RTAI: Embedded Linux VS Legacy RTOS

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Introduction

Linux VS RTOS

Linux VS RTOS

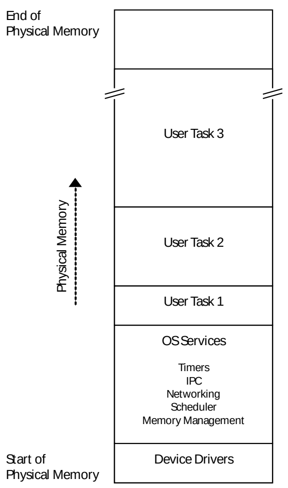
Linux (or Linux Embedded)

- General purpose OS;
- MMU;
- Kernel call through syscall (software interrupt).

RTOS like VxWorks, pSOS, Nucleus

- Special Purpose OS;
- Flat Memory model;
- Kernel call through well defined function calls.

Linux VS RTOS

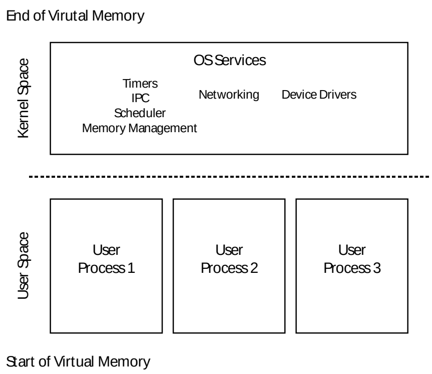


RTOS flat memory model

MAJOR DRAWBACK:

No memory protection

Linux VS RTOS



Linux memory model

QUESTIONS:

RT in kernel space?

…mantain legacy approach

RT in user space?

…exploit memory protection

Linux

From the User Space

As a soft RTOS

Linux

Real-Time constraints in:

- Multimedia application;
- VoIP;
- Audio and videos streaming;
- …

Linux is a soft real-time system.

Linux

Features of an RTOS:

- Multitasking/multithreading
- Priorities
- Priority inheritance
- Preemption
- Interprocess communication and synchronization
- Dynamic memory allocation

Linux

Why Linux isn't (or wasn't soft) Real Time

- Coarse Grained Synchronization
- Paging
- "Fairness" in Scheduling
- Request Reordering
- Batching

Linux User Space Example

Interrupt flow in Linux for a task waiting for an I/O from disk:

- The I/O is complete. The device raises an interrupt. This cause the block device driver's ISR to run.
- The ISR checks the driver wait queue and finds a task waiting for I/O. It then calls one of the wake-up family functions. The function removes the task from the wait queue and adds it to the scheduler run queue.
- The kernel then calls the function `schedule()` when it gets to a point where scheduling is allowed.
- Finally `schedule()` finds the next suitable candidate for running. The kernel context switches to our task if it has sufficient high priority to get scheduled.

Linux User Space Example

Kernel response time:

- Interrupt latency
- ISR duration
- Scheduler latency
- Scheduler duration

…how was (or will be) improved to have a deterministic and possibly low latency response

Linux User Space Example

Interrupt Latency

PROBLEMS:

- Disabling all interrupts for a long time (removal of all global cli in kernel 2.5);
- Registering a fast interrupt handler by improperly written device driver (mostly a programmer error).

Linux User Space Example

ISR duration

SOLUTION:

Interrupt handler in two stages

BUT:

Soft irq are not deterministic

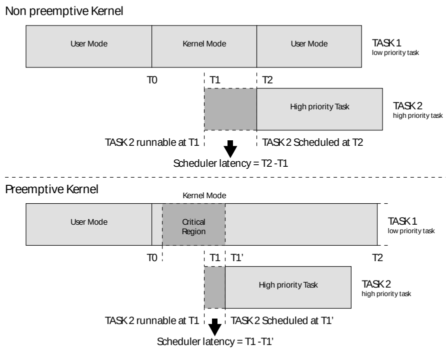
Linux User Space Example

Scheduler latency

PROBLEMS:
- Nonpreemptive nature of the kernel
- Interrupt disable times

SOLUTIONS:
- Kernel Preemption – by Robert Love
- Low-Latency Patches – by Ingo Molnar and Andrew Morton

Linux User Space Example



Scheduler latency in preemptable and nonpreemptable kernels

Linux User Space Example

Scheduler duration

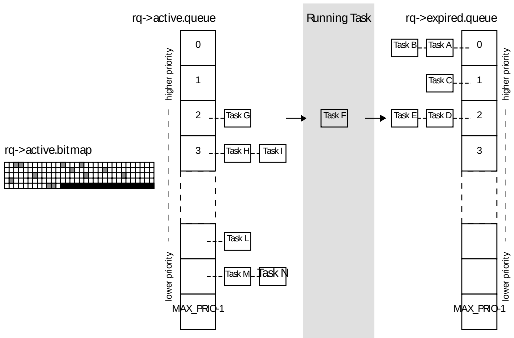
PROBLEMS:

- Non deterministic and slowly goodness and recalculation loop
- Different context switch time between processes and threads (no solution)

SOLUTION:

O(1) Scheduler – Ingo Molnar

Linux User Space Example



Scheduler latency in preemptable and nonpreemptable kernels

Linux

Not only User Space

Approaches for an hard RTOS

Linux hard RTOS

Approaches:

- Mono kernel (changing the source code along different Vanilla kernel)
- Dual kernel (only small changes to the Linux code)

Linux hard RTOS

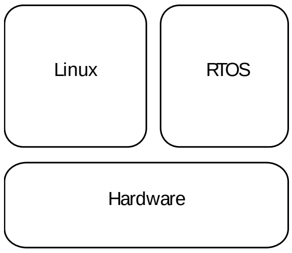
Dual kernel
(most free)

- RTAI/Xenomai
- RTLinuxFree
- …

Mono kernel
(most commercials)

- BlueCat Linux
- Cadenux
- Metrowerks
- MontaVista Linux
- RTLinuxPro
- TimeSys Linux
- …

Linux hard RTOS



Dual kernel approach: two OSs sharing the same hardware, how?

ADEOS

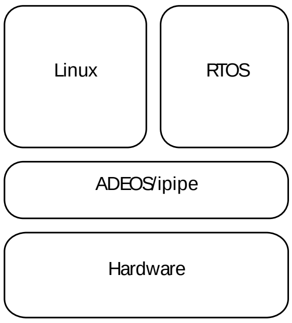
Adaptive Domain Environment for Operating Systems

ADEOS

Nano kernel
Open source

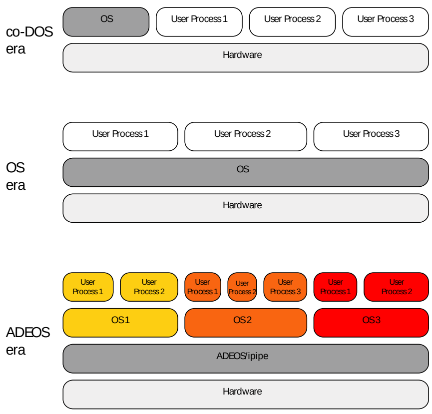
NEW NAME:
ADEOS/ipipe
CHANGES:
- Functions name
- Various improvements

ADEOS



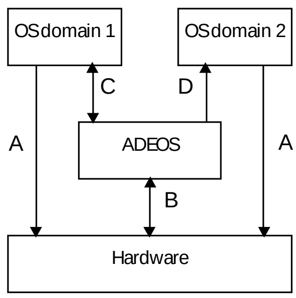
Dual Kernel with ADEOS/ipipe nano kernel

ADEOS



Many different OS (or multiple istance of the same OS) running on the same machine sharing the same hardware.

ADEOS



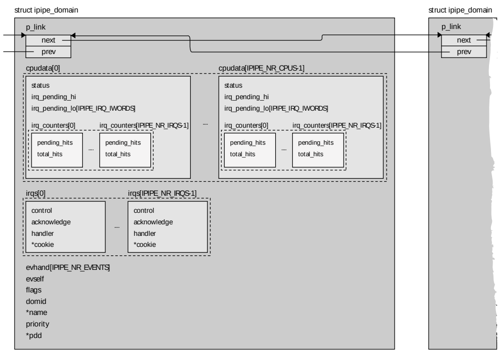
ADEOS/ipipe paths

ADEOS

Basics:

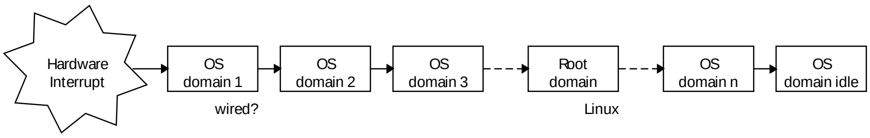
- Domains
- Pipeline
- Interrupts
- Events

ADEOS



ADEOS/ipipe Domain descriptor

ADEOS



ADEOS/ipipe interrupts/events pipeline
(on interrupt)

ADEOS

Interrupts

PROPERTIES:

- Asynchronous
- Raised in Hardware
- Maskable (a domain could be stalled)
- Propagated down the pipeline
- Logged (Optimistic interrupt protection scheme)

ADEOS

Events

PROPERTIES:
- Synchronous
- Raised mostly for software cause
- Non maskable
- Propagated from the source domain up the pipeline
- Immediate dispatching

ADEOS

```
struct ipipe_domain domain_desc;
void domain_entry (int iflag) {
    if (iflag) {
          ipipe_virtualize_irq(...);
          ipipe_virtualize_irq(...);
          ipipe_virtualize_irq(...);
          ipipe_catch_event(...);
    }
    for (;;)
          ipipe_suspend_domain();
}
int init_module (void) {
    struct ipipe_domain_attr attr;
    ipipe_init_attr (&attr);
    attr.name = "MyDomain";
    attr.priority = IPIPE_ROOT_PRIO + 100; /* Precede Linux in the pipeline */
    attr.entry = &domain_entry;
    return ipipe_register_domain(&domain_desc,&attr);
}
void cleanup_module (void) {
    return ipipe_unregister_domain(&domain_desc);
}
```

ADEOS/ipipe domain creation example

ADEOS

References:

- Karim Yagmour et others (OperSys Inc)
- www.adeos.org

RTAI

Real Time Application Interface

by Dipartimento di Ingegneria Aereospaziale dell'Università di Milano (DIAPM)

RTAI

History (1/2):

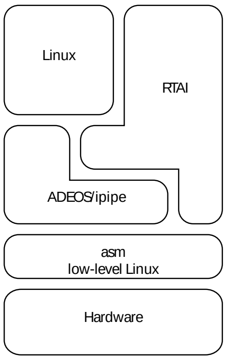
- In the first it was PCDOS-DIAPM-RTOS (16bits real mode);
- Than it was implemented in 32 bits real/protected mode;
- Approaching Linux (2.0.25);
- NMT-RTL appear and goes on DIAPM-RTL variant was born
- RTHAL-RTAI patch for 2.2.xx kernel ready (beginning 1999)

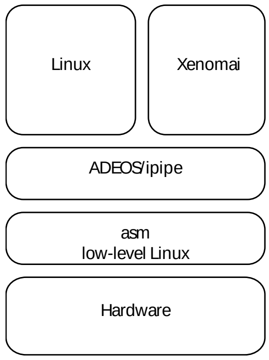
RTAI

History (2/2):

- April 1999 first version of RTAI for UP and SMP;
- Jan 2001 NMT-RTL now RTLinux was patented;
- Jun 2002 ADEOS was firstly released;
- ADEOS substitutes RTHAL and from now no patent problems;
- LXRT scheduler was introduced;
- More than one branch of RTAI;
- October 2005 Fusion branch become a stand-alone distribution Xenomai;

RTAI VS Xenomai





RTAI immediate dispatching

Xenomai

RTAI pipeline (no immediate dispatching)

RTAI VS Xenomai

RTAI

Currently ported on:
- ARM
- I386, ia64 (SMP, MUP)
- PowerPC

Run:
- Kernel
- User

Main goal :
- Fast dispatching

API interface:
- RTAI
- Posix 1003.1b
- RTDM

Xenomai

Currently ported on:
- ARM
- i386, ia64 (SMP)
- PowerPC, PowerPC64 (SMP)
- Blackfin

Run:
- Kernel
- User

Main goal :
- Portability

API interface:
- Xenomai native
- Posix 1003.1b
- RTAI
- VxWorks
- pSos+
- VRTX
- uITRON
- RTDM

RTAI VS Xenomai

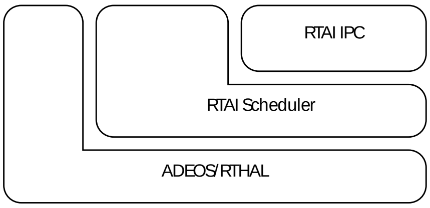
From our tests:

LESS INTEGRATION PROBLEMS:
Xenomai
BETTER PERFORMANCE:
RTAI (immediate dispatching)
EASY APPLICATION PORTING:
Xenomai
DEBUGGING SUPPORT:
Both
CLEAR, AND WELL ORGANIZED SOURCE CODE:
Xenomai

RTAI

Immediate dispatching

RTAI



Basics:

- ADEOS/RTHAL
- RTAI Scheduler
- RTAI IPC

RTAI

ADEOS/RTHAL

PROVIDES:

- Immediate Interrupts dispatching
- Interrupt registering/deregistering functions
- PIC management routines
- Hardware Timers (8254/APIC) management routines
- registering/deregistering timers handler functions
- Trap handlers registering/deregistering functions
- Provides `rt_printk`/`rt_synch_printk`
- Syscall dispatching

RTAI

ADEOS/RTHAL interrupts

Pure ADEOS Xenomai

```
Raised an External interrupt n
 CPU decode phase
  CPU call IDT[n] entry
   linux/arch/i386/kernel/entry.S:404 interrupt[n]()
    linux/arch/i386/kernel/entry.S:475 common_interrupt()
     linux/arch/i386/kernel/ipipe-root.c: __ipipe_handle_irq(struct pt_regs
   regs)
     detect head Domain (Xenomai) is wired
      linux/kernel/ipipe/core.c: __ipipe_dispatch_wired(struct ipipe_domain
   *head, unsigned irq)
      call Xenomai interrupt handler (registered with rthal_irq_request)
```

RTHAL ADEOS modified patch

```
Raised an External interrupt n
 CPU decode phase
  CPU call IDT[n] entry
   linux/arch/i386/kernel/entry.S:404 interrupt[n]()
    linux/arch/i386/kernel/entry.S:475 common_interrupt()
     rtai/base/arch/i386/hal/hal.immed:1474 rtai_hirq_dispatcher(struct
   pt_regs regs)
     call RTAI interrupt handler (register with rt_request_irq)
```

RTAI

ADEOS/RTHAL interrupts

And Linux interrupts?

Before RTAI

```
Raised an External interrupt n
 CPU decode phase
  CPU call IDT[n] entry
   linux/arch/i386/kernel/entry.S:404 interrupt[n]()
    linux/arch/i386/kernel/entry.S:416 common_interrupt()
     linux/arch/i386/kernel/irq.c:54 do_IRQ(struct pt_regs *regs)
      linux/kernel/irq/handle.c:118 __do_IRQ(unsigned int irq, struct pt_regs *regs)
       linux/kernel/irq/handle.c:79 handle_IRQ_event(unsigned int irq, struct pt_regs *regs, struct irqaction
    *action)
       loop throught the actions and call the interrupt handlers
```

With RTAI

```
Raised an External interrupt n
 CPU decode phase
  CPU call IDT[n] entry
   linux/arch/i386/kernel/entry.S:404 interrupt[n]()
    linux/arch/i386/kernel/entry.S:475 common_interrupt()
     rtai/base/arch/i386/hal/hal.c:1474 rtai_hirq_dispatcher(struct pt_regs regs)
     call RTAI interrupt handler
     rtai/base/include/asm-i386/rtai_hal.h:275 hal_pend_domain_uncond(irq, domain,cpuid)
     rtai/base/include/asm-i386/rtai_hal.h:285 hal_fast_flush_pipeline(cpuid)
      linux/arch/i386/kernel/ipipe-core.c: __ipipe_sync_stage(unsigned long syncmask)
       for every interrupt pended in the log do
        call handler
         linux/arch/i386/kernel/irq.c:54 do_IRQ(struct pt_regs *regs)
          linux/kernel/irq/handle.c:118 __do_IRQ(unsigned int irq, struct pt_regs *regs)
           linux/kernel/irq/handle.c:79 handle_IRQ_event(unsigned int irq, struct pt_regs *regs, struct irqaction
    *action)
           loop throught the actions and call the interrupt handlers
```

RTAI

8254

Native RTAI timer, it supports at least two modes that are used:

- Periodic Mode
- Oneshot Mode

This timer is used in:

- UP
- SMP

Counter 0 shared with Linux.

APIC

In the beginning was used only with multiprocessor hardware. Same modes:

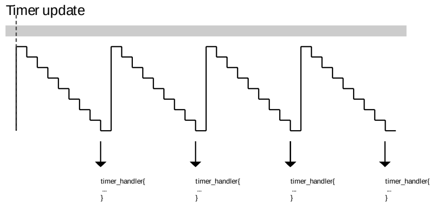
- Periodic Mode
- Oneshot Mode

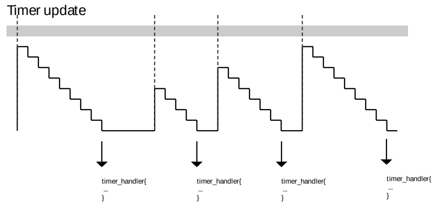
Used in:

- SMP
- MUP

ADEOS/RTHAL timers

RTAI





Periodic Mode

Automatic timer register reload

Oneshot Mode

Compulsory timer register update

RTAI

```
bstatic int irq_handler(int irq, void *cookie) {
    // do something in IRQ handler

    rt_enable_irq(vmechip_irq);
    return IRQ_HANDLED;
}
static int VGD4_init(void) {
    result = rt_request_irq(vmechip_irq, VGD4_irqhandler, 0, 1);
    if (result != 0) {
            printk(KERN_ERR"VGD4 driver: can't get assigned pci irq vector %02X\n", vmechip_irq);
            return -1;
    } else {
            rt_enable_irq(vmechip_irq);
    }

    return 0;
}
static void VGD4_exit(void) {
    rt_disable_irq(vmechip_irq);
    rt_release_irq(vmechip_irq);

    return;
}
```

ADEOS/RTHAL interrupt handler registration example

RTAI

Scheduler

PROVIDES:

- Task creation/destruction routine
- Task suspend/yield/sleep routine
- Task Timer related function
- Scheduling disciplines/policy
- LXRT Linux (user space) Real-Time capability
- Task interface with IPC mechanisms

RTAI

Scheduler

MAIN ENTITY:
task

```c
typedef struct rt_task_struct {
    long *stack __attribute__ ((__aligned__ (L1_CACHE_BYTES)));
    int uses_fpu;
    int magic;
    volatile int state, running;
    unsigned long runnable_on_cpus;
    long *stack_bottom;
    volatile int priority;
    int base_priority;
    int policy;
    int sched_lock_priority;
    struct rt_task_struct *prio_passed_to;
    RTIME period;
    RTIME resume_time;
    RTIME periodic_resume_time;
    RTIME yield_time;
    int rr_quantum;
    int rr_remaining;
    int suspdepth;
    struct rt_queue queue;
    int owndres;
    struct rt_queue *blocked_on;
    struct rt_queue msg_queue;
    int tid;     /* trace ID */
    unsigned long msg;
    struct rt_queue ret_queue;
    void (*signal)(void);
    FPU_ENV fpu_reg __attribute__ ((__aligned__ (L1_CACHE_BYTES)));
    struct rt_task_struct *prev;
    struct rt_task_struct *next;
    struct rt_task_struct *tprev;
    struct rt_task_struct *tnext;
    struct rt_task_struct *rprev;
    struct rt_task_struct *rnext;

    /* Appended for calls from LINUX. */
    long *fun_args;
    long *bstack;
    struct task_struct *lnxtsk;
    long long retval;
    char *msg_buf[2];
    long max_msg_size[2];
    char task_name[16];
    void *system_data_ptr;
    struct rt_task_struct *nextp;
    struct rt_task_struct *prevp;

    /* Added to support user specific trap handlers. */
    RT_TRAP_HANDLER task_trap_handler[HAL_NR_FAULTS];

    /* Added from rtai-22. */
    long unblocked;
    void *rt_signals;
    volatile unsigned long pstate;
    unsigned long usp_flags;
    unsigned long usp_flags_mask;
    unsigned long force_soft;
    volatile int is_hard;

    void *trap_handler_data;
    struct rt_task_struct *linux_syscall_server;

    /* For use by watchdog. */
    int resync_frame;

    /* For use by exit handler functions. */
    XHDL *ExitHook;

    RTIME exectime[2];
    struct mcb_t mcb;

    /* Real time heaps. */
    struct rt_heap_t heap[2];

    volatile int scheduler;

#ifdef CONFIG_RTAI_LONG_TIMED_LIST
    rb_root_t rbr;
    rb_node_t rbn;
#endif
    struct rt_queue resq;
} RT_TASK __attribute__ ((__aligned__ (L1_CACHE_BYTES)));
```

RTAI

task **RT_TASK**

3 double linked lists:

- fields prev/next **task list**
- fields rprev/rnext **ready list**
- fields fprev/fnext **timed list**

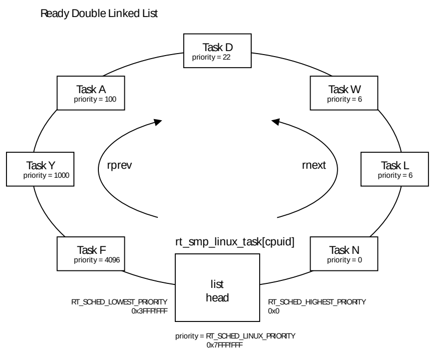
A list head for every CPU
`rt_smp_linux_task[cpuid]`

RTAI

task **RT_TASK**
task list

INSERTION POLICY:
Add every new created task
LIST ORDER:
FIFO
NOTE:
Tail task next = 0

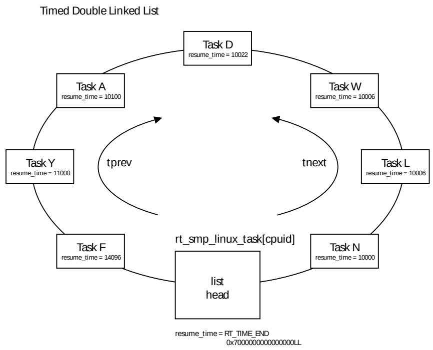
RTAI



task **RT_TASK**
ready list

INSERTION POLICY:
Add ready task
REMOVE POLICY:
First task after the head
LIST ORDER:
Sorted on `rt_task.priority`
MOST PRIORITARY:
0
LESS PRIORITARY:
RT_SCHED_LINUXPRIO

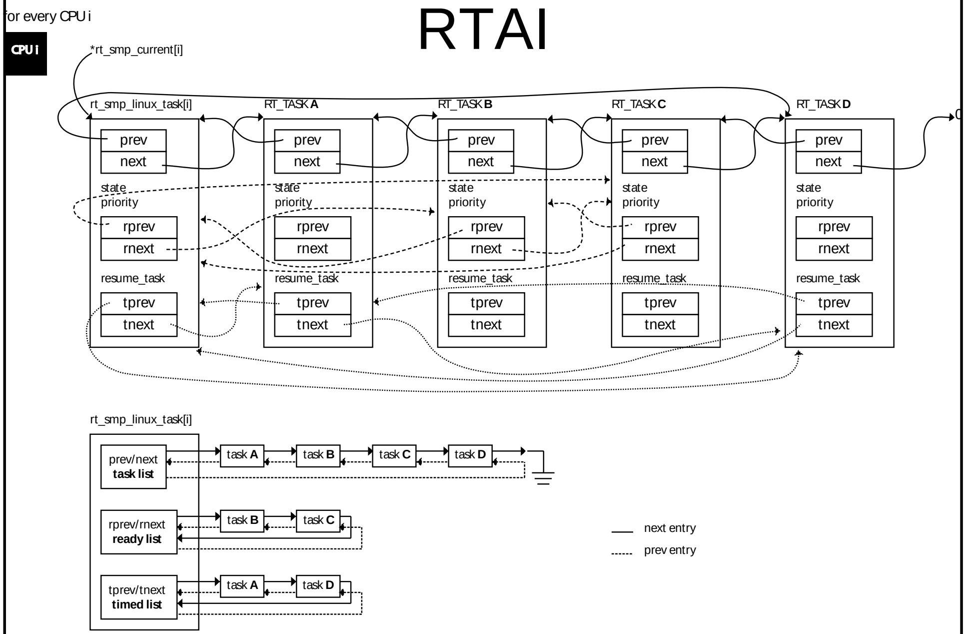
RTAI



task **RT_TASK**
timed list

INSERTION POLICY:
Add timed task
REMOVE POLICY:
First n deadlined tasks after the head
LIST ORDER:
Sorted on `rt_task.resume_time`
MOST PRIORITARY:
0
LESS PRIORITARY:
MAX_TIME

RTAI



RTAI

Scheduler

Scheduling policy:

- RMS
- EDF
- FIFO, **default scheduler**
- RR

RTAI

Scheduler

Scheduling point:

- on timer interrupt
- on ISR exit
- on task self-suspending

Self-suspending examples:

- Yield
- Suspend
- Sleep

RTAI

Scheduler

LXRT

Scheduler kernel

Scheduler user

RTAI

```
void task_body (long cookie) {
    int i,l;
    while(1){
            for(i=0; i<100; i++) {
                        l += i*(l+i);
            }
            printk(KERN_ERR"kernel_task executed\n");
            rt_task_wait_period();
    }
}
int init_module (void) {
    int err;
    err = rt_task_init(&task_desc, task_body, 0, TASK_STKSZ, TASK_PRIO, 0, 0);
    if (err != 0) {
            printk(KERN_ERR"error module loading\n");
            return -1;
    }
            rt_set_oneshot_mode();
    start_rt_timer(0);
    rt_task_make_periodic_relative_ns(&task_desc, 10000000, 10000000000);
    return 0;
}
void cleanup_module(void) {
    stop_rt_timer();
    rt_task_delete(&task_desc);
}
```

Scheduler task creation example

RTAI

IPCs

PROVIDES:

- Bits (a sort of signals)
- Fifo
- Message
- Mailbox
- Message queue
- NetRPC (now require RTNet)
- Semaphore
- Shared memory

RTAI

RTAI References:
Paolo Mantegazza, DIAPM
www.rtai.org

Xenomai References:
www.xenomai.org