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A Software Development Kit for CeDIMES

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CAPSL Technical Note 10

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Abstract

CeDIMES is an FPGA based multiprocessor emulation system under development at CAPSL [7, 8]. Its first goal is to accomplish the hardware emulation of a single-chip Embedded Cyclops system. Such an emulator would be the first hardware implementation of the BlueGene/C cellular architecture proposed by IBM [2]. Concurrently with the hardware implementation, system software (compiler, assembler, linker, RTS, loader, debugger, etc.) has to be developed so that end users can write, compile and execute applications that take advantage of the new platform. To overlap as much as possible hardware and system software development, a functional simulator, the CeDIMES System Simulator, has been implemented on a Linux box and used for testing system software tools. A Run-Time System that supports a Pthread-like programming model has been developed and tested with several multithreaded applications such as a vector dot-product and a more sophisticated Mandelbrot-set generator [6].

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1 Introduction

In this technical note, we present a work-in-progress report on the system software support for a class of cellular multiprocessor-on-a-chip architecture. This work is part of a more comprehensive research program focused on programming methods and software infrastructure for cellular architectures actively pursued at CAPSL [5]. Our next discussion will focus on the particular realization of IBM's Blue Gene cellular architecture known as Embedded Cyclops or CyclopsE [2, 1]. More specifically, we will refer to CeDIMES, the first hardware implementation of CyclopsE, materialized by means of the DIMES platform (Delaware Iterative Multiprocessor Emulation System) — a general purpose FPGA based emulation system under development at CAPSL.

Blue Gene/Cyclops is an architecture that follows the cellular concept proposed by IBM [2]. Each chip contains a number of processors and each processor consists of multiple thread units, and a single floating point unit. Each processor is a simple (in-order issue) 32-bit processor operating at a moderate clock rate. The memory hierarchy of the Blue Gene architecture is deep, having registers, caches, on-chip and off-chip memories. More specifically, within a chip, there are multiple memory banks and all the processors in a chip have access to them. The memory banks together form an on-chip shared memory system for the processors. Lastly, there is an off-chip memory associated with each chip. The off-chip memory of all chips form a distributed memory/address space. The program execution model supported is shared memory programming within a chip and message passing across chips.

The document is organized as follows. First we give an overview of the CeDIMES emulator, then proceed to describe a functional simulator of such a cellular platform. As part of the system software, a compiler suite targeted for Embedded Cyclops and a run-time system produced for this system are explained in sections 4 and 5 respectively. Since the user console will be at a host machine, specific software components such as a boot loader, section 7, a host-RTS, section 8, and a debugger, section 9, will be presented as well.

2 CeDIMES Emulator

This section provides a brief introduction to the Embedded Cyclops emulator system currently under development at CAPSL. More precisely, it presents the main features implemented by such an emulator. Should the reader is interested in further details, these can be found in the DIMES and DIMES/P documentation [7, 8].

CeDIMES is an FPGA-based board, which is plugged into the PCI bus of a host machine, that emulates a single-chip Embedded Cyclops system. However, the size of the FPGA used for this hardware implementation imposes several constraints on the Cyclops system that can be realized. For instance:

- It has limited hardware: two processors with four thread units each.

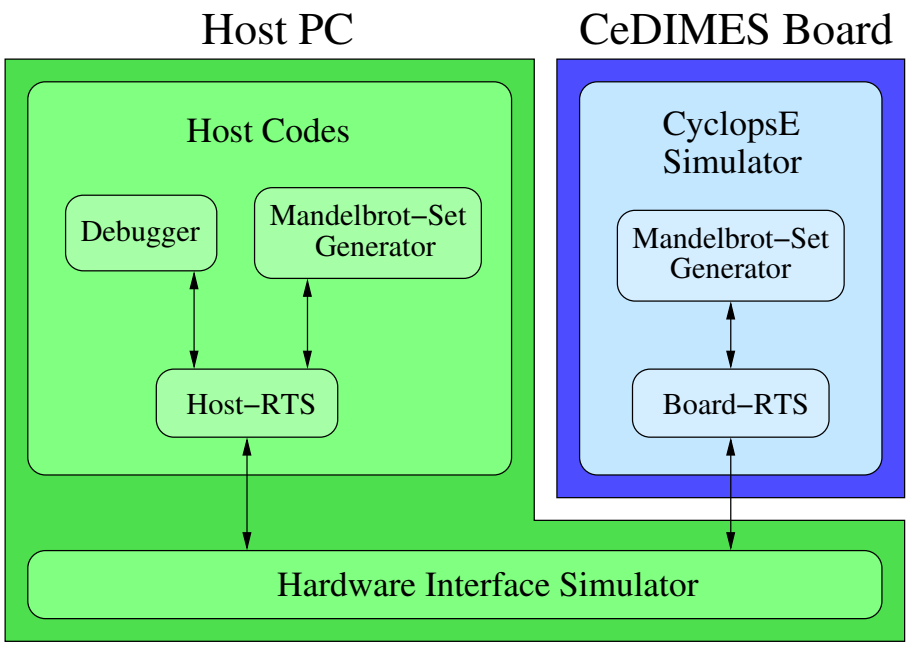

Figure 1: CeDIMES System Simulator Block Diagram

- It has limited memory: 16k scratch pad (i.e. local per processor data memory) and 64k global memory.

Moreover, it has limited support for the CyclopsE instruction set. For instance, SYNC and ICI instructions are not supported yet, and SLEEP can not be executed after a branch instruction.

Memory and instruction set support limitations are not due to the iterative emulator approach but to resource constaints and hardware bugs in the design, respectively. These issues will be fixed in a near future. For instance, the next version of the CeDIMES emulator will tackle the resource constraint issue. It will consist of eight processors with four thread units each, and have 128k scratch pad and 512k global memory available.

3 CeDIMES Simulator

A functional simulator of the CeDIMES system has been developed. It is implemented with two Pthreads, to run the host machine code and an Embedded Cyclops simulator independently of each other, see Figure 1.

One of the simulator's Pthreads (left box in Figure 1) runs exclusively the host codes, i.e., the software that when the hardware CeDIMES platform becomes available will run on the host. The host side software consists of: an application, that provides the console to its peer process running on the board; host run-time system, intended to provide an interface layer

for application developers to communicate with, control and run programs on the CeDIMES board; object file loader, to load and start the execution of programs in the CeDIMES board; and hardware interface simulator, which behaves like the host-PCI interface available in the CeDIMES emulator. Concurrently, the second Pthread mimics the behavior of the CeDIMES board (right box in Figure 1). This is achieved by means of a functional simulator of an Embedded Cyclops single-chip system, which runs the unmodified user's application linked to the Cyclops run-time system. Such a simulator was provided by IBM, extended at CAPSL with multithreading capabilities and tailored according to the hardware specification of the CeDIMES emulator.

Before using the CeDIMES system simulator, the user needs to be aware of a constraint that applies to the application's source code: `main()` has to be renamed into `application_main()` which is called by the simulator. In the future, if the simulator is implemented with two processes instead of Pthreads, no modification will be required.

4 Embedded Cyclops Compiler Suite

We use the GNU C compiler infrastructure version 2.95.2 retargeted to the CyclopsE instruction set. The initial work of retargeting the compiler suite was carried out by IBM, with Cygwin as the development environment. At CAPSL, the compiler tool set was then ported onto the Linux operating system. For further information on how to download and install the compiler suite the reader is referred to the appendix A.

5 Cyclops Run-Time System

In this section we discuss the implementation of a run-time system for the CeDIMES cellular architecture. Our RTS consists of a set of libraries that provide the required functionality such as bootstrapping, elapsed time measurement, thread creation and termination, mutex handling, and cross-platform memory allocation. The later also requires of the host RTS participation, which is the topic of section 8. However, this section will focus on the RTS that runs on the CeDIMES board.

5.1 Cyclops Thread Library

We start by discussing an implementation of our Program eXecution Model (PXM) on the CeDIMES cellular architecture. The first implementation of our PXM is influenced by the popular Pthread model and uses a direct mapping of software threads into hardware thread units. Upon initialization, a software thread is given control over a well determined region of the on-chip memory, which is allocated to every physical thread unit at boot time. This enables fast thread creation and reuse. As in the Pthread model, a waiting thread (waiting on

an external event/synchronization) goes to sleep; such a thread is woken up by another thread through a hardware interrupt/signal.

Under our PXM, thread execution is non-preemptive. In other words, after a software thread is assigned to a hardware thread unit by the RTS, it will run in the hardware thread unit until completion. Furthermore, the RTS will not swap out a sleeping thread and reassign the idle hardware resources to another software thread.

Since the user is responsible for creating, synchronizing and terminating threads, a minimal set of functionality for writing parallel programs for our cellular platform has been identified and provided to the user as a library. We call it the Cyclops thread or cthread library.

`cthread_create()` – Run user provided function in next available thread unit. If no thread unit is available, it returns an error condition. One parameter can be passed to the thread function.

`cthread_exit()` – Caller thread terminates its execution.

`cthread_join()` – Caller waits for a thread to terminate.

`cthread_self()` – Returns own thread ID (11bits).

`cthread_sleep()` – Caller thread is suspended for a given number of clock cycles or indefinitely.

`cthread_resume()` – Awake a suspended thread.

`cthread_sync()` – Wait for all accesses to memory, that were initiated by the calling thread, to be completed in memory. All this function does is a SYNC instruction.

The 16k of local per processor available memory, are evenly split among the four thread units, see Figure 2 (left). Thread units have the stack placed in the assigned 4k region of scratch-pad memory. At the end of the run-time stack area towards which the stack grows, the RTS puts each thread's thread-unit-unique area where GPRs are saved when an interrupt occurs. The compiler tool set and run-time system software have also agreed that GPR 2, which points to a thread-unit-unique area, can be used both to check for stack overflow and to address the thread-unit-unique area, see Figure 2 (center). At the beginning of the thread-unit-unique area, four memory words have been reserved for a special purpose, see Figure 2 (right). The first is used as a lock to guarantee atomic transactions on the remaining three words. The thread unit status, enabled/disabled, and the software thread status, running/asleep, are stored in the second word. Words three and four hold the function address and optional argument specified by the user when a new thread is created. Upon completion the thread overwrites the optional parameter with the exit code.

Besides thread management, Cyclops thread library provides a mutex object that allows mutual-exclusion via acquiring and releasing locks. The following functionality is also part of the cthread library.

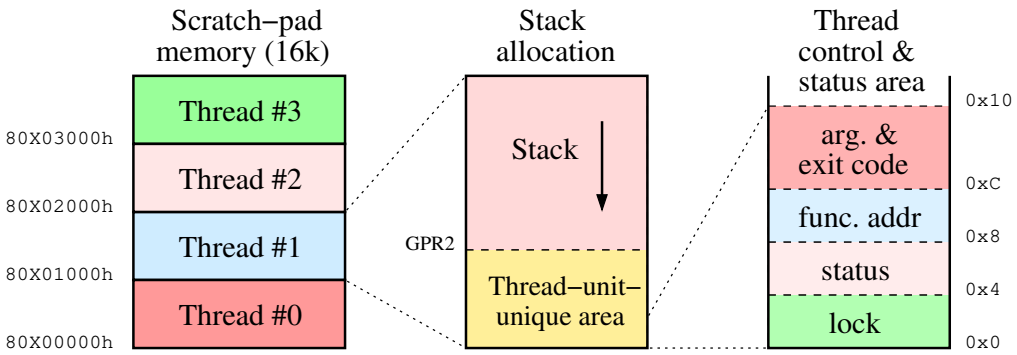

Figure 2: Scratch-pad Memory Organization

`cthread_mutex_init()` – Initialize a mutex object.

`cthread_mutex_destroy()` – Destroy a mutex object.

`cthread_mutex_lock()` – Lock a mutex. If the mutex is already locked, the calling thread will block until the mutex becomes available.

`cthread_mutex_trylock()` – This function is identical to `cthread_mutex_lock` except that if the mutex is currently locked, the call returns immediately.

`cthread_mutex_unlock()` – Unlock a mutex, if this was previously locked by the calling thread.

A mutex has two pieces of state — a "locked" bit and a queue. When the mutex is not locked, the queue is empty. Otherwise, the queue contains 0 or more thread IDs representing asleep threads waiting to acquire the lock. When the mutex is unlocked while the queue is not empty, the first queue entry is removed and its thread awaken, implying it now has the lock. In the current version, the queues are allocated in global memory within the .data section. For this reason, there is a limited number of mutexes and the queues' size is defined by a constant in the RTS. A queue can hold up to eight thread identifiers, allowing additional thread units to do a busy wait.

5.1.1 CeDIMES Memory Model

This section provides the programmer the basic information regarding the memory model actually supported by the CeDIMES system. It is *not* an exhaustive reference of Cyclops memory model, as the programmer will have explicit knowledge by reading specific documentation on the subject [3, 4, 5].

The facts the programmer needs to be aware of, in order to write data-race free parallel programs are the following:

- The compiler does not take care of the memory model. Furthermore, the compiler is not even aware of any parallel execution constructs, which are explicitly handled by the programmer.
- The hardware design of CeDIMES network switch is such that global memory follows the Sequential Consistency (SC) memory model.
- The scratch-pad memory does not follow the SC model. Therefore, the programmer must use the SYNC instruction or call the `cthread_sync` function. Yet, the SYNC instruction has not been implemented in CeDIMES.
- The stack is placed by the RTS in scratch-pad memory. Since accesses to this memory area cannot be synchronized among threads, mutexes and any other data objects the programmer might implement for similar purposes must be placed in global memory, in other words, cannot be declared as local variables.

5.2 Cyclops Clock Library

Each chip has one Timer register and each thread unit has a Timer Alarm special purpose register. They are both controlled by the RTS to provide two time functions with different degree of resolution: `cclock_ns()` reads the chip Timer SPR that is counted up at a rate of one count per processor cycle. Assuming a cycle time of 2 ns, the Timer value wraps approximately every 8.59 seconds. `cclock_us()` returns the number of microseconds since the board was reset. It is counted up continuously based on the Timer register, wrapping from the value $2^{32} - 1$ to 0 every 70 minutes approximately.

5.3 Cyclops Memory Library

The RTS also implements an atom table that is used by the host to identify data structures within the DIMES-based memory. Because of this property, it may be used to communicate with the host. However, it is not meant for memory allocation in general. For that purpose, the programmer should use `malloc()` and `free()`.

The atom table consists of a number or tag, size and pointer triplets. Each time an object is requested to be allocated by calling `cmem_malloc()` and the tag parameter can not be found in the atom table, the board RTS creates a new entry in the atom table. Such an entry contains the tag and size parameters passed by the function call as well as a pointer to the object allocated in memory.

To access such an object from the host, the program calls the functions `read_atom_mem()` or `write_atom_mem()` to either read or write data into the object. These operations are handled by the host RTS. First, it makes a copy of the atom table managed by the RTS running on the board. Once the memory address of the target object is known, functions provided by the hardware interface are called to read from or write into the object. Obviously all this process

is carried out by the RTS without the user's program intervention, hence avoiding the use of magic numbers, nor needing to re-compile user code if the RTS memory allocation scheme is changed.

A point worth noticing is that there are two atom tables enabled in the RTS. An application atom table accessible to the user through the `cmem_malloc()` function, and a system atom table only seen by the host/Cyclops RTS. The latter contains atoms such as buffers used by the CeDIMES monitor, and the application atom table itself. Since the host needs to know the location of the system atom table in advance, we have decided to store its address in memory location 0x00. When bootstrapping, the host RTS shall know how to find the system atom table and carry out all required initializations.

The RTS relies on the standard C library functions such as `malloc()` and `free()` to manage the heap. Since threads' stack is placed in the scratch pad memory, all global memory not used by the application is managed as heap. Therefore, the heap can grow up to the 128k global memory upper limit.

5.3.1 Atom Tables

Atom tables is a technique used by operating systems to refer to data allocations that are shareable between processes: The OS maintains a map of "identifier – data". These identifiers have to be unique and somehow known to the process, either by hard-coding the identifier within the program at compile-time, or the process queries some external store for the identifier at runtime. The data field usually refers to a handler that provides access to a system object.

Similarly, the goal of CeDIMES RTS atom table is to allow the host identify data structures within the board memory, which in turn, makes communication between board and host possible. Any addresses generated within the DIMES-based part are specific to DIMES, and meaningless on the host. A direct dereference of such a memory-pointer value would be meaningless on the host, just as it would be as if pointers were passed between two different processes: those memory references refer to different memory spaces. The atom table provides the host-based software a way of identifying objects that have a built-in type within DIMES, without having to fix up memory addresses and offsets within the host-based software that references those memory locations within the DIMES board itself.

Note the mention of built-in type objects: Linked lists would not work. For instance, a singly-linked list has a pointer to the next element. That pointer is an address. How should that DIMES-based address be translated by the host? It can't at all. Thus the atom table. This uses identifiers to reference objects. The programmer chooses those identifiers at compile-time. Thus there is a static number of identifiers within any running code (they cannot be generated at run-time) so dynamic allocation of a linked list that may be used in an identical way by both the host and DIMES is impossible. Only address fix-ups performed via the atom table are meaningful, and those entries within the atom table are allocated at compile-time, not run-time.

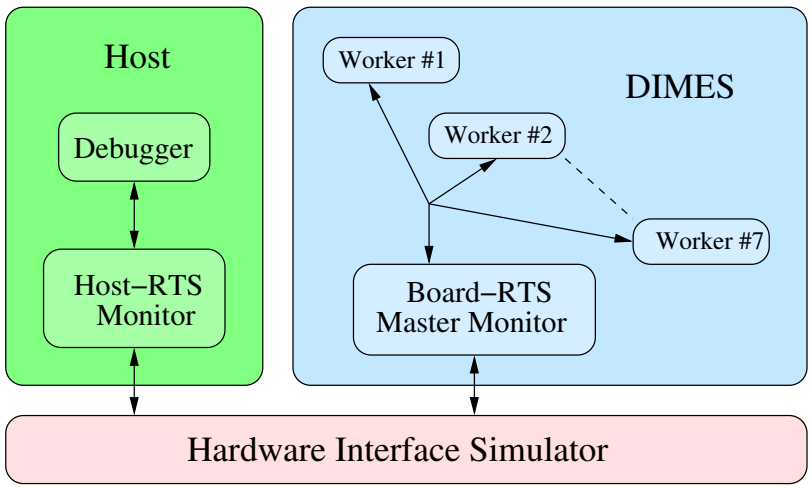

Figure 3: Monitor Software Architecture

In summary: the programmer cannot do dynamic memory allocation *and* directly share that data with the host using the atom table as it is currently implemented.

5.4 Cyclops Monitor Library

To debug a program in the CeDIMES platform, the user needs access to the debugger, as described in section 9, and enable a monitor in CeDIMES RTS. Resource constraints lead us to the decision of having the monitor disabled by default. Hence, it is the user responsibility to enable the monitor and recompile the RTS. Such a procedure is described in detail in appendix D.

Once the monitor is enabled, the RTS handles control of execution over to the monitor program instead of the user's program. The monitor runs exclusively in thread unit 0, while remaining thread units are available for launching user's code on them, see Figure 3.

A fundamental principle of operation for the debugger is not to lose control of the board. That requires that messages sent from the host must always be replied by the board, which guarantees the status of the board and hence, of the program being debugged, is always well known by the user. Since external interrupts are not implemented in CeDIMES. The only method to ensure such a responsive monitor is to have it running all the time, i.e. exclusively in one thread unit.

Under these conditions, a simple protocol is implemented to establish a communication channel between host and board. According to our protocol, the monitor running in thread 0, master monitor, waits until a message from the host is received. The monitor then checks its correctness, and if needed it relays it to the remaining threads, where the monitor, slave monitor, should be temporally running after the user's code trapped into supervisor mode (either because the user sent a stop command or because execution reached a breakpoint). Once the requested operation is performed, either by the master or slave monitor, the master monitor replies to the host with the result. Slave monitors only reply directly to the host when

reporting events such as thread creation or destruction, or whenever execution is stopped at a breakpoint or stopped by user.

As mentioned in section 2, the I-Cache Invalidate instruction (ICI) is not implemented. Therefore, when a breakpoint is enabled, program execution is carried out by repeatedly single-stepping instructions. If ICI were implemented, breakpoints would trap into supervisor mode and the monitor would take over the execution. However, since it is not, there is no guarantee the modified program (that with a breakpoint set) will be executed, which can happen if the instruction where the breakpoint is set is already loaded into I-cache. After each user's single instruction is executed, the monitor determines whether execution, i.e. the program counter, has reached an enabled breakpoint and stops if that is the case. While in this mode, execution is approximately 100 times slower. The execution of a single instruction of the user's program requires a context switch from monitor to user mode, execution of the user's instruction, and a second context switch back to the supervisor mode, due to the single-step interrupt. The whole switching process represents an overhead of 100 instructions approximately, hence the slowness.

6 Hardware Interface

To enable the communication between host and board software components within the simulator, functions to be performed by the hardware host-PCI interface, have to be provided by the simulator.

The hardware host-PCI interface provides two basic operations such as reading from CeDIMES memory into the host machine memory and writing into the board memory, as well as procedures to reset both the FPGA board and the emulated thread units. All this functionality is supplied as well by the simulator hardware interface, to the extend required by the simulator, so that host and board sides can communicate under the simulator as if they were running in the hardware platform.

`hardware_reset()` – FPGA reset. Resets all internal registers, initializes I-cache directory and the branch history table.

`dimes_reset()` – Execution reset. Sets the instruction pointer in all thread units to 0x20.

`ll_read_mem()` – Read data from CeDIMES memory into the host machine.

`ll_write_mem()` – Write data from the host machine into CeDIMES memory.

The first version of the CeDIMES simulator, which should be considered as a prototype, is implemented with Pthreads. This means, host side and board side share memory within the simulator process. As a consequence, an implementation of such a hardware interface was possible with simple memory copy functions.

The hardware host-PCI interface imposes a restriction in the use of the read and write memory operations when operating with the actual board: memory locations (both at the

host and board) have to be word aligned (32-bit). Byte transfers were possible but at the expense of a reduced host-board bandwidth. Hence, the option was disregarded for this first implementation.

7 CeDIMES Boot Loader

In order to load and start the execution of a program in the CeDIMES board, a boot loader is also provided. This tool is based on the hardware interface common to hardware (emulator) and software (simulator) implementations of the CeDIMES system. Therefore it works with no modification in both platforms.

The general procedure followed by the boot loader is described below:

- Reset the FPGA board (system reset).
- Load an elf32 object file onto the board. Such file contains the user's code linked with the run-time system that will start running on the board at the end of the reset cycle.
- Initialize the run-time system on the board. For instance, variables that manage the heap are set with the memory address and size of the memory pool used as heap.
- Set the program counter of all thread units to 0x20 and start the execution.

Such a process is mandatory for programs that are to be run in both the host and board sides and make use of the host-RTS [1]. Projects built by the rules 'board' and 'deb' in appendix A include the full boot loader.

For launching programs that are intended to be run only on the CeDIMES board and demand no service of the host-RTS, a stand-alone boot loader is also available. This tool basically loads and starts the execution of an elf32 object file on the board, and then waits for the oncoming exit code from the board. In appendix A, we explain how to build such a tool.

8 Host Run-Time System

The CeDIMES host side RTS or host-RTS is intended to provide an interface layer for application developers to communicate with, control and run programs on the CeDIMES board. It provides functions for simple loading and execution of programs, as well as supporting more advanced debugging features. It is designed in such a way as to be extensible, so functionality can be added as needed without interfering with already existing features.

This section provides a high level overview of the included functions and their functionality. It is *not* a technical reference, as the programmer will have explicit knowledge of the

[1] Remember that the Cyclops memory library requires of the host-RTS participation.

required parameters for each function. These functions serve as a method to hide the low level communication of the host/board RTS.

`load()` – Load a file onto the board.

`run()` – Initial start of the program.

`continue_exec()` – Continues execution from a halted state.

`exit_pid()` – Exit a process.

`read_registers()` – Read either the general or special purpose registers.

`write_registers()` – Write either the general or special purpose registers.

`set_bp()` – Set a breakpoint.

`del_bp()` – Delete a breakpoint.

`single_step()` – Single step.

`query_board()` – Query the board for an event. This is called to query the board for events such as a thread being created, destroyed or stopped at a breakpoint.

`read_atom_mem()` – Used to update the local copy of the atom table as well as read individual elements. Note: Additionally it reads the contents of the memory region connected to the specified entry.

`write_atom_mem()` – Write an entry into the atom table. Note: Doesn't write an entry into the atom table. It updates the contents of the memory region connected to the entry instead.

The host RTS and CeDIMES RTS communicate using a simple command and reply format, both utilizing the same underlying packet structure. All of the functions initialize packets and send them using calls to lower level read and write functions. Packets are sent to a defined CeDIMES receive buffer. After sending, the host begins querying the CeDIMES transmit buffer, in order to obtain a status reply from the board. After the host receives the reply packet, it clears the CeDIMES transmit buffer. It is then free to issue another command, or in the case of a read/write register, read/write the register buffer. These details are exactly what the host RTS is intended to hide.

9 CeDIMES Debugger

This section discusses the basics of the CeDIMES debugger, an assembly level debugger that allows program debugging of the application side that runs in the CeDIMES board. Particularly, it provides the user a description on how to use the basic set of commands.

1. Creating an executable file.

   Before the CeDIMES debugger can be used, the program must be compiled using the CyclopsE compiler. The 32-bit Cyclops compiler command name is cyclopsE-linux-elf-gcc.

2. Starting the CeDIMES simulator and debugger.

   The debugger is started by using the command along with the binary file to debug. For example, to debug a program called test.bin, enter:

   ```
   ./dimes-sim test.bin
   ```

   If the .bin file exists, CeDIMES simulator and debugger will start to work and the following information will be displayed in the screen:

   ```
   ...
   Please input the command, use space to separate
   >
   ```

   The omited information . . . is the simulator's initial information and "`>`" is the debugger's prompt meaning a command can be typed in. To debug the program, first you should use the `run` command to start it, then stop it. Once the program is stopped you can use other commands to debug the program. Of course, before running the program, the user can also use some commands to check the status and set breakpoints. Next, we will introduce all commands one by one.

3. Checking registers and mode information.

   The CeDIMES debugger allows for checking the content of general and special purpose registers, the status of the current default mode and display breakpoint information by using `info arg` command, where `arg` can be either spr, gpr, mode or break. For example, to display the contents of the special purpose registers, enter:

   ```
   > info spr
   ```

   The contents of s1 - s13 will be displayed in 8 items each line. To display the contents of the general purpose registers, enter:

   ```
   > info gpr
   ```

   The contents of r0 - r63 will be displayed in 8 items each line. Note: r0 always displays as 0 since its value has been architecturally fixed.

   The info command can also be used to view the values of the default running mode. To display the values of current running mode, enter:

   ```
   > info mode
   ```

Prints out the default thread ID, processor number, chip number and process ID. They are initialized as zero when the debugger starts up but can be changed using the `set` command, described below.

Some commands require of parameters such as thread ID, processor number, chip number or process ID. To overcome the hassle of asking the user to type them in every time they are needed, the debugger defines a default set of values (default mode), which will be used whenever the user does not specify them at the command line. Having a default set of parameters allows the user to consider such parameters as optional instead of mandatory.

4. Modify data.

   The CeDIMES debugger provides the `set` command to modify the content of general or special purpose registers and the value of default running mode. For example, to modify the special purpose register s1, enter:

   ```
   > set s1 = 18
   ```

   or

   ```
   > set s1 = 0x12
   ```

   Note: we use the prefix `0x` to enter data in hexadecimal format.

   To modify the general purpose register r20, enter:

   ```
   > set r20 = 255
   ```

   or

   ```
   > set r20 = 0xff
   ```

   The command to change the default mode is `set mode arg1, [arg2, arg3, arg4]`, where `arg1` is the thread ID, `arg2` processor number, `arg3` chip number, and `arg4` process ID. Being `arg1` mandatory and all others optional. This function only accepts numbers in decimal base.

   ```
   > set mode 1 2 3 4
   ```

   Changes the default mode to thread ID 1, processor number 2, chip number 3 and PID 4.

5. Set and delete breakpoints.

   Breakpoints allow the user to temporarily suspend the execution of the program. They can be set prior to starting the program or after stopping at another breakpoint. The debugger will stop execution immediately before executing the line where the breakpoint is set. In CeDIMES debugger, both `b` and `break` commands are valid for setting breakpoints. We use `b` here. The format of the command is: `b arg`., where `arg` is the address in hexadecimal where the breakpoint will be set. To set a breakpoint at the illegal or privileged instruction interrupt vector, enter:

```
> b *0xA0
```

To list the breakpoints enabled in the current session, enter:

```
> info break
```

The number of a breakpoint is assigned by the debugger. Use this number when deleting a specific breakpoint. The command of delete breakpoint is `db arg`, being `arg` a breakpoint number. To delete breakpoint number 3, enter:

```
> db 3
```

To delete all breakpoints, enter:

```
> db *
```

6. Execute the program.

   To run the program, enter:

   ```
   > r [pid]
   ```

   This command may only be used to start the program execution. If a breakpoint is reached or execution is halted for another reason, this command cannot be used to continue the program trace. The optinal argument is used to give a special process ID for running, otherwise the default number specified by the default mode is used.

7. Continue.

   To continue the execution after the debugger pauses for a breakpoint, enter:

   ```
   > c [pid]
   ```

   The program continues to execute from the next line of the break point. To continue executing process 4, enter:

   ```
   > c 4
   ```

   To continue the process with the process number of default running mode, enter:

   ```
   > c
   ```

   All the next steps which use pid as a option is similar with this.

8. Single-Step Execution.

   The step command may be used to start the program execution, continue after a breakpoint, and to single-step through the program's execution (step cannot be used to set command line parameters). The command is `si [arg]`, `arg` = pid.

   To execute a single step on process 4, enter:

   ```
   > si 4
   ```

9. Exiting a process.

   To exit a process, enter:

   ```
   > exit [pid]
   ```

   It will cause an exit from the process which process ID = pid.

10. Stop running.

    To stop running a program, enter:

    ```
    > s [pid]
    ```

11. Load a file.

    To load a file, enter:

    ```
    > l object_file
    ```

12. Display code and data from memory.

    The `x/` command is used to dump instructions or data from memory. The value of the program counter is used as the default starting point. `x/` is followed by a number of instructions and `i` or a number of words and `d`. For example, to display 20 instructions, enter:

    ```
    > x/20i
    ```

    To dump 20 words from memory, enter:

    ```
    > x/20d
    ```

13. Quitting the debugger.

    To quit the CeDIMES Debugger, enter:

    ```
    > q
    ```

    A confirmation is required for this command.

References

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[5] Guang Gao, Juan del Cuvillo, Ziang Hu, Robert Klosiewicz, Clement Leung, Jason McGuiness, Hirofumi Sakane, and Yingping Zhang. Programming method and software infrastructure for cellular architecture. CAPSL Technical Memo 48, Department of Electrical and Computer Engineering, University of Delaware, Newark, Delaware, July 2003. In ftp://ftp.capsl.udel.edu/pub/doc/memos.

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[7] Hirofumi Sakane, Levent Yakay, and Vishal Karna. DIMES/P hardware technical manual. CAPSL Technical Note 12, Department of Electrical and Computer Engineering, University of Delaware, Newark, Delaware, September 2003. In preparation.

[8] Hirofumi Sakane, Levent Yakay, Vishal Karna, Clement Leung, and Guang R. Gao. DIMES: A rapid prototyping platform for multiprocessor design. CAPSL Technical Memo 46, Department of Electrical and Computer Engineering, University of Delaware, Newark, Delaware, September 2003. In preparation.

A CeDIMES Software Development Kit Installation

This section will guide you through the installation of the CeDIMES Software Development Kit.

A.1 Requirements

The SDK for CeDIMES is only available at CAPSL CVS repository. In order to checkout the source files, you must have a CAPSL account.

Environment variables may be defined and exported (and included in your ~/.bashrc file preferably) to set the CVS repository where the SDK files are.

To access from a CAPSL local machine:

```
export CVSROOT=/m/tremblay/cyclops/cvsroot                                    (1)
```

When access from a remote machine is required:

```
export CVS_RSH=ssh                                                            (2)
export CVSROOT=:ext:username@tremblay.capsl.udel.edu:/tremblay/cyclops/cvsroot
```

where username is the actual user's name.

To install the Software Development Kit, you need a C compiler with the C libraries installed. The SDK has been tested with GCC 2.95.4/glibc 2.2.

A.2 Installation

At this moment, source files, executables and temporary files are kept under a common directory tree. To create all the required directories type:

```
mkdir -p ~/cyclops/src/                                                       (3)
mkdir -p ~/cyclops/local/
mkdir -p ~/cyclops/build/
```

Installation scripts expect the environment variable `CYCLOPS_HOME` to point at the root of the directory tree. You may want to define and export it (and include it in your ~/.bashrc file preferably) before proceeding with the installation.

```
CYCLOPS_HOME=${HOME}/cyclops/                                                 (4)
```

The next step is to check out the SDK from the CVS server. To do so enter the following commands on the command line:

```
cd ~/cyclops/src/                                                             (5)
cvs checkout -r demo_app_rel_1 gcc-2.95.2
cvs checkout -r demo_app_rel_1 newlib-1.10.0
cvs checkout -r demo_app_rel_1 binutils-2.11.2
cvs checkout cysim32
cvs checkout testsuites
cvs checkout -P dimes
```

Then you need to compile all these files and install the executables and libraries. Let us start with the compiler tool set. To do so, please use the install script available at file:///usa/jcuvillo/cyclops/public/dimes/doc/install.sh [2]. But before starting with the installation add the `~/cyclops/local/bin/` directory to your `$PATH` variable. CyclopsE executables will be put in this directory.

After the script does its job, the reader is encouraged to test the compiler tool set and CyclopsE simulator, and then to proceed with the installation of the SDK. The procedure to perform this test is described in appendix B.3.

Continuing with the installation. First, we must ensure the latest release of the crt0 file as well as the run-time system supporting libraries are installed in the directory where the linker looks for by default. Type:

```
cd ~/cyclops/src/dimes/mon/                                    (6)
make clean
make crt0
```

Finally, to build CeDIMES specific tools, type:

```
cd ~/cyclops/src/dimes/                                        (7)
./configure --target=cyclopsE-linux-elf      \
            --prefix=$CYCLOPS_HOME/local     \
            --srcdir=$CYCLOPS_HOME/src/dimes
make clean
make config
make <option>
```

where `<option>` could be any of the following:

run To build the stand-alone boot loader described in section 7. This tool can only be built on a machine that has the CeDIMES board and software libraries installed.

board To build CeDIMES system boot loader. The user has to modify the `USRS` Makefile variable, which specifies user's object code to be link to the boot loader. This program can only be built on a machine that has the CeDIMES board and software libraries installed.

sim To build CeDIMES system simulator.

deb To build CeDIMES debugger and run it in the simulator.

Once the installation of the CeDIMES SDK is completed the reader is advised to run a simple set of tests in order to verify the system is working. Appendix B.4 explains how to accomplish this.

[2] Only accessible within CAPSL main network

B CeDIMES Software Development Kit Usage

B.1 Compiler Tool Set Usage

To compile, use `cyclopsE-linux-elf-gcc`. Do not forget to add `-lc` or `-lm` if the standard C or math library is needed, or `-lcrts` when the run-time system libraries are required, or any necessary include paths.

If the assembler is needed, use `cyclopsE-linux-elf-as` with the `-memb` option to generate code for the Embedded Cyclops.

B.2 CeDIMES SDK Usage

To run any of the CeDIMES specific tools simply call the program followed by the name of the elf32 object file.

cyclopsE-linux-elf-run The stand-alone boot loader can be used to load and start running programs in the CeDIMES board when no RTS support is required on the host-side. Programs such as those contained in our test suite, which require of no host-board communication, but for loading the object file into the board and returning an exit code at the end of the execution, can be launched with this tool.

dimes-board When the user requires peer processes to be launched in both the board and host, `dimes-board` is the tool to use.

dimes-sim CeDIMES system simulator provides the same features as the `dimes-board` tool. The only difference is that the elf32 object file is run in a functional simulator instead of the real CeDIMES board.

B.3 Testing the Compiler Tool Set and CyclopsE Simulator

As soon as the compiler tool set and CyclopsE simulator are set up, the reader should confirm all tools are working properly. For this purpose there is a test suite consisting of 140 programs (89 C, 2 C++, and 49 fortran) and a script, `test-sim.sh` that compiles and runs in the simulator every single program. At the end, it prints out a report with the number of successes and compilation and simulation failures. To start with the test just type on the command line:

```
cd ~/cyclops/src/testsuites/                                    (8)
./test-sim.sh
```

At the time of writing, two programs run fail: `it_memacc.c` and `20001201.f`. You might get some other failures but this is no reason for concern. A problem with the installation usually causes a whole bunch of programs to fail. Should that be the case, the reader have to go back to appendix A and start the process again.

B.4 Testing the CeDIMES SDK Installation

After the latest version of the RTS libraries are installed, and the stand-alone boot loader is built (`make run`), a similar test to that performed above can be carried out. First, we use the simulator as target platform:

```
cd ~/cyclops/src/testsuites/                                    (9)
./test-sim.sh -lcrts
```

Note the extra parameter provided in this case. It tells the script to link the new RTS library (adding a -lcrts switch). Not providing such a parameter will cause compilation failures for all the programs.

The CeDIMES board can also be used to run the test programs. To do so type:

```
cd ~/cyclops/src/testsuites/                                    (10)
./test-board.sh
```

Once both tests are completed, the reader will see similar reports as before. The results are not the same though. For instance, there are some programs that would had hang up if they were executed on the board. To prevent the second script from stalling, these "bad" programs are skipped, hence the last number reported. Additional failures or problems are also due to the RTS requiring more memory or the unavailability of services such as file I/O. Nonetheless, an occasional run fail should not discourage the reader, since in the end it also validates the installation.

Testing the CeDIMES Run-Time System

The multithreading capabilities of the CeDIMES run-time system are not tested by default. Yet, a set of simple programs aim to testing specific functionality such as thread creation and termination, mutex handling, and elapsed time measurement, is also ready to be used. The procedure to kick off the testing script is similar as before.

```
cd ~/cyclops/src/testsuites/                                    (11)
./test-board.sh rts
```

In this case thirteen programs are compiled and executed on the board, of which, `mutex_long1` and `mutex_long2` take 10 and 8 minutes, respectively to complete. Obviously, no error should occur.

Finally, to verify the correct operation of the atom table a specific CeDIMES tool has to be build, as well as the program to be run on the board. All this can be done by typing:

```
cd ~/cyclops/src/dimes/                                         (12)
make clean
make board
cyclopsE-linux-elf-gcc -o atom_table mon/examples/atom_table.c -lcrts
./dimes-board atom_table
```

Intentionally, we made the source code for these programs easy to read and find (they are all available in `./dimes/mon/examples`), so programmers can learn fast how to write their own programs with the CeDIMES SDK.

C Cyclops Thread Library Reference Information

cthread_ret_code cthread_create(cthread_t *thread, void *(*start_routine)(void *), void *arg)

Runs the user provided function in next available thread unit. If no thread unit is available, it returns an error condition. One parameter can be passed to the thread function.

cthread_ret_code cthread_exit(void *status)

Caller thread terminates its execution returning and the exit status specified by *retval* is made available to any successful join with the terminating thread.

cthread_ret_code cthread_join(cthread_t thread, void **status)

Caller is waits for the target thread to terminate. If it returns succesfully, the value passed to **cthread_exit()** by the terminating thread will be placed in the location referenced by *thread_return*.

cthread_ret_code cthread_self(void)

Returns own thread ID (11bits).

cthread_ret_code cthread_sleep(const cycles_t cycles)

Caller thread is suspended for a given number of clock cycles, maximum 255, or indefinitely if *cycles* is 0.

cthread_ret_code cthread_resume(const cthread_t thread)

Awakes a suspended thread.

cthread_ret_code cthread_sync(void)

Waits for all accesses to memory, that were initiated by the calling thread, to be completed in memory. All this function does is a SYNC instruction.

cthread_ret_code cthread_mutex_init(cthread_mutex_t *mutex)

Initializes a mutex object.

cthread_ret_code cthread_mutex_destroy(cthread_mutex_t *mutex)

Destroys a mutex object.

cthread_ret_code cthread_mutex_lock(cthread_mutex_t *mutex)

Locks a mutex. If the mutex is already locked, the calling thread will block until the mutex becomes available.

cthread_ret_code cthread_mutex_trylock(cthread_mutex_t *mutex)

This function is identical to **cthread_mutex_lock()** except that if the mutex is currently locked, the call returns immediately.

cthread_ret_code cthread_mutex_unlock(cthread_mutex_t *mutex)

Unlocks a mutex, if this was previously locked by the calling thread.

cclock_t cclock_t cclock_n(void)
Returns clock ticks (1 tick = 2ns).

cclock_t cclock_t cclock_u(void)
Returns the number of microseconds since the board was reset.

void *cmem_malloc (const tag_t tag, const size_t size)
Allocates dynamic memory and assigns it the tag *tag*.

void cmem_free (const tag_t tag)
Frees dynamic memory it *tag* matches.

D Monitor-Enabled Cyclops Run-Time System

To debug applications using CeDIMES SDK, first you have to enable the monitor functionality of the RTS, which is disabled by default, and build the corresponding library.

Once the SDK is installed the procedure to get monitor support is quite simple:

cd into the `./dimes/mon` directory. Edit `Makefile`. Go to line #31 and enable the variable declaration `EXTRA_FLAGS = -DECY_RTS_MONITOR`. In file `crt0.S`, uncomment the symbol definition `ECY_RTS_MONITOR=yes` in line #24. Finally, type on the command line:

```
make crt0                                                    (13)
make mon
```

to get the RTS and monitor libraries compiled and installed properly for you. Hereafter, you should append the library flags `-lcrts` and `-lcmon` to all your linker commands when building a program with debug support. Be aware that this procedure has to be undone whenever monitor support is not needed any more.