

OPEN SOURCE REAL TIME OPERATING SYSTEMS OVERVIEW *

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Abstract

Modern control systems applications are often built on top of a real time operating system (RTOS) which provides the necessary hardware abstraction as well as scheduling, networking and other services. Several open source RTOS solutions are publicly available, which is very attractive, both from an economic (no licensing fees) as well as from a technical (control over the source code) point of view. This contribution gives an overview of the RTLinux and RTEMS systems (architecture, development environment, API etc.). Both systems feature most popular CPUs, several APIs (including Posix), networking, portability and optional commercial support. Some performance figures are presented, focusing on interrupt latency and context switching delay.

1 INTRODUCTION

Apart from hard-real time interrupt handling and scheduling services, there are other OS features of interest, such as the available APIs, target CPU architectures and BSPs (board support packages), support for multiple processors, networking, file systems, dynamic object loading, memory protection and so on.

Other important issues are licensing terms, development environment and debugging tools and the availability of these tools for specific host platforms.

The next section gives an overview of RTL and RTEMS looking at some of these issues. In section 3, some performance measurements are presented comparing the results for RTL and RTEMS to a commercial system (vxWorks).

2 RTLINUX AND RTEMS OVERVIEW

2.1 RTLinux

General Information RTL development started at the New Mexico Institute of Mining and Technology and is now maintained by FSMLabs Inc. which also offers commercial support. The basic mechanism is protected by a US patent; RTL (having a license for using the mechanism) itself is licensed under the terms of the GPL.

RTL is distributed as a patch against certain versions of Linux and a collection of kernel modules.

Further information about RTL is available at [1].

* Thanks to Ric Claus for kindly borrowing me the MVME2306 computer

System Architecture The basic idea of RTL is striking simple: A slim layer of software is “hooked” into standard Linux’ interrupt handlers and interrupt enabling/disabling primitives, thereby effectively taking over the machine which is then managed by a special real-time scheduler. Linux continues to run as a low priority task.

The real-time core manages all hardware interrupts, dispatching them appropriately, either to Linux or to real-time threads. The interrupt manager never allows Linux to disable interrupts. Instead, Linux disabling an IRQ actually invokes an RTL hook which marks the target interrupt as “disabled”. If the interrupt manager detects such a marked IRQ, it holds off dispatching it to Linux until the corresponding call to re-enable the IRQ in question is intercepted.

Linux being a low priority task with no direct access to the interrupt hardware implies that any real-time thread introduced into the system can only very weakly interact with Linux (through special communication channels) and may only build upon the services of the RTL core, such as synchronization primitives and the scheduler. Note that this low-level environment does not provide a C or “math” library nor any of Linux’ standard system services like networking, file systems or drivers. While the former (C library) functionality is easy to add, providing the latter is far more complex for obvious reasons. Communication with user space processes is established through special “real-time fifo” devices.

Following the philosophy of RTL, most of an application should be implemented in user space, as ordinary Linux programs. Only the real-time critical tasks go into a special module which is loaded into kernel memory using Linux’ standard kernel-module loader.

API and General Features Version 3.1 of RTL offers (a subset of) the POSIX (1003.13) “pthreads”, semaphores, condition variables and a proprietary interface to the interrupt subsystem. As already mentioned, no C-library is provided per-se. RTL special features include periodic scheduling with high timing resolution.

While high timing resolution is certainly desirable, its usefulness is reduced to some degree by the relatively high latencies (see measurement section).

As a consequence of the layered system architecture with Linux on top of the RTL core, an RTL application must be carefully separated into real-time critical and non-critical parts. Only the latter may use the powerful features of

Linux, both in kernel or user space. Critical tasks *must not* e.g. write files or access non-RT drivers but they must delegate this work to non-real time code.

Supported Target Architectures RTL supports a subset of the CPUs and platforms supported by Linux. x86, PowerPC, Alpha and MIPS are currently supported by RTL; at least on x86, SMP is supported.

Development Environment RTL development is usually done using the well-known GNU tool chain which has been ported to a wide variety of host platforms. The RTL core provides support for debugging real-time modules.

2.2 RTEMS

General Information RTEMS stands for “Real Time Executive for Multiprocessor Systems”, where the original meaning of the letter *M*, namely “Missile” and later “Military” has eventually reached a civilian status.

RTEMS was developed by OaR Corp. on behalf of the US DoD and is licensed under a GPL variant. OaR coordinates development efforts and offers commercial support for RTEMS and other related services.

RTEMS has reached production quality and is used by military, industrial and scientific projects. EPICS, a control systems software which is widely used in the accelerator community, has been ported to RTEMS as of the new 3.14 EPICS release.

More information about RTEMS can be found at [2].

System Architecture RTEMS was designed as a true RTOS from scratch, targeting embedded systems, possibly with less memory. Consequently, various system components are partitioned into separate modules (“managers” in RTEMS terminology) which are linked to the application as needed. The system can further be tailored to an application’s specific needs by choosing appropriate configuration parameters.

A typical RTEMS application is built by compiling the application itself, which must provide the necessary configuration parameters, and linking it to the desired RTEMS managers (which are provided in libraries) thereby creating an executable for downloading to the target system or burning into ROM etc.

Since RTEMS is an RT system “from the ground up”, all system services and libraries are directly available to any application task.

API and General Features RTEMS features POSIX (1003.1b), ITRON and “classic/native” APIs in C and ADA (native API only) language bindings. The usual components of an RTOS are available, such as multitasking (thread creation and control), synchronization primitives (mutexes, semaphores, message queues, events etc.), schedulers (fifo/round robin, rate monotonic), clocks etc.

RTEMS provides a port of the BSD TCP/IP networking stack and supports multiple (possibly heterogeneous) CPUs.

As in vxWorks, memory protection is not available; the system and application software share the same, flat memory space.

RTEMS itself does not ship a shell as powerful as vx-Works’ nor does it offer a dynamic loader. However, there are ongoing efforts of creating application programs providing the respective features.

The only file systems currently implemented are a remote TFTP and a “in memory” (ramdisk) file system.

Supported Target Architectures RTEMS is designed to be easily portable and consequently it supports many CPU architectures, such as m68k, ColdFire, Hitachi SH, Intel i386, Intel i960, MIPS, PowerPC, SPARC, AMD A29k and HP PA-RISC.

Development Environment RTEMS uses the GNU tool chain.

3 RESPONSE TIME PERFORMANCE TEST

A key property of any hard-real time system is its “response time”, i.e. the time it takes for the system to react to some external event under worst case conditions. Two important terms shall be defined here:

“Interrupt Latency” The time it takes from a device asserting an interrupt line until the system dispatching the corresponding interrupt handler (ISR) shall be called *interrupt latency*.

“Context Switch Delay” This term defines the time it takes to schedule a task. It involves the scheduler determining which task to run, saving the current task context and restoring the new one.

Of course, it is practically impossible to find the worst case conditions given the huge number of possible state combinations that can occur in a computer system.

Therefore, a statistical approach is taken to create “worst case” conditions. The idea is to let the system operate under heavy load for some time while measuring the latencies. The maximal delay recorded during the test is then assumed to reflect the “worst case”.

3.1 Test Algorithm

A PowerPC 604 CPU (300MHz) on a MVME2306, PReP compatible board by Motorola was chosen to perform the measurements. BSPs for RTL, RTEMS and VxWorks were available, allowing for comparison of the three systems on the same target hardware.

The MVME2306 (like most PPC platforms) features timer hardware with a reasonable resolution, which can be set up to generate periodic interrupts. Because the running timer is readable “on-the fly”, a precise measurement of latencies can easily be accomplished.

The test software package [3] consists of an initialization routine, an interrupt handler (ISR) and a simple “measurement” procedure.

The initialization code sets up the timer hardware, connects the ISR to the respective interrupt and spawns a task (MT) executing the measurement procedure at the highest priority available on the system under test.

The ISR determines the interrupt latency by reading the timer and notifies the MT by releasing a semaphore on which the MT blocks. This causes the system to schedule the MT (having become the highest priority runnable task), which, reading the running timer is able to determine the time that elapsed from the ISR releasing the semaphore until the MT actually getting hold of the CPU. After recording the delay, the MT again blocks on the semaphore.

This simple test was performed on a system heavily loaded with low priority tasks, networking and serial I/O traffic causing a large volume of interrupts (also at a priority lower than the timer hardware IRQ).

According to the definition, a hard-real time system must guarantee that the latencies experienced by the high priority ISR and MT stay below a certain *hard* limit, regardless of the amount of low-priority load (note that interrupts inherently have a higher priority than any normal task, hence a low-priority interrupt still interrupts a high-priority task).

Hence, the maximal recorded latencies during the test constitute a measure for the quality of a given system.

3.2 Results

The test was performed on the same hardware under the RTL, RTEMS and VxWorks systems. 2'000'000 timer interrupts were generated at a rate of 4kHz and the maximal and average latencies were recorded. Measurements were made under both, idle and loaded conditions.

The load that was imposed on the system under test consisted of “flood pinging” its network interface from a host computer, while letting a low priority thread copy characters from a TCP socket (connected to the host’s “chargen” port) to the serial (RS-232) console. Thus, the loaded system was subject to heavy interrupt and kernel activity involving scheduling, synchronization primitives, networking and driver code sections among others.

The results are shown in Tab. 1. The idle systems all exhibit comparable figures. The situation changes, however, quite dramatically under load: Whereas RTEMS and VxWorks show similar performance, RTL’s latencies are substantially higher on the loaded system. This is not really surprising given the far more complex interrupt dispatching that is needed to manage and emulate the Linux interrupts.

Somewhat surprising is RTEMS’ increased scheduling latency when using the pthread API, as one would assume the implementation to merely consist of an inexpensive wrapper to the native API. Given the good performance of the latter, one can expect however, that making improvements should be relatively straightforward.

As can be seen, the average latencies are about an order

	Interrupt max	Latency avg $\pm\sigma$	Context max	Switching avg $\pm\sigma$
<i>Idle System</i>				
RTL	13.5	(1.7 \pm 0.2)	33.1	(8.7 \pm 0.5)
RTEMS ¹	14.9	(1.3 \pm 0.1)	16.9	(2.3 \pm 0.1)
RTEMS	15.1	(1.3 \pm 0.1)	16.4	(2.2 \pm 0.1)
VxWorks	13.1	(2.0 \pm 0.2)	19.0	(3.1 \pm 0.3)
<i>Loaded System</i>				
RTL	196.8	(2.1 \pm 3.3)	193.9	(11.2 \pm 4.5)
RTEMS ¹	19.2	(2.4 \pm 1.7)	213.0	(10.4 \pm 12.7)
RTEMS	20.5	(2.9 \pm 1.8)	51.3	(3.7 \pm 2.0)
VxWorks	25.2	(2.9 \pm 1.5)	38.8	(9.5 \pm 3.2)

¹using pthreads

Table 1: Latency measurement results. All times are in μ s. VxWorks and RTEMS use native threads unless otherwise noted. RTL uses the pthread API.

of magnitude less than the respective maxima. Although our statistical test gives some lower bound of the maximal latencies, it is impossible to draw conclusions about the true worst case figures which are obviously extremely difficult to establish.

Usually, the interrupt handling parts of any system are highly hardware-architecture dependent. Therefore, while representative for the PowerPC, the interrupt latency figures stated here can not easily be generalized to other CPU architectures.

4 CONCLUSION

RTEMS and RTL are two quite different open-source RTOS solutions.

RTEMS seems to offer both, core features and performance which are comparable to a commercial system like VxWorks.

RTL could be interesting in situations, where the full power of a desktop system is needed, enhancing such a system by hard-real time features. This comes, however, at the expense of higher latencies (compared to RTEMS or VxWorks) and limitations of system services that are available to the real-time tasks.

Finally, it should be noted, that the simple benchmark presented in this paper does by no means constitute a thorough performance evaluation and comparison, an arduous task to which the interested reader is encouraged to contribute.

5 REFERENCES

- [1] <http://www.rtlinux.com>
- [2] <http://www.rtems.com>
- [3] <http://www.slac.stanford.edu/~strauman/rtoslat/>