Dual Operating System Architecture for Real-Time Embedded Systems

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Outline

1  Introduction
   - Virtualization and Real-Time
   - ARM TrustZone
   - VMM requirements

2  VMM architecture
   - SafeG, a TrustZone monitor
   - Cyclic scheduling
   - Priority-based scheduling

3  Implementation

4  Evaluation

5  Conclusions and future work
Virtualization for Real-Time Embedded Systems

App: Execute GPOS and RTOS applications on a single platform

- GPOS kernel patches (e.g., Linux RT patch)
  - Soft Real-Time only, low security and reliability
- Hybrid kernels (e.g., Xenomai, RTAI, RTLinux, Linux on ITRON)
  - Hard Real-Time, native performance but no isolation
Virtualization for Real-Time Embedded Systems

- Hardware extensions (e.g., multicore)
  - Increased price and power consumption
  - Underutilization of RTOS core
- VMM/Hypervisors (e.g., OKL4, XtratuM, Integrity OS)
  - Good isolation with some overhead
  - Paravirtualization is hard to maintain

Diagram:

```
Apps   Apps   Apps   Apps
Guest OS Guest OS Guest OS Guest OS
  modification    modification    modification    modification
Hypervisor
Hardware

Apps   Apps   Apps
Guest OS Guest OS Guest OS
  modification    modification
Microkernel
Hardware
```
Virtualization challenges

- Modifications to the GPOS are difficult to maintain
- It is not possible to provide complete isolation
  - Bus masters as DMA or GPUs can bypass protections
  - Virtualizing them would severely damage performance
  - Hardware-assisted Virtualization

- Embedded virtualization requires Integrated Scheduling
  - Some GPOS tasks and interrupts require a certain QoS
  - Not all RTOS activities need high priority
ARM TrustZone

- System-wide approach to security (e.g., authentication, DRM)
  - Trust and Non-Trust states (orthogonal to privileges)
  - Monitor mode to switch between them

- ARM 1176 and Cortex-A series
VMM requirements

- Support concurrent execution of a GPOS and an RTOS
- Spatial isolation of the RTOS
- Time isolation of the RTOS
- Integrated scheduling of GPOS soft-real time tasks and interrupts
- Mechanisms to implement health monitoring and device sharing
- No modifications to the GPOS core
- Minimum size. Easy to verify.
SafeG: Implementation of the TrustZone monitor

- Runs with interrupts disabled (FIQ and IRQ)
- Isolation: RTOS runs in Trust state, GPOS in Non-Trust state
- RTOS interrupts (FIQ) can not be disabled by the GPOS (IRQ)
- The GPOS is represented as an RTOS task
  - RTOS interface (e.g., \(\mu\)ITRON) can be used on the GPOS
SafeG

Execution paths

1. An FIQ occurs in Trust state
2. An FIQ occurs in Non-Trust state (SafeG switches to Trust state)
3. An IRQ occurs in Non-Trust state
4. SafeG switches state after an SMC call
SafeG

Health monitoring

- Mechanisms to monitor, suspend, resume and restart the GPOS
Black box vs. Integrated cyclic scheduling

- Synchronization of internal and global scheduler

(a) RTOS GPOS RTOS GPOS RTOS GPOS RTOS GPOS RTOS

(b) RTOS GPOS RTOS GPOS RTOS GPOS RTOS GPOS RTOS

- Integrated approach for synchronized cyclic scheduling

- Global and local schedulers not synchronized!!
Latency in integrated cyclic scheduling

- FIQ interrupts and High priority tasks

(a) FIQ latency not affected

(b) Priorities and cyclic scheduling together
Idle approach

- GPOS interrupts and tasks scheduled as RTOS idle task
- Long latencies (e.g., IRQ handlers)
ITask-RTask-BTask approach

- ITask: GPOS interrupts latency
- RTask: Gives a QoS to GPOS (budget-period)
- BTask: like Idle approach
VMM architecture

Priority-based scheduling

**ITask-RTask-BTask Timeline**

- **RTOS**
  - **t1**
  - **Lat. Han.**
  - **t1**
  - **ITASK**
  - **FIQ'**
  - **GPOS interrupt as IRQ**

- **SafeG**
  - **GPOS interrupt, configured temporarily as FIQ, arrives**
  - **FIQ**
  - **SMC IRQ**

- **GPOS**
  - **FIQ**
  - **IRQ'**
  - **GPOS IRQ handler is executed**
  - **GPOS scheduler, tasks, etc.**

- **ITASK**
  - **ITASK starts consuming capacity**
  - **ITASK consumed all its capacity. An overrun timer generates a FIQ**

- **ITASK budget is replenished**

- **ITASK budget replenishment handler arrives**

- **task 2 can execute now**

- **t2**

- **overrun**

- **t2**

- **buffer**

- **budget**

- **t2**

- **ITASK and configures the GPOS interrupt as FIQ**

- **The Overrun handler suspends ITASK and configures the GPOS interrupt as FIQ**

- **tasks 1 and 2 are activated**
Implementation

- **Platform:**
  - ARM PB1176JZF-S (210Mhz, 128MB, 32KB Cache)

- **RTOS:** TOPPERS/ASP
  - Added overrun handlers (for deferrable servers)
  - Implemented TrustZone device drivers

- **GPOS:** GNU/Linux
  - High Vector table (0xFFFFF0000)
  - Memory and devices allocation
SafeG overhead

<table>
<thead>
<tr>
<th>Path</th>
<th>WCET</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) While RTOS runs FIQ occurs</td>
<td>0.7μs</td>
</tr>
<tr>
<td>(2) While GPOS runs FIQ occurs</td>
<td>1.6μs</td>
</tr>
<tr>
<td>(3) While GPOS runs IRQ occurs</td>
<td>1.2μs</td>
</tr>
<tr>
<td>(4) Switch from RTOS to GPOS</td>
<td>1.5μs</td>
</tr>
<tr>
<td>(5) Switch from GPOS to RTOS</td>
<td>1.7μs</td>
</tr>
<tr>
<td>From ASP IRQ vector until IRQs enabled</td>
<td>5.1μs</td>
</tr>
</tbody>
</table>
SafeG code verifiability

- Code and data size (in bytes)

<table>
<thead>
<tr>
<th></th>
<th>text</th>
<th>data</th>
<th>bss</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SafeG</td>
<td>1520</td>
<td>0</td>
<td>448</td>
<td>1968</td>
</tr>
<tr>
<td>ASP</td>
<td>34796</td>
<td>0</td>
<td>83140</td>
<td>117936</td>
</tr>
<tr>
<td>Linux</td>
<td>1092652</td>
<td>148336</td>
<td>89308</td>
<td>1330296</td>
</tr>
</tbody>
</table>

- SafeG size is 1/60 of the size of ASP
- 304 bytes in .bss are just for the context
- 4 forks in total: only 8 types of tests needed
**RTOS isolation**

- Latency of the ASP and Linux system timer interrupt
  - ASP timer interrupt latency increased 2us (bounded)
ITask experiment

- Measure the Serial driver interrupt latency on Linux
- RTOS tasks:

<table>
<thead>
<tr>
<th>task</th>
<th>priority</th>
<th>period</th>
<th>duration</th>
<th>utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>high</td>
<td>50ms</td>
<td>10ms</td>
<td>20%</td>
</tr>
<tr>
<td>2</td>
<td>low</td>
<td>300ms</td>
<td>100ms</td>
<td>33%</td>
</tr>
</tbody>
</table>

- ITask period: 30ms, budget: 2ms
- Serial driver latency (in $\mu$s):

<table>
<thead>
<tr>
<th>approach</th>
<th>min</th>
<th>avg</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>alone</td>
<td>15.7</td>
<td>15.81</td>
<td>19.47</td>
</tr>
<tr>
<td>idle</td>
<td>14.6</td>
<td>22681</td>
<td>113833</td>
</tr>
<tr>
<td>itask</td>
<td>15.45</td>
<td>2292</td>
<td>30275</td>
</tr>
</tbody>
</table>
RTask experiment

- Execute the cyclictest program in the GPOS
  - Periodic thread that measures the wake up latency

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**Cyclictest**

- Maximum latency using RTASK (server period=30ms): 36.2ms
- Maximum latency using idle approach: 139.3ms
Conclusions

- **SafeG**
  - A reliable dual hypervisor for embedded real-time systems

- **VM Integrated Scheduling**
  - Cyclic scheduler
  - ITask-RTask-BTask approach

- **ARM TrustZone security extensions**
  - Useful for virtualization
  - Proposal: Cache separation
  - Proposal: Instruction for context switch
Future work

- Refine Integrated Scheduling with voluntary return
  - Fine-grained control of tasks and interrupts
  - May require GPOS core modifications
- Android on the Non-Trust side
- Inter-VM communications
- Multi-core porting (Cortex-A9)
Questions

Thank you for your attention
ご清聴ありがとうございます