Introduction to Real-Time kernels

Task States
Generic architecture of Real-Time kernels
Typical structures and functions of Real-Time kernels
Last lecture (2)

• Computational models (**real-time model**)
• Real-time tasks: periodic, sporadic and aperiodic
• Temporal constraints of types: **deadline**, window, synchronization and distance
• Implementation of tasks using **multitasking kernels**
• **Logic** and **temporal** control
• **Event-triggered** and **time-triggered** tasks
Task states

**Task creation**

Association between executable code (e.g. a “C” language function) to a private variable space (private stack) and a management structure - *task control block (TCB)*

**Task execution**

Concurrent execution of the task's code, using the respective private variable space, under control of the kernel. The kernel is responsible for activating each one of the task's jobs, when:

- A period has elapsed (periodic)
- An associated external event has occurred (sporadic)
**Task states**

**Execution of task instances (jobs)**

After being activated, task’s jobs wait in a queue (the **ready queue**) for its time to execute (i.e., for the CPU)

The ready queue is sorted by a given criterion (**scheduling** criterion). In real-time systems, most of the times this criterion is **not** the arrival order!
Task states

Task instances may be waiting for execution (ready) or executing. After completion of each instance, the task stay in the idle state, waiting for its next activation.

Thus, the basic set of dynamic states is: idle, ready and execution.
Other states: blocked

Whenever an executing task tries to use a **shared resource** (e.g. a memory buffer) that is already being used in **exclusive mode**, the task cannot continue executing. In this case it is moved to the **blocked state**. It remains in this state until the moment in which the **resource is released**. When that happens the task goes to the **ready state**.
Self suspension (sleep)

In certain applications tasks need to **suspend its execution** for a given amount of **time** (e.g. waiting a certain amount of time after requesting an ADC conversion), before completing its execution. In that case tasks move the **suspended state**.
Basic services

- Task management (create, delete, initial activation, state)
- Time management (activation, policing, measurement of time intervals)
- Task scheduling (decide what jobs to execute in every instant)
- Task dispatching (putting jobs in execution)
- Resource management (mutexes, semaphores, etc.)
Management structures

**TCB (task control block)**

This is a fundamental structure of a kernel. It stores all the relevant information about tasks, which is then used by the kernel to manage their execution.

**Common data (not exhaustive)**

- Task identifier
- Pointer to the code to be executed
- Pointer to the private stack (for context saving, local variables, ...)
- Periodic activation attributes (task type (periodic/sporadic), period, initial phase, etc)
- Criticality (**hard**, **soft**, non **real-time**)
- Other attributes (**deadline**, priority)
- Dynamic execution state and other variables for activation control, e.g. SW timers, absolute deadline, ...
Management structures

**RTKPIC's TCB**

typedef struct {
    unsigned char id; /* task id - 0..14 */
    void (*func_ptr)(void); /* task first instruction address */
    unsigned char state; /* task state */
    unsigned int period; /* task period in ticks */
    unsigned int deadline; /* task deadline relative to activation */
    unsigned long nx_activ; /* task next activation in absolute ticks */
    unsigned long nx_deadline; /* task next deadline in absolute ticks */
    unsigned char priority; /* task priority */
} TASK;

/* Number of tasks */
#define NTASKS 14 /* main + 13 user tasks */

/* Task Control Table */
TASK tcb[NTASKS]
Management structures

**TCB structure**

TCBs are often defined in a *static array*, but are normally *structured* as *linked lists* to facilitate operations and searches over the task set. E.g., the ready queue (list of ready tasks sorted by a given criteria) is maintained as a linked list. These linked lists may be implemented e.g. through indexes. *Multiple lists may (and usually do) coexist!*
Example: TCB structure of RTKPIC18

The RTKPIC18 was designed to handle applications with a small number of tasks. For this reason no lists were implemented. Consequently, whenever it is needed to do a search (e.g. to handle periodic task activations), the whole TCB set must be checked.

/* Tick handler code */
for (temporary_i = 1; temporary_i < n_task; temporary_i++)
{
    temporary_task_i = tcb + temporary_i;
    if (temporary_task_i->nx_activ == system_clock)
    {
        /* new activation */
        if ((temporary_task_i->state == READY) || (temporary_task_i->state == RUN))
            deadline_miss |= (0x01 << temporary_i);
        /* deadline missing */
        temporary_task_i->state = READY;
        temporary_task_i->nx_activ += temporary_task_i->period;
        if ((preempt_sys == PREEMPT) || (run_task_id == 0))
            Call_scheduler = 1;  /* New task READY: Call scheduler */
        if (sch_alg == EDF)
            Call_EDF = 1;        /* Call EDF priority set */
    }
}
Access to shared resources

Exclusive access shared resources (critical sections), have to be managed in an appropriate way, to allow access by only one task in any instant (as for the CPU). A simple way to do it is using atomic flags (mutexes), monitors (non preemptive execution) or semaphores.

For the case of semaphores it is needed a structure (semaphore control block – SCB) that holds its state as well as the list of tasks that are waiting for access.
Management functions

**Time management**

Time management is another critical activity on kernels. It is required to:

- **Activate** periodic tasks
- **Check** if temporal constraints are met (e.g. deadline violations)
- **Measure** time intervals (e.g. self-suspension)

It is based on a **system timer**. This timer can be configured in two modes:

- **Periodic tick**: generates periodic interrupts (**system ticks**). The respective ISR handles the time management. All **temporal attributes** (e.g. period, deadline, waiting times) must be **integer multiples of the clock tick**.

- **Single-shot/One-shot/tickless**: the timer is configured for generating interrupts only when there are periodic task activations or other similar events (e.g. the termination of a task self-suspension interval).
Management functions

**Tick-based systems**

The **tick** defines the system's temporal resolution. Smaller ticks corresponds to better resolutions. E.g. 10ms tick => task periods: $T_1=20\text{ms}$, $T_2=1290\text{ms}$, $T_3=25\text{ms}$

The tick handler is code that is executed periodically. Thus it **consumes CPU time**, representing **overhead** ($C_{\text{tick}}/T_{\text{tick}}$). The bigger the tick, the lower the overhead!!

**Compromise is needed:**

$$\text{tick} = \text{GCD} \left( T_i, \ i=1..N \right)$$

E.g. $T_1=20\text{ms}$, $T_2=1290\text{ms}$, $T_3=25\text{ms}$ => GCD(20,1290,25)=5ms

However it mus be assured that tick > min_tick, which is imposed by the CPU processing capacity!
Measurement of time intervals

In tick-based systems, the kernel keeps a variable that counts the number of ticks since the system boot.

- e.g. in the RTKPIC kernel “unsigned long system_clock”, accessed by the macro get_sys_time()

- **With tick=10ms, this variable wraps around after 1.6 years**

Better precision is achieved if the timer is read directly. However, bigger time ranges may imply using SW managed variables.

E.g. in Pentium CPUs, with a 1GHz clock, the TSC **wraps around after 486 years !!!**
Management functions

**Scheduler**

The scheduler selects *which task to execute* among the (eventually) several ready tasks.

In real-time systems must be based on a deterministic criteria, which must allow computing an upper bound for the time that a given task may have to wait on the ready queue.

![Scheduler Diagram]

- **Scheduler**: Defines the queue order.
- **Ready queue**: Contains tasks ready to be executed.
- **Queue Head**: The first task in the ready queue.
- **
  \[ J_1 \quad J_2 \quad \ldots \quad J_n \]
  
  Depicts the order of tasks in the queue.
Management functions

Dispatch

• Puts in execution the task selected by the scheduler

• For preemptive systems it may be needed to preempt (suspend the execution) of a running task. In these cases the dispatch mechanism must also manipulate the stack.

Tick interrupt

Task 1 executing

Task 1 Stack

Dynamic variables

CPU registers

SP(1)

Task handler

Dispatch function (...) tcb1.SP=SP SP=tcb2.SP

rti

SP(2)

Task 2 Stack

CPU registers

Task 2 starts executing
Based on an older RTOS for X86 developed at the UA (ReTMiK)

- Tick based
- For PIC18FXXX
- Task code is cyclic
- Scheduler is part of the kernel
- Allows preemption control
- IPC via global variables
- Monolithic application (kernel + application code in a single executable file)
SHaRK – Soft and Hard Real Time Kernel
http://shark.sssup.it/

- Research kernel, main objective is flexibility in terms of scheduling and shared resource management policies
- POSIX (partially compat.)
- For x86 (>= i386 with MMU) architectures
- Cyclic task
- Several IPC methods
- Concept of Task Model (HRT, SRT, NRT, per, aper) and Scheduling Module
- Policing, admission control
- Monolithic application

```c
void * TaskBody (void *arg){
  /* Init code */
  while (cond) {
    /* Task code */
    task_endcycle( );
  }
  /* terminates if “cond” */
  return my_val;
}
```
Xenomai: Real-Time Framework for Linux
http://www.xenomai.org/

- Allow the use of Linux for Real-Time applications
- Dynamically loadable modules
- Tasks may execute and kernel or user space
- POSIX (partially compat.)
- Cyclic tasks
- Support to several IPC mechanisms, both between RT and NRT tasks (pipe, queue, buffer, ...)

```c
// A task
void task_a(void *cookie) {
    /* Set task as periodic */
    err=rt_task_set_periodic(NULL, TM_NOW, TASK_A_PERIOD_NS);
    for(;;) { // Forever
        err=rt_task_wait_period(&overruns);
        // Task load
    }
    return;
}

// Main
int main(int argc, char *argv[]) {
    .... // Init code
    /* Create RT task */
    err=rt_task_create(&task_a_desc, "Task a", TASK_STKSZ, TASK_A_PRIO, TASK_MODE);
    rt_task_start(&task_a_desc, &task_a, 0);
    ....
    /* wait for termination signal */
    wait_for_ctrl_c();
    return 0;
}
```
Summary of lecture 3

• The **task states**
  – States and transition diagram

• The **generic architecture** of a RT kernel

• The basic components of a RT kernel, its structure and functionalities

• Some examples: RTKPIC18, SHaRK and XENOMAI