Implementation of Real-Time Systems

Real-Time Requirements

- A real-time specification will include certain time constraints, such as:
  - Relative to a designated event (or to some absolute time, which can be regarded as an event):
    - An event should not occur *until* a given time has elapsed.
    - An event should should not occur *after* a given time has elapsed.
    - A certain computational activity must take place before an event.
  - Responding to one kind of event takes priority over responding to another.

How do processors deal with such constraints?

- Responding to external events:
  - **Polling**: Processor cycles through a series of tests for external flags raised by events. The time of a cycle can be determined by counting machine cycles and knowing the clock rate.
  - **Interrupts**: Raising a flag causes an interrupt, which directs the processor to an appropriate ISR (Interrupt Service Routine)

How do processors deal with such constraints?

- Timing:
  - Processors incorporate a clock running at a known rate. Therefore it is simple to construct an **interval timer**, which counts the number of ticks elapsed:

    elapsed time = # of ticks / clock rate
    (in ticks per sec)

How do processors deal with such constraints?

- An interval timer can be:
  - sampled for elapsed time
  - generate an interrupt when it has counted down to 0, given a set initial value
    - The latter are often called “watchdog” timers.
- Dedicated external timers may also be used and sampled by the processor.

Example: Interval Timers in Solaris

- #include <sys/time.h>
- int getitimer(int which,
  struct itimerval *value);
- int setitimer(int which,
  const struct itimerval *value,
  struct itimerval *ovalue);

Example: Interval Timers in Solaris

- struct itimerval is defined to include:
  - struct timeval it_value;   /* current value */
    - time until next expiration
  - struct timeval it_interval; /* timer interval*/
    - time to reload when interval expires
- struct timeval includes:
  - time_t tv_sec   /* seconds */
  - long   tv_nsec   /* nanoseconds */

Example: *More* Interval Timers in Solaris

- int timer_create(clockid_t clock_id,
                      struct sigevent *evp,
                      timer_t *timerid);

  where clock_id is one of:
  - CLOCK_REALTIME (wall clock)
  - CLOCK_VIRTUAL (user CPU usage)
  - CLOCK_PROF (user and system CPU)

Example: More Interval Timers in Solaris

- int timer_settime(timer_t timerid,
              int flags,
              const struct itimerspec *value,
              struct itimerspec *ovalue);
- int   timer_gettime(timer_t   timerid,
              struct   itimerspec *value);
- int timer_getoverrun(timer_t timerid);

Example microprocessor widely-used for real-time

Intel 8051 (MCS-51 family)

- 40-pin package
- 8-bit word length
- 1 instruction = 2 bytes
- 4k bytes ROM (set at factory per user spec.)
- 128 bytes RAM (on chip)
- 64K RAM addressing limit
- 32 I/O lines
- 2 16-bit timers, which work in various modes
- 5 interrupt sources (2 external)
- 1 duplex serial port

Intel 8051

- Each processor cycle has 6 states x 2 phases = 12 ticks.
- Timers are *incremented* once per cycle.
- Timers can also be used as event counters.

Intel 8051

- Events that can trigger interrupt:
  - Timer 0 Overflow.
  - Timer 1 Overflow.
  - Reception/Transmission of Serial Character.
  - External Event 0.
  - External Event 1.
- Each type of interrupt has a different ISR address.
- Interrupts can be disabled individually.
- Interrupt priorities are set in registers.

Intel 8051
Interrupt Sequence

- On interrupt:
  - The current Program Counter is saved on the stack, low-byte first (yes, there is a stack-pointer register).
  - Interrupts of the same and lower priority are blocked.
  - In the case of Timer and External interrupts, the corresponding interrupt flag is cleared.
  - Program execution transfers to the corresponding interrupt handler vector address.
  - The Interrupt Handler Routine executes.
- On return:
  - Two bytes are popped off the stack into the Program Counter to restore normal program execution.
  - Interrupt status is restored to its pre-interrupt status.

Intel 8051

- Programming: C or Assembler
- Many derivatives, by several vendors
- Extension: 8052 (additional capabilities)
- Tutorial:
  `http://www.8052.com/tut8051.htm`

Real-Time Operating Systems

Real-Time Operating Systems

- INTEGRITY (Green Hills Software)
- QNX (QNX Software Systems)
- RT-Mach (CMU)
- RTMX O/S (Open BSD + Realtime extensions)
- Solaris (Sun)
- Spring Kernel (U. of Massachusetts)
- VRTX (Mentor Graphics)
- VxWorks (Wind River Systems)
  and many, many others
- Some links:
  `http://www.cis.ksu.edu/~gxa2007/os/realtime.html`

Requirements for RTOS's

- Multi-threading with:
  - priorities
  - preemption (including of the kernel itself)
  - programmable scheduling
  - predictable thread-switching latency
  - synchronization and mutual exclusion mechanism that have predictable delay
  - priority inheritance mechanism
- Timers that can trigger events
- Interrupt handlers (also predictable)

Examples from VxWorks

- VxWorks processes are similar to threads in that they all share a common memory space.
- VxWorks provides time-sliced (round-robin) process scheduling, with preemption based on priority.
- The scheduler can be disabled on a per-task basis by calling
  taskLock() and taskUnlock()

Examples from VxWorks

- Task spawning is currently not Posix:
  - taskSpawn(name, priority, options, stacksize, main, arg1, …, arg10): create and activate a new thread
  - taskOptionsSet()
  - taskSuspend(), taskResume(), taskRestart(), taskDelay()
  - nanosleep()

Examples from VxWorks

- Semaphores have a timeout option:
  - If no one posts the semaphore within the specified timeout period, the waiting task continues anyway (without decrementing the value)
- For a non-binary semaphore, semFlush() wakes up all waiting processes.
- Semaphore queue can be specified as either Priority Queue or FIFO.
- Priority inheritance is an option with Priority queue semaphores.

Examples from VxWorks

- Posix semaphores are also available
- Message queues and pipes are available
- Watchdog timers:
  - Run for a settable length of time.
  - If not cancelled within that time, a settable function is called.

A tale of Priority Inversion in VxWorks

- “What really happened on Mars”, *etc*.

  http://www.research.microsoft.com/research/os/mbj/Mars_Pathfinder/

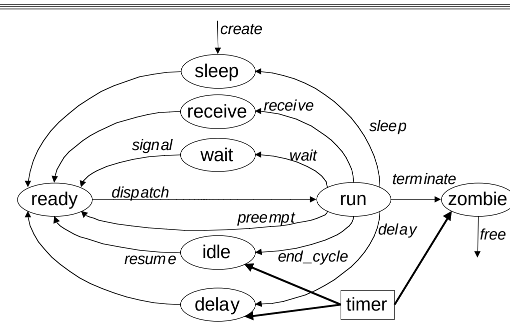
RT case study

Structure of DiCK (Didactic C Kernel)

(from Buttazzo, Hard Real-Time Computing Systems, Kluwer, 1997)

system call layer	creation termination	communication synchronization	utility services
processor management	scheduling		dispatching
	list management		
machine layer	creation termination	communication synchronization	utility services

DiCK Process State Transitions

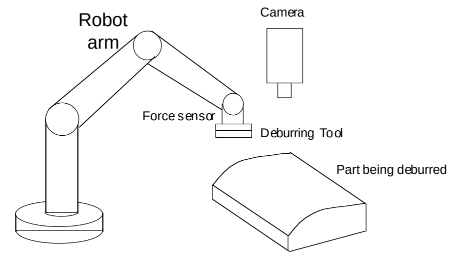


Robot Control Example

(from Buttazzo, Hard Real-Time Computing Systems, Kluwer, 1997)

- Puma 560 robot arm with wrist force/torque sensor
- CCD camera
- Arm has to exert desired forces on the object surface and follow the surface contour using visual feedback from a camera, e.g. in a deburring operation.

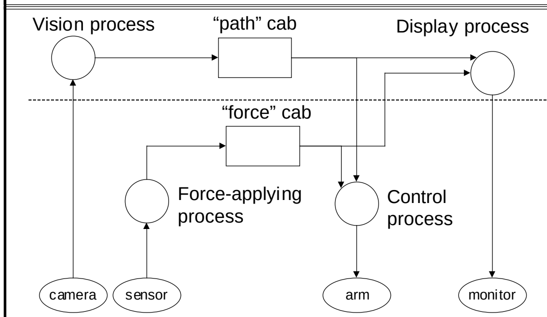
Robot Arm with Deburring Tool



Robot Control

- Organization:
  - Two servo loops communicating via “cabs”
  - Low-level loop:
    - image acquisition
    - force reading
    - robot control
  - High-level loop:
    - scene analysis
    - surface reconstruction

Process Structure



CAB = Cyclical Asynchronous Buffer

- One-to-many communication channel
- At each instant contains the latest message or data inserted
- Message is not consumed; it remains in the CAB until over-written.
- No blocking on either writing or reading.

CAB (2)

- If receiver is faster than sender, the same message may be reread multiple times.
- If sender is faster, a message can be overwritten before it has been read.
- The structure of a CAB guarantees the semantics of reading an integral datum or message, as opposed to a hybrid.
- The inner workings reveal multiple buffers.

Examples where CABs are Useful

- **Graphics**: Multiple updates to the screen per physical refresh: If update is slow, don't want to see stale information; just get the latest.
- **Vision**: Multiple frame updates per use if processing is slow.
- **Sensing**: Device constantly produces new information whether or not requested.

CAB Primitives (1)

- Insert a message:
  - Task must reserve a buffer from the CAB
  - Copy message into the buffer
  - Put the buffer into the CAB structure as most-recent
  - Code:

```
buf_pointer = reserve(cab_id);
… put message into *buf_pointer …
putmes(buf_pointer, cab_id);
```

CAB Primitives (2)

- Get a message:
  - Get the pointer to the most recent message
  - Use data in the message
  - Release the pointer
  - Code:

```
mes_pointer = getmes(cab_id);
… use message from *mes_pointer
unget(mes_pointer, cab_id);
```

CAB Primitives (3)

- The maximum number of buffers is specified in the open_cab primitive.
- This should be 1 more than the number of tasks that write to the CAB.

Robotic Application Processes

- **Sensor process**: periodically reads force/torque sensor into "force" CAB.
  - Must have guaranteed execution time: 20 ms. period. Missing causes instability.
- **Vision process**: periodically reads CCD buffer and computes next direction. Data put in "path" CAB.
  - Must have period of 80 ms.
  - Missing deadline causes tracking to fail.

Robotic Application Processes

- **Robot control process**: Computes target points for arm. Hybrid position/force control moves end-effector along a direction tangential to the object surface, applying a force normal to the surface all the while.
  - 28 ms period, imposed by the communication protocol of the robot
  - Missed deadline could cause gouging or breakage.

Robotic Application Processes

- **Surface representation process**: based on force/torque data and the direction being pursued.
  - Soft task with period 60 ms.

Program using the “DiCK” (Didactic C Kernel) primitives

(from Buttazzo, Hard Real-Time Computing Systems, Kluwer, 1997)

```
#include “dick.h”
#define TICK          1.0   /* system tick (1 ms)    */
#define T1           20.0   /* period for force      */
#define T2           80.0   /* period for vision     */
#define T3           28.0   /* period for control    */
#define T4           80.0   /* period for display    */
#define WCET1       0.300   /* exec time for force   */
#define WCET2       4.780   /* exec time for vision  */
#define WCET3       1.183   /* exec time for control */
#define WCET4       2.230   /* exec time for display */
```

Program (2)

```
cab   fdata;     /* CAB for force data              */
cab   angle;     /* CAB for path angles             */
proc  force;     /* force sensor acquisition        */
proc  vision;    /* camera acquisition & processing */
proc  control;   /* robot control process           */
proc  display;   /* robot trajectory display        */
```

Program (3)

```
proc main()
{     ini_system(TICK);
      fdata = open_cab(“force”, 3*sizeof(float), 3);
      angle = open_cab(“path”,    sizeof(float), 3);
      create(force,   HARD, PERIODIC, T1, WCET1);
      create(vision,  HARD, PERIODIC, T2, WCET2);
      create(control, HARD, PERIODIC, T3, WCET3);
      create(display, HARD, PERIODIC, T4, WCET4);
      activate_all();
      while( sys_clock() < LIFETIME ) /* do nothing */ ;
      end_system();
}
```

Program (4)

```
proc force()
{
float* fvect;
      while( 1 )
            {
            fvect = reserve(fdata);          CAB command
            read_force_sensor(fvect);
            putmes(fvect, fdata);
            end_cycle();                     Turn over control
            }                                to scheduler
}
```

Program (5)

```
proc control()
{
float *fvect, *alfa;
float x[6];
      while( 1 )
            {
            fvect = getmes(fdata);           CAB commands
            alfa = getmes(angle);
            control_law(fvect, alfa, x);
            send_robot(x);
            unget(fvect, fdata);
            unget(alfa, angle);
            end_cycle();
            }
}
```

Program (6)

```
proc vision()
{
float *alfa;
char image[256][256];
      while( 1 )
            {
            get_frame(image);
            alfa = reserve(angle);          CAB commands
            *alfa = compute_angle(image);
            putmes(alfa, angle);
            end_cycle();
            }
}
```

Program (7)

```
proc display()
{
float *fvect, *alfa;
float point[3];
      while( 1 )
            {
            fvect = getmes(fdata);          CAB commands
            alfa = getmes(angle);
            surface(fvect, *alfa, point);
            draw_pixel(point);
            unget(fvect, fdata);
            unget(alfa, angle);
            end_cycle();
            }
}
```

Languages & Models for Real-Time Systems

Why look at Languages?

- A language can be considered to be a large class of specific applications.
- If the language is properly implemented, the applications are implemented as a consequence.

Why Models?

- A model is an abstract version of the solution to a problem.
- Models are often prologues to being able to express the application in a specific language.

Ada 95 Language Features Pertinent to Real-Time and Parallelism

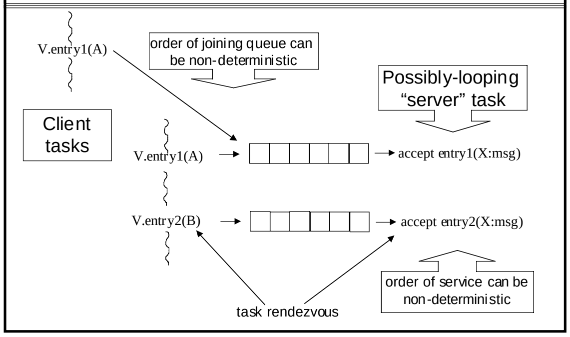
(see http://www.adahome.com/rm95/rm9x-toc.html)

- Tasking (threads), dynamic priorities
- **accept** statement: task interacts with environment
- **select** statement: respond to alternate requests (non-deterministically)
- **delay** option: specifies minimum time delay
- **when** clause: part of case statement

Ada speak

- **entry**: declaration of an interaction point with a task type
- entry-call:
  taskName.entryName(…params…)
- **accept**:
  code for servicing an entry & rendezvous
- **select**:
  code for choosing among entries (implicitly queued) and delays.

Diagrammatic Model of Typical Ada Processing by Loop



Non-determinism using Select

```
task Protected_Variable is
  entry Read(X: out Item);
  entry Write(X: in Item);
end;

PV: Protected_Variable;

PV.Read(A)

PV.Write(B)
```

Note: Implicit queuing of entry calls.

```
task body Protected_Variable is
  V: Item;
begin
  accept Write(X: in Item) do
    V := X;
  end;
  loop
    select
      accept Read(X: out Item) do
        X := V;
      end;
    or
      accept Write(X: in Item) do
        V := X;
      end;
    end select;
  end loop;
end Protected_Variable;
```

Semaphore in Ada

Guarantees mutual exclusion

```
protected type Semaphore (Start_count :Integer := 1) is
    entry wait;
    procedure signal;
    function Count return integer;
private
    Current_count :integer := start_count;
end;

protected body Semaphore is
    entry wait when Current_count > 0 is
    begin
        Current_Count := Current_count - 1;
    end;

    entry signal is
    begin
        Current_Count := Current_count + 1;
    end;
end Semaphore;
```

Non-determinism + Termination

Used only if other entries uncallable.

```
task body Protected_Variable is
  V: Item;
begin
  accept Write(X: in Item) do
    V := X;
  end;
  loop
    select
      accept Read(X: out Item) do
        X := V;
      end;
    or
      accept Write(X: in Item) do
        V := X;
      end;
    or
      terminate;
    end select;
  end loop;
end Protected_Variable;
```

"Unconditional" Alternative

```
task multiple_entry is
        entry increment;
        entry decrement;
    end multiple_entry;

    task body multiple_entry is
        i : integer;
    begin
        select
            accept increment;
            i := i + 1;
        or
            accept decrement do
                i := i - 1;
            end decrement
        else
            perform_some_processing;
        end select;
    end;
```

Selected if no other *current* alternatives.

“when” conditions

```
task body Buffering is
  N: constant := 8;        -- for instance
  A: array (1 .. N) of Item;
  I, J: Integer range 1 .. N := 1;
  Count: Integer range 0 .. N := 0;
begin
  loop
    select
      when Count < N =>
      accept Put(X: in Item) do
        A(I) := X;
      end;
      I := I mod N+1; Count := Count+1;
    or
      when Count > 0 =>
      accept Get(X: out Item) do
        X := A(J);
      end;
      J := J mod N+1; Count := Count-1;
    end select;
  end loop;
```

“when” conditions: readers/writers

```
task body Control is
  Readers: Integer := 0;
begin
  accept Write(X: in Item) do
    V := X;
  end;
  loop
    select
      accept Start;
      Readers := Readers+1;
    or
      accept Stop;
      Readers := Readers-1;
    or
      when Readers = 0 =>
      accept Write(X: in Item) do
        V := X;
      end;
    end select;
  end loop;
end Control;
```

Delay Alternative

```
select
  accept Read( ... ) do
  ...
  end;
or
  accept Write( ... ) do
  ...
  end;
or
  delay 10*Minutes;
  -- time out statements
end select;
```

Selected if no other alternatives within indicated time

Autonomous Periodic Tasks (one loop for each task)

```
task body Periodic_Task is
  Next_Time : Calendar.Time := Task_Start_Time;
begin
  delay (Task_Start_Time - Calendar.Clock);
  loop
    -- do work
    Next_Time := Next_Time + Task_Period;
    delay (Next_Time - Calendar.Clock);
  end loop;
end Periodic_Task;
```

Not the same delay as in the select statement.

Problem with Previous Approach

- Delay jitter:
  - A task can be preempted between reading clock and starting its delay, making the delay end later than planned.
  - Cumulative effect is that deadlines can be missed.
  - A better approach is to use a central dispatcher task.

Dispatcher Model

```
task body Periodic_Dispatcher is
begin
  loop
    accept Clock_Interrupt;
    loop
      -- Determine which task to activate next
      select
        Selected_Task.Activate;
      else
        -- Handle missed deadline
      end select;
    end loop;
  end loop;
end Periodic_Dispatcher
```

Highest Priority

```
task body Periodic_Task is
begin
  loop
      accept Activate;
    end loop;
end Periodic_Task
```

Better Model: Use builtin *delay_until*

```
task body Periodic_Task is
  Next_Time : Calendar.Time := Task_Start_Time;
begin
  delay_until (Task_Start_Time);
  loop
    -- do work
    Next_Time := Next_Time + Task_Period;
    begin
      delay_until (Next_Time);
    exception
      when Calendar.Time_Error => -- handle missed deadline;
    end;
  end loop;
end Periodic_Task;
```

Priority Issues

- To get Ada to use the Priority Ceiling Protocol:

  pragma Locking_Policy(Ceiling_Locking);

- Recall that PCP guarantees:
  - Execution of a high-priority task can be delayed by at most one lower priority task per call.

Sources

- A lot of these examples are from:
  ftp://ftp.aw.com/aw.computer.science/Barnes4e/code.txt
  which in turn are from: Barnes, J. G. P. *Programming in Ada*. (4th edition) Addison-Wesley, 1994.
- See also:

  - Ben-Ari, M. Principles of Concurrent and DistributedProgramming. Prentice-Hall International, 1990.
  - Alan Burns and Andy Wellings. Concurrency in Ada. Cambridge University Press, 1995.
  - Kjell Nielsen and Ken Shumate. Designing large real-time systems with Ada. Multiscience Press, Inc. 1988.
  - Mark W. Borger, Mark H. Klein, Robert A. Veltre. Real-Time Software Engineering in Ada: Observations and Guidelines. Tech. Rept. CMU/SEI-89-TR-22, 1989. http://www.sei.cmu.edu/publications/documents/89.reports/89.tr.022.html

Also discusses RMA, PCP