Real Time Linux Scheduling Comparison

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Who am I?

Software Developer and Architect at Altera Corporation
- Open Source Development Activities in Austin, Texas

Open source projects
- Linux – LTSI, Real-time and Custom for ARM SOCs
- UBoot

Technologies …
- Altera FPGA IP Enablement
- Embedded Software and Systems
- Ethernet, IEEE 1588
- Automated testing
Agenda

- Introduction to Real Time Linux & LTSI
- Creating a Custom Real Time Linux Kernel
- A Methodology for Comparing Scheduling Latency
- Some interesting results
What is “Real Time”?

- Does it mean “really fast”? 
- Maybe…. usually means “fast enough”
- Determined by application requirements
- The application defines the speed requirements …
  - Temperature measurement < 1000 ms
  - Button/GUI response < 100 ms
  - Simple motor control (frequency inverter) < 10 ms
  - Multi-axis simple control application < 1 ms
  - Sampling of analogue values < 100 µs
  - High precision servo control < 10 µs
Hard vs Soft Real Time

Hard vs soft refers to how much predictability or determinism is required.

- **Soft Real Time**
  - on average timing is always met
  - Sometimes there might be a missed timing but system catches up
  - OK for non critical systems
    - eg. Audio, video
  - Loss of quality but no fatal error ...

- **Hard Real Time**
  - **Every** deadline has to be met
  - Otherwise results in system failure
    - eg. CNC machine, ABS, Engine management
### Real-Time Classifications

<table>
<thead>
<tr>
<th>Type of Real Time</th>
<th>Characteristics</th>
<th>Use Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Real Time</td>
<td>Subjective Scheduling deadlines, depends on the application</td>
<td>Media rendering on mainstream operating systems, network I/O, flash access</td>
</tr>
<tr>
<td>95% Real Time</td>
<td>Real time requirements met 95% of the time, system can compensate 5% of the time.</td>
<td>Voice Communications, data acquisition</td>
</tr>
<tr>
<td>100% Real Time</td>
<td>Real time requirements met 100% of the time else manufacturing defects can occur</td>
<td>Factory automation where failure results in manufacturing defects</td>
</tr>
<tr>
<td>Safe Real Time</td>
<td>Real time requirements met 100% of the time else serious injury or death can occur</td>
<td>Flight and weapons control, life critical medical equipment</td>
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</tbody>
</table>
LTSI and Real-Time Linux

LTSI Announced in October 2011 at LinuxCon Europe
- Create a supported Linux kernel for the embedded systems life cycle
- Industry managed kernel as common ground for the embedded industry
- Mechanisms for upstreaming activities from embedded systems engineers

Real Time Linux
- A set of patches developed over the years to provide soft real time capabilities by allowing pre-emption in the Linux kernel and additional features to improve scheduling determinism.
Sources of Non-Deterministic Latency

Latency is “the interval between stimulus and response”
- Latin root – latēns: “to lie hidden”

“Nondeterministic” can mean the $\Delta T$ latency between “stimulus” and “response” falls outside of an accepted upper and lower bound, or cannot be predicted. Known as “Latency Jitter”

Latency can come from multiple sources ….
- Unbounded Priority and Interrupt Inversion
- Scheduling latency (depends on scheduling policies)
- Interrupt latency
- Caching and TLB effects – especially in multiprocessors
- Paging I/O Latency
- Memory access latency

Scheduling Latency
1) ISR
2) Scheduler Invoked
3) Task Picked
4) Context Switch
Preempt RT Patch

- Linux RT Preempt is a 95% Real Time System
- RT Preempt Changes …
  - Threaded Interrupts
  - Pre-emptible mutual exclusion (“Sleeping” Spinlocks)
  - Priority Inheritance
  - High Resolution Timer
  - Real time scheduling policies – SCHED_RR and SCHED_FIFO
- “Real Time” applications are expected to make good choices in the application design
  - Make sure commonly used memory ispaged in
  - Smart processor and memory management
  - Smart priority assignment and management

- Simply using the RT Preempt patch does not solve all problems. Users must do some work too.
- User must be careful with affinities and priorities
Creating a rebased Linux-RT Kernel

- Checkout the latest 3.10-ltsi kernel
- Checkout the same branch of the Stable Linux RT Kernel
- Rebase …
Creating a Rebased Linux-RT Branch

A developer can create their own rebased Linux-RT branch from a customized kernel using rebase

Example steps ....

```bash
git clone http://git.rocketboards.org/linux-socfpga.git
cd linux-socfpga
git fetch linux-socfpga
git checkout -b socfpga-3.10-ltsi-rt-rebase origin/socfpga-3.10-ltsi
git remote add linux-rt git://git.kernel.org/pub/scm/linux/kernel/git/rt/linux-stable-rt.git
git fetch linux-rt
git checkout -b linux-rt-3.10 linux-rt/v3.10-rt
git checkout socfpga-3.10-ltsi-rt-rebase
git rebase linux-rt-3.10 ...
```

Iterate: Resolve conflicts, git rebase –continue
Building and Testing the Real Time Kernel

- CONFIG_PREEMPT_RT_FULL
- High Resolution Timer
- Make sure power management is off
- Build test …
  - allconfig
  - allmodconfig
- See online tutorial
How to tell if RT Linux build is Working

- Use the rt-tests, found at …
  - git://git.kernel.org/pub/scm/linux/kernel/git/clrkwlms/rt-tests.git

- Source code …

- cat /sys/kernel/realtime …
  - Present and “1” if a realtime kernel
  - Otherwise, not present
Evaluating Latency

- Comparing averages or max values may not yield interesting results – need comparative statistics to see full potential of latency jitter benefits.

- Measurement Methodology
  - Benchmark uses get time of day as a way to measure request to response latency, multiple block memory read/write threads, multiple ping floods
  - Collect 5000 samples, collect into bins for a histogram
  - Collect “online” statistics for mean, skew, kurtosis, and percentiles
  - Statistics given are accurate to within two decimals points with 95% confidence

- Altera’s Socfpga-3.10-ltsi kernel without RT Preempt patches
- Altera’s Socfpga-3.10-ltsi-rt kernel – Same as above with RT Preempt patches applied
- Measured on Altera’s Cyclone 5 SOC
Characteristic Workload

- Multiple ping floods – simultaneous transmit and receive network traffic
- Dedicated memory thrashing threads per CPU
  - Large block memory allocation, random reads and writes
- Dedicated threads per CPU uses clock_gettime and clock_nanosleep to cycle threads through process states
- Difference between requested sleep time and measured sleep time is defined to be “scheduling latency” and collected for comparison
- User could create custom workload that’s characteristic of their system design

Disclaimer: This is not intended to be exemplary for all RT use cases!
Data Collection Core for Measurements and Comparison

```c
ret = clock_gettime(clock[ptctx->clksrc], (&now));
if (ret != 0) {
    fail();
}
req.tv_sec = 0;
req.tv_nsec = 100*(1000*1000);
ret = clock_nanosleep(clock[ptctx->clksrc], 0, &req, NULL);
if (ret != 0) {
    fail();
}
ret = clock_gettime(clock[ptctx->clksrc], (&next));
if (ret != 0) {
    fail();
}
diff = calcdiff(next, now);
int delta = (int)(diff-timens(req))/1000;
ptctx->pm_q5->push(delta);
ptctx->pm_q50->push(delta);
ptctx->pm_q99->push(delta);
ptctx->pm_q95->push(delta);
ptctx->pstats->push(delta);
```
Statistics Collection

- Percentiles collected “online” using the Piecewise Parabolic Method
- Means, Standard Deviation, and data moment statistics collected in real time using optimized “online” algorithms for collecting statistics
  - See Welford’s Algorithm – efficient and numerically stable
  - Methods presented by Timothy Terriberry used to maintain and compute higher order data moments (standard deviation, skew and kurtosis).
- Implemented as a simple, portable, reusable C++ class for applications
- Cumulative and moving averages, standard deviation, skewness, kurtosis, and percentiles.
Statistics Review
Scheduling Latency Jitter Comparison

### 3.10 Kernel with RT Preempt Patch, Fully Loaded

- \( \mu = \sim 67 \)
- \( \sigma = \sim 12 \)
- Skew = \( \sim 0.1 \)
- Kurtosis = \( \sim 2 \)
- 5th Perc = \( \sim 46 \)
- 95th Perc = \( \sim 86 \)
- 99th Perc = \( \sim 100 \)

### Vanilla 3.10 Kernel, Fully Loaded

- \( \mu = \sim 75 \)
- \( \sigma = \sim 67 \)
- Skew = \( \sim 30 \)
- Kurtosis = \( \sim 1000 \)
- 5th Perc = \( \sim 46 \)
- 95th Perc = \( \sim 100 \)
- 99th Perc = \( \sim 110 \)
Observations

- Mean comparison shows a clear improvement from vanilla kernel to RT kernel.
- Review of other statistics show that outliers are greatly reduced in RT kernel (skewness and kurtosis).
- Standard deviation is greatly improved in RT kernel.
- The 5\textsuperscript{th} percentile is about the same – indicating a “hard” lower bound.
Thank You
References

- LTSI Update: [http://lwn.net/Articles/484337/](http://lwn.net/Articles/484337/)
- Real Time Preemption Overview: [http://lwn.net/Articles/146861/](http://lwn.net/Articles/146861/)
- Altera SOFPGA LTSI-RT Kernel
  - [http://www.rocketboards.org/foswiki/Documentation/AlteraSoCLTSIRTKernel](http://www.rocketboards.org/foswiki/Documentation/AlteraSoCLTSIRTKernel)
Welford’s Method

- Single pass algorithm – useful for online data.
- A “current” value can be maintained as data samples become available.
- Numerical stability is pretty good
- Computationally efficient
- This algorithm yields mean, standard deviation, and variance.

\[
\begin{align*}
M_1 &= 0, S_1 = 0 \\
M_i &= M_{i-1} + \frac{x_i - M_{i-1}}{i} \\
S_i &= S_{i-1} + (x_i - M_{i-1})(x_i - M_i)
\end{align*}
\]

Equation 4 - Welford's Method
Higher order moments ....

- Central moments are maintained
- Updated by a “push” operation as samples arrive
- Numerically stable

\[
\begin{align*}
\delta &= x - m \\
\mu &= m' = m + \frac{\delta}{n} \\
M_2' &= M_2 + \delta^2 \frac{n-1}{n} \\
M_3' &= M_3 + \delta^3 \frac{(n-1)(n-2)}{n^2} - \frac{3\delta M_2}{n} \\
M_4' &= M_4 + \frac{\delta^4(n-1)(n^2 - 3n + 3)}{n^3} + \frac{6\delta^2 M_2}{n^2} - \frac{4\delta M_3}{n}
\end{align*}
\]

Equation 5 - Central Moments Difference Equations
Piecewise Parabolic (P2) Method

- Maintains 5 markers on a cumulative distribution curve
- Sample arrives, markers are updated
- Markers correspond to $p/2$, $p$, $(1+p)/2$ and the maximum quantile
- Heights are adjusted using a Piecewise Parabolic (P2) formula.