A Processor Extension for Cycle-Accurate Real-Time Software

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Basic Idea

Q: How do you make software run at a precise speed?

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A: Give it access to a clock.

One Usual Way: Timers

Period timer interrupt triggers scheduler

Large period reduces overhead

Linux uses a 10 ms clock

Result: OS provides 10 ms resolution at best

Higher precision requires more overhead

Or NOPs/cycle counting

Code from Linux arch/i386/kernel/timers/timer_none.c

```
delay_none:
 0:   push   %ebp
 1:   mov    %esp,%ebp
 3:   sub    $0x4,%esp
 6:   mov    0x8(%ebp),%eax
 9:   jmp    10

10:   jmp    20

20:   dec    %eax
21:   jns    20

23:   mov    %eax,-4(%ebp)
26:   leave
27:   ret
```

Tricky

Clock speed + cache behavior + branch behavior + ?

This example worries about cache alignment

Very much an assembly-language trick

1000s of lines of code in Linux needed for busy wait

Related Work: Giotto

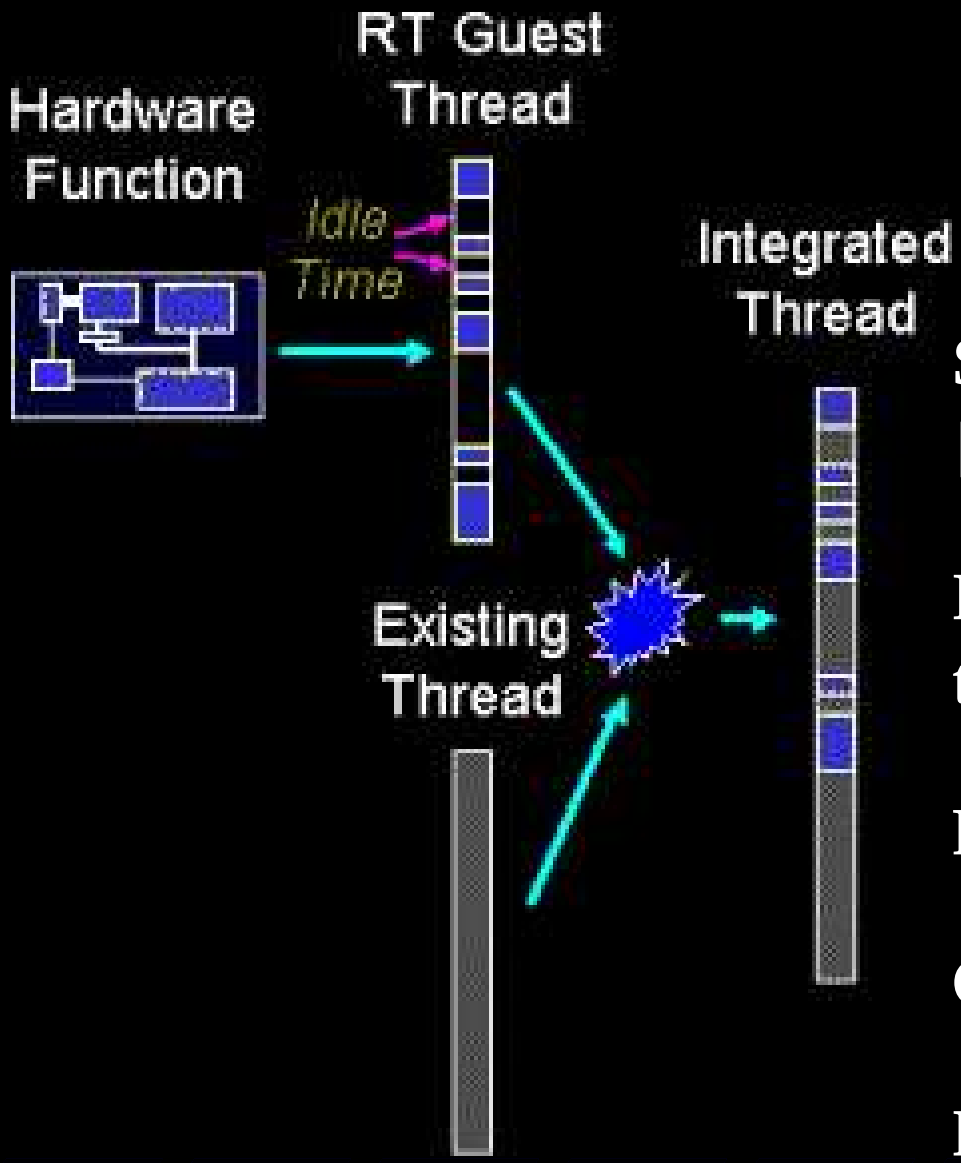
Giotto [Henzinger, Horowitz, Kirsch, Proc. IEEE 2003]

The RTOS style: specify a collection of tasks and modes. Compiler produces schedule (task priorities).

Precision limited by periodic timer interrupt.

```
mode forward() period 200 {
  actfreq 1 do leftJet(leftMotor);
  actfreq 1 do rightJet(rightMotor);
  exitfreq 1 do point(goPoint);
  exitfreq 1 do idle(goIdle);
  exitfreq 1 do rotate(goRotate);
  taskfreq 2 do errorTask(getPos);
  taskfreq 1 do forwardTask(getErr);
}
```

Related Work: STI



Software Thread Integration [Dean, RTSS 1998]

Insert code for a non-real-time thread into a real-time thread.

Pad the rest with NOPs

Often creates code explosion

Requires predictable processor

Related Work: VISA

VISA [Meuller et al., ISCA 2003]

Run two processors:

- Slow and predictable
- Fast and unpredictable

Start tasks on both.

If fast completes first, use extra time.

If fast misses a checkpoint, switch over to slow.

Our Solution/Processor

MIPS-like processor with 16-bit data path as proof of concept

One additional “deadline” instruction:

dead *timer*, *timeout*

Wait until *timer* expires, then immediately reload it with *timeout*.

Programmer's Model

General-purpose Registers

15 0

$0 (= 0)
$1
$2
⋮
$13
$14
$15

Timers

15 0

$t0
$t1
$t2
$t3

Program counter

15 0

$pc

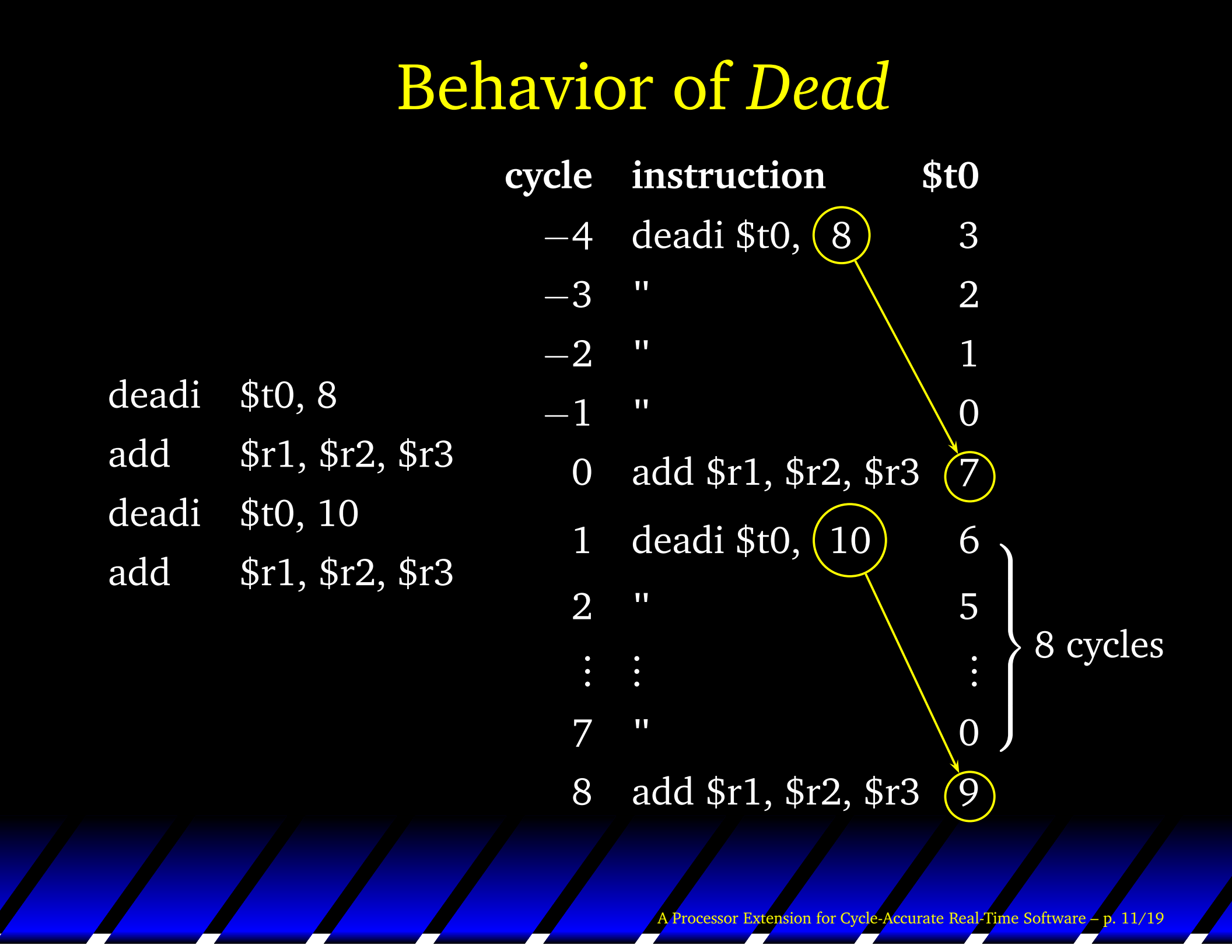
Instructions

add	Rd, Rs, Rt	or	Rd, Rs, Rt
addi	Rd, Rs, imm16	ori	Rd, Rs, imm16
and	Rd, Rs, Rt	sb	Rd, (Rt + Rs)
andi	Rd, Rs, imm16	sbi	Rd, (Rs + offset)
be	Rd, Rs, offset	sll	Rd, Rs, Rt
bne	Rd, Rs, offset	slli	Rd, Rs, imm16
j	target	srl	Rd, Rs, Rt
lb	Rd, (Rt + Rs)	srli	Rd, Rs, imm16
lbi	Rd, (Rs + offset)	sub	Rd, Rs, Rt
mov	Rd, Rs	subi	Rd, Rs, imm16
movi	Rd, imm16	dead	T, Rs
nand	Rd, Rs, Rt	deadi	T, imm16
nandi	Rd, Rs, imm16	xnor	Rd, Rs, Rt
nop		xnori	Rd, Rs, imm16
nor	Rd, Rs, Rt	xor	Rd, Rs, Rt
nori	Rd, Rs, imm16	xori	Rd, Rs, imm16

Behavior of *Dead*

```
deadi   $t0, 8
add     $r1, $r2, $r3
deadi   $t0, 10
add     $r1, $r2, $r3
```

cycle	instruction	$t0
−4	deadi $t0, 8	3
−3	"	2
−2	"	1
−1	"	0
0	add $r1, $r2, $r3	7
1	deadi $t0, 10	6
2	"	5
⋮	⋮	⋮
7	"	0
8	add $r1, $r2, $r3	9



Idioms: Straightline Code

```
deadi   $t0, 42
  ⋮
deadi   $t0, 58
  ⋮
deadi   $t0, 100
```

First block will take at least 42 cycles.

Second block: at least 58 cycles.

Idioms: Loops

```
L1:
        ⋮
        deadi   $t0, 42
        ⋮
        bne     $r1, $r2, L1
```

Put a deadline in a loop:

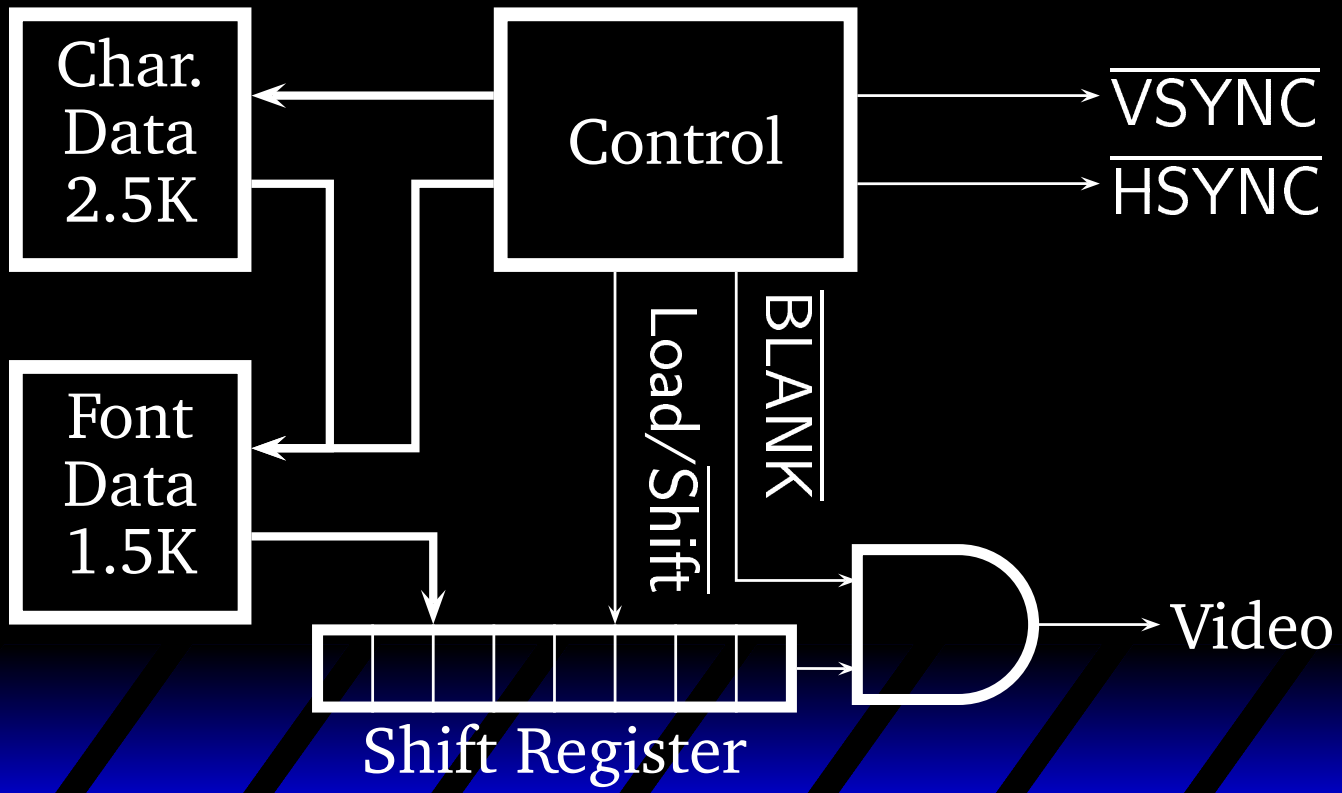
Each iteration will take at least 42 cycles.

Case Study: Video

80 × 30 text-mode display

25 MHz pixel clock

Pixel shift register in hardware; everything else in software



Case Study: Video

```
   movi   $2, 0              ; reset line address
row:
   movi   $7, 0              ; reset line in char
line:
   deadi  $t1, 96            ; h. sync period
   movi   $14, HS+HB
   ori    $3, $7, FONT       ; font base address
   deadi  $t1, 48            ; back porch period
   movi   $14, HB
   deadi  $t1, 640           ; active video period
   mov    $1, 0              ; column number
char:
   lb     $5, ($2+$1)        ; load character
   shli   $5, $5, 4          ; *16 = lines/char
   deadi  $t0, 8             ; wait for next character
   lb     $14, ($5+$3)       ; fetch and emit pixels
   addi   $1, $1, 1          ; next column
   bne    $1, $11, char
   deadi  $t1, 16            ; front porch period
   movi   $14, HB
   addi   $7, $7, 1          ; next row in char
   bne    $7, $13, line      ; repeat until bottom
   addi   $2, $2, 80         ; next line
   bne    $2, $12, row       ; until at end
```

Two nested loops:

- Active line
- Character

Two timers:

- $t1 for line timing
- $t0 for character output

78 lines of assembly

Replaces 450 lines of VHDL (1/5th)

Case Study: Serial Receiver

```
   movi $3, 0x0400      ; final bit mask (10 bits)
   movi $5, 651         ; half bit time for 9600 baud
   shli   $6, $5, 1     ; calculate full bit time

wait_for_start:
   bne   $15, $0, wait_for_start
got_start:
   wait  $t1, $5        ; sample at center of bit
   movi $14, 0          ; clear received byte
   movi $2, 1           ; received bit mask
   movi $4, 0           ; clear parity
   dead $t1, $6         ; skip start bit
receive_bit:
   dead $t1, $6         ; wait until center of next bit
   mov  $1, $15         ; sample
   xor    $4, $4, $1    ; update parity
   and   $1, $1, $2     ; mask the received bit
   or     $14, $14, $1  ; accumulate result
   shli   $2, $2, 1     ; advance to next bit
   bne   $2, $3, receive_bit
check_parity:
   be     $4, $0, detect_baud_rate
   andi  $14, $14, 0xff  ; discard parity and stop bits
```

Sampling rate under software control

Standard algorithm:

1. Find falling edge of start bit
2. Wait half a bit time
3. Sample
4. Wait full bit time
5. Repeat 3. and 4.

Implementation

Synthesized on a Xilinx Spartan-3 FPGA

Coded in VHDL

Runs at 25 MHz

Unpipelined

Uses on-chip memory

Conclusions

- Instruction-level access to timers enable precise real-time control
- *Dead* instruction waits for timeout, then reloads synchronously
- Prototype MIPS-like processor runs at 25 MHz
- Text-mode video display 1/5 the size of VHDL
- Serial controller similarly simple

Future Work

- Implementing extension on an H8-compatible processor
- GCC development chain
- Direct access to *dead* instruction in C