#### GENERAL DESCRIPTION

The N.I.G.E. Machine is a complete micro-computer system hosted within an FPGA development board, the Digilent Nexys 4

#### FEATURES

* CUSTOM 32 BIT SOFTCORE CPU
  + Stack machine design
  + Microcode based
  + 100 MHz clock frequency
* HIGH INSTRUCTION THROUGHPUT
  + 3 stage CPU pipeline
  + One instruction per clock cycle throughput for most instructions
* DETERMINISTIC EXECUTION
  + All instructions, including conditional branches, jumps and local memory accesses complete in constant time
* HIGH CODE DENSITY
  + Single byte instruction encoding
* VERY LOW INTERRUPT LATENCY
  + Interrupt routine begins 4 clock cycles following the interrupt signal
* FAST BRANCH INSTRUCTIONS
  + Conditional and unconditional branches execute in 2 clock cycles
* HARDWARE SUPPORTED EXCEPTION HANDLING
  + FORTH words CATCH and THROW are atomic machine language instructions
  + Full exception procedure completes in 3 clock cycles via hardware support
* HARDWARE SUPPORTED MULTITASKING
  + Hardware support for 32 tasks
  + Full task switch completes in 2 clock cycles via hardware support
  + Configurable task order
  + 4 KiB private task memory areas
  + Virtual interrupts
* LOCAL AND EXTERNAL MEMORY
  + 128 KiB local FPGA memory
  + 32 bit memory databus
  + Fetch/store longword, word or byte
  + Non-aligned fetch/store supported
  + 16 MiB external dynamic RAM
* FORTH SYSTEM SOFTWARE
  + ANSI FORTH (with minor exceptions)
  + Interpretive and compiled environment
  + No external tool chain required
* FULL SET OF BUILT-IN PERIPHERALS
  + VGA output (640\*480 to full HD)
  + 256 on screen colors , 12 bit color range
  + User-definable character based graphics
  + RS232, keyboard, SPI, P-MOD ports
* SD CARD STORAGE
  + Onboard microSD card slot
  + FAT file system provided in FORTH
* EXTENDABLE DESIGN
  + User hardware interfaces via memory-mapped registers and interrupts
  + AXI4 format external memory interface
  + PC based cross assembler for the FORTH system software included
* OPEN SOURCE VHDL DEIGN FILES
  + Dual GPL/commercial license

#### APPLICATIONS

* Rapid prototyping of experimental scientific apparatus
* Projects involving the dual development of custom hardware and custom software
* Any microcomputer application

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# 1. Overview

At the hardware level N.I.G.E. Machine is organized as a series of modules centered on a 32 bit custom softcore CPU (Figure 1. The N.I.G.E. Machine system diagram).



Figure . The N.I.G.E. Machine system diagram

The CPU interfaces with a number of distinct blocks of memory via separate databuses. Local memory ("SRAM") is comprised of BLOCK RAM units within the FPGA. External memory ("PSDRAM") is comprised of a separate dynamic RAM chip located outside of the FPGA on the Nexys 4 development board. These memories are accessed via separate memory controllers that provide specific functionality to the N.I.G.E. Machine. In addition, there are four memory blocks that are organized as stacks (the parameter stack, the return stack, the subroutine stack and the return stack).

The CPU also interfaces with a hardware register module fabricated from FPGA logic elements. The module provides a set of registers that are memory mapped to the CPU address space. These registers serve a number of functions such as input/output ports and system control settings.

The interrupt controller is responsible for accepting and prioritizing external interrupt request and passing them to the CPU. The system clocks module provides a variety of clock signals to other modules, including the main 100 MHz system clock. The other input/output modules are the RS232 controller, the PS/2 keyboard controller, the SPI controller, and the VGA controller.

#### 1.1. SOFTCORE CPU

The softcore CPU is a 32 bit stack machine optimized for the FORTH programming language (many of the machine language instructions provided by the CPU are FORTH language primitives). The CPU has been designed with a number of features to enhance its suitability for embedded applications.

###### High instruction throughput

The CPU features a three-stage execution pipeline that delivers throughput of one instruction per clock cycles for most instructions.

###### Deterministic execution

All instructions, including conditional branches and local memory accesses, execute in a non-varying number of cycles. In addition the execution pipeline has been designed so that there are no conflict states that could result in missed cycles. This provides deterministic execution and enables periodic signals to be generated without jitter.

###### High code density

The CPU uses microcode rather than a hardwired decoder. This enables a relatively large number of control lines to be driven by a relatively small opcode. As a result all machine language instructions are encoded in a single byte, excluding any literal data.

###### Fast interrupt response time

Since the CPU is a stack machine there is no requirement to save and restore a register when entering or leaving interrupt service routines. The N.I.G.E. Machine's typical interrupt response time is only 4 clock cycles: 2 cycles to branch to the interrupt vector table plus by 2 cycles to branch through the vector to the interrupt routine itself.

###### Fast branch performance

On the N.I.G.E. Machine conditional and unconditional branches (BEQ and BRA) execute in 2 clock cycles.

###### Fast exception handling

The N.I.G.E. Machine includes dedicated hardware stacks for subroutines and exception frames and implements CATCH and THROW as atomic machine language instructions that execute in 2 and 3 cycles respectively. The subroutine and exception stacks are hidden from the FORTH environment.

Fast multitasking

The N.I.G.E. Machine features hardware multitasking. 32 tasks are available. Full task switches execute in 2 clock cycles. Both cooperative and pre-emptive multitasking modes are supported.

#### 1.2. LOCAL MEMORY ("SRAM")

Local memory comprises 128KiB of general memory space available to the CPU. This memory space is byte addressed. It may contain both code and data without restriction. The CPU stores words and longwords in big endian format. SRAM memory space has been optimized for the FORTH language and the needs of embedded systems as follows:

###### Fast memory access

SRAM is implemented with FPGA BLOCK RAM. All load and store instructions to/from SRAM execute deterministically in 2 clock cycles

Flexible memory access

The databus between the CPU and SRAM is 32 bits wide. The CPU features separate machine language instructions for the load/store of byte, word and long word data.

Misaligned access is supported via the SRAM controller module: longword and word data may be written to or read from any byte address with no clock cycle penalty.

#### 1.3. EXTERNAL MEMORY ("PSDRAM")

External memory comprises 16MiB of storage within a separate pseudo-static dynamic RAM (PSDRAM) module on the Nexys 4 development board. The CPU is able to load/store longwords, words and bytes to/from PSDRAM using the same machine language instructions as SRAM. However the CPU is unable to execute code from PSDRAM.

The PSDRAM memory space is byte addressed but word and longword access must be aligned. The CPU stores words and longwords in big endian format. CPU access to PSDRAM is mediated by the DMA controller that also mediates access by the VGA controller to the screen buffer. As a result of this arrangement CPU access to PSDRAM is not deterministic.

# Appendix 1. System specifications

|  |  |  |
| --- | --- | --- |
| **Version** | **v2.0** | **v4.0** |
| 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 | As left plus  1024 x 768  1920 x 1080 |
| Display format | Character graphics (8 x 8 pixel) and pixel graphics | Character graphics (16 x 16 pixel, adjustable) 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 -- rem 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) | | (u1 u2 – u-rem u-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 task and switch execution to the next-to-execute task. | | ( --) | ( --) |

|  |  |  |  |
| --- | --- | --- | --- |
| 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 | 2 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 (v4.0, 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 | 0x03AFFF |
| Character RAM | 8 KB | 0x03B000 | 0x03CFFF |
| Palette RAM | 2 KB | 0x03D000 | 0x03D7FF |
| Subroutine and exception local variables | 2 KB | 0x03D800 | 0x03DFFF |
| USER data area | 2 KB | 0x03E000 | 0x03EFFF |
| Multitasking control | 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 100 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 Nexys4 seven segment display | 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 |
| INTERLACE | Number of interlace scanlines | R/W | 0x03F84C | 260172 |
| CHARWIDTH | Width of each character in pixels less 1 | R/W | 0x03F850 | 260176 |
| CHARHEIGHT | Height of each character in pixels less 1 | R/W | 0x03F854 | 260180 |
| VGAROWS | Number of complete character rows | R/W | 0x03F858 | 260184 |
| VGACOLS | Number of complete character columns | R/W | 0x03F85C | 260188 |

#### Hardware registers - bit level

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Register/bit** | **4** | **3** | **2** | **1** | | **0** | |
| MODE | n/a | 0 = 16/16 color mode  1= 256/0 color mode | 000 = Display off  001 = 640 \* 480  010 = 800 \* 600  010 = 1024 \* 768  100 = 1902 \* 1080 | | | | |
| 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 | ‘’Amiga’’ blue | 0x05A | 148 | 100% | 33% |
| 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

The N.I.G.E. Machine operates a round-robin multitasker. Task switching may be preemptive or cooperative.

|  |  |  |
| --- | --- | --- |
| **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 task to take n stack parameters (... pn) and execute task XT. Return the number of the task allocated to this task ( VM) and true if successful, or false if all tasks are currently otherwise allocated. The newly created task will be positioned in the round-robin sequence immediately after the current task. Tasks 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 task and switch CPU execution to the next-to-execute task |
| 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 task VM to sleep by removing it from the list of executing tasks. VM remains allocated and can be woken at a later time |
| WAKE | ( VM --) | Wake task VM by inserting it into the list of executing tasks immediately following the current task |
| STOP | ( VM --) | Deallocate task VM and remove it from the list of executing tasks. Task VM may now be recycled by RUN |
| VIRQ | ( XT VM --) | Virtual interrupt. Cause task 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 task VM is next scheduled to execute. (VIRQ does not cause execution to pass to task VM early/out of sequence) |
| THIS-VM | ( -- VM) | Return the number of the currently executing task. Tasks are numbered 0 through 31. A power-on task 0 will be executing the FORTH system software |
| THIS-SLEEP | ( --) | Put the currently executing task to sleep by taking it out of the list of executing tasks. The task 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 task to sleep and take it out of the list of executing tasks. The task 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 task XOR 255, or 0 if not acquired. |
| RELEASE | ( sem --) | Release the binary semaphore (sem). See also ACQUIRE |
| PREEMPTIVE | ( n --) | Enable preemptive multitasking with period of n instructions between task switches. If n = 0 then preemptive multitasking is disabled. |

#### 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  4 - 1920 \* 1080  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. Hardware multitasking Control

The N.I.G.E. Machine has hardware multitasking 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 hardware multitasking core, and the state of the next-to-execute VM is concurrently loaded from the hardware multitasking core into the CPU. Such a task switch occurs in 2 clock cycles and requires no support from a task monitor in software.

Multitasking control is achieved through configuring a set of memory mapped 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 hardware multitasking control in the default mode of round-robin, cooperative multitasking (see Appendix 7). This appendix contains further details of hardware multitasking 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 | 0x03F000 | 258048 |
| CURRENTVM | The number of the currently executing task. Tasks are numbered 0 through 31. A power-on task 0 will be executing the FORTH system software | R | 0x03F004 | 258052 |
| INTERVAL | The interval for pre-emptive multitasking, in clock cycles. If INTERVAL = 0 then pre-emptive multitasking is off. | R/W | 0x03F008 | 258056 |

#### 12.2 Task Control

There are 32 task control registers, one corresponding to each task. 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 hardware multitasking core as the number of the next-to-execute task. Thus if TASKCONTROL0 has the lowest 5 bits set as "000010", then when task #0 yields the CPU at a pause instruction then CPU execution will pass to task #2. The remaining 11 bits of each register are not interpreted by the hardware multitasking 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 tasks to efficiently handle the insertion or removal of new tasks.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Function** | **R/W** | **Hex** | **Dec** |
| TASKCONTROL0 | Task control of task 0 | R/W | 0x03F200 | 258560 |
| TASKCONTROL1 | Task control of task 1 | R/W | 0x03F204 | 258564 |
| Etc. |  |  |  |  |

#### 12.3 PC Override registers

There are 32 PC override registers, each 20 bits wide. By default, when a task 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 task 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 task 0 | R/W | 0x03F400 | 259072 |
| PCOVERRIDE 1 | Task control of task 1 | R/W | 0x03F404 | 259076 |
| 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 task 0 | R/W | 0x03F600 | 259584 |
| VIRQ 1 | Virtual interrupt of task 1 | R/W | 0x03F604 | 259586 |
| Etc. |  |  |  |  |

#### 12.5 Hardware interrupts

There is no interaction between hardware multitasking and hardware interrupts. Interrupts are handled by whichever task 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