Software Aspects in Control Systems

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Robotic Systems

Implementation of a Control System

The implementation of control systems is based on an algorithm that is characterised by the execution of a **timed loop** of a set of activities:

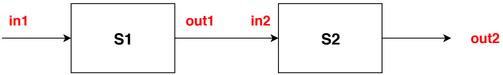
- Starting of the activities on the basis of a **sampling time**, ΔT
- Reading of input variables
- Execution of one step of the control algorithm
- Writing of the results to the outputs

Algorithm

while *True* **do**
  On each ΔT;
  $in \leftarrow read\_input()$;
  $out \leftarrow compute\_control()$;
  $write\_output(out)$;
end

Implementation of a Control System

When the whole system is made of several sub-systems, at first sight, each of them must be implemented in a **different (computational) loop**, and all the loops should be executed **concurrently**



System S1

while *True* **do**
  On each ΔT_1;
  $in1 \leftarrow read\_input1()$;
  $out1 \leftarrow compute\_S1()$;
  $write\_output1(out1)$;
end

System S2

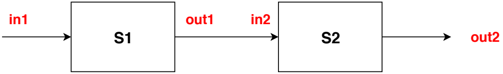
while *True* **do**
  On each ΔT_2;
  $in2 \leftarrow read\_input2()$;
  $out2 \leftarrow compute\_S2()$;
  $write\_output2(out2)$;
end

Since the sub-systems are interconnected, a certain **form of communication** between the "loops" must be implemented: in the case in figure, variable $out1$ of $S1$ is also the input of $in2$ of $S2$.

However, if the periods are the same $\Delta T_1 = \Delta T_2 = \Delta T$, we can "fuse" both the loops:

System S1+S2

while *True* **do**
  On each ΔT;
  $in1 \leftarrow read\_input1()$;
  $out1 \leftarrow compute\_S1()$;
  $in2 \leftarrow out1$;
  $out2 \leftarrow compute\_S2()$;
  $write\_output2(out2)$;
end

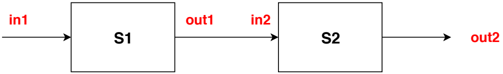


Implementation of a Control System

At the same time, when one of the intervals is a **integer multiple** of the other, $\Delta T_1 = n \Delta T_2$, we can implement the system as:

System S1+S2

while *True* **do**
    On each ΔT_2;
    $count \leftarrow count + 1$;
    if $count = n$ **then**
        $count \leftarrow 0$;
        $in1 \leftarrow read\_input1()$;
        $out1 \leftarrow compute\_S1()$;
    end
    $in2 \leftarrow out1$;
    $out2 \leftarrow compute\_S2()$;
    $write\_output2(out2)$;
end



The Fourier Series

Any (periodic) signal $s(t)$ can be represented as a linear combination of sinusoids and cosinusoids with coefficientes a_i and b_i:

$$s(t) = \frac{a_0}{2} + \sum_{n=1}^{N} [a_n \cos(\frac{2\pi}{T} nt) + b_n sin(\frac{2\pi}{T} nt)]$$

In other words, the original signal can be constructed using a **linear combination of sinusoids at different frequencies**

A signal coming from a sensor can be considered a signal of the type indicated

Choosing the Sampling Time for Sensors

Nyquist–Shannon Sampling Theorem

Any (periodic) signal $s(t)$ can be **reconstructed** when it is **sampled** at a frequency f_{sample} that is **at least two times** the frequency of the sinusoid with maximum frequency

Choosing the Control Period

- The **Control Period** is used in the **discretization** of a system, in which the state matrix A becomes:

$$A' = A\Delta T + I$$

- Since the stability and the behaviour of the discretized system depend on the **eigenvalues** of A', the choice of ΔT plays a fundamental role
- Theoretically ΔT must be chosen by meeting the following (give x the state vector):

$$\frac{\Delta x}{\Delta T} \simeq 0$$

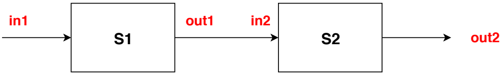
Task Subdivision

Task Subdivision

Software organisation of a control system

- A set of **tasks**, each implementing a single sub-system
- A **scheduling environment** able to execute such tasks each with its **own period**
- A **communication environment** among tasks, able to support data interchange and synchronisation among tasks

Example: Tasks of Control System



Let us consider the system in figure and suppose that $S2$ has a period ΔT, and $S1$ has a period $4\Delta T$

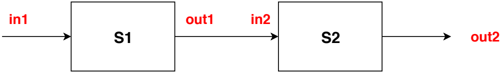
Task_S1()

$in1 \leftarrow read\_input1();$
$out1 \leftarrow compute\_S1();$
$write\_output1(out1);$

Task_S2()

$in2 \leftarrow read\_input2();$
$out2 \leftarrow compute\_S2();$
$write\_output2(out2);$

Example: Scheduling and Communication in a Control System



Let us consider the system in figure and suppose that $S2$ has a period ΔT, and $S1$ has a period $4\Delta T$

System S1+S2

```
while True do
    On each ΔT;
    count ← count + 1;
    if count = 4 then
        count ← 0;
        Task_S1();
        in2 ← out1;
    end
    Task_S2();
end
```

Components

- **Red:** Tasks
- **Green:** Scheduler
- **Blue:** Communication

Task Models

Structured Models

- A **function** (task body) that implements the behaviour of the single system
- A **data structure** that embeds the data about the state of the task/system

Object Model

- A **class** that represents the sub-system with...
- a **main method** (e.g. `run()`) that implements the behaviour of the single system
- a **set of attributes** that embeds the data about the state of the task/system

Managing Periods

A **timer hardware**, configured using the period ΔT, with a procedure that is activated when the timer elapsed:

Adopted Solutions

- A shared global variable, in polling
- A *callback* procedure associated to the timer
- Invocation of blocking procedure that *waits for* the timer event

In any case, a library framework, or an operating system, is needed, able to offer the management of the timer

Managing Periods

Interrupt Service Routine + Polling of a Shared Variable

```
bool timer_elapsed ← false;

TimerISR () begin
    timer_elapsed ← true;
end

Main () begin
    while True do
        if timer_elapsed then
            timer_elapsed ← false;
            // Do the control tasks
        end
    end
end
```

Managing Periods

Callback Procedure associated to the Timer

TimerCallback *()* **begin**

```
// Do the control tasks
```

end

Main *()* **begin**

$SetTimerCallback(\Delta T, TimerCallback)$;

```
// ... do other things
```

end

Managing Periods

Blocking Procedure waiting for the Timer Event

```
Main () begin
    SetupTimer(ΔT);
    while True do
        WaitTimerEvent();
        // Do the control tasks
    end
end
```

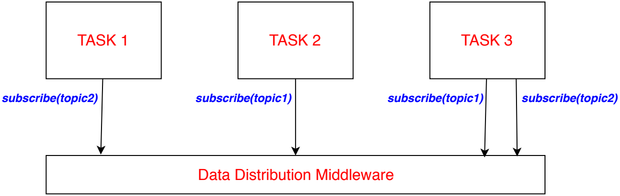
Task Communication

Adopted Solutions

- Shared Variables, with critical sections when the access is done by concurrent tasks
- References amoung objects (when the implementation is object-oriented), with critical sections if needed
- Use of a communication middleware

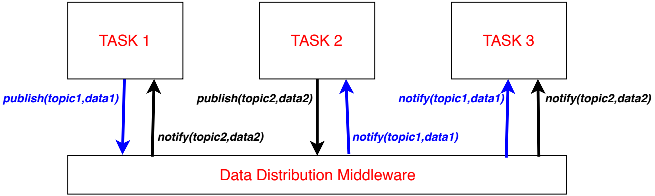
Publisher/Subscriber Model (Data Distribution Model)

- Exchanged data are modelled by means of **structured types** and identified by a **topic**
- Tasks interested in a certain *topic* call a **subscribe** function by specifying the topic itself



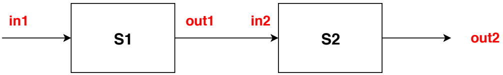
Publisher/Subscriber Model (Data Distribution Model)

- The tasks producing a data with a certain *topic* calls a **publish** function, specifying topic and *data*
- Tasks which have a subscription receive **notify** with published data



Some Communication Middlewares

- **uORB:** communication middleware for embedded systems (centralised)
- **CORBA-DDS (Data Distribution Service):** communication middleware based on a standard by the Object Management Group (centralised and distributed)
- **ROS (Robot Operating System:** communication middleware specifically designed for robotic systems (centralised and distributed)
- **MQTT (Message Queue Telemetry Transport):** a lightweigth standard communication protocol (publisher/subscriber) specifically designed for IoT systems (centralised and distributed)



Task S1

while *True* **do**
- On each ΔT_1;
- $in1 \leftarrow read\_input1()$;
- $out1 \leftarrow compute\_S1()$;
- $publish(''mydata'', out1)$;

end

Task S2

$subscribe(''mydata'')$;
while *True* **do**
- $in2 \leftarrow wait\_data(''mydata'')$;
- $out2 \leftarrow compute\_S2()$;
- $write\_output2(out2)$;

end

Real-Time Operating Systems

Real-Time Operating Systems

- The execution of control tasks requires **guaranteed times**, otherwise the consequences may be dangerous (above all when the system is safety-critical)
- If ΔT_c is the "worst-case" execution times of a task and ΔT its period, then the following must be met: $\Delta T_c < \Delta T$
- However, the remaning time $\Delta T - \Delta T_c$ must be such that the system can perform other activities

Feasibility Condition

- Feasibility condition of N periodic tasks:

$$\sum_{i=1}^{N} \frac{\Delta T_{c_i}}{\Delta T_i} < 1$$

where ΔT_{c_i} is **worst-case execution time** of the task i and ΔT_i is the **periodo** of the task i

Characteristics of Schedulers in **Multi-tasking** RTOSs

- Task Scheduling in RTOS is performed by means of **task priorities**
- Priorities are **fixed** and does not change as it happens instead in "general-purpose" operating systems
- The **priority** is assigned (statically or dynamically) on the basis of the **time characteristics** of the task (i.e. the more "urgent" the task the higher its priority)

Scheduling Policies in RTOS

- **Round-Robin (RR) with Priority:** the scheduler selects the READY task with the highest priority and executes it, preempting it at the next “scheduling tick” (or if the task goes autonomously in “sleep” due to a blocking system call)
- **FIFO (with Priority):** the scheduler selects the READY task with the highest priority and executes it, preempting it only due to a blocking system call

Some RTOSs

- **FreeRTOS.** Real-time Kernel for embedded systems (open-source)
- **NuttX.** Real-time Kernel for embedded systems (open-source, used in autopilots of drones)
- **RTAI.** Real-time Linux Kernel (open-source)
- **QNX.** Real-time Kernel Unix-like (proprietario)
- **VxWorks.** Real-time Kernel Unix-like (proprietario)

Soft Real-Time Scheduling in Linux

Linux System Call to control Scheduling

Set of the Scheduling Policy

```
int sched_setscheduler(pid_t pid, int policy,
                  struct sched_param * param);
```

- **pid**, the process idenitifier of which we want to change the scheduling policy (0 = “this process”)
- **policy**, the scheduling policy: SCHED_OTHER, SCHED_RR, SCHED_FIFO
- **param**, additional parameters, among them the **priority** (from 1 to 99)

Priority

```
struct sched_param {
...
int sched_priority;
...
};
```

Custom Scheduling Example

A main that runs 3 children

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sched.h>

int child_process(int id)
{
  ...
}

int main(int argc, char **argv)
{
    int i, status;
    printf("Starting␣3␣children...\n");

    for (i = 0; i < 3;i++) {
        pid_t pid = fork();
        if (pid == 0) {
            child_process(i);
            exit(0);
        }
    }

    printf("Waiting...\n");
    while (wait(&status) > 0) {};
    printf("End...\n");
}
```

Custom Scheduling Example

```
int child_process(int id)
{
    struct sched_param params;
    int i,k;

#ifdef FIFO
    params.sched_priority = sched_get_priority_max(SCHED_FIFO);
    if (sched_setscheduler(0, SCHED_FIFO, &params) < 0) {
        perror("cannot␣set␣the␣scheduler");
    }
    printf("Setting␣priority␣%d\n", params.sched_priority);
#endif

#ifdef RR
    params.sched_priority = sched_get_priority_max(SCHED_RR);
    if (sched_setscheduler(0, SCHED_RR, &params) < 0) {
        perror("cannot␣set␣the␣scheduler");
    }
    printf("Setting␣priority␣%d\n", params.sched_priority);
#endif

    usleep(500000);
    printf("Child␣%d␣started\n", id);
    for (i = 0;i < 10;i++) { /* 10 iterations */
        printf("Child␣%d,␣iteration␣%d\n", id, i);
        for (k = 0; k < 100000000;k++) {} /* losing time ... */
    }
    return 0;
}
```

Custom Scheduling Example

Test with SCHED_OTHER

```
$ taskset --cpu-list 1 sudo ./sched_test
Starting 3 children...
Waiting...
Child 2 started
Child 2, iteration 0
Child 1 started
Child 1, iteration 0
Child 0 started
Child 0, iteration 0
Child 1, iteration 1
Child 2, iteration 1
Child 0, iteration 1
Child 2, iteration 2
Child 0, iteration 2
Child 1, iteration 2
Child 2, iteration 3
Child 0, iteration 3
Child 1, iteration 3
Child 2, iteration 4
....
End...
```

Custom Scheduling Example

Test with SCHED_FIFO

```
$ taskset --cpu-list 1 sudo ./sched_test
Starting 3 children...
Waiting...
Setting priority 99
Setting priority 99
Setting priority 99
Child 2 started
Child 2, iteration 0
Child 2, iteration 1
Child 2, iteration 2
...
Child 2, iteration 9
Child 1 started
Child 1, iteration 0
Child 1, iteration 1
Child 1, iteration 2
...
Child 1, iteration 9
Child 0 started
Child 0, iteration 0
Child 0, iteration 1
Child 0, iteration 2
...
Child 0, iteration 9
End...
```

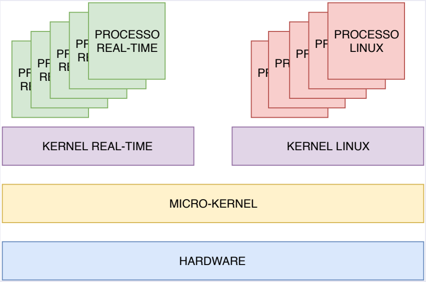
Real-Time Linux

Latencies & RTLinux

- The scheduling policies allow a developer the implementation of soft real-time tasks in Linux
- But some parts of the Linux kernel are not pre-emptible thus uncontrallable latencies can occour
- For example, the management of virtual memory (swapping) introduces unpredictable latencies
- **RTLinux** overcomes such limits by patching some parts of Linux kernel thus allowing the execution of hard real-time tasks

RTAI

- RTAI is widley used to support real-time processes on Linux
- It is a kernel patch that uses the “virtualisation” model
- The Linux kernel is replaced by a micro-kernel upon which the both the “classic” Linux kernel and the real-time Kernel (added by RTAI) run



PREEMPT_RT Patch

- From the release 3.0, the Linux kernel has been made preemptible through a patch provided by te Linux Foundation(*)
- This patch, with the preemption, offers a series of systems calls to support real-time tasks:
  - Suppor for timer and timer-based task
  - Scheduling policies
  - Stack control
  - Memory control

(*) = https://wiki.linuxfoundation.org/realtime/start

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