldb v29
sta 89
stb 90
lda v71
ldb v57
sta 91
stb 92
lda v120
ldb v67
sta 93
stb 94
goto DrawTriangle
func after2ndTriangleDrawingIsComplete
lda v66
sta 48
lda nafter3TriangleDrawingIsComplete
sta 104
lda v81
ldb v31
sta 89
stb 90
lda v84
ldb v55
sta 91
stb 92
lda v124
ldb v59
sta 93
stb 94
goto DrawTriangle
func after3TriangleDrawingIsComplete
lda v138
sta 48
lda nafter4TriangleDrawingIsComplete
sta 104
lda v14
ldb v60
sta 89
stb 90
lda v14
ldb v96
sta 91
stb 92
lda v141
ldb v98
sta 93
stb 94
goto DrawTriangle
func after4TriangleDrawingIsComplete
goto restart
end
```

```
#DrawTriangle
func DrawTriangle
#input x1, y1, x2, y2, x3, y3
#uses [89 - 104]
#89:x1, 90:y1, 91:x2, 92:y2, 93:x3, 94:y3, 95:ox, 96:oy,
#xd:97, yd:98, absxd:99, absyd:100, maxd:101,
#incx:102, incy:103, 104:nextlocation
lda 89
sta 95
lda 90
sta 96
lda 91
ldb 89
sub
sta 97
lda 92
ldb 90
sub
sta 98
#now get abs of xd and yd and put it in abs(x/y)d
lda 97
sta 35
lda nafter1stABSinTriDrawer
sta 37
goto absoluteVal
func after1stABSinTriDrawer
lda 36
sta 99
lda 98
sta 35
lda nafter2ndABSinTriDrawer
sta 37
goto absoluteVal
func after2ndABSinTriDrawer
lda 36
sta 100
#calculate max(absxd, absyd)
lda 99
ldb 100
sta 38
stb 39
lda ninTriDrawerFunctionafterMaxfunc
sta 41
goto maximumVal
func inTriDrawerFunctionafterMaxfunc
lda 40
sta 101
#if maxd == 0 return
lda 101
ldb v0
aeqb
ifa exitTriDrawerP1
#shift xd left by 10
lda 97
shla 10
sta 97
lda 98
shla 10
sta 98
#do the first division function calculating incx
lda 97
```

```
sta 42
ldb 101
stb 43
lda nafterCalcIncXinTriFunc
sta 45
goto divider_Function2
func afterCalcIncXinTriFunc
lda 44
shra 10
sta 102
#do the second division function calculating incx
lda 98
sta 42
ldb 101
stb 43
lda nafterCalcIncYInTriDrawA
sta 45
goto divider_Function2
func afterCalcIncYInTriDrawA
lda 44
shra 10
sta 103
lda 97
shra 10
sta 97
lda 98
shra 10
sta 98
lda v0
sta 89
sta 90
#now pass to the looper function
lda nexitTriDrawerP1
sta 120
lda 95
sta 105
lda 96
sta 106
lda 102
sta 109
lda 103
sta 110
lda 97
sta 114
lda 98
sta 115
lda 89
ldb 90
sta 116
stb 117
lda 93
ldb 94
sta 118
stb 119
goto DrawTriangleLoop
func exitTriDrawerP1
lda 104
goa
end
```

The program below in the left column allows the 2nd half of the triangle drawing program. The right column shows the code to clear the screen.

```
#TriangleDrawerLoopA
func DrawTriangleLoop
#uses [105 - 120]
#input x1, y1, ox, oy, incx, incy, xd, yd
#105:ox, 106:oy, 107:x, 108:y, 109:incx, 110:incy,
111:l1, 112:l2, 113:l3, 114:xd,
#115:yd, 116:x1, 117:y1, 118:x3, 119:y3,
120:nextLocation
func TriloopRestartlineDrawerLoopA
lda 116
shra 10
sta 107
lda 117
shra 10
sta 108
lda 107
ldb 105
add
sta 107
lda 108
ldb 106
add
sta 108
lda nAfterLineDrawinTriDrawerLoopAR
sta 72
lda 107
sta 59
lda 108
sta 60
lda 118
sta 61
lda 119
sta 62
goto lineDrawerFunctionPart1
func AfterLineDrawinTriDrawerLoopAR
lda 116
ldb 109
add
sta 116
lda 117
ldb 110
add
sta 117
lda nafterLogicalEndinTriDrawerLoopA
sta 58
lda 107
ldb 105
sub
sta 50
lda 114
sta 51
lda 108
ldb 106
sub
sta 52
lda 115
sta 53
goto logicalEnd
func afterLogicalEndinTriDrawerLoopA
lda 57
ifa exitTriDrawerLoopA
goto TriloopRestartlineDrawerLoopA
func exitTriDrawerLoopA
lda 120
goa
end
```

```
#screen clear function
func screenClear
#yax:87, nextLocation:88
lda v0
sta 87
func screenClearLineLooper
lda v0
sta 59
lda v160
sta 61
lda 87
sta 60
sta 62
lda
nafterLineDrawinClearScreenLooperddf
sta 72
goto lineDrawerFunctionPart1
func
afterLineDrawinClearScreenLooperddf
lda 87
inca
sta 87
lda 87
ldb v120
altb
ifa screenClearLineLooper
lda 88
goa
end
```

The first two columns below show the first half of the line drawing program, the right column shows the second half

```
#lineDrawerFunctionPart1
func lineDrawerFunctionPart1
#input x1, y1, x2, y2
#uses [59 - 72]
#59:x1, 60:y1, 61:x2, 62:y2, 63:ox, 64:oy,
#xd:65, yd:66, absxd:67,  absyd:68, maxd:69,
#incx:70, incy:71, 72:nextlocation
lda 59
sta 63
lda 60
sta 64
lda 61
ldb 59
sub
sta 65
lda 62
ldb 60
sub
sta 66
#now get abs of xd and yd and put it in abs(x/y)d
lda 65
sta 35
lda nafter1stABSinlineDrawerFunctionPart1
sta 37
goto absoluteVal
func after1stABSinlineDrawerFunctionPart1
lda 36
sta 67
lda 66
sta 35
lda nafter2ndABSinlineDrawerFunctionPart1
sta 37
goto absoluteVal
func after2ndABSinlineDrawerFunctionPart1
lda 36
sta 68
#calculate max(absxd, absyd)
lda 67
ldb 68
sta 38
stb 39
lda ninDrawerFunctionPart1afterMaxfunc
sta 41
goto maximumVal
func inDrawerFunctionPart1afterMaxfunc
lda 40
sta 69
#if maxd == 0 return
lda 69
ldb v0
aeqb
ifa exitLineDrawerP1
#shift xd left by 10
lda 65
shla 10
sta 65
lda 66
shla 10
sta 66
```

```
#do the first division function calculating incx
lda 65
sta 42
ldb 69
stb 43
lda nafterCalcIncX
sta 45
goto divider_Function2
func afterCalcIncX
lda 44
shra 10
sta 70
#do the second division function calculating incx
lda 66
sta 42
ldb 69
stb 43
lda nafterCalcIncY
sta 45
goto divider_Function2
func afterCalcIncY
lda 44
shra 10
sta 71
lda 65
shra 10
sta 65
lda 66
shra 10
sta 66
lda v0
sta 59
sta 60
#now pass to the looper function
lda nexitLineDrawerP1
sta 86
lda 63
sta 73
lda 64
sta 74
lda 70
sta 77
lda 71
sta 78
lda 65
sta 82
lda 66
sta 83
lda 59
ldb 60
sta 84
stb 85
goto lineDrawerLoopA
func exitLineDrawerP1
lda 72
goa
end
```

```
#lineDrawerLoopA
func lineDrawerLoopA
#uses []
#input x1, y1, ox, oy, incx, incy, xd, yd
#73:ox,  74:oy,  75:x,  76:y,  77:incx,  78:incy,  79:l1,
80:l2, 81:l3, 82:xd,
#83:yd, 84:x1, 85:y1, 86:nextLocation
func loopRestartlineDrawerLoopA
lda 84
shra 10
sta 75
lda 85
shra 10
sta 76
lda 75
ldb 73
add
sta 75
lda 76
ldb 74
add
sta 76
lda nAfterPixelSetinlineDrawerLoopA
sta 49
lda 75
sta 46
lda 76
sta 47
goto setPixelF
func AfterPixelSetinlineDrawerLoopA
lda 84
ldb 77
add
sta 84
lda 85
ldb 78
add
sta 85
lda nafterLogicalEndinDrawerLoopA
sta 58
lda 75
ldb 73
sub
sta 50
lda 82
sta 51
lda 76
ldb 74
sub
sta 52
lda 83
sta 53
goto logicalEnd
func afterLogicalEndinDrawerLoopA
lda 57
ifa exitDrawerLoopA
goto loopRestartlineDrawerLoopA
func exitDrawerLoopA
lda 86
goa
end
```

The line drawer and triangle drawing functions use a special logical function to calculate when the line drawing should end (otherwise the line would continue indefinitely). This function is shown in the left column. Two division functions are used, one outputs a floating point number and another outputs an integer. Both the division functions use a look up tables as the reciprocal function generator. The function to retrieve a lookup table output is shown in the bottom box.

```
#logicalEndFunction
func logicalEnd
#uses memory [50 - 54]
INPUT is x, xd, y, y2
#50:x, 51:xd, 52:y, 53:yd, 54:l1, 55:l2, 56:l3, 57:ans, 58:nextLocation
lda 51
ldb 50
sub
sta 35
lda nafterABS1LogicalEndFunc
sta 37
goto absoluteVal
func afterABS1LogicalEndFunc
lda 36
sta 54
lda 53
ldb 52
sub
sta 35
lda nafterABS2LogicalEndFunc
sta 37
goto absoluteVal
func afterABS2LogicalEndFunc
lda 36
sta 55
lda 54
ldb 55
add
ldb v4
altb
sta 57
lda 58
goa
end
```

```
func divider_Function2
#(x / y)
# uses memory [42 - 45]
# 42:x, 43:y, 44:ans, 45:next location
lda 42
shla 10
sta 42
ldb 43
stb 29
lda naftergetLUTinDividerF2
sta 27
goto getLUTVal
func aftergetLUTinDividerF2
lda 28
sta 31
lda 42
sta 30
lda naftermultiplierDividerFuncF2
sta 34
goto multiplier
func aftermultiplierDividerFuncF2
lda 33
shra 10
sta 44
lda 45
goa
end
```

```
#division function
func divider_Function
#(x / y)
# uses memory [23 - 26]
# 24 : x, 25 : y, 26 : ans, 23 : next location
lda 24
shla 10
sta 24
ldb 25
stb 29
lda naftergetLUTinDivider
sta 27
goto getLUTVal
func aftergetLUTinDivider
lda 28
sta 31
lda 24
sta 30
lda naftermultiplierDividerFunc
sta 34
goto multiplier
func aftermultiplierDividerFunc
lda 33
shra 20
sta 26
lda 23
goa
end
```

```
#grab the divisor from LUT
func getLUTVal
#memory used [27 - 29]
# 29: denomenator, 28: outputvalue, 27: next line
#get memory location of memLocation, store it in output value
lda 29
ldb v300
add
bisa
ldafb
sta 28
lda 27
goa
end
```

The last functions required are the multiplier function, the absolute function and the division function, these are shown below:

```
func multiplier
#uses memory [30 - 34]
#30:x,    31:y,    32:looper,    33:ans,
34:nextLocation
lda v0
sta 32
sta 33
ldb 31
aeqb
ifan loop_in_multiplier
goto end_multiplier
func loop_in_multiplier
#add em
lda 33
ldb 30
add
sta 33
#increment loop i
lda 32
inca
sta 32
ldb 31
altb
ifa loop_in_multiplier
func end_multiplier
lda 34
goa
end
```

```
func absoluteVal
#uses memory [35 - 37]
#35:inp, 36:ans, 37:nextLocation
lda 35
ldb v0
altb
ifa continueWithAbsValFunc
lda 35
sta 36
lda 37
goa
func continueWithAbsValFunc
lda 35
not
inca
sta 36
lda 37
goa
end
```

```
func maximumVal
# returns max(a,b)
#uses memory [38 - ]
# 38:a,  39:b,   40:ans,   41:nextLocation
lda 38
ldb 39
agtb
ifa amorethanb
stb 40
lda 41
goa
func amorethanb
lda 38
sta 40
lda 41
goa
end
```

A total of 637 lines of assembly are required to draw three triangles, refresh the frame buffer and repeat the process.

FPGA IMPLEMENTATION

The DE1 board was used to implement these designs. Using the AHDL hardware description language and the Quartus II integrated development environment, these designs were implemented with success. The AHDL modules used are provided below, beginning with the ones for the VGA driver.

THE IMAGE INDEXER

```
subdesign GetImageIndex(
xPoint[9..0] :INPUT;
yPoint[9..0] :INPUT;
outIndex[14..0] :OUTPUT;
)
variable
xAx[14..0] : NODE;
yAx[14..0] : NODE;
yAxAddSh5[14..0] : NODE;
yAxAddSh7[14..0] : NODE;
yadd[14..0] : NODE;

begin
xAx[14..0] = (GND,GND, GND,GND,GND, GND, GND, xPoint[9..2]);
yAx[14..0] = (GND,GND, GND,GND,GND, GND, GND, yPoint[9..2]);
yAxAddSh5[14..0] = (yAx[9..0], GND, GND, GND, GND, GND);
yAxAddSh7[14..0] = (yAx[7..0], GND, GND, GND, GND, GND, GND, GND);
yadd[14..0] = yAxAddSh5[14..0] + yAxAddSh7[14..0];
outIndex[14..0] = xAx[14..0] + yadd[14..0];
end;
```

THE COUNTER USED IN THE VGA DRIVER

```
SUBDESIGN AVGACOUNTER(
clk_in :INPUT;
reset :INPUT;
set_maximum :INPUT;
max_num[18..0] :INPUT;
count_out[18..0] :OUTPUT;
)
VARIABLE
ffs[18..0] : JKFF;
BEGIN
	ffs[].clk = clk_in;
	IF reset == B"1" THEN
		ffs[].j = (0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0);
		ffs[].k = (1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1);
	ELSIF set_maximum == B"1" THEN
			IF ffs[].q >= max_num[] THEN
				ffs[].j = (0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0);
				ffs[].k = (1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1);
			ELSE
				ffs[].j = ffs[].q + 1;
				ffs[].k = !(ffs[].q + 1);
			END IF;
	ELSE
		ffs[].j = ffs[].q + 1;
		ffs[].k = !(ffs[].q + 1);
	END IF;
	count_out[] = ffs[].q;
END;
```

VGA Signal Generator Module

```
INCLUDE "AVGACOUNTER.inc";

SUBDESIGN AVGASYNCMOD(
	clk25_in : INPUT;
	x_pos[18..0] : OUTPUT;
	y_pos[18..0] : OUTPUT;
	av_sync, ah_sync :OUTPUT;
	send_data :OUTPUT;
)
VARIABLE
syncCounterV :AVGACOUNTER;
syncCounterH :AVGACOUNTER;
data_out :NODE;
BEGIN
	IF syncCounterH.count_out[] == 639 THEN
		syncCounterV.clk_in = B"1";
	ELSE
		syncCounterV.clk_in = B"0";
	END IF;
	syncCounterV.reset = B"0";
	syncCounterV.max_num[] = 520;
	syncCounterV.set_maximum = B"1";

	syncCounterH.clk_in = clk25_in;
	syncCounterH.reset = B"0";
	syncCounterH.max_num[] = 799;
	syncCounterH.set_maximum = B"1";


	data_out = (syncCounterV.count_out[] >= 41 AND syncCounterV.count_out[] < 521 AND syncCounterH.count_out[] >= 160
AND syncCounterH.count_out[] < 800);
	av_sync = (syncCounterV.count_out[] >= 10 AND syncCounterV.count_out[] < 12);
	ah_sync = (syncCounterH.count_out[] >= 16 AND syncCounterH.count_out[] < 112);
	send_data = data_out;
	IF data_out == B"1" THEN
		x_pos[] = syncCounterH.count_out[] - 160;
		y_pos[] = syncCounterV.count_out[] - 41;
	ELSE
		x_pos[] = 0;
		y_pos[] = 0;
	END IF;

END;
```

ALU Module Part 1

```
subdesign ALU_PC(
		OPCODE[5..0] :INPUT;
		INVAL[31..0] :INPUT;
		RA_IN[31..0] :INPUT;
		RB_IN[31..0] :INPUT;
		PC_IN[31..0] :INPUT;

		RA_OUT[31..0] :OUTPUT;
		RB_OUT[31..0] :OUTPUT;
		PC_OUT[31..0] :OUTPUT;
)
begin
		if OPCODE[] == 9 then -- bisa
			RB_OUT[31..0] = RA_IN[31..0];
			RA_OUT[31..0] = RA_IN[31..0];
			PC_OUT[31..0] = PC_IN[31..0] + 1;
		elsif OPCODE[] == 10 then --goto
			PC_OUT[31..0] = INVAL[31..0];
			RA_OUT[31..0] = RA_IN[31..0];
			RB_OUT[31..0] = RB_IN[31..0];
		elsif OPCODE[] == 11 then --goa
			PC_OUT[31..0] = RA_IN[31..0];
			RA_OUT[31..0] = RA_IN[31..0];
			RB_OUT[31..0] = RB_IN[31..0];
		elsif OPCODE[] == 12 and RA_IN[31..0] != 0 then --ifa
			PC_OUT[31..0] = INVAL[31..0];
			RA_OUT[31..0] = RA_IN[31..0];
			RB_OUT[31..0] = RB_IN[31..0];
		elsif OPCODE[] == 13 and RA_IN[31..0] == 0 then -- ifan
			PC_OUT[31..0] = INVAL[31..0];
			RA_OUT[31..0] = RA_IN[31..0];
			RB_OUT[31..0] = RB_IN[31..0];
		elsif OPCODE[] == 14 then --altb
			RB_OUT[31..0] = RB_IN[31..0];
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			if RA_IN[31..0] < RB_IN[31..0] then
				RA_OUT[31..0] = 1;
			else
				RA_OUT[31..0] = 0;
			end if;
		elsif OPCODE[] == 15 then -- aeqb
			RB_OUT[31..0] = RB_IN[31..0];
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			if RA_IN[31..0] == RB_IN[31..0] then
				RA_OUT[31..0] = 1;
			else
				RA_OUT[31..0] = 0;
			end if;
		elsif OPCODE[] == 16 then --agtb
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			RB_OUT[31..0] = RB_IN[31..0];
			if RA_IN[31..0] > RB_IN[31..0] then
				RA_OUT[31..0] = 1;
			else
				RA_OUT[31..0] = 0;
			end if;
		elsif OPCODE[] == 17 then --add
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			RB_OUT[31..0] = RB_IN[31..0];
			RA_OUT[31..0] = RA_IN[31..0] + RB_IN[31..0];
		elsif OPCODE[] == 18 then --inca
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			RA_OUT[31..0] = RA_IN[31..0] + 1;
			RB_OUT[31..0] = RB_IN[31..0];
		elsif OPCODE[] == 19 then --deca
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			RA_OUT[31..0] = RA_IN[31..0] - 1;
			RB_OUT[31..0] = RB_IN[31..0];
		elsif OPCODE[] == 20 then --sub
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			RA_OUT[31..0] = RA_IN[31..0] - RB_IN[31..0];
			RB_OUT[31..0] = RB_IN[31..0];
		elsif OPCODE[] == 21 then --or
			PC_OUT[31..0] = PC_IN[31..0] + 1;
			RA_OUT[31..0] = RA_IN[31..0] # RB_IN[31..0];
			RB_OUT[31..0] = RB_IN[31..0];
```

ALU Module Part 2

```
	elsif OPCODE[] == 22 then -- and
		PC_OUT[31..0] = PC_IN[31..0] + 1;
		RA_OUT[31..0] = RA_IN[31..0] & RB_IN[31..0];
		RB_OUT[31..0] = RB_IN[31..0];
	elsif OPCODE[] == 23 then --xor
		PC_OUT[31..0] = PC_IN[31..0] + 1;
		RA_OUT[31..0] = RA_IN[31..0] $ RB_IN[31..0];
		RB_OUT[31..0] = RB_IN[31..0];
	elsif OPCODE[] == 24 then --not
		PC_OUT[31..0] = PC_IN[31..0] + 1;
		RA_OUT[31..0] = RA_IN[31..0] $ (GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND,GND);
		RB_OUT[31..0] = RB_IN[31..0];
	elsif OPCODE[] == 25 then --shla
		PC_OUT[31..0] = PC_IN[31..0] + 1;
		RB_OUT[31..0] = RB_IN[31..0];
		if INVAL[31..0] == 0 then
			RA_OUT[31..0] = RA_IN[31..0];
		elsif INVAL[31..0] == 1 then
			RA_OUT[31..0] = (RA_IN[30..0], GND);
		elsif INVAL[31..0] == 2 then
			RA_OUT[31..0] = (RA_IN[29..0], GND, GND);
		elsif INVAL[31..0] == 3 then
			RA_OUT[31..0] = (RA_IN[28..0], GND, GND, GND);
		elsif INVAL[31..0] == 4 then
			RA_OUT[31..0] = (RA_IN[27..0], GND, GND, GND, GND);
		elsif INVAL[31..0] == 5 then
			RA_OUT[31..0] = (RA_IN[26..0], GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 6 then
			RA_OUT[31..0] = (RA_IN[25..0], GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 7 then
			RA_OUT[31..0] = (RA_IN[24..0], GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 8 then
			RA_OUT[31..0] = (RA_IN[23..0], GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 9 then
			RA_OUT[31..0] = (RA_IN[22..0], GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 10 then
			RA_OUT[31..0] = (RA_IN[21..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 11 then
			RA_OUT[31..0] = (RA_IN[20..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 12 then
			RA_OUT[31..0] = (RA_IN[19..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 13 then
			RA_OUT[31..0] = (RA_IN[18..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 14 then
			RA_OUT[31..0] = (RA_IN[17..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 15 then
			RA_OUT[31..0] = (RA_IN[16..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 16 then
			RA_OUT[31..0] = (RA_IN[15..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 17 then
			RA_OUT[31..0] = (RA_IN[14..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 18 then
			RA_OUT[31..0] = (RA_IN[13..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 19 then
			RA_OUT[31..0] = (RA_IN[12..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 20 then
			RA_OUT[31..0] = (RA_IN[11..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		elsif INVAL[31..0] == 21 then
			RA_OUT[31..0] = (RA_IN[10..0], GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND);
		end if;
```

ALU Module Part 3

```
	elsif OPCODE[] == 26 then --shra
		RB_OUT[31..0] = RB_IN[31..0];
		PC_OUT[31..0] = PC_IN[31..0] + 1;
		if INVAL[31..0] == 0 then
			RA_OUT[31..0] = RA_IN[31..0];
		elsif INVAL[31..0] == 1 then
			RA_OUT[31..0] = (GND, RA_IN[31..1]);
		elsif INVAL[31..0] == 2 then
			RA_OUT[31..0] = (GND, GND, RA_IN[31..2]);
		elsif INVAL[31..0] == 3 then
			RA_OUT[31..0] = (GND, GND, GND, RA_IN[31..3]);
		elsif INVAL[31..0] == 4 then
			RA_OUT[31..0] = (GND, GND, GND, GND, RA_IN[31..4]);
		elsif INVAL[31..0] == 5 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, RA_IN[31..5]);
		elsif INVAL[31..0] == 6 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, RA_IN[31..6]);
		elsif INVAL[31..0] == 7 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, RA_IN[31..7]);
		elsif INVAL[31..0] == 8 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..8]);
		elsif INVAL[31..0] == 9 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..9]);
		elsif INVAL[31..0] == 10 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..10]);
		elsif INVAL[31..0] == 11 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..11]);
		elsif INVAL[31..0] == 12 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..12]);
		elsif INVAL[31..0] == 13 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..13]);
		elsif INVAL[31..0] == 14 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..14]);
		elsif INVAL[31..0] == 15 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..15]);
		elsif INVAL[31..0] == 16 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..16]);
		elsif INVAL[31..0] == 17 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..17]);
		elsif INVAL[31..0] == 18 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..18]);
		elsif INVAL[31..0] == 19 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..19]);
		elsif INVAL[31..0] == 20 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..20]);
		elsif INVAL[31..0] == 21 then
			RA_OUT[31..0] = (GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, GND, RA_IN[31..21]);
		end if;
	else
		RA_OUT[31..0] = RA_IN[31..0];
		RB_OUT[31..0] = RB_IN[31..0];
		PC_OUT[31..0] = PC_IN[31..0] + 1;
	end if;

end;
```

CPU & VGA DRIVER PART 1

```
Include "AVGASYNCMOD.inc";
Include "GetImageIndex.inc";
Include "myRam.inc";
Include "ONEHZCLOCK.inc";
Include "TheProgram.inc";
Include "TheMemory.inc";
Include "ALU_PC.inc";

subdesign MyProjA(
CLOCK_50 :INPUT;
VGA_HS, VGA_VS :OUTPUT;
VGA_R[3..0] :OUTPUT;
VGA_G[3..0] :OUTPUT;
VGA_B[3..0] :OUTPUT;
LEDR[1..0] :OUTPUT;
)
variable
VgaController :AVGASYNCMOD;
jkff25 :JKFF;
ImageIndexer :GetImageIndex;
imageMemory : myRam;
keyPressed : NODE;
PC[31..0] : DFF;
RA[31..0] : DFF;
RB[31..0] : DFF;
DATAIN[31..0] :DFF;
OPCODE[5..0] :DFF;
State[1..0] :DFF;
mem : TheProgram;
prog : TheMemory;
alu : ALU_PC;
ohc : ONEHZCLOCK;
begin
defaults
mem.address[9..0] = 0;
mem.data[31..0] = 0;
mem.wren = GND;
imageMemory.address_a[14..0] = 0;
imageMemory.wren_a = GND;
imageMemory.data_a[3..0] = 0;
end defaults;
--cpu clock, only for this
ohc.CLKIN50 = CLOCK_50;
--
LEDR[1..0] = State[1..0].q;
--Preliminary Setup:>
imageMemory.inclock = CLOCK_50;
keyPressed = ohc.OUTCLK;
State[1..0].clk = keyPressed;
OPCODE[5..0].clk = keyPressed;
DATAIN[31..0].clk = keyPressed;
PC[31..0].clk = keyPressed;
RA[31..0].clk = keyPressed;
RB[31..0].clk = keyPressed;
prog.wren = GND;
prog.data[39..0] = 0;
```

CPU & VGA DRIVER PART 2

```
prog.clock = CLOCK_50;
prog.address[9..0] = PC[9..0].q;
mem.clock = CLOCK_50;
alu.OPCODE[5..0] = OPCODE[5..0].q;
alu.INVAL[31..0] = DATAIN[31..0].q;
alu.RA_IN[31..0] = RA[31..0].q;
alu.RB_IN[31..0] = RB[31..0].q;
alu.PC_IN[31..0] = PC[31..0].q;
--
--actual program execution
if State[1..0] == 0 then
        RA[31..0].d = RA[31..0].q;
        RB[31..0].d = RB[31..0].q;
        PC[31..0].d = PC[31..0].q;
        DATAIN[31..0].d = prog.q[34..3];
        OPCODE[5..0].d = (GND, prog.q[39..35]);
        State[1..0].d = 1;
elsif State[1..0] == 1 then
        OPCODE[5..0].d = OPCODE[5..0].q;
        DATAIN[31..0].d = DATAIN[31..0].q;
        if OPCODE[5..0] == 27 then
                State[1..0].d = 2;
                RA[31..0].d = RA[31..0].q;
                RB[31..0].d = RB[31..0].q;
                PC[31..0].d = PC[31..0].q;
        elsif OPCODE[5..0] >= 0 and OPCODE[5..0] < 9 then
                --a control / memory operation
                State[1..0].d = 0;
                PC[31..0].d = PC[31..0].q + 1;
                if OPCODE[5..0] == 0 or OPCODE[5..0] == 1 then
                        RA[31..0].d = RA[31..0].q;
                        RB[31..0].d = RB[31..0].q;
                elsif OPCODE[5..0] == 2 then --lda
                        mem.address[9..0] = DATAIN[9..0].q;
                        RA[31..0].d = mem.q[31..0];
                        RB[31..0].d = RB[31..0].q;
                elsif OPCODE[5..0] == 3 then --ldb
                        mem.address[9..0] = DATAIN[9..0].q;
                        RA[31..0].d = RA[31..0].q;
                        RB[31..0].d = mem.q[31..0];
                elsif OPCODE[5..0] == 4 then --ldafb
                        mem.address[9..0] = RB[9..0].q;
                        RA[31..0].d = mem.q[31..0];
                        RB[31..0].d = RB[31..0].q;
                elsif OPCODE[5..0] == 5 then --sta
                        mem.wren = VCC;
                        mem.address[9..0] = DATAIN[9..0].q;
                        mem.data[31..0] = RA[31..0].q;
                        RA[31..0].d = RA[31..0].q;
                        RB[31..0].d = RB[31..0].q;
                elsif OPCODE[5..0] == 6 then --stb
                        mem.wren = VCC;
                        mem.address[9..0] = DATAIN[9..0].q;
                        mem.data[31..0] = RB[31..0].q;
                        RA[31..0].d = RA[31..0].q;
                        RB[31..0].d = RB[31..0].q;
                elsif OPCODE[5..0] == 7 then --staib
                        mem.wren = VCC;
                        mem.address[9..0] = RB[9..0].q;
                        mem.data[31..0] = RA[31..0].q;
                        RA[31..0].d = RA[31..0].q;
                        RB[31..0].d = RB[31..0].q;
```

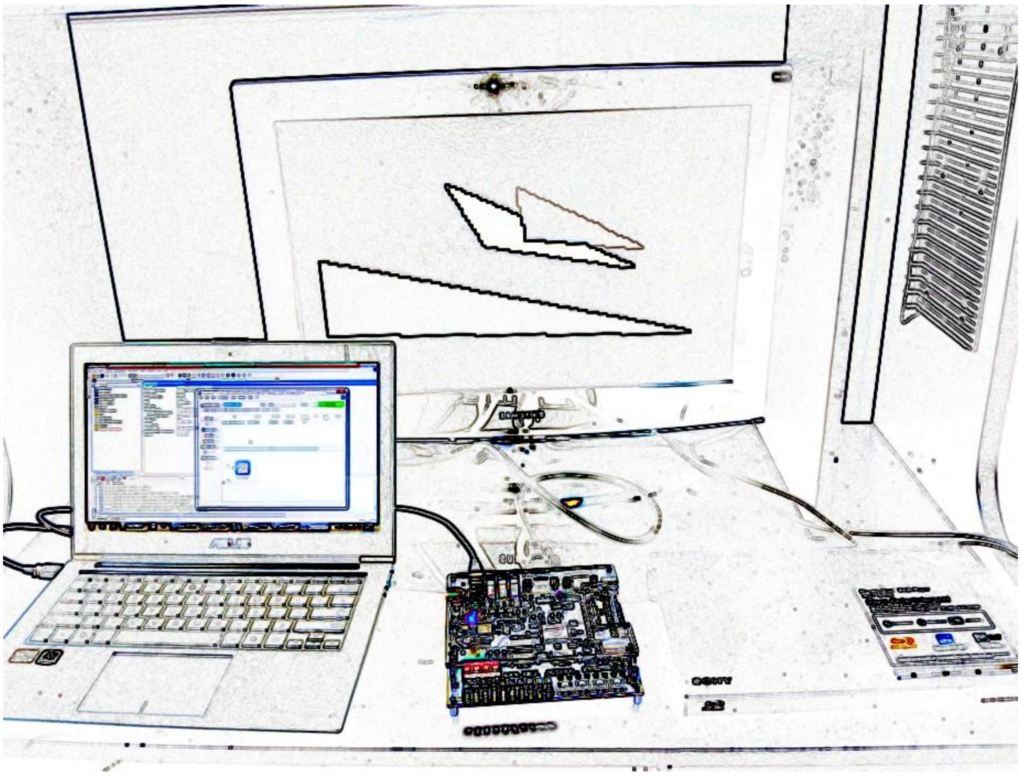
CPU & VGA DRIVER PART 3

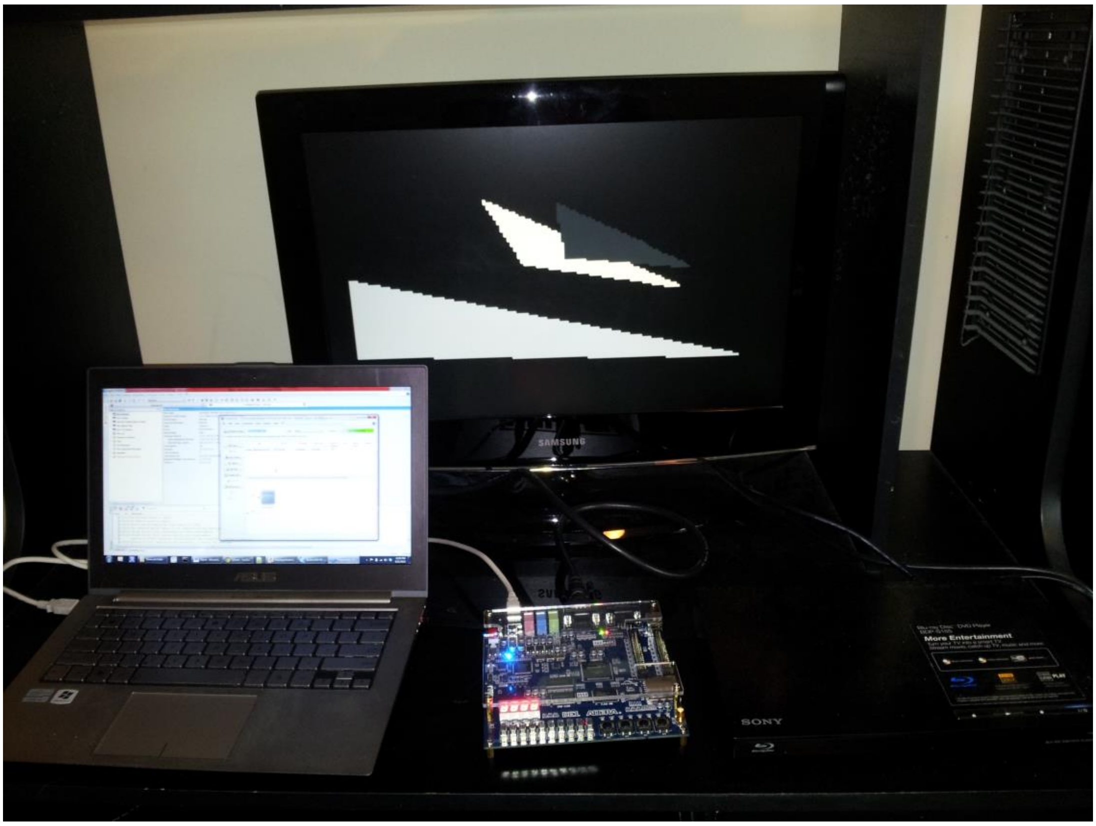
```
            elsif OPCODE[5..0] == 8 then --setim
                RA[31..0].d = RA[31..0].q;
                RB[31..0].d = RB[31..0].q;
                imageMemory.wren_a = VCC;
                imageMemory.address_a[14..0] = RB[14..0].q;
                imageMemory.data_a[3..0] = RA[3..0].q;
                --other memory things
            end if;
        else
            --an ALU or PC operation
            State[1..0].d = 0;
            RA[31..0].d = alu.RA_OUT[31..0];
            RB[31..0].d = alu.RB_OUT[31..0];
            PC[31..0].d = alu.PC_OUT[31..0];
        end if;
else
    RA[31..0].d = RA[31..0].q;
    RB[31..0].d = RB[31..0].q;
    PC[31..0].d = PC[31..0].q;
    DATAIN[31..0].d = DATAIN[31..0].q;
    OPCODE[5..0].d = OPCODE[5..0].q;
    State[1..0].d = 0;
end if;
--end program execution
--VGA DRIVER
jkff25.j = VCC;
jkff25.k = VCC;
jkff25.clk = CLOCK_50;
VgaController.clk25_in = jkff25.q;
VGA_HS = !VgaController.ah_sync;
VGA_VS = !VgaController.av_sync;
--sending data:
ImageIndexer.xPoint[9..0] = VgaController.x_pos[9..0];
ImageIndexer.yPoint[9..0] = VgaController.y_pos[9..0];
--end sending data
--image memory indexing:
imageMemory.address_b[14..0] = imageIndexer.outIndex[14..0];
imageMemory.outclock = !CLOCK_50;
imageMemory.wren_b = GND;
imageMemory.data_b[3..0] = 0;

IF VgaController.send_data == VCC THEN
            VGA_R[3..0] = 0;
            VGA_G[3..0] = imageMemory.q_b[3..0];
            VGA_B[3..0] = imageMemory.q_b[3..0];
    ELSE
            VGA_R[3..0] = 0;
            VGA_G[3..0] = 0;
            VGA_B[3..0] = 0;
    END IF;
--END VGA Driver
end;
```

FINAL PROJECT OUTCOME

The project works successfully, below are some pictures showing it in use.





YouTube videos are can also be views in these links: http://www.youtube.com/watch?v=taQ5eouGpJs, http://www.youtube.com/watch?v=v-oTsPKXnSg