A VHDL Forth Core for FPGAs

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Abstract

The Forth programming language is typically implemented to run on some particular microprocessor. Several Forth engines have been designed that execute Forth instructions directly, typically in a single clock cycle. With the advent of high density FPGAs it has become feasible to implement a high-performance Forth core in an FPGA. This paper describes the design of a Forth core using VHDL that has been implemented on a Xilinx Spartan II FPGA. Examples are presented of high-level Forth programs that are compiled to VHDL code that implements a ROM embedded in the FPGA.

Keywords: Forth core, VHDL, FPGA, Stack-based microprocessor

1. Introduction

Forth has been implemented on many microprocessors including the Motorola 68HC12 [6]. As the density of an FPGA (in terms of the number of equivalent gates) has increased while its cost has decreased, it is becoming feasible to consider putting all functions, including a microprocessor core, into the same FPGA forming a true System-on-a-Chip (SOC). The software running on the microprocessor core would also be stored in the form of instructions in the same FPGA.

Forth is a programming language that uses a data stack and postfix notation. Chuck Moore invented Forth in the late 1960s while programming minicomputers in assembly language. His idea was to create a simple system that would allow him to write many more useful programs than he could using assembly language. The essence of Forth is simplicity -- always try to do things in the simplest possible way. Forth is a way of thinking about problems in a modular way. It is modular in the extreme. Everything in Forth is a word and every word is a module that does something useful. There is an action associated with Forth words. The words execute themselves. In this sense they are very object-oriented. Forth words accept parameters on the data stack, execute themselves, and return the answers back on the data stack.

Forth has been implemented in a number of different ways. Chuck Moore's original Forth had what is called an *indirect-threaded* inner interpreter. Other Forths have used what is called a *direct-threaded* inner interpreter. These inner interpreters get executed every time you go from one Forth word to the next; i.e. all the time. A unique version of Forth called *WHYP* (pronounced *whip*) has recently been described in a book on embedded systems [6]. WHYP stands for Words to Help You Program. WHYP is what is called a *subroutine-threaded* Forth. This means that the subroutine calling mechanism that is built into the 68HC12 is used to go from one WHYP word to the next. In other words, WHYP words are 68HC12 subroutines.

Inasmuch as Forth (and WHYP) programs consist of sequences of words, the most often executed instruction is a call to the next word; i.e. executing the inner interpreter (NEXT) in traditional Forths, or calling a subroutine in WHYP. Over 25% of the execution time of a typical Forth program is used up in calling the next word [12]. To overcome this problem, Chuck Moore designed a computer chip, called NOVIX, in the mid-eighties which could call the next word (equivalent to a subroutine call) in a single clock cycle [3]. Many of the Forth primitive instructions would also execute in a single clock cycle. The design of the NOVIX chip was eventually sold to Harris Semiconductor where it was redesigned as the RTX 2000 [4]. Similar 32-bit Forth engines were also developed [9,10,11,12]. In the late eighties Chuck Moore designed a 32-bit microprocessor called ShBoom that had 64 8-bit instructions and was designed to interface to DRAM [13]. Later Chuck Moore and C. H. Ting designed the MuP21 that has been described by Ting [14,15]. In 1999 we designed the W8X microcontroller [5] that was based on ideas developed in these early Forth engines. It was designed using VHDL [1] and has been implemented in a Xilinx FPGA

by students in a junior-level course at Oakland University [7]. A variation of the W8X, the W8Z, that implements only those instructions used in a particular program has also been implemented on FPGAs [8].

This paper describes the design of a complete 16-bit Forth core that has been implemented on a Xilinx Spartan II FPGA. Section 2 describes the overall architecture of the F16 Forth Core. The data stack and data stack instructions are described in Section 3. The function unit, which implements arithmetic, logical, shifting, and relational instructions is detailed in Section 4. The operation of the return stack and the return stack instructions are discussed in Section 5. The operation of the control unit is described in Section 6. Some examples of running Forth programs on this core implemented in a Xilinx Spartan II FPGA are given in Section 7. The operation of the FC16 Forth core is summarized in Section 8.

2. The FC16 Forth Core

The FC16 is a high-performance microprocessor that can be implemented on an FPGA to execute embedded programs. The overall structure of the FC16 is shown in Figure 1. The data busses in this figure are 16 bits wide and each instruction is a 16-bit word. The FC16 contains four main components, the data stack, *DataStack,* the function unit, *Funit16,* the return stack, *ReturnStack*, and the controller, *FC16_control.* The FC16 also contains a program counter, *PC*, whose output, *P*, containing the address of the next instructions, is the input to the program ROM shown outside the FC16 core in Figure 2. The output of the ROM is the signal, *M*, which can be loaded into the instruction register, *IR*, pushed onto the data stack through the multiplexer, *Tmux*, or loaded into the program counter, *PC*, through the multiplexer, *Pmux*.

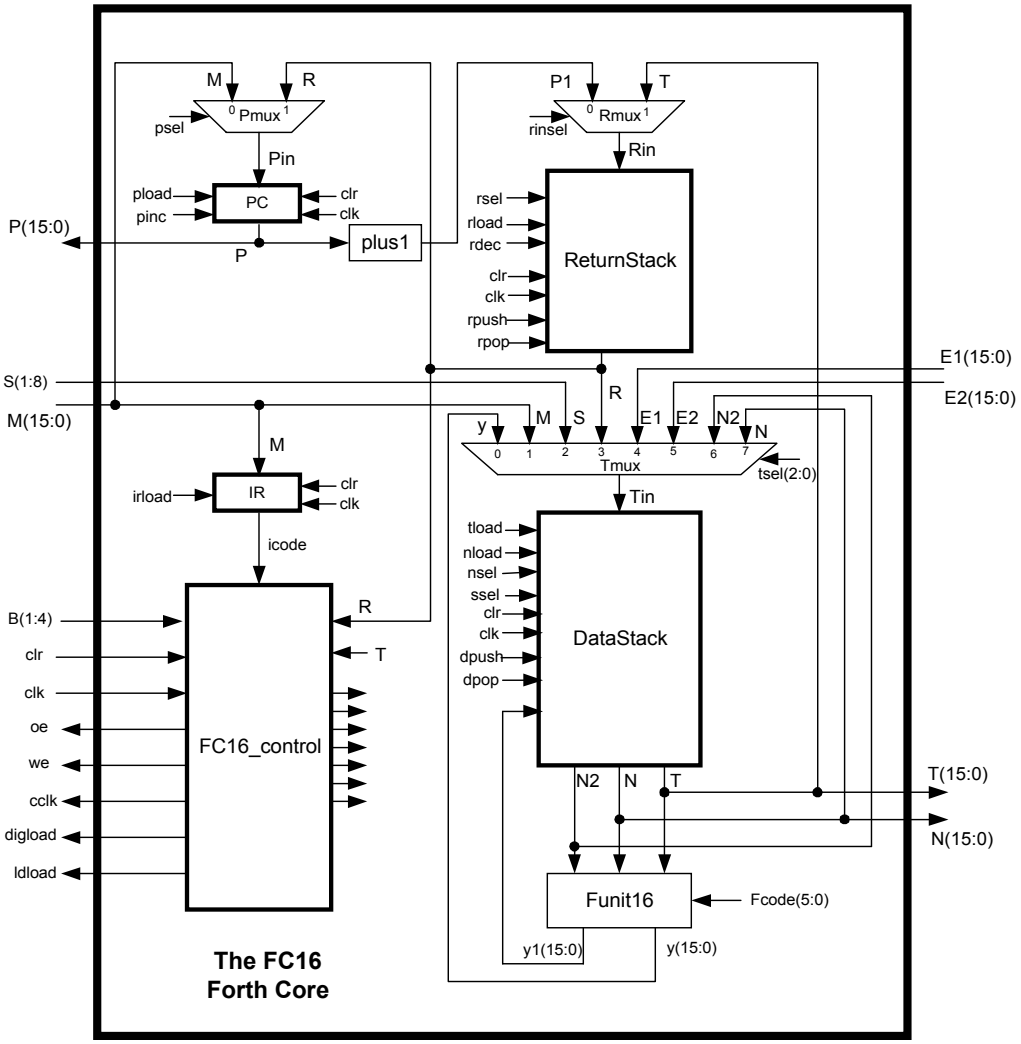

Figure 1 Functional diagram of the FC16 Forth core

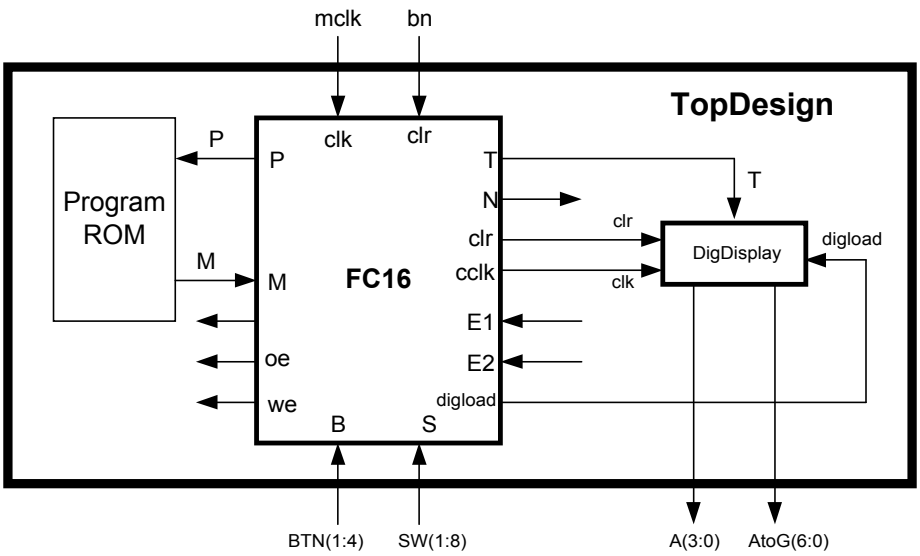

Figure 2 Example of a top-level design using the FC16 Forth core

A simple example of using the FC16 core is shown in Figure 2. This particular example represents the top-level VHDL design that was downloaded to a Xilinx Spartan II FPGA on a Digilab 2 development board produced by Digilent, Inc. [2]. Figure 2 shows a module called *DigDisplay* that provides the signals needed to display the contents of *T* as a 16-bit hex value on four common-anode 7-segment displays on a DIO1 board developed by Digilent, Inc. [2].

Other memory and I/O modules could be added to the top-level design shown in Figure 2. For example, a RAM module would input data from the *N* bus (the second element on the data stack) and the address from the *T* bus (the top element on the data stack). The output of the RAM would be fed back to the top of the data stack through the *E1* bus. The write enable signal, *we*, would be used to write data to the RAM module. A ROM module containing constant data would connect its address input to the *T* bus and its output to the *E2* bus. Special Forth words for accessing these RAM and ROM modules will be described in Section 6.

The top of the data stack can be loaded from eight different signals through the 8-to-1 multiplexer, *Tmux*, shown in Figure 1. One of these signals is *S*, whose lower 8-bits can be connected to external switches. The upper 8 bits are zeros. The instruction *S@* will push the value of *S* onto the data stack. The next section provides a more detailed description of the operation of the data stack.

3. The Data Stack

The FC16 data stack is a modified 32x16 stack. Table 1 shows the basic stack operations performed by the FC16. The architecture of this data stack is shown in Figure 3. Figure 4 shows a 32x16 stack implemented using a 32x16 LogiCore dual port block RAM controlled by a stack controller. The stack controller implements the stack as a traditional stack with push and pop instructions including full and empty flags. When *push* is '1' and *pop* is '0', the stack pushes the value at *d(15:0)* to the write address, *wr_addr,* the memory address that represents the next empty location in memory. Both *wr_addr* and the read address, *rd_addr*, are simultaneously decremented. After the operation is complete, the output *q(15:0)* contains the value on top of the stack. When *pop* is '1' and *push* is '0', both the read and write addresses are incremented. Unlike a traditional stack, when both *pop* and *push* are '1', the top element is replaced with *d(15:0)* without pushing the stack.

Table 1 FC16 Data Stack Operations

Opcode	Name	Function
0000	NOP	No operation
0001	DUP	Duplicate T and push data stack. N <= T; N2 <= N
0002	SWAP	Exchange T and N. T <= N; N <= T
0003	DROP	Drop T and pop data stack. T <= N; N <= N2
0004	OVER	Duplicate N into T and push data stack. T <= N; N <= T; N2 <= N
0005	ROT	Rotate top 3 elements on stack clockwise. T <= N2; N <= T; N2 <= N
0006	-ROT	Rotate top 3 elements on stack counter-clockwise. T <= N; N <= N2; N2 <= T
0007	NIP	Drop N and pop rest of data stack. T is unchanged. N <= N2
0008	TUCK	Duplicate T into N and push rest of data stack. N2 <= T
0009	ROT_DROP	Drop N2 and pop rest of data stack. T and N are unchanged. Equivalent to ROT DROP
000A	ROT_DROP_SWAP	Drop N2 and pop rest of data stack. T and N are exchanged. Equivalent to ROT DROP SWAP

The FC16 data stack shown in Figure 3 consists of two 16-bit registers for the top and second elements of the data stack followed by the modified 32x16 stack shown in Figure 4. These registers, *Treg* and *Nreg*, serve as 'false top' and 'false second' elements in the data stack, respectively. This architecture is necessary to support single-clock-cycle execution of instructions involving the top three stack elements.

The input to the top register, *Treg*, can be from one of eight possible sources using the 8-to-1 multiplexer shown in Figure 1. The input to the second element in the register stack, *Nreg*, can be from either *Treg*, one of the outputs from the function unit, *y1*, or the top of the modified stack, *stack32x16*. The data stack instructions operate at most on the top three elements of the data stack. The modifications to *stack32x16* described above are necessary to support operations involving the third stack element. The instruction *ROT*, for example, moves the value in *Treg* to *Nreg*, the value in *Nreg* to the top of the *stack32x16* (the third element in the data stack) and the value on the top of the *stack32x16* to *Treg*. This has the effect of rotating the top three elements of the data stack. For this instruction, *T1* is multiplexed into *Nreg*, *N* is multiplexed into the *stack32x16*, and *N2* is externally multiplexed into *Treg*. In this case the top of the modified stack is replaced with the value in *Nreg* without pushing or popping the stack. To allow this operation, *wr2_addr* is multiplexed between *wr_addr*, the next available empty space in memory for writing and *rd_addr*, the present top of the stack, shown in Figure 4. The FC16 data stack can execute all of the stack operations listed in Table 1 in a single clock cycle while using chip real estate efficiently.

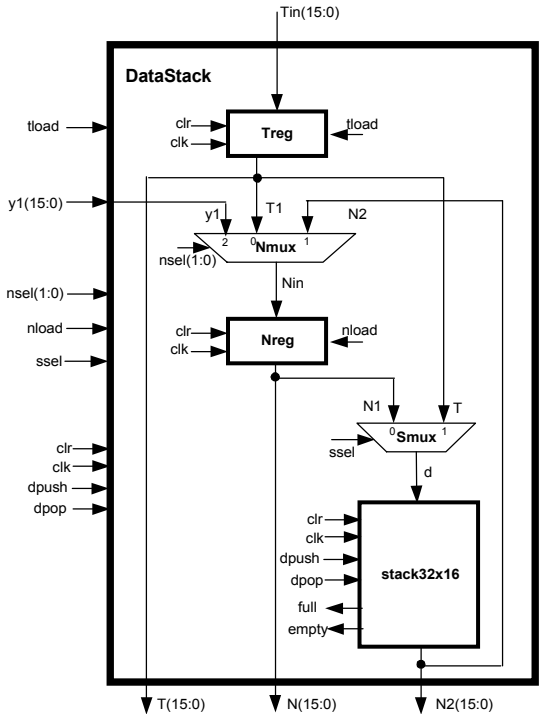

Figure 3 The data stack

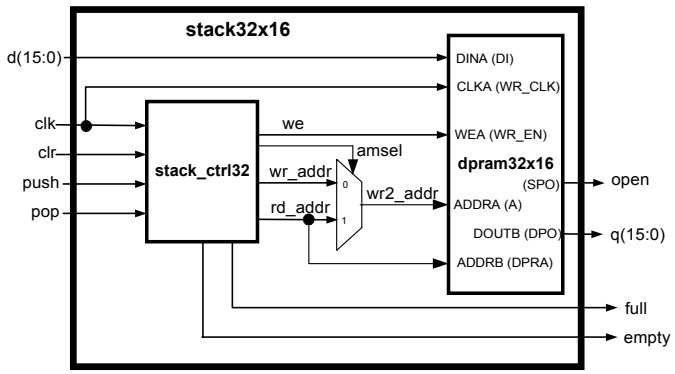

Figure 4 Stack created by a dual-port RAM

4. The Function Unit

The function unit performs arithmetic, logical, shifting, and relational operations on the top elements of the data stack. *T, N,* and *N2*, the top three elements of the data stack, respectively, and a 6-bit function selection signal, *Fcode*, are inputs to the function unit. Table 2 shows the instructions for the function unit.

Table 2 Instructions for the FC16 Function Unit

Opcode	Name	Function
0010	+	Pop N and add it to T
0011	-	Pop T and subtract it from N
0012	1+	Add 1 to T
0013	1-	Subtract 1 from T
0014	INVERT	Complement all bits of T
0015	AND	Pop N1 and AND it to T
0016	OR	Pop N1 and AND it to T
0017	XOR	Pop N1 and AND it to T
0018	2*	Logic shift left T
0019	U2/	Logic shift right T
001A	2/	Arithmetic shift right T
001B	RSHIFT	Pop T and shift N1 T bits to the right
001C	LSHIFT	Pop T and shift N1 T bits to the left
001D	mpp	multiply partial product (used for multiplication)
001E	shldc	shift left and decrement conditionally (used for division)
0020	TRUE	Set all bits in T to '1'
0021	FALSE	Clear all bits in T to '0'
0022	NOT 0=	TRUE if all bits in T are '0'
0023	0<	TRUE if sign bit of T is '1'
0024	U>	T <= TRUE if N > T (unsigned), else T <= FALSE
0025	U<	T <= TRUE if N < T (unsigned), else T <= FALSE
0026	=	T <= TRUE if N = T, else T <= FALSE
0027	U>=	T <= TRUE if N >= T (unsigned), else T <= FALSE
0028	U<=	T <= TRUE if N1 <= T (unsigned), else T <= FALSE
0029	<>	T <= TRUE if N /= T, else T <= FALSE
002A	>	T <= TRUE if N1 > T (signed), else T <= FALSE
002B	<	T <= TRUE if N1 < T (signed), else T <= FALSE
002C	>=	T <= TRUE if N1 >= T (signed), else T <= FALSE
002D	<=	T <= TRUE if N1 <= T (signed), else T <= FALSE

The function unit has two 16-bit outputs *y(15:0)* and *y1(15:0)* as shown in Figure 1. The primary output, *y*, is multiplexed into the top of the data stack for performing unary and binary operations. For operations having answers larger than 16 bits, such as multiplication or division, *y1* is input into the data stack and multiplexed into *Nreg* so that *Treg*:*Nreg* will contain the 32 bit answer.

The arithmetic and logical operations operate on the top elements of the stack and output the result to be placed on top of the stack. The shifting operations operate on values from the top of the stack. The relational operators output X"FFFF" or X"0000" if the top two elements of the stack are or are not accordingly related, respectively. Among these instructions are two instructions *MPP* and *SHLDC* for implementing multiplication and division, respectively. Listing 1 contains a program that will multiply the value in *Treg* by the value in *Nreg* and place the 32-bit product in *Treg:Nreg* in 19 clock cycles using partial product multiplication, *MPP*. Listing 2 contains a program that will divide a 32 bit numerator located in *N2:N* by a 16 bit denominator located in *T* and place the quotient in *Treg* and the remainder in *Nreg* in 18 clock cycles. The FC16 executes all of the instructions in Table 2 in a single clock cycle.

Listing 1 Unsigned Multiplication

```
LIT X"0000"
MPP MPP MPP MPP MPP MPP MPP MPP
MPP MPP MPP MPP MPP MPP MPP MPP
ROT_DROP
```

Listing 2 Unsigned Division

```
-ROT
SHLDC SHLDC SHLDC SHLDC SHLDC SHLDC SHLDC SHLDC
SHLDC SHLDC SHLDC SHLDC SHLDC SHLDC SHLDC SHLDC
ROT_DROP_SWAP
```

5. The Return Stack

The FC16 return stack, shown in Figure 5, is a modified 32x16 stack made from a *stack32x16* described in Section 3, and a single register, *R*. Table 3 shows the return stack instructions.

Table 3 FC16 Return Stack Operations

Opcode	Name	Function
0030	>R	"To-R" Pop T and push it on return stack
0031	R>	"R-from" Pop return stack R and push it into T
0032	R@	"R-fetch" Copy R to T and push register stack
0033	R>DROP	"R-from-drop" Pop return stack R and throw it away
0103	DRJNE	Decrement R and jump if R is not zero
0104	CALL (:)	Call subroutine (colon)
0105	RET (;)	Subroutine return (semi-colon)

The *R* register serves as a 'false top' of the return stack with multiplexed inputs and the option to decrement the registered output. The instruction *DRJNE* decrements the value on the top of the return stack and jumps to an address in memory if the value is not equal to zero. If the top of the return stack is equal to zero, execution proceeds to the next valid instruction in the program. This instruction is used to implement the *NEXT* in a *FOR…NEXT* loop.

The top-of-stack output, *R(15:0)*, is multiplexed to the top of the data stack and to the program counter, *PC,* as shown in Figure 1. The input to the return stack can be either the top of the data stack or the program counter plus one. These inputs make it possible to push values from the data stack to the return stack and to push the return address of a subroutine call. The *RET* instruction at the end of a subroutine pops the address from the return stack into the program counter.

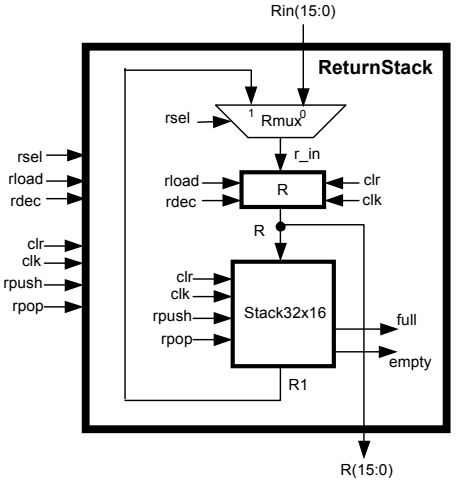

Figure 5 The return stack

6. The Controller

The module *FC16_control* shown in Figure 1 is a control unit implemented as a Mealy state machine. This state machine has three states: *Fetch*, *Execute*, and *Execute-Fetch*. Figure 6 shows the state-transition diagram for the controller. This controller begins in the fetch state to 'fetch' the next instruction from the external program ROM. If the instruction requires only a single clock cycle to execute, the current instruction is executed and the next instruction is read from the program ROM in the Execute-Fetch state. The instructions continue to be executed and fetched at the same time an instruction that requires more than one clock cycle is fetched. Instructions with inline data or addresses, for example, are two clock-cycle instructions, one to execute the instruction and one to fetch the next instruction while ignoring the inline information.

These multi-cycle instructions have been assigned opcodes with a '1' in the 8th bit position. For instructions requiring multiple clock cycles, the controller executes the current

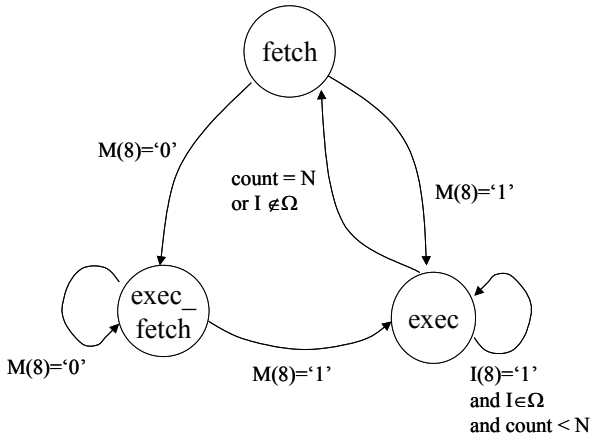

Figure 6 State diagram for the controller

instruction without 'fetching' the next word from the program ROM. Following the last clock cycle the controller returns to the fetch state to 'fetch' the next instruction.

For the instructions related to the function unit, the six least significant bits of the instruction corresponds directly to the function select signal, *Fcode(5:0)*. The controller sets the *load*, *push*, and *pop* data stack signals appropriately to perform arithmetic, relational, logical, or shifting operations on the top elements of the data stack. In the same clock cycle the result, output by the function unit, is placed on top of the data stack and the operands are removed. Instructions that have not been introduced yet in this paper are given in Table 4.

Table 4 Other Instructions

Opcode	Name	Function	Number of Clock Cycles
0034	@	Fetch the byte at address T in RAM and load it into T	1
0036	ROM@	Fetch the byte at address T in ROM and load it into T	1
0037	S@	Fetch the 8-bit byte from Port S and load it into T	1
0038	DIG!	Write the 4 hex digits in T to the digit register DigReg	1
0039	LD!	Store T to the LED register LDreg	1
0100	LIT	Load inline literal to T and push data stack	2
0101	JMP	Jump to inline address	2
0102	JZ	Jump if all bits in T are '0' and pop T	2
0106	JB1LO	Jump if input pin B1 is LO	2
0107	JB2LO	Jump if input pin B2 is LO	2
0108	JB3LO	Jump if input pin B3 is LO	2
0109	JB4LO	Jump if input pin B4 is LO	2
010A	JB1HI	Jump if input pin B1 is HI	2
010B	JB2HI	Jump if input pin B1 is HI	2
010C	JB3HI	Jump if input pin B1 is HI	2
010D	JB4HI	Jump if input pin B1 is HI	2
010E	RAMSTORE	Store the byte in N at the address in T. Pop both T and N	2

For branching instructions, the program counter, *PC* is loaded with the inline address, *M*. Most multiple cycle instructions execute on the first clock cycle and fetch the next instruction to avoid executing inline information as an instruction. In some cases, multiple clock-cycle instructions will require multiple cycles of execution. For example, the instruction, *RAMSTORE*, requires two clock cycles. In the first clock cycle, the data in *Nreg* is stored in the external RAM at the address in *Treg* and the address in *Treg* is popped from the data stack. During the second clock cycle, the leftover data which is now in *Treg* is popped from the data stack. Instructions of this type, denoted as belonging to set Ω in Figure 6, remain in the *Execute* state with different control outputs for each clock cycle as necessary. This implementation easily extends the FC16 to support N-clock cycle instructions.

7. Programming Example

The FC16 Forth core described in the previous sections has been implemented in a Xilinx Spartan II FPGA on the Digilab2 board shown in Figure 7. This board together with the DIO1 board also shown in Figure 7 is produced by Digilent, Inc. [2]. The simple Forth program shown in Listing 3 waits for button 4 on the DIO1 board to be pressed (*waitb4*), reads the values of the eight switches (*S@*), converts the lower 4-bit hex value to ASCII (*hex2asc*), and then displays this ASCII code on the 7-segment displays (*DIG!*). In Figure 7 the switches are set to 00001011 (hex B) and after pressing button 4 the 7-segment displays shows 0042 (the ASCII code of B).

Figure 7 Digilab 2 and DIO1 boards from Digilent, Inc.

The Forth program in Listing 3 is compiled to the VHDL code shown in Listing 4 using a compiler adapted from a C++ program described in [6]. The

VHDL code shown in Listing 4 is the contents of the program ROM shown in Figure 2.

Note that the FC16 program in Listing 4 begins with a jump to the main program at address 14. The main word is always the last word defined in a Forth program such that the addresses of all previously defined words will be known. The compiler will translate the word *waitb4* to the following two jump instructions:

```
JB4HI,          --14    : main
X"0014",        --15      BEGIN
JB4LO,          --16        waitb4
X"0016",        --17
```

Listing 3 Hex2asc Forth Program

```
\       Convert hex to ASCII
HEX

: hex2asc       ( n -- asc )
                0F AND          \ mask upper nibble
                DUP 9 >         \ if n > 9
                IF
                  37 +          \   add $37
                ELSE
                  30 +          \ else add $30
                THEN ;

: main          ( -- )
                BEGIN
                  waitb4        \ wait for btn4
                  S@            \ read switches
                  hex2asc       \ hex to ascii
                  DIG!          \ display result
                AGAIN ;
```

The instruction *JB4HI X"0014"* will loop on itself as long as signal *B(4)* is high. This will be the case if button 4 is being pressed and therefore waits for the button to be released. The instruction *JB4LO X"0016"* will loop on itself as long as signal *B(4)* is low. It will therefore wait for button 4 to be pressed.

The Forth *IF* statement is compiled to the FC16 *JZ* instruction, which jumps if the flag in *T* is false. The *JZ* instruction is also used for the Forth *WHILE* and *UNTIL* instructions. The Forth *ELSE* statement is compiled to the FC16 *JMP* instruction, as is the Forth word *AGAIN*.

Listing 4 VHDL code generated from Hex2asc Forth program

```
type rom_array is array (0 to 30) of STD_LOGIC_VECTOR (15 downto 0);
constant rom: rom_array := (
       JMP,             --0
       X"0014",         --1
       LIT,             --2     : hex2asc
       X"000f",         --3       0F
       andd,            --4       AND
       dup,             --5       DUP
       LIT,             --6
       X"0009",         --7       9
       gt,              --8       >
       JZ,              --9       IF
       X"0010",         --a
       LIT,             --b
       X"0037",         --c         37
       plus,            --d         +
       JMP,             --e       ELSE
       X"0013",         --f
       LIT,             --10
       X"0030",         --11        30
       plus,            --12        +
       RET,             --13      THEN ;
       JB4HI,           --14    : main
       X"0014",         --15      BEGIN
       JB4LO,           --16        waitb4
       X"0016",         --17
       sfetch,          --18        S@
       CALL,            --19        hex2asc
       X"0002",         --1a
       digstore,        --1b        DIG!
       JMP,             --1c      AGAIN ;
       X"0014",         --1d
       X"0000"          --1e
       );
```

8. Summary

The FC16 is a high-performance Forth core that has been implemented on a Xilinx Spartan II FPGA. Of the 63 Forth instructions that have been implemented, 51 of them execute in a single clock cycle. Forth has always been an extensible language in the sense that the programmer defines new words which get added to the dictionary and essentially become a part of the language. With the development of this flexible Forth core that is used in an FPGA, the Forth hardware has also become extensible. It is an easy matter for the user to add new hardware instructions that will perform specific operations on new hardware I/O modules. For example, it is possible to make the top of stack, *T*, a shift register that could interface to external serial devices using the standard SPI interface [7]. By including a timer module, the FC16 could become a very useful high-performance, low-cost microcontroller. Adding a UART would allow interactive communication with the FC16 through a standard asynchronous serial line. Many of these types of modules are available as precompiled LogiCore modules.

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