|  |
| --- |
|  |
| The N.I.G.E. Machine |
| Reference Manual |
|  |
| **Andrew Read (andrew81244@outlook.com)** |
| **Document last updated: December 2014** |

|  |
| --- |
| The N.I.G.E machine, its design and its source code are Copyright (C) 2012-2014 by Andrew Richard Read and dual licensed. (1) For commercial or proprietary use you must obtain a commercial license agreement with Andrew Richard Read (andrew81244@outlook.com) (2) You can redistribute the N.I.G.E. Machine, its design and its source code and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation, either version 3 of the License, or (at your option) any later version. The N.I.G.E Machine is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details. You should have received a copy of the GNU General Public License along with this repository. If not, see http://www.gnu.org/licenses |

Contents

[1. Installation and set-up 3](#_Toc407800877)

[1.1 Introduction 3](#_Toc407800878)

[1.2 Set-up preliminaries 3](#_Toc407800879)

[1.3 Quick start 3](#_Toc407800880)

[1.4 Full start 4](#_Toc407800881)

[1.5 Optional SD card interface 4](#_Toc407800882)

[2. Using the N.I.G.E. machine as a FORTH microcomputer 5](#_Toc407800883)

[2.1 ANSI FORTH 5](#_Toc407800884)

[2.2. File System 5](#_Toc407800885)

[2.3 Memory address regions 5](#_Toc407800886)

[2.4 VGA display 6](#_Toc407800887)

[2.5 Other input/output 8](#_Toc407800888)

[2.6 Exception handling 9](#_Toc407800889)

[2.6 Multitasking 9](#_Toc407800890)

[3. Customizing the system software 10](#_Toc407800891)

[3.1 Running the cross-assembler 10](#_Toc407800892)

[3.2 Structure of the system software 10](#_Toc407800893)

[3.3 Updating the system software 11](#_Toc407800894)

[4. Customizing the system hardware 13](#_Toc407800895)

[Appendix 1. System specifications 15](#_Toc407800896)

[Appendix 2. CPU instruction set 16](#_Toc407800897)

[Appendix 3. Memory map (v2.0, Nexys 2) 27](#_Toc407800898)

[Appendix 4. Memory map (v3.0, Nexys 4) 29](#_Toc407800899)

[Appendix 5. Palette RAM color table 31](#_Toc407800900)

[Appendix 6. Implementation of ANSI FORTH words 32](#_Toc407800901)

[Appendix 7. System specific FORTH words 38](#_Toc407800902)

[Appendix 8. Further system specific words 44](#_Toc407800903)

[Appendix 9. Cross-assembler 48](#_Toc407800904)

[Appendix 10. FORTH system dictionary structure 51](#_Toc407800905)

[Appendix 11. Interrupt Vector Table 52](#_Toc407800906)

[Appendix 12. Virtualization Control 53](#_Toc407800907)

# 1. Installation and set-up

## 1.1 Introduction

The N.I.G.E. Machine is a user-expandable micro-computer system that runs on an FPGA development board. It has been designed specifically for the rapid prototyping of experimental scientific hardware or other devices. The key components of the system include a stack-based softcore CPU optimized for embedded control, a FORTH software environment, and a flexible digital logic layer that interfaces the micro-computer components with the external environment.

The N.I.G.E Machine is presently available for both the Digilent Nexys 2 (1200K gate) and Nexys 4 FPGA boards.

Further information on the N.I.G.E. Machine design is available in two papers presented at EuroFORTH 2012 and 2013:

* <http://www.complang.tuwien.ac.at/anton/euroforth/ef12/papers/>
* <http://www.complang.tuwien.ac.at/anton/euroforth/ef13/papers/>

Two short video introductions are also available:

* <http://www.youtube.com/watch?v=0v-HuVLRoUc>
* <http://www.youtube.com/watch?v=0Kj5EMdnkMk>

## 1.2 Set-up preliminaries

* Install Xilinx ISE version 14.6
  + The N.I.G.E. Machine is being developed on ISE 14.6, so using this version will avoid compatibility issues
* Install a suitable GIT repository manager, e.g.:
  + <http://www.syntevo.com/smartgithg>
* Clone the open-source N.I.G.E. Machine repository from GitHub to your local machine
  + Remote repository location:
    - <https://github.com/Anding/N.I.G.E.-Machine>
  + To preserve absolute file references used by ISE, the local directory for the repository must be exactly as follows:
    - E:\N.I.G.E.-Machine
* Within the local repository, switch to the appropriate branch for your Nexys board:
  + Nexys 2 (1200K gate) v2.0
  + Nexys 4 v3.0 (default branch)

## 1.3 Quick start

* Attach a VGA monitor, keyboard (PS/2 - Nexys 2 or USB - Nexys 4), and 5V power supply
* Set the FPGA board jumper wires according to the Nexys reference manuals
* Configure the FPGA board with the pre-compiled N.I.G.E. Machine bit file
  + Nexys 2: E:\N.I.G.E.-Machine\board\_Nexys 2\_1200\_v2.0.bit
  + Nexys 4: E:\N.I.G.E.-Machine\board\_Nexys 4\_v3.0.bit
* The N.I.G.E. Machine is now running as a FORTH microcomputer
  + See chapter 2 for further guidance

## 1.4 Full start

* Unzip the file Xilinx\_ISE.zip to the local repository folder
  + E:\N.I.G.E.-Machine
* The Xilinx project files should now be found in
  + E:\N.I.G.E.-Machine\Xilinx\_ISE
  + Watch out for inadvertent folder duplication (“\Xilinx\_ISE\Xilinx\_ISE”) caused by the unzip process or absolute project file references used by ISE will be invalid
* Double click on the ISE project file
  + E:\N.I.G.E.-Machine\Xilinx\_ISE\NIGE\_Machine.xise
* The N.I.G.E. Machine design files are now open in Xilinx ISE
* Synthesize the design files
* Configure the Nexys board with the newly compiled N.I.G.E. Machine bit file
  + E:\N.I.G.E.-Machine\Xilinx\_ISE\[xxx].bit

## 1.5 Optional SD card interface

* Nexys 2: utilize a full-size SD card and a Digilent SD card PMOD device plugged into port A
  + <http://www.digilentinc.com/Products/Detail.cfm?NavPath=2,401,513&Prod=PMOD-SD>
* Nexys 4: utilize a micro-SD card and the micro-SD slot on the Nexys board
* Format the SD card as FAT32
  + Both normal (<2GB) and high capacity (>2GB) SD cards are acceptable
  + The card must be formatted as FAT32 irrespective of capacity
* Copy all of the files from the following folder onto the SD card
  + E:\N.I.G.E.-Machine\Software
* Insert the SD card into the slot on the PMOD (Nexys 2) or the directly into board (Nexys 4)
* See chapter 2 for further guidance on using the SD card as a file system

# 2. Using the N.I.G.E. machine as a FORTH microcomputer

## 2.1 ANSI FORTH

At power-on the N.I.G.E. Machine is a self-contained microcomputer with FORTH system software. As far as possible the system software has been designed to be compliant with ANSI FORTH. Some minor ANSI deviations were allowed given the constraints of an embedded system. See appendix 6 for a list of the ANSI FORTH words that are available on the N.I.G.E. Machine and appendix 7 for a list of N.I.G.E. Machine specific control words.

## 2.2. File System

###### 2.2.1 SD card usage and file system navigation

The N.I.G.E. Machine uses SD cards for file system external storage. See Chapter 1 for SD card set-up details. At power-on the only available file access word is INCLUDE. Prepare and insert an SD card, then issue the following commands to make available additional ANSI FORTH words from the file access and other word sets.

MOUNT \ Mount an SD card and initialize FAT32 data

INCLUDE SYSTEM.F \ SYSTEM.F extends the FORTH system software

The N.I.G,E. Machine reads and writes filenames in 8+3 format only (e.g. “FILENAME.EXT”), but directory structures are supported. The file path directory separator character is either forward slash “/” or back slash “\”, and these may be used interchangeably. A leading slash or a double slash (“//” or “\\”) within a file path are interpreted as go-up-one-directory-level. No special character is used to specify the root folder.

Examples:

S” PROJECT/TEST.F” \ specify the file TEST.F in the PROJECT directory beneath \ the current directory

S” \B\DATA.TXT” \ go up one level from the current directory and down   
 \ again into folder B to specify the file DATA.TXT

###### 2.2.2 New-line character

The system software recognizes LF as the line terminator disregards CR characters. The WRITE-LINE word terminates lines with CRLF. The N.I.G.E. Machine can therefore read and process both Windows and LINUX format files, but files are written in Windows format.

## 2.3 Memory address regions

The N.I.G.E. Machine address space is spanned in bytes. It comprises three separate memory regions:

1. System memory is available for storage of the FORTH dictionary and other data. This is referred to as SRAM in the N.I.G.E. Machine documentation. System memory is comprised of FPGA BLOCK RAM and is the only memory from which the CPU can fetch and execute code.
2. Memory mapped hardware registers that control the operation of the N.I.G.E. Machine or connect to external pins on the FPGA. These registers are implemented in FPGA fabric logic and route directly into the N.I.G.E. Machine’s own functional modules.
3. The external pseudo-static dynamic RAM chip included on the Nexys boards. This memory is referred to as PSDRAM. The N.I.G.E. Machine CPU can fetch and store data from PSDRAM, but cannot execute code there. PSDRAM is also used to hold the VGA screen display buffer. Access to PSDRAM is arbitrated by a direct memory access controller module within the N.I.G.E. Machine.

In terms of the choice of RAM for data storage, SRAM has the advantage that it is fast (1 clock cycle access) and deterministic. However total capacity is limited to tens of kilobytes. PSDRAM is more plentiful (16 megabytes), but access is slower and subject to arbitration with the VGA display.

The CPU has separate instructions for byte, word and long-word memory access and the corresponding FORTH words C!, C@, W!, W@, !, @ are available in system software.

Access to SRAM does not need to be aligned. Both words and long-words can successfully be read/written to odd address boundaries without penalty. PSDRAM access on the other hand must be aligned: words can only be accessed on even address boundaries and long-words accessed on address boundaries divisible by four.

The N.I.G.E. Machine is big-endian format. Memory access for words and long-words is such that the highest value byte is placed in the lowest memory address.

Appendices 3 and 4 provide complete memory maps for the N.I.G.E. Machine v2.0 and v3.0

## 2.4 VGA display

The N.I.G.E. Machine outputs standard VGA signals through the VGA D-sub connector on the Nexys boards.

This section of the user manual describes the display technical characteristics, while appendix 7 documents a set of N.I.G.E. Machine specific FORTH display command words, and appendices 2 and 3 document the hardware registers that may be accessed directly for controlling the display.

###### 2.4.1 Display organization

The N.I.G.E. Machine display is character graphics based. There are 256 different character codes and each character is 8 pixels high by 8 pixels wide. The first 128 characters are drawn from the ANSI character set and there are 128 additional custom characters. All of these characters are soft-programmable by writing to the 2KB CHARACTER RAM that resides within the SRAM address space.

Each character position on screen comprises a single word in memory. The top left character on screen corresponds to the first address of the screen buffer in memory. Within each word, the high byte (stored at the lower memory address) contains the color information while the low byte (stored at the higher memory address) references the character code.

###### 2.4.2 Interlace mode

The N.I.G.E. Machine VGA display is able to interlace two additional scan lines between each row of character graphics to assist the readability of text. This is known as interlace mode and soft-selectable on or off.

1 INTERLACE \ Sets interlace mode

0 INTERLACE \ Sets non-consolidated mode

###### 2.4.3 Display resolution

The N.I.G.E. Machine display output is soft-selectable between the following VGA modes:

|  |  |  |  |
| --- | --- | --- | --- |
| VGA mode (binary) | VGA pixel resolution | Character resolution (non-interlace mode) | Character resolution (interlace mode) |
| 00 | VGA display off | n/a | n/a |
| 01 | 640\*480 | 80\*60 | 80\*48 |
| 10 | 800\*600 | 100\*75 | 100\*60 |
| 11\* | 1024\*768 | 128\*96 | 128\*77 |

\*VGA resolution of 1024\*768 is only available on the N.I.G.E. machine v3.0.

2 VGA \ Sets 800\*600 VGA mode

###### 2.4.4 Screen buffer

The display screen buffer is held in PSDRAM memory. The location of the start of the screen buffer is soft-programmable and can be redirected by writing to the SCREENPLACE hardware register. (Or equivalently, via the SCREENPLACE FORTH variable). The default location of the start of the screen buffer can be read from the SCREENBASE FORTH constant.

In normal input and output the FORTH system software automatically moves the start location of the display buffer through a fixed range of memory to achieve faster screen refreshes when scrolling the display. The screen buffer location is returned to its default location when the screen is cleared through a CLS command, or when repeated screen scrolls have brought the screen buffer to the end of its allocated range.

User application may allocate their own block of PSDRAM for display purposes and relocate the screen buffer there for the duration of their execution. When the location of the screen buffer is restored to its prior value the display will revert accordingly.

###### 2.4.5 Color modes

The N.I.G.E. Machine has two color modes. These define the way that the color byte for each character is interpreted.

* In 16/16 color mode the highest 4 bits of the color byte define the background color and the lowest 4 bits define the foreground color of that character.

0 COLORMODE \ Set 16/16 color mode

* In 256/0 color mode all 8 bits of the color byte define the foreground color of that character. In this mode the background color for the whole screen is determined by the value of the BACKGROUND hardware register. 256/0 color mode is the power-on default.

1 COLORMODE \ Set 256/0 color mode

Interpretation of the foreground and background colors differs between the N.I.G.E. Machine v2.0 and v3.0.

###### 2.4.6. v2.0 color output

The Nexys 2 board has a color output range of 8 bits. In 256/0 color mode an 8 bit color code is directly interpreted as an RGB value (RRRGGGBB format). The BACKGROUND hardware register is 8 bits wide.

In 16/16 color mode, the 4 bits are also directly interpreted as an RGB value that is hard-wired extrapolated to 8 bits.

###### 2.4.7. v3.0 color output

The Nexys 4 board has a color output range of 12 bits (4096 colors). In 256/0 color mode, the foreground color value (0-255) indexes a word in 16 bit PALETTE RAM from which the actual 12 bit RGB color code is read (RRRRGGGGBBBB format). PALETTE RAM is pre-defined with a range of colors (see Appendix 5) but is also soft-programmable. The BACKGROUND hardware register is 16 bits wide (of which the lowest 12 bits are used).

In 16/16 color mode, the foreground color value (0-15) indexes the first 16 words in PALETTE RAM as above but the 16 background colors are pre-defined in hardware.

## 2.5 Other input/output

In the default configuration the N.I.G.E. Machine includes a single RS232 port.

In the N.I.G.E. Machine v2.0 the RS232 port is connected directly to the Nexys 2 board’s RS232 D-sub connector. However the Nexys 4 board does not include a D-sub connector. For the N.I.G.E. Machine v3.0 a PMOD RS232 expansion should be connected to PMOD socket C, lower pin row. Alternatively it is possible to re-route the RS232 port to the Nexys 4 board’s RS232/USB interface. Comment/uncomment the relevant NET definitions in the FPGA constraints file to make this change:

1. E:\N.I.G.E.-Machine\Software\Board\_Nexys 4.ucf

RS232 communication over an RS232/USB adapter may be less reliable due to buffer/latency issues in the adapter or PC driver. Appendix 7 documents N.I.G.E. Machine specific RS232 input/output words.

The UART adapter is hardwired to 8 bits, 1 stop bit, no parity, no handshaking. The baud rate is user configurable. Default settings are as follows:

v2.0, Nexys 2: 9,600 baud

v3.0, Nexys 4: 57,600 baud

## 2.6 Exception handling

The N.I.G.E. Machine incorporates CATCH and THROW as single machine language instructions. QUIT operates using a master CATCH statement that calls the main user interaction system loop. If an error is thrown that is not trapped by user code, then it will be caught by the CATCH statement within QUIT.

QUIT assumes that any error codes it receives are counted strings, which it will display as an error message. A straightforward way for user code to abort execution and return an error message is as follows

c" My error message" THROW \ Abort execution and return to QUIT

## 2.7 Multitasking

The N.I.G.E. Machine has virtualization capabilities built into the soft-core CPU. There are 32 virtual machines (VM's) within the CPU and each VM is capable of running a separate software task (see Appendix 12). The FORTH system software includes various support words for launching and controlling tasks which are described in Appendix 7.

The virtualization core has the flexibility to operate whichever model for taking sequencing is best suited for the application at hand. The default model provided by the FORTH system software is cooperative, round-robin sequencing.

# 3. Customizing the system software

The system software is written in assembly language. A two-pass cross-assembler is available to prepare the necessary binary files from the assembly language source.

The CPU instruction set is documented in Appendix 2. Because the N.I.G.E. Machine CPU is designed as a FORTH processor, the instruction set is essentially a sub-set of the most primitive FORTH words. The cross assembler provides additional macros corresponding to higher-level FORTH word, mostly for flow control. Appendix 9 documents the cross assembler macros and directives.

## 3.1 Running the cross-assembler

The cross assembler should be run in an ANSI FORTH environment such as a PC running VFX FORTH. The command to run the cross assembler is ASMX. The N.I.G.E. Machine system software source file is E:\N.I.G.E.-Machine\System\FORTH.ASM.

INCLUDE ASMX.F \ include the cross assembler

S” E:\N.I.G.E.-Machine\System\FORTH.ASM” ASMX  
\ cross-assemble the system software

The three output files are as follows, and **they will always be placed in the folder E:\N.I.G.E.-Machine\System** to maintain integrity of the absolute file references used by Xilinx ISE.

* SRAM.BIN
  + Binary file suitable for transfer to the N.I.G.E. Machine by boot-loader
* SRAM.TXT
  + Text file that is used during simulation with the Xilinx ISE simulator
* SRAM.COM
  + Text file that is used when Xilinx ISE generates the SRAM memory module. Note that the SRAM module must be explicitly regenerated in ISE each time the system software source is reassembled

All of the output files are placed in this folder “E:\N.I.G.E.-Machine\System”, so it is important that the exact directory structure of the source file depository is maintained.

## 3.2 Structure of the system software

The system software comprises three regions:

* Interrupt vector table
* Interrupt handlers
* FORTH dictionary

###### 3.2.1 Interrupt vector table

Valid interrupts redirect program counter execution to the appropriate location in the interrupt vector table. Each table is two bytes long and should be constructed as follows.

1. A two byte branch instruction (BRA) to an interrupt handler, for an active interrupt
2. An RTI NOP (return from interrupt, no operation) combination, for an inactive interrupt

The interrupt vector table is documented in appendix 11.

###### 3.2.1 Interrupt handlers

Interrupt handler should be placed within the range of a branch instruction (i.e. in the first 8Kb of system memory). All interrupt handlers must be terminated with an RTI instruction rather than an RTS instruction, as this signals the interrupt controller than new interrupts may be processed.

See chapter 4 for more details on the operation of the interrupt controller and interrupt priority.

###### 3.2.2 FORTH dictionary

The structure of the FORTH system is documented in appendix 10. Note that if the dictionary is extended then the dictionary word LAST (which is also the last definition in the source file FORTH.ASM) must be updated accordingly.

###### 3.2.3 Exception handling

The N.I.G.E. Machine incorporates CATCH and THROW as single machine language instructions. The N.I.G.E. Machine implementing of the FORTH words CATCH and THROW operate as usual as per their ANSI definitions. However there is a slight usage difference for the machine language instruction CATCH as follows: In an assembly language program the machine language instruction CATCH must be followed by the machine language instruction ZERO in all cases.

This is to ensure the correct behavior when a word that is called by CATCH returns via RTS rather than THROW. In the case of return via RTS the return address is the instruction immediately following CATCH, and so the execution thread will proceed to the instruction ZERO, thus showing the correct ANSI FORTH behavior. In the case of return via THROW the return address is the instruction immediately following CATCH plus one, so the execution thread will step over the instruction ZERO but retain the THROW code on the top of stack.

For example:

#.l subroutine \ load the subroutine address on stack

CATCH \ call the subroutine

ZERO \ RTS returns here

... \ n THROW (n != 0) returns here

## 3.3 Updating the system software

The most straightforward way to test the system software is to transfer the completed binary machine code file to the FPGA board on a temporary basis using the boot loader. However the file transferred by boot loader will be lost when the board is powered off or the FPGA is reprogrammed. To incorporate the revised system software on a permanent basis the FPGA configuration .bit file needs to be regenerated with the revised machine code file.

In either case the first step is to re-assemble the updated system software and confirm that a new binary file has been created:

* E:\N.I.G.E.-Machine\System\SRAM.bin

Note that this **exact filepath and filename** must be used to ensure compatibility with the absolute file references used by Xilinx ISE.

###### 3.3.1 Using the boat loader to update the system software until power off

**Nexys 2, v2.0**

The Digilent Adept application should be used to transfer the file SRAM.bin to via the Epp interface into register 0xFF. The system will automatically reset when the transfer is started and reboot with the new system software.

**Nexys 4, v3.0**

The Digilent Adept application is not compatible with the Nexys 4 board and so the boot loader utilizes transfer via the RS232 port.

* Establish an RS232 connection between the PC and the Nexys 4 board. (See section 2.5)
* Press the CPU reset button on the Nexys 4 board. The board will reset for 4 seconds
* Immediately transfer the file SRAM.bin to the Nexys 4 board via the RS232 interface at the UART default settings of 57,600 baud, 8 bits, 1 stop bit, no parity, no handshaking. A blue LED on the Nexys 4 board will light during transfer. Ensure that the binary file is transferred without modification (e.g. no CR/LF substitutions)
* At the end of the 4 second reset reboot will occur with the new system software. This will be retained in memory until either the board is switched off or the FPGA is reprogrammed.

###### 3.3.2 Updating the FPGA configuration file for a permanent system software update

The procedure for permanently updating the FPGA configuration bit file is as follows:

* Open the SRAM core in Xilinx ISE
  + inst\_SYS\_RAM
* Generate the core and the regenerate the programming file in ISE. **Note that the filepath to the Xilinx memory core initialization module must be exactly as follows:**
  + E:\N.I.G.E.-Machine\System\SRAM.coe
* Transfer the FPGA configuration .bit file to the Nexys board in the usual manner

# 4. Customizing the system hardware

The N.I.G.E. Machine is designed at the outset to be extended for specific applications through customized hardware that control or interact with external apparatus. The overall scheme for doing this is as follows:

* Customized hardware is developed as VHDL (or Verilog) modules within the N.I.G.E. Machine design project
* The custom modules interface with the outside world either through the electronic components available on the Nexys board (e.g. LED’s, microphone, etc.) or through circuits attached to the PMOD expansion ports. Digilent supply a range of ready-made PMOD circuits that may be suitable for a variety of purposes
  + <http://www.digilentinc.com/Products/Catalog.cfm?NavPath=2,401&Cat=9>
* The custom modules interface with the N.I.G.E. Machine through either or both of two channels:
  + Additional user-defined hardware registers (that extend the list documented in appendices 3 and 4). These hardware registers may be readable, writable or both. The CPU access them through normal memory fetch and store instructions, while the bit level signals are routed directly into the design of the custom hardware module
  + Additional user-defined system interrupts (that extend the list documented in appendix 11). After creating additional system interrupts appropriate entries will need to be created for them in the interrupt vector table and appropriate interrupt handlers will need to be developed. This will involve customizing the system software in assembly language (see chapter 3)
* Extending the hardware registers and interrupts involves making changes to the following modules in the project design files. In general this should be as straightforward as duplicating the existing logic for each new item using the design file comments as a guide:
  + Inst\_HW\_Registers
  + Inst\_Interrupt
* The FORTH system software is used to debug, test, and develop the necessary control applications for the customized hardware. Because FORTH can be used as an interpreted language, and because the N.I.G.E. Machine includes native keyboard and video display interfaces, the benefits of both rapid prototyping and fast execution speed are available to enhance software development compared with a traditional embedded development using a remote editor and compiler

In addition the N.I.G.E. Machine design is released under a dual license with open source rights for non-commercial use (please see the cover page of this manual for further details.) The design of the system itself can be remade.

This manual cannot fully describe the process of custom hardware development in VHDL or Verilog, but some further suggestions in respect of the N.I.G.E. Machine are made as follows:

* Testing design changes in the electronic simulator (Xilinx ISM) is essential before testing in hardware. For this purpose a faster-to-simulate SRAM module (RAM\_for\_Testbench) is provided. Comment out the instance of SYS\_RAM in Board\_Nexys4 and comment in RAM\_for\_Testbench. The principal advantage is that this module can read a revised SRAM.bin file directly without being regenerated, thus saving time
* Regression testing of CPU functionality is also essential after modifications are made. Several regression test programs are provided in the folder E:\N.I.G.E.-Machine\System to test the CPU instructions set, memory access and other functions. They can be run in both the electronic simulator and in hardware. Each test in the sequence is announced via the seven-segment display. If a test fails then its sequence number will remain on display. If the complete sequence of tests completes successfully then the value 0xFF is displayed
* It is critical to ensure that the new design meets timing. ISE SmartXplorer is very helpful for obtaining the best place and route for a given design and optimizing timing

# Appendix 1. System specifications

|  |  |  |
| --- | --- | --- |
| **Version** | **v2.0** | **v3.0** |
| Circuit board | Digilent Nexys 2 (1200K gate) | Digilent Nexys 4 |
| FPGA family | Xilinx Spartan-3E | Xilinx Artix-7 |
| CPU data format | 32 bits | 32 bits |
| CPU pipeline | 3 stage | 3 stage |
| CPU throughput | 1 instruction per clock-cycle for most instructions | 1 instruction per clock-cycle for most instructions |
| Embedded control optimizations | Deterministic execution CPU  Low latency interrupts  PC branch in 2 clock cycles | Deterministic execution CPU  Low latency interrupts  PC branch in 2 clock cycles |
| System clock frequency | 50 MHz | 100 MHz |
| On-chip static RAM | 50 KB | 136 KB |
| External PSDRAM | 16 MB | 16 MB |
| Interrupts | Yes | Yes |
| VGA modes | 640 x 480  800 x 600 | 640 x 480  800 x 600  1024 x 768 |
| Display format | Character graphics (8 x 8 pixel) and pixel graphics | Character graphics (8 x 8 pixel) only |
| Display color depth | 256 colors (8 bit) | 256 colors on screen from a palette of 4096 colors (12 bit) |
| Other input/output ports | PS/2 keyboard  RS232  SPI port for SD card interface  PMOD ports for user expansion | USB keyboard  RS232  SPI port for SD card interface  PMOD ports for user expansion |

# Appendix 2. CPU instruction set

|  |  |  |  |
| --- | --- | --- | --- |
| **Assembler mnemonic** | **Instruction length (bytes)** | **Encoding** | **Duration (cycles)** |
| **Description** | | **Parameter stack effect ( before -- after)**  **3rd 2nd 1st on stack** | **Return stack effect** |

|  |  |  |  |
| --- | --- | --- | --- |
| NOP | 1 byte | 0x00 | 1 cycle |
| No operation | | ( --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| DROP | 1 byte | 0x01 | 1 cycle |
| Remove top item from parameter stack | | ( x --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| DUP | 1 byte | 0x02 | 1 cycle |
| Duplicate the top stack item | | ( x -- x x) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| SWAP | 1 byte | 0x03 | 1 cycle |
| Exchange the two top stack items | | ( x y -- y x) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| OVER | 1 byte | 0x04 | 1 cycle |
| Make a copy of the second item on the stack | | ( x y -- x y x) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| NIP | 1 byte | 0x05 | 1 cycle |
| Dispose of the second item on the stack | | ( x y -- y) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| ROT | 1 byte | 0x06 | 1 cycle |
| Rotate the top three stack times so that the second item becomes top | | (x y z -- z x y) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| >R | 1 byte | 0x07 | 1 cycle |
| Remove the top item from the parameter stack and place it on the return stack | | ( x --) | ( -- x) |

|  |  |  |  |
| --- | --- | --- | --- |
| R@ | 1 byte | 0x08 | 1 cycle |
| Copy the top item from the return stack to the parameter stack | | ( -- x) | ( x -- x) |

|  |  |  |  |
| --- | --- | --- | --- |
| R> | 1 byte | 0x09 | 1 cycle |
| Remove the top item from the return stack and place it on the parameter stack | | ( -- x) | ( x --) |

|  |  |  |  |
| --- | --- | --- | --- |
| PSP@ | 1 byte | 0x0A | 1 cycle |
| Load the parameter stack with the current value of the parameter stack pointer. The stack pointer is the count of items currently on the stack and also directs the CPU datapath to the first stack item held in SRAM | | ( -- PSP) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| CATCH | 1 byte | 0x0B | 2 cycles |
| Branch to the subroutine at address n. Advance the exception, subroutine and return stacks accordingly. The CATCH machine language instruction must be followed by the ZERO machine language instruction in all cases. | | ( n -- ) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| RESETSP | 1 byte | 0x0C | 1 cycle |
| Reset the parameter, return, subroutine and exception stacks to zero. | | ( --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| THROW | 1 byte | 0x0D | 1 cycle / 3 cycles |
| If n=0 then drop the value from the parameter stack and do nothing (1 cycle). If n != 0 then return execution to the address immediately following the calling CATCH plus one, retain the value on the top of the parameter stack, and pop the subroutine and returns stacks accordingly. | | ( n – n | --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| + | 1 byte | 0x0E | 1 cycle |
| Add two 32 bit integer numbers. x3 = x1 + x2 | | ( x1 x2 -- x3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| - | 1 byte | 0x0F | 1 cycle |
| Subtract two 32 bit integer numbers.   x3 = x1 - x2 | | ( x1 x2 -- x3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| NEGATE | 1 byte | 0x10 | 1 cycle |
| Negate a 32 bit integer in two’s complement format | | (x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 1+ | 1 byte | 0x11 | 1 cycle |
| Add 1. x2 = x1 + 1 | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 1- | 1 byte | 0x12 | 1 cycle |
| Subtract 1. x2 = x1 - 1 | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 2/ | 1 byte | 0x13 | 1 cycle |
| Arithmetic shift right. Rotate bits 31 - 1 to bits 30 - 0, and maintain the value of bit 31 | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| ADDX | 1 byte | 0x14 | 1 cycle |
| Add two integers with extend flag as carry. The extend flag resides within the datapath and is not otherwise accessible to software. The flag is only affected by arithmetic instructions. See the D+ FORTH word | | ( x1 x2 -- x3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| SUBX | 1 byte | 0x15 | 1 cycle |
| Subtraction with extend flag as borrow. The extend flag resides within the datapath and is not otherwise accessible to software. The flag is only affected by arithmetic instructions. See the D- FORTH word | | ( x1 x2 -- x3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| = | 1 byte | 0x16 | 1 cycle |
| Returns -1 (true) if x1 = x2 | | ( x1 x2 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| <> | 1 byte | 0x17 | 1 cycle |
| Returns -1 (true) if x1 <> x2 | | ( x1 x2 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| < | 1 byte | 0x18 | 1 cycle |
| Returns -1 (true) if x1 < x2 | | ( x1 x2 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| > | 1 byte | 0x19 | 1 cycle |
| Returns -1 (true) if x1 > x2 | | ( x1 x2 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| U< | 1 byte | 0x1A | 1 cycle |
| Returns -1 (true) if u1 < u2, where u is unsigned | | ( u1 u2 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| U> | 1 byte | 0x1B | 1 cycle |
| Returns -1 (true) if u1 > u2, where u is unsigned | | ( u1 u2 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 0= or NOT | 1 byte | 0x1C | 1 cycle |
| Returns -1 (true) if x1 = 0. Equivalent to Boolean NOT | | ( x1 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 0<> | 1 byte | 0x1D | 1 cycle |
| Returns -1 (true) if x1 <> 0 | | ( x1 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 0< | 1 byte | 0x1E | 1 cycle |
| Returns -1 (true) if x1 < 0 | | ( x1 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 0> | 1 byte | 0x1F | 1 cycle |
| Returns -1 (true) if x1 > 0 | | ( x1 -- flag) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| ZERO or FLASE | 1 byte | 0x20 | 1 cycle |
| Place zero (false) on the stack. Equivalent to ZERO | | ( -- 0) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| AND | 1 byte | 0x21 | 1 cycle |
| Bitwise AND | | ( x1 x2 -- x3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| OR | 1 byte | 0x22 | 1 cycle |
| Bitwise OR | | ( x1 x2 -- x3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| INVERT | 1 byte | 0x23 | 1 cycle |
| Bitwise INVERT (also known as bitwise NOT) | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| XOR | 1 byte | 0x24 | 1 cycle |
| Bitwise XOR | | ( x1 x2 -- x3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| LSL or 2\* | 1 byte | 0x25 | 1 cycle |
| Logical shift left (equivalent to multiply by 2). Bit 0 is set to 0 | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| LSR | 1 byte | 0x26 | 1 cycle |
| Logical shift right. Bit 31 is set to 0 | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| XBYTE | 1 byte | 0x27 | 1 cycle |
| Sign extend a byte to 32 bits | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| XWORD | 1 byte | 0x28 | 1 cycle |
| Sign extend a word to 32 bits | | ( x1 -- x2) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| MULTS | 1 byte | 0x29 | 5 cycles |
| Multiply two signed 32 bit integers to produce a 64-bit integer that is held in the top two stack positions, higher word is top of stack | | ( x1 x2 -- d3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| MULTU | 1 byte | 0x2A | 1 cycle |
| Multiply two unsigned 32 bit integers to produce a 64-bit integer that is held in the top two stack positions, higher word is top of stack | | ( u1 u2 -- ud3) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| DIVS | 1 byte | 0x2B | 42 cycles |
| Divide two 32-bit signed numbers to produce a 32-bit quotient (top of stack) and a 32-bit remainder (next on stack) | | (x1 x2 -- u-rem u-quot) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| DIVU | 1 byte | 0x2C | 41 cycles |
| Divide two 32-bit unsigned numbers to produce a 32-bit quotient (top of stack) and a 32-bit remainder (next on stack) | | (x1 x2 -- rem quot) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| FETCH.L | 1 byte | 0x2D | 2 cycles in SRAM |
| Fetch a longword from memory, big endian | | ( addr -- n) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| STORE.L | 1 byte | 0x2E | 2 cycles in SRAM |
| Store a longword in memory, big endian | | ( n addr --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| FETCH.W | 1 byte | 0x2F | 2 cycles in SRAM |
| Fetch a word from memory, big endian | | ( addr -- n) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| STORE.W | 1 byte | 0x30 | 2 cycles in SRAM |
| Store a word in memory, big endian | | ( n addr --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| FETCH.B | 1 byte | 0x31 | 2 cycles in SRAM |
| Fetch a byte from memory | | ( addr -- n) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| STORE.B | 1 byte | 0x32 | 2 cycles in SRAM |
| Store a byte in memory | | ( n addr --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| ?DUP | 1 byte | 0x33 | 2 cycles |
| Duplicate the top stack item only if non zero | | (x -- x x | x) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| LOAD.B or #.B | 2 bytes | 0x34, x1 | 2 cycles |
| Fetch inline byte to stack and zero extend | | ( -- x) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| LOAD.W or #.W | 3 bytes | 0x35, x2, x1 | 2 cycles |
| Fetch inline word to stack and zero extend. High byte first | | ( -- x) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| LOAD.L or #.L | 5 bytes | 0x36, x4, x3, x2, x1 | 2 cycles |
| Fetch inline longword to stack. Highest byte first | | ( -- x) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| JMP | 1 byte | 0x37 | 2 cycles |
| Redirect program execution to the address on the parameter stack | | ( addr --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| JSL | 4 bytes | 0x38, x3, x2, x1 | 2 cycles |
| Redirect program execution to the address specified by the following 3 bytes (highest byte first). Place the original next following instruction address on the return stack | | ( --) | ( -- addr) |

|  |  |  |  |
| --- | --- | --- | --- |
| JSR | 1 byte | 0x39 | 2 cycles |
| Redirect program execution to the address on the parameter stack and place the original next following instruction address on the return stack | | ( addr --) | ( -- addr) |

|  |  |  |  |
| --- | --- | --- | --- |
| TRAP | 1 byte | 0x3A | 2 cycles |
| Jump to the trap vector (address 0x02) and place the original next following instruction address on the return stack. Used for breakpoint debugging | | ( --) | ( -- addr) |

|  |  |  |  |
| --- | --- | --- | --- |
| RETRAP | 1 byte | 0x3B | 2 cycles |
| Return from subroutine, execute one program instruction and trap again. Used for single step debugging | | ( --) | ( addr --)  ( -- addr) |

|  |  |  |  |
| --- | --- | --- | --- |
| RTI | 1 byte | 0x3C | 2 cycles |
| Return from an interrupt routine. Similar to RTS but also changes the interrupt controller state to allow further interrupts | | ( --) | (addr --) |

|  |  |  |  |
| --- | --- | --- | --- |
| PAUSE | 1 byte | 0x3D | 2 cycles |
| Task switch. Yield execution of the current virtual machine and switch execution to the next-to-execute virtual machine. | | ( --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| RTS | 1 byte | 0x40 | 2 cycles |
| Return from a subroutine that was entered via a JSR or BSR instruction | | ( --) | ( addr --) |

|  |  |  |  |
| --- | --- | --- | --- |
| ,RTS | 1 byte | (0x40 OR opcode) | 1 cycle |
| As RTS but is a compound for any single-cycle instruction that does not itself reference or impact the return stack. The compound instruction saves one cycle and one byte on each subroutine return (e.g. DROP,RTS). | | ( --) | ( addr --) |

|  |  |  |  |
| --- | --- | --- | --- |
| BEQ | 2 bytes | (0x80 OR hi), lo | 3 cycles |
| Branch if the top of stack item is zero. The top 6 bits of the branch offset are in the first instruction byte, the bottom 8 bits of the branch address follow in a second instruction byte. The branch offset is calculated from the address of the second byte | | ( flag --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| BRA | 2 bytes | (0xC0 OR hi), lo | 3 cycles |
| Branch. The top 6 bits of the branch offset are in the first instruction byte, the bottom 8 bits of the branch address follow in a second instruction byte. The branch offset is calculated from the address of the second byte | | ( --) | ( --) |

# Appendix 3. Memory map (v2.0, Nexys 2)

#### Overall memory map

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Region** | **Implementation** | **Size** | **Bottom** | **Top** |
| System memory | FPGA block RAM | 50 KB | 0x000000 | 0x00F7FF |
| Hardware registers | FPGA logic | 2 KB | 0x00F800 | 0x00FFFF |
| External memory | PSDRAM chip | 16 MB | 0x010000 | 0xFFFFFF |

#### System memory

|  |  |  |  |
| --- | --- | --- | --- |
| **Region** | **Size** | **Bottom** | **Top** |
| Forth system software and user applications | 44 KB | 0x000000 | 0x00AFFF |
| Parameter stack | 2 KB | 0x00E000 | 0x00E7FF |
| Return stack | 2 KB | 0x00E800 | 0x00EFFF |
| Character RAM | 2 KB | 0x00F000 | 0x00F7FF |

#### Hardware registers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Function** | **R/W** | **Hex** | **Dec** |
| SCREENPLACE | Pointer to the start of the character/text screen buffer in external memory | R/W | 0xF800 | 63488 |
| GFXPLACE | Pointer to the start of the pixel graphics screen buffer in external memory | R/W | 0xF804 | 63496 |
| BACKGROUND | Screen background color | R/W | 0xF808 | 63496 |
| MODE | Graphics mode - see below for bit level | R/W | 0xF80C | 63500 |
| RS232DIN | RS232 data in | R | 0xF810 | 63504 |
| RS232DOUT | RS232 data out. Writing to this register triggers the RS232 port to output the byte | W | 0xF814 | 63508 |
| RS232UBRR | UBRR = 50,000,000 / (baud +1) / 16 |  | 0xF818 | 63512 |
| RS232STAT | RS232 port status - see below for bit level |  | 0xF81C | 63516 |
| PS2DIN | PS/2 port data in | R | 0xF820 | 63520 |
| SYSCOUNT | Unsigned 32 bit counter clocked at 50 MHz | R | 0xF824 | 63524 |
| MSCOUNT | Unsigned 32 bit counter clocked at 1 KHz | R | 0xF828 | 63528 |
| IRQMASK | Interrupt request mask - see below | R/W | 0xF82C | 63532 |
| SEVENSEG | 4 character seven segment output on the Nexys 2 board | W | 0xF830 | 63536 |
| SWITCHES | 8 switch inputs on the Nexys 2 board | R | 0xF834 | 63540 |
| SPIDATA | SPI data byte. Writing to this register triggers the SPI transmit/receive cycle | R/W | 0xF838 | 63544 |
| SPICONTROL | Control of SPI port - see below for bit level | R/W | 0xF83C | 63548 |
| SPISTATUS | Status of SPI port - see below for bit level | R | 0xF840 | 63552 |
| SPICLKDIV | SPI clock = 50,000,000 / SPICLKDIV | W | 0xF844 | 63556 |
| VBLANK | Bit 0 is set during the VGA vertical blank interval and cleared otherwise | R | 0xF848 | 63560 |

# Appendix 4. Memory map (v3.0, Nexys 4)

#### Overall memory map

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Region** | **Implementation** | **Size** | **Bottom** | **Top** |
| System memory | FPGA block RAM | 136 KB | 0x000000 | 0x03F7FF |
| Hardware registers | FPGA logic | 2 KB | 0x03F800 | 0x03FFFF |
| External memory | PSDRAM chip | 16 MB | 0x040000 | 0xFFFFFF |

#### System memory

|  |  |  |  |
| --- | --- | --- | --- |
| **Region** | **Size** | **Bottom** | **Top** |
| Forth system software and user applications | 128 KB | 0x000000 | 0x01FFFF |
| Not used - reserved for expansion | 108 KB | 0x020000 | 0x03D7FF |
| Character RAM | 2 KB | 0x03D000 | 0x03D7FF |
| Palette RAM | 2 KB | 0x03D800 | 0x03DFFF |
| Parameter stack | 2 KB | 0x03E000 | 0x03E7FF |
| Return stack | 2 KB | 0x03E800 | 0x03EFFF |
| Exception and subroutine stacks | 2 KB | 0x03F000 | 0x03F7FF |

#### Hardware registers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Function** | **R/W** | **Hex** | **Dec** |
| SCREENPLACE | Pointer to the start of the character/text screen buffer in external memory | R/W | 0x03F800 | 260096 |
| BACKGROUND | Screen background color | R/W | 0x03F808 | 260104 |
| MODE | Graphics mode - see below for bit level | R/W | 0x03F80C | 260108 |
| RS232DIN | RS232 data in | R | 0x03F810 | 260112 |
| RS232DOUT | RS232 data out. Writing to this register triggers the RS232 port to output the byte | W | 0x03F814 | 260116 |
| RS232DIVIDE | DIVIDE = 100,000,000 / baud rate | W | 0x03F818 | 260120 |
| RS232STATUS | RS232 port status - see below for bit level | R | 0x03F81C | 260124 |
| PS2DIN | PS/2 port data in | R | 0x03F820 | 260128 |
| SYSCOUNT | Unsigned 32 bit counter clocked at 50 MHz | R | 0x03F824 | 260132 |
| MSCOUNT | Unsigned 32 bit counter clocked at 1 KHz | R | 0x03F828 | 260136 |
| IRQMASK | Interrupt request mask - see below | R/W | 0x03F82C | 260140 |
| SEVENSEG | 8 character seven segment output on the Nexys 2 board | W | 0x03F830 | 260144 |
| SWITCHES | 16 switch inputs on the Nexys 2 board | R | 0x03F834 | 260148 |
| SPIDATA | SPI data byte. Writing to this register triggers the SPI transmit/receive cycle | R/W | 0x03F838 | 260152 |
| SPICONTROL | Control of SPI port - see below for bit level | R/W | 0x03F83C | 260156 |
| SPISTATUS | Status of SPI port - see below for bit level | R | 0x03F840 | 260160 |
| SPICLKDIV | SPI clock = 100,000,000 / SPICLKDIV | W | 0x03F844 | 260164 |
| VBLANK | Bit 0 is set during the VGA vertical blank interval and cleared otherwise | R | 0x03F848 | 260168 |

#### Hardware registers - bit level

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Register/bit** | **4** | **3** | **2** | **1** | | **0** | |
| MODE | 0 = interlace off  1 = interlace on | 0 = 16/16 color mode  1= 256/0 color mode | 000 = Display off  001 = 640 \* 480  010 = 800 \* 600  010 = 1024 \* 768 | | | | |
| RS232STATUS | n/a | n/a | n/a | | Transfer bus enable | | Read data available (strobe) | |
| IRQMASK | MS | PS/2 | RS232 TBE | | RS232 RDA | | n/a | |
| SPI CONTROL | n/a | 0 = clock rests lo  1 = clock rests hi | 0 = latch then shift  1= shift then latch | | 0 = MOSI default lo  1 = MOSI default hi | | 0 = CS lo  1 = CS hi | |
| SPI STATUS | n/a | MISO | Write protect | | Chip detect | | SD transfer bus ready | |

# Appendix 5. Palette RAM color table

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Color #** | **Color** | **RGB** | **Hue** | **Saturation** | **Luminescence** |
| 0 | Black | 0x000 | 0 | 0% | 0% |
| 1 | Grey | 0x888 | 0 | 0% | 50% |
| 2 | Silver | 0xBBB | 0 | 0% | 75% |
| 3 | White | 0xFFF | 0 | 0% | 100% |
| 4 | Red | 0xF00 | 0 | 100% | 50% |
| 5 | Yellow | 0xFF0 | 60 | 100% | 50% |
| 6 | Green | 0x0F0 | 120 | 100% | 50% |
| 7 | Cyan | 0x0FF | 180 | 100% | 50% |
| 8 | Blue | 0x00F | 240 | 100% | 50% |
| 9 | Magenta | 0xF0F | 300 | 100% | 50% |
| 10 | Maroon | 0x800 | 0 | 100% | 25% |
| 11 | Olive | 0x880 | 60 | 100% | 25% |
| 12 | Dark green | 0x080 | 120 | 100% | 25% |
| 13 | Teal | 0x088 | 180 | 100% | 25% |
| 14 | Navy | 0x008 | 240 | 100% | 25% |
| 15 | Purple | 0x808 | 300 | 100% | 25% |
| 16-255 | various |  |  |  |  |

# Appendix 6. Implementation of ANSI FORTH words

Thus appendix is organized in alignment with the word sets of the ANSI FORTH standard and documents the availability of these words on the N.I.G.E. Machine.

* For the ANSI CORE word set, “status” indicates whether the word has been implemented on the N.I.G.E. Machine (Y/N). An asterisk indicates that the word is implemented but with some limitation as compared with the ANSI FORTH specification.

* For the optional ANSI word sets, only those words implemented on the N.I.G.E. Machine are listed. Where a filename (e.g. “SYSTEM.F”) is indicated, the word must be included from that file on an appropriately mounted SD card.

#### CORE words

|  |  |  |
| --- | --- | --- |
| Word | Status | Notes |
| ! | Y | See also W! |
| # | N | Use U# instead. Division with a 64-bit dividend is not implemented on the N.I.G.E. Machine. |
| #> | N | Use U#> instead. See #. |
| #S | N | Use U#S instead. See #. |
| ‘ | Y |  |
| ( | Y |  |
| \* | Y |  |
| \*/ | Y\* | The intermediate value is single (32-bit) precision only |
| \*/MOD | Y\* | The intermediate value is single (32-bit) precision only |
| + | Y |  |
| +! | Y | See also W+! and C+! |
| +LOOP | Y |  |
| , | Y | See also W, M, and $, |
| - | Y |  |
| . | Y |  |
| .” | Y |  |
| / | Y |  |
| /MOD | Y |  |
| 0< | Y |  |
| 0= | Y |  |
| 1+ | Y |  |
| 1- | Y |  |
| 2! | N | Less suitable for a big-endian processor |
| 2\* | Y |  |
| 2/ | Y |  |
| 2@ | N | Less suitable for a big-endian processor |
| 2DROP | Y |  |
| 2DUP | Y |  |
| 2OVER | Y |  |
| 2SWAP | Y |  |
| : | Y |  |
| ; | Y |  |
| < | Y |  |
| <# | Y |  |
| = | Y |  |
| > | Y |  |
| >BODY | N | Would be a no operation in the N.I.G.E. Machine FORTH environment. Will not be implemented for space and efficiency reasons |
| >IN | Y |  |
| >NUMBER | Y |  |
| >R | Y |  |
| ?DUP | Y |  |
| @ | Y |  |
| ABORT | Y |  |
| ABORT” | N | Will not be implemented for space and efficiency reasons |
| ABS | Y |  |
| ACCEPT | Y | Tab characters are interpreted as white space |
| ALIGN | Y | No-operation on the N.I.G.E. Machine |
| ALIGNED | Y | Alignment is taken to the next highest longword boundary |
| ALLOT | Y |  |
| AND | Y |  |
| BASE | Y | The variable BASE is held on the exception stack and upon EXIT or THROW its value is restored the value it held before CATCH |
| BEGIN | Y |  |
| BL | Y |  |
| C! | Y | See also W! |
| C, | Y | See also W, |
| C@ | Y | See also W@ |
| CELL+ | Y |  |
| CELLS | Y |  |
| CHARS | Y | No-operation on the N.I.G.E. Machine |
| CONSTANT | Y |  |
| COUNT | Y |  |
| CR | Y |  |
| CREATE | Y |  |
| DECIMAL | Y |  |
| DEPTH | Y |  |
| DO | Y |  |
| DOES> | Y |  |
| DROP | Y |  |
| DUP | Y |  |
| ELSE | Y |  |
| EMIT | Y |  |
| ENVIRONMENT? | N | Will not be implemented for space and efficiency reasons |
| EVALUATE | Y |  |
| EXECUTE | Y | Tab and new-line characters are interpreted as white spaces |
| EXIT | Y |  |
| FILL | Y | See also FILL.W |
| FIND | Y |  |
| FM/M | N | Will not be implemented for space and efficiency reasons |
| HERE | Y |  |
| HOLD | Y |  |
| I | Y |  |
| IF | Y |  |
| IMMEDIATE | Y |  |
| INVERT | Y |  |
| J | Y |  |
| KEY | Y |  |
| LEAVE | Y |  |
| LOOP | Y |  |
| LSHIFT | Y |  |
| M\* | Y |  |
| MAX | Y |  |
| MIN | Y |  |
| MOD | Y |  |
| MOVE | Y |  |
| NEGATE | Y |  |
| OR | Y |  |
| OVER | Y |  |
| POSTPONE | Y |  |
| QUIT | Y |  |
| R> | Y |  |
| R@ | Y |  |
| RECURSE | Y |  |
| REPEAT | Y |  |
| ROT | Y |  |
| RSHIFT | Y |  |
| S” | Y | Multiple buffers are provided in interpret mode.  See also C” and ,” |
| S>D | N | Equivalent to FALSE on the N.I.G.E. Machine. |
| SIGN | Y |  |
| SM/REM | N | Division with a 64-bit dividend is not supported |
| SOURCE | Y |  |
| SPACE | Y |  |
| SPACES | Y |  |
| STATE | Y |  |
| SWAP | Y |  |
| THEN | Y |  |
| U. | Y |  |
| U< | Y |  |
| UM\* | Y |  |
| UM/MOD | N | Division with a 64-bit dividend is not supported |
| UNLOOP | Y |  |
| UNTIL | Y |  |
| VARIABLE | Y |  |
| WHILE | Y |  |
| WORD | Y |  |
| XOR | Y |  |
| [ | Y |  |
| [‘] | Y |  |
| [CHAR] | Y |  |
| ] | Y |  |

#### CORE EXTENSION words

|  |  |  |
| --- | --- | --- |
| Word | File | Notes |
| .( |  |  |
| .R |  |  |
| 0<> |  |  |
| 0> |  |  |
| <> |  |  |
| ?DO |  |  |
| AGAIN |  |  |
| BUFFER: |  | Allocates space in PSDRAM. Suitable for larger data blocks. See also SBUFFER: which allocates space in SRAM |
| C” |  | In the interpretation state C” will copy the text until the following “ to the PAD as a counted string and return its address |
| CASE |  |  |
| COMPILE, |  |  |
| DEFER |  |  |
| ENDCASE |  |  |
| ENDOF |  |  |
| FALSE |  | Returns 0 |
| HEX |  |  |
| INTERPRET |  | Interpret a line from the input buffer |
| IS |  |  |
| MARKER |  |  |
| NIP |  |  |
| OF |  |  |
| PAD |  |  |
| PARSE |  |  |
| PICK |  |  |
| RESTORE-INPUT |  | SAVE-INPUT and RESTORE-INPUT use internal variables to store the input source specification. RESTORE-INPUT does not return a flag |
| SAVE-INPUT |  | See RESTORE-INPUT |
| TRUE |  |  |
| U.R |  |  |
| U> |  |  |
| UNUSED |  |  |
| WITHIN |  |  |
| \ |  |  |

#### DOUBLE-NUMBER words

|  |  |  |
| --- | --- | --- |
| D+ |  |  |
| D- |  |  |

#### EXCEPTION words

|  |  |  |
| --- | --- | --- |
| CATCH |  | The N.I.G.E. Machine system software has a top-level CATCH that assumes throw codes are counted strings which it will display as part of an error message |
| THROW |  | Use c" My error message" THROW to abort execution and return to QUIT with an error message |

#### FACILITY words

|  |  |  |
| --- | --- | --- |
| KEY? |  | See also KKEY?, SKEY? and SKEY? |
| MS |  |  |

#### FILE ACCESS words

|  |  |  |
| --- | --- | --- |
| CLOSE-FILE | SYSTEM.F |  |
| CREATE-FILE | SYSTEM.F |  |
| DELETE-FILE | SYSTEM.F |  |
| FILE-POSITION | SYSTEM.F |  |
| FILE-SIZE | SYSTEM.F |  |
| OPEN-FILE | SYSTEM.F |  |
| R/O | SYSTEM.F |  |
| R/W | SYSTEM.F |  |
| READ-FILE | SYSTEM.F |  |
| READ-LINE | SYSTEM.F |  |
| REPOSITION-FILE | SYSTEM.F |  |
| RESIZE-FILE | SYSTEM.F |  |
| W/O | SYSTEM.F |  |
| WRITE-FILE | SYSTEM.F |  |
| WRITE-LINE | SYSTEM.F |  |
| FLUSH-FILE | SYSTEM.F |  |
| INCLUDE |  |  |
| RENAME-FILE | SYSTEM.F |  |

#### MEMORY words

|  |  |  |
| --- | --- | --- |
| ALLOCATE | SYSTEM.F |  |
| FREE | SYSTEM.F |  |
| RESIZE | SYSTEM.F |  |

#### PROGRAMMING TOOLS words

|  |  |  |
| --- | --- | --- |
| .S |  |  |
| ? |  |  |
| DUMP |  |  |
| SEE | TOOLS.F |  |
| WORDS |  |  |
| STATE |  |  |

#### STRING words

|  |  |  |
| --- | --- | --- |
| COMPARE |  | See also $= |
| SLITERAL |  | See also CLITERAL |

#### SEARCH-ORDER words

|  |  |  |
| --- | --- | --- |
| DEFINITIONS |  |  |
| FIND |  |  |
| FORTH-WORDLIST |  |  |
| GET-CURRENT |  |  |
| GET-ORDER |  |  |
| SEARCH-WORDLIST |  |  |
| SET-CURRENT |  |  |
| SET-ORDER |  |  |
| WORDLIST |  |  |

# Appendix 7. System specific FORTH words

This appendix lists N.I.G.E. Machine specific FORTH words in addition to those included in the ANSI word sets. The words are organized by function. Where a filename is indicated in parenthesis (e.g. SYSTEM.F), that file must be included from an appropriately mounted SD card. This list focuses on commonly used words. Appendix 8 lists further N.I.G.E. Machine specific words more relevant to customization of the system software.

#### Local variables

Local variable syntax is based on VFX FORTH and this documentation is adapted from the VFX FORTH documentation. A maximum of 16 local variables are permitted on the N.I.G.E. Machine.

{: ni1 ni2 ... | lv1 lv2 ... -- o1 o2 :} defines named inputs, local variables, and outputs. The items between {: and | are named inputs. The items between | and -- are local variables. The items between -- and :} are comments. The named inputs are automatically copied from the data stack on entry. Named inputs and local variables can be referenced by name within the word during compilation. The output names are dummies to allow a complete stack comment to be included.

{ is accepted in place of {: and } in place of :}. Named inputs and locals return their values when referenced, and must be preceded by -> or TO in order to perform a store. VALUE types are not implemented on the N.I.G.E. Machine therefore -> and TO are only applicable to local variables.

|  |  |  |
| --- | --- | --- |
| **Word** | **Stack effect** | **Description** |
| {: or { | ( --) | Begin a list of named inputs and local variables |
| | | ( --) | Separator between named inputs and local variables |
| -- | ( --) | Terminate a list of named inputs and local variables |
| :} or } | ( --) | Terminate a list of named inputs and local variables |

#### Multitasking

By default the N.I.G.E. Machine operates a cooperative, round-robin multitasker.

|  |  |  |
| --- | --- | --- |
| **Word** | **Stack effect** | **Description** |
| USER | ( offset <name> --) | Create a user variable with name, <name>, at offset bytes from the start of the user area. The FORTH word <name> will be accessible by all tasks, but each task has access only to its local copy. The first available slot for application specific user variables is at n = 44, and 980 free storage bytes are available from that point. |
| +USER | ( size <name> --) | Create a user variable with name, <name>, of size bytes at the next available offset in the user variable area |
| RUN | ( … pn n XT -- VM# true | false) | Find and initialize a new virtual machine to take n stack parameters (... pn) and execute task XT. Return the number of the virtual machine allocated to this task ( VM) and true if successful, or false if all virtual machines are currently otherwise allocated. The newly created task will be positioned in the round-robin sequence immediately after the current task. Virtual machines are numbered 0 through 31. Note that XT must either be an infinite loop or contain code to self-abort the task |
| PAUSE | ( --) | Task switch. Yield CPU execution of the current virtual machine and switch CPU execution to the next-to-execute virtual machine |
| SINGLE | ( --) | Disable multitasking. PAUSE instructions will be treated as a NOP. By default multitasking is enabled at power-on on the N.I.G.E. Machine |
| MULTI | ( --) | Enable multitasking. Note that if there is only a single active task then PAUSE will be treated as NOP |
| SLEEP | ( VM --) | Put virtual machine VM to sleep by removing it from the list of executing virtual machines. VM remains allocated and can be woken at a later time |
| WAKE | ( VM --) | Wake virtual machine VM by inserting it into the list of executing tasks immediately following the current task |
| STOP | ( VM --) | Deallocate virtual machine VM and remove it from the list of executing virtual machines. Virtual machine VM may now be recycled by RUN |
| VIRQ | ( XT VM --) | Virtual interrupt. Cause virtual machine VM to branch to the subroutine at XT and then return to its prior point of execution. The virtual interrupt will occur at the time when virtual machine VM is next scheduled to execute. (VIRQ does not cause execution to pass to virtual machine VM early/out of sequence) |
| THIS-VM | ( -- VM) | Return the number of the currently executing virtual machine. Virtual machines are numbered 0 through 31. A power-on virtual machine 0 will be executing the FORTH system software |
| THIS-SLEEP | ( --) | Put the currently executing virtual machine to sleep by taking it out of the list of executing virtual machines. The virtual machine may be woken by another task. Note that THIS-SLEEP should be used instead of THIS-VM SLEEP to ensure correct task switching behavior |
| THIS-STOP | ( --) | Deallocate the currently executing virtual machine to sleep and take it out of the list of executing virtual machines. The virtual machine may now be recycled by RUN. Note that THIS-STOP should be used instead of THIS-VM STOP to ensure correct task switching behavior |
| ACQUIRE | ( sem --) | Acquire the binary semaphore (sem) or wait in a busy loop until it becomes free. Note that a semaphore can be any FORTH variable with global scope. Semaphores are minimum single byte in length (word or longword length variables may also be used). A semaphore contains the number of the latest successfully acquiring virtual machine XOR 255, or 0 if not acquired. |
| RELEASE | ( sem --) | Release the binary semaphore (sem). See also ACQUIRE |

#### System

|  |  |  |
| --- | --- | --- |
| **Word** | **Stack effect** | **Description** |
| RESET | ( --) | Reset the N.I.G.E. Machine to power on configuration but otherwise preserve memory contents |
| COUNTER | ( -- ms) | Current count of the rolling 32 bit millisecond counter |
| SEVENSEG | (n --) | Display a 32 bit value on the Nexys 4 eight character, seven segment, LED display |

#### Screen display

|  |  |  |
| --- | --- | --- |
| BACKGROUND | (x --) | Set the current screen background color to the specified value. The color is specified as a 8 bit (v2.0) or 12 bit (v 3.0) value in the form RRRGGGBB or RRRRGGGGBBBB |
| INK | ( addr --) | **Byte length** FORTH variable holding the foreground color to be used by EMIT. Access with C! |
| INTERLACE | ( flag --) | Sets or unsets interlace mode. In interlace mode there are 2 blank (background color) scan lines between each row of 8 bit high characters. The number of screen rows (ROWS) is adjusted accordingly |
| VGA | ( n --) | Sets the VGA mode:  0 - display off  1 - 640 \* 480  2 - 800 \* 600 (default)  3 - 1024 \* 768  The number of screen rows (ROWS) and columns (COLUMNS) are also adjusted accordingly |
| COLORMODE | ( n --) | Sets the color mode (see section 2):  0 - 16/16  1 - 256/0 (default) |
| CLS | ( --) | Clear the screen |
| HOME | ( --) | Position the cursor at the top left screen position without clearing the screen |
| TAB | ( -- addr) | VARIABLE pointing to the current size of tab stops. The default is 3 |

#### SD card and FAT file system

|  |  |  |
| --- | --- | --- |
| MOUNT | ( --) | Mount an SD card and initialize the FAT32 data structures. Call MOUNT after inserting or replacing an SD card |

#### SD card and FAT file system (SYSTEM.F)

|  |  |  |
| --- | --- | --- |
| DIR | ( --) | List the current directory |
| CD | “FILEPATH” | Set the current directory to FILEPATH |
| DELETE | “FILEPATH” | Delete the directory given as FILEPATH |

#### RS232 port

|  |  |  |
| --- | --- | --- |
| SEMIT | ( x --) | Emit a character to the RS232 |
| SKEY? | ( -- flag) | Check if a character is waiting to be read from the 256 byte circular buffer maintained for the RS232 port |
| SKEY | ( -- n) | Wait for and read the next character available at the RS232 port |
| STYPE | ( c-addr n --) | Type a string to the RS232 (asynchronous operation) |
| SEMIT | ( x --) | Emit a character to the RS232 |
| SZERO | (--) | Abandon all waiting characters in the RS232 input buffer and reset the buffer pointer to zero |
| BAUD | (n --) | Set the baud rate to n - CHECK THIS FOR NEW CLOCK RATE |
| >REMOTE | ( --) | Redirect FORTH environment output to the RS232. The redirection vectors are held on the exception stack and reset upon EXIT or THROW to their values as at before CATCH. |
| >LOCAL | ( --) | Redirect FORTH environment output to the screen. See >REMOTE. |
| <REMOTE | ( --) | Receive FORTH environment input from the RS232. See >REMOTE. |
| <LOCAL | ( --) | Receive FORTH environment input from the keyboard. See >REMOTE. |

#### Memory (SYSTEM.F)

|  |  |  |
| --- | --- | --- |
| MEM.SIZE | ( addr -- n) | Return the size of an allocated memory block |
| AVAIL | ( --) | Show free memory block list |
| UNAVAIL | ( --) | Show used memory block list |

#### Compiler extensions

|  |  |  |
| --- | --- | --- |
| HERE1 | ( -- addr) | VARIABLE pointing to the dictionary pointer for the PSDRAM dictionary space. Only used by BUFFER: |
| INLINESIZE | ( -- addr) | VARIABLE pointing to the maximum code-length in bytes that the compiler will compile inline rather than as a subroutine call. The default value is 10 and the minimum allowable is 9 since certain code, such as LOOP code, must be compiled inline |
| W, | (w -- ) | Allocate 2 bytes in the dictionary and store a word from the stack |
| M, | (addr u --) | Allocate and store u bytes from addr into the dictionary. u is not saved in the dictionary. Compiles a string or other block of data from memory |
| $, | ( addr u --) | Allocate and store u bytes from addr into the dictionary. u is is compiled as the first byte. Compiles a counted string. |
| LITERAL | ( n --) | Compile a literal to the dictionary |
| CLITERAL | ( addr u --) | Compile to the dictionary a string literal as an executable that will be re-presented at run time as a counted string c-addr |

#### Programming tools (TOOLS.F)

|  |  |  |
| --- | --- | --- |
| DASM | ( addr n --) | Disassemble n bytes starting at address addr. Note that DASM does not identify literal strings within word definitions and so disassembly will become unreliable when they are encountered |
| SIZEOF | ( xt -- n) | Return the size of an executable |
| .’ | (addr -- c-addr n true | false) | If addr points to an executable FORTH word, provide the name of the word and return true. Otherwise return false |

#### Editor (EDITOR.F)

The editor is a simple keyboard based file text editor primarily intended for editing FORTH language source files on the SD card file system. The FORTH words to launch the editor and keyboard commands are listed below.

|  |  |  |
| --- | --- | --- |
| EDIT | “FILENAME” | Open an existing file and launch the editor |
| EDITNEW | “FILENAME” | Create a new file on the SD card and launch the editor |
| Page up, page down, cursor keys | | Cursor movement |
| Home | | Move cursor to first line of file |
| End | | Move cursor to last line of file |
| Backspace, delete | | Character deletion |
| Esc | | Exit without saving changes |
| F1 | | Save changes and exit |
| F2 | | Save changes and continue |

#### Other supporting words

|  |  |  |
| --- | --- | --- |
| BINARY | ( --) | Set BASE = 2 |
| NOT | ( n – n) | Equivalent to 0= |
| XBYTE | ( n – n) | Sign extend a byte on the stack to 32 bits |
| XWORD | ( n –n) | Sign extend a word on the stack to 32 bits |
| W@ | ( addr – n) | Fetch a word from memory |
| W! | ( n addr --) | Store a word in memory |
| FILL.W | ( addr n w --) | Fill a region of memory with n words w. FILL.W utilizes the STORE.W machine language instruction and is faster than FILL in accessing PSDRAM |
| UPPER | (x -- X) | Convert one ASCII character to uppercase |
| DIGIT | ( char base -- n true | char false ) | Convert a single ASCII character to a number in the given base |
| NUMBER? | ( c-addr u - false | n true ,) | Convert an ASCII string to a number and return with a success or failure flag |
| COMP | ( n1 n2 – n) | Return -1 if n1<n2, +1 if n1>2, 0 if n1=n2 |
| $= | ( c-addr1 u1 c-addr2 u2 -- flag) | Test two strings for equality. Case insensitive |
| MASK@ | ( addr mask -- u) | Fetch the longword at address addr bitwise though the read-enable mask. Equivalent to @ followed by OR |
| MASK! | ( u addr mask --) | Store the longword u at address addr bitwise through the write-enable mask |

# Appendix 8. Further system specific words

This appendix documents the remainder of N.I.G.E. Machine specific words likely to be relevant to customization of the FORTH system software.

#### Screen display

|  |  |  |
| --- | --- | --- |
| VEMIT | ( n --) | Emit a character to the VDU and process any screen-codes (e.g. CR or BACKSPACE) accordingly. Move the current screen cursor position forward |
| VTYPE | ( c-addr n --) | Type a string to the VDU and process any screen-codes (e.g. CR or BACKSPACE) accordingly. Move the current screen cursor position forward |
| EMITRAW | ( n --) | Emit a character to the VDU without processing any screen-codes. Move the current screen cursor position forward |
| TYPERAW | ( c-addr n --) | Type a string to the VDU without processing any screen-codes. Move the current screen cursor position forward |
| CSR-PLOT | ( x --) | Plot the specified ASCII character at the current cursor position. Does not change the cursor position. |
| CSR-ADDR | ( -- addr) | Return the memory address of the current cursor position (as held by CSR-X and CSR-Y) within the screen buffer in PSDRAM |
| CSR-X | ( -- col) | Return the current column position of the cursor |
| CSR-Y | ( -- row) | Return the current row position of the cursor |
| CSR-ON | ( --) | Plot the cursor symbol at the current cursor position. The character at that position is saved in an internal variable. (Used by ACCEPT) |
| CSR-OFF | ( --) | Unplot the cursor symbol from the current cursor position and restore the character which was previously there. (Used by ACCEPT) |
| CSR-FWD | ( --) | Advance the cursor by one character |
| CSR-BACK | ( --) | Move back the cursor by one character |
| CSR-TAB | ( --) | Advance the cursor to the next tab stop |
| NEWLINE | ( --) | Scroll the screen downwards by one line of text and return the cursor to the first column of the blank line below |
| SCROLL | ( n -- flag) | Scroll the screen fwd or back n lines within the 120 line frame buffer. Returns true if out of range or false otherwise |
| ROWS | ( -- rows) | Return the current number of screen rows. |
| COLS | ( -- cols) | Return the current number of screen columns. |
| SCRSET | ( --) | Set the ROWS and COLS internal variables according to the current screen configuration. Used by INTERLACE and SCREENMODE |
| SCREENBASE | ( -- addr) | CONSTANT address of the pre-allocated screen buffer |
| SCREENPLACE | ( -- addr) | VARIABLE holding the current address of the screen buffer. This variable address is a memory-mapped hardware register. Default is SCREENBASE |
| VWAIT | ( --) | Wait for the VGA vertical blank interval. Used prior to writing to or moving the screen buffer |

#### SD card and FAT file system

|  |  |  |
| --- | --- | --- |
| SD.init | ( --) | Reset the SD card, check the SD version number and initialize the card |
| SD.sector-code | ( n -- b4 b3 b2 b1) | Take a sector number n, scale according to the SD card version and split into bytes in preparation for a SD care read or write sector command |
| SD.select&check | ( --) | Asset SD card chip select and wait for the card to signal ready |
| SD.read-sector | ( addr n --) | Read 512 bytes from sector n into a buffer at addr |
| SD.write-sector | ( addr n --) | Write 512 byte to sector n from addr |
| FAT.read-long | ( addr n -- x) | Get a little endian longword (x) from the buffer at address (addr) and position (n) |
| FAT.write-long | ( x addr n --) | Write a little endian longword (x) to the buffer at address (addr) and position (n) |
| FAT.read-word | ( addr n -- x) | Get a little endian word (x) from the buffer at address (addr) and position (n) |
| FAT.write-word | ( x addr n --) | Write a litte endian word to the buffer at address (addr) and position (n) |
| FAT.UpdateFSInfo | ( --) | Update the FAT32 FSInfo sector with next free cluster |
| FAT.clus2sec | ( n -- n) | Given a valid cluster number return the number of the first sector in that cluster |
| FAT.get-fat | ( cluster -- value) | Return the FAT entry (value) for the given cluster |
| FAT.put-fat | ( value cluster --) | Place value in the FAT location for the given cluster |
| FAT.string2filename | ( addr n -- addr) | Convert an ordinary string to a short FAT filename |
| FAT.find-file | ( addr n -- dirSector dirOffset firstCluster size flags TRUE | FALSE) | Find a file with filename (addr n) in the current directory. Return FALSE if not found or TRUE and file system parameters otherwise |
| FAT.load-file | (addr firstCluster  --) | Load a file to memory at address addr, specifying the file by the number of its first cluster |

#### SD card and FAT file system (SYSTEM.F)

|  |  |  |
| --- | --- | --- |
| FAT.FindFreeCluster | ( -- n) | Return the first cluster on the disk |
| FAT.save-file | ( addr size firstCluster) | Save a file to disk assuming size <> 0 |
| FAT.FindFreeEntry | ( dirCluster -- dirSector dirOffset TRUE | FALSE) | Find the first available entry in a directory |
| FAT.size2space | ( size -- space) | Rule for the space to allocate to a file |
| FAT.new-file | ( dirSector dirOffset firstCluster size fam -- fileid ior) |  |
| FAT.copynonblank | ( out-addr in-addr -- out-addr+1) | copy a non-space character from in-out |
| FAT.Filename2String | (addr -- addr n) | convert a short FAT filename to an ordinary string |

#### PS/2 keyboard

|  |  |  |
| --- | --- | --- |
| KKEY? | ( -- flag) | Check if a character is waiting to be read from the 256 byte circular buffer maintained for the PS/2 keyboard |
| KKEY | ( -- n) | Wait for and read the next character available from the PS/2 keyboard. Returns the ASCII code for the key |
| PS2DECODE | ( n -- n) | Decode a PS/2 scan code into ASCII. Returns 0 if there is no valid ASCII match. (PS2DECODE is called directly by the PS/2 interrupt routine during normal operation.) |

# Appendix 9. Cross-assembler

Assembler lines consist of up to four fields separate by white spaces in the following format. White spaces are the SPACE and TAB characters.

LABEL INSTRUCTION VALUE COMMENT

#### 1. LABEL

Any legitimate FORTH identifier can be used as an optional label. The identifier will become a CONSTANT in the hosting FORTH environment. The value assigned to the label is the current program counter address.

#### 2. INSTRUCTION

An instruction is one of the following:

* the assembler mnemonic for a CPU instruction (documented in Appendix 1)
* an assembler macro command (documented below)
* an assembler directive (documented below)

#### Assembler macro commands

|  |  |
| --- | --- |
| IF | Flow command. Identical operation to the corresponding FORTH word |
| WHILE |  |
| THEN |  |
| ELSE |  |
| BEGIN |  |
| AGAIN |  |
| REPEAT |  |
| UNTIL |  |
| DO |  |
| LOOP |  |
| +LOOP | Note that +LOOP is only implemented to support positive increments |
| UNLOOP |  |
| J | Note: use R@ for I |

#### Assembler directives

|  |  |
| --- | --- |
| CMD | Usage: CMD .” Hello World”  Execute the remainder of the line as a FORTH expression in the hosting FORTH environment |
| EQU | Usage: label EQU value  Assign the value to the label. Note that label will become a FORTH word in the hosting FORTH environment. Value may be a numerical value or a FORTH expression. Precede a hexadecimal value with HEX. Note that the cross assembler automatically resets to DECIMAL at the start of each new line of code |
| DC.S | Usage: DC.S some text  Include the following text (until end of line) as a string of characters in memory. Note that the text is not counted or terminated. Take care of (unintended) spaces and tabs between the text and the end of line as these will be included by the assembler |
| DC.L | Usage: DC.L 65536 356 24  Define one or more constant longword. Include the following values as 4 byte long-word constants in memory. **The values are given in reverse order, with the last value in the list placed in the lowest memory location.** |
| DC.W | Usage: DC.L HEX 0CD FF  Define one or more constant words. Include the following values as 2 byte word constants in memory. **The values are given in reverse order, with the last value in the list placed in the lowest memory location** |
| DC.B | Usage: DC.B 255  Define constant byte. Include the following values as a byte constants in memory. **The values are given in reverse order, with the last value in the list placed in the lowest memory location** |
| DS.L | Usage: DS.L 12  Define storage longwords. Reserve the following value number of longwords in memory and initialize to zero. In this example 48 bytes will be reserved and initialized zero. |
| DS.W | Usage: DS.W 8  Define storage words. Reserve the following value number of longwords in memory and initialize to zero. In this example 16 bytes will be reserved |
| DS.B | Usage: DS.B 1  Define storage words. Reserve the following value number of longwords in memory and initialize to zero. In this example 1 byte will be reserved |

#### 3. VALUE

Value is applicable to certain CPU instructions and assembler directives. The value field is evaluated in the hosting FORTH environment. It may therefore be simple number or a FORTH expression. Precede a hexadecimal values with HEX. Note that the cross assembler automatically resets to DECIMAL at the start of each new line of code.

#### Supporting FORTH words that may be useful in the VALUE field

|  |  |
| --- | --- |
| REL | Defined by the assembler as  : rel 1+ - ; |
| DEL | Defined by the assembler as  : del 1- - ; |

#### 4. COMMENT

The comment characters are “;” and “(“. The assembler ignores all text from the comment character to end of line. An optional “)” character may be used for presentation purposes with “(“ but is not required.

# Appendix 10. FORTH system dictionary structure

The FORTH system software uses a dictionary structure as follows

|  |  |  |
| --- | --- | --- |
| **Field** | **Length** | **Description** |
| LINK field | 4 bytes | Points to the NAME field of the previous FORTH word. Set to zero for the last word in the dictionary. |
| NAME field (first byte) | 1 byte | The first byte of the NAME field is organized as follows  bit 7: PRECEDENCE bit. Always set to 1  bit 6: IMMEDIATE bit. Set for immediate words only  bit 5: SMUDGE bit. Set to hide a word in the dictionary  bits 4-0: LENGTH of the name in bytes (0 - 32 bytes) |
| NAME field (remaining bytes) | [LENGTH] bytes | NAME in ASCII characters. Length as given by the LENGTH field in byte 1 of the field. The FORTH interpreter/compiler is case insensitive. |
| SIZE field | 2 bytes | The SIZE field is organized as follows  bit 15: MUSTINLINE. Set to force inline compilation  bit 14: NOINLINE. Set to prevent inline compilation  bits 13-0: SIZE of the executable in bytes |
| CODE field | [x] bytes | Executable code. Size as given by the SIZE field. |

There is no explicit parameter field in this dictionary structure because the FORTH system software is subroutine threaded. Words created with CREATE are allocated a parameter field immediately after the in-line executable code.

# Appendix 11. Interrupt Vector Table

The default CPU interrupt vector table is as follows:

|  |  |  |
| --- | --- | --- |
| **System memory location** | **Interrupt name** | **Interrupt description** |
| 0x00 | RESET | Power-on and system reset execution address |
| 0x02 | TRAP | Vector for TRAP and RETRAP instructions. Available for program debugging. |
| 0x04 | RS232RDA | Triggered by Read Data Available strobe on the RS232 port. The native interrupt handler places incoming data in a 256 byte buffer that is accessed via the SKEY? And SKEY words. |
| 0x06 | RS232TBE | Triggered by Transfer Bus Enable on the RS232 port. Used by the STYPE word for asynchronous RS232 output. |
| 0x08 | PS2 | Triggered by data available strobe on the PS/2 port. The native interrupt handler places incoming data in a 256 byte buffer that is accessed via the KKEY? And KKEY words. Note that on the Nexys 4 board, USB keyboard inputs are converted to PS/2 scan codes by the Nexys 4 interface. |
| 0xA0 | MS | Milliseconds interrupt. Used by the TIMEOUT word. |
| 0xC0 - | various | Available for user expansion |

# Appendix 12. Virtualization Control

The N.I.G.E. Machine has virtualization capabilities built into the soft-core CPU. At any one time the CPU will be executing a single task upon the current VM. When a task switch occurs, the state of the currently executing VM is saved to the virtualization core, and the state of the next-to-execute VM is concurrently loaded from the virtualization core into the CPU. Such a task switch occurs in 2 clock cycles and requires no support from a virtual machine monitor in software.

Multitasking control is achieved through configuring a set of memory mapped Virtualization Control registers and by inclusion of the machine language instruction PAUSE in application program code. The FORTH system software contains words to handle all aspects of virtualization control in the default mode of round-robin, cooperative multitasking (see Appendix 7). This appendix contains further details of virtualization control at the hardware level that would be relevant to customizing the FORTH system software or developing an alternative multitasking model.

#### 12.1 Simple registers

The following memory mapped registers are concerned with multitasking at the overall level

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Function** | **R/W** | **Hex** | **Dec** |
| SINGLEMULTI | Enable ('1') or disable ('0') multitasking. If a PAUSE machine language instruction instruction is encountered with multitasking disabled then it will be treated as a NOP | R/W | 0x03B800 | 243712 |
| CURRENTVM | The number of the currently executing virtual machine. Virtual machines are numbered 0 through 31. A power-on virtual machine 0 will be executing the FORTH system software | R | 0x03B804 | 243716 |
| INTERVAL | The interval for pre-emptive multitasking, in clock cycles. If INTERVAL = 0 then pre-emptive multitasking is off. | R/W | 0x03B808 | 243720 |

#### 12.2 Task Control

There are 32 task control registers, one corresponding to each virtual machine. The registers are 16 bits wide and are memory mapped with read and write access. The lower 5 bits of each register are interpreted directly by the virtualization core as the number of the next-to-execute virtual machine. Thus if TASKCONTROL0 has the lowest 5 bits set as "000010", then when virtual machine #0 yields the CPU at a pause instruction then CPU execution will pass to virtual machine #2. The remaining 11 bits of each register are not interpreted by the virtualization core and may be used to assist with the implementation of various multi-tasking models.

In the FORTH system software, bit 15 of each task control register indicates whether that VM has already been assigned ('1') or not ('0'), and bits 5 to 9 are a backwards pointer to the previously executing task. The scheduler utilizes the linked list structure thus created between executing virtual machines to efficiently handle the insertion or removal of new tasks.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Function** | **R/W** | **Hex** | **Dec** |
| TASKCONTROL0 | Task control of virtual machine 0 | R/W | 0x03BA00 | 244224 |
| TASKCONTROL1 | Task control of virtual machine 1 | R/W | 0x03BA04 | 244228 |
| Etc. |  |  |  |  |

#### 12.3 PC Override registers

There are 32 PC override registers, each 20 bits wide. By default, when a virtual machine resumes execution its program counter is restored to the next-to-execute instruction within that task at the point where it previously yielded. However if a non-zero instruction address is waiting in the PC override register of a particular task when it resumes execution then program flow will be redirected to that address. The PC override register is automatically zero'd after this occurs so that on the following occasion a yield and resume cycle will proceed as normal.

The FORTH system software uses the PC override register to direct the execution flow of a newly assigned virtual machine to the common startup code for a new task. The common startup code proceeds to reset all stack pointers to zero, initialize system user variables and exception stack variables, copy stack parameters passed from the initiating task and then jump to the execution token provided by the initiating task.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Function** | **R/W** | **Hex** | **Dec** |
| PCOVERRIDE0 | Task control of virtual machine 0 | R/W | 0x03BC00 | 244736 |
| PCOVERRIDE 1 | Task control of virtual machine 1 | R/W | 0x03BC04 | 244740 |
| Etc. |  |  |  |  |

#### 12.4 Virtual Interrupt registers

There are 32 virtual interrupt registers, each 20 bits wide. If a non-zero instruction address is waiting in the virtual interrupt of a particular task when it resumes execution then (a) the saved value of the program counter that would have been otherwise restored is placed onto the return (and subroutine) stacks, and (b) program flow will be redirected to the virtual interrupt address. The virtual interrupt override register is automatically zero'd after this occurs so that on the following occasion a yield and resume cycle will proceed as normal.

Access to the virtual interrupt functionality is provided in the FORTH system software by the VIRQ word.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Function** | **R/W** | **Hex** | **Dec** |
| VIRQ0 | Virtual interrupt of virtual machine 0 | R/W | 0x03BE00 | 245248 |
| VIRQ 1 | Virtual interrupt of virtual machine 1 | R/W | 0x03BE04 | 245252 |
| Etc. |  |  |  |  |

#### 12.5 Hardware interrupts

There is no interaction between virtualization and hardware interrupts. Interrupts are handled by whichever virtual machine is executing when the interrupt occurs. However interrupts should not themselves include a PAUSE instruction since if an interrupt does not exit properly through its own RTI instruction then the machine will remain blocked to all further interrupts.

#### 12.6 Alternative multitasking models

A straightforward method for implementing a priority scheduling scheme for multitasking would be to allocate a single task as the scheduling task and write to the task control register such that each other task returned to the scheduling task when yielding execution. The scheduling task would run code to determine which task to run next and then update the lower 5 bits of its own task control register accordingly