AUTOBEST:
A United AUTOSAR-OS
And ARINC 653 Kernel

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Motivation

• Automotive and Avionic industry begin to face similar challenges:
  – Hyper integration: increasing HW & SW complexity
  – Energy consumption
  – Certification effort
  – Cost pressure
  – Security issues
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• Automotive and Avionic industry begin to face similar challenges:
  – Hyper integration: increasing HW & SW complexity
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  – Certification effort
  – Cost pressure
  – Security issues

• But both industries use different OS standards!
  – Can't we challenge this with a single, unified operating system?
  – Combine avionics safety with the resource-efficiency of automotive systems?
  – And (probably) make it faster than existing systems?
Outline

• AUTOSAR and ARINC 653
  – Short introduction
  – Task models
  – Partitioning concepts
  – Challenges

• AUTOBEST
  – Architecture
  – Lazy priority switching
  – Static Futexes

• Conclusions & Outlook
AUTOSAR

OS Concepts:
- Tasks
- ISRs
- Event driven
- Fixed-priority scheduling
- Statically configured at compile time
- Isolation: group tasks into OS-Applications

Here: focus on AUTOSAR-OS, the OS kernel

Source: http://www.autosar.org
ARINC 653 Standard:
- Part 1 - Required Services
- Part 2 - Extended Services
- Part 3 - Conformity
- Part 4 - Subset Services
ARINC 653 Standard:
- Part 1 - Required Services
- Part 2 - Extended Services
- Part 3 - Conformity
- Part 4 - Subset Services

OS Concepts:
- Robust partitioning in space and time
- Processes (=Tasks) as executing entities
- Time driven and event driven
- Fixed-priority task scheduling, TDMA partition scheduling
- Task synchronization and partition communication means

Source: ARINC 653 specification
AUTOSAR

- 4 task states
- Preemptive scheduling
- Waiting:
  - per-task event bitmask
- A task terminates when its job is complete
Task Model

AUTOSAR
- 4 task states
- Preemptive scheduling
- Waiting:
  - per-task event bitmask
- A task terminates when its job is complete

ARINC 653
- Additional transitions
- Waiting:
  - Single-bit events
  - Semaphores
  - Buffers and blackboards
  - Queuing and sampling ports
Separation & Isolation

- **AUTOSAR**
  - *OS-Applications*
  - Optional concept
  - Memory protection
  - Configurable access to objects in other Applications

\[ \text{AUTOSAR OS Kernel} \]

\[ \text{ARINC 653 Kernel} \]
Separation & Isolation

- **AUTOSAR**
  - **OS-Applications**
  - Optional concept
  - Memory protection
  - Configurable access to objects in other Applications

- **ARINC 653**
  - **Partitions**
  - Mandatory concept
  - Complete isolation
  - Explicit inter-partition communication means
Time Partitioning

Time partitioning separates partitions and drives time-triggered tasks
AUTOSAR repeating Schedule Tables

Schedule Table Duration

Offset

Delay

• activate tasks
• set event

Expiry Point

Time

AUTOSAR Schedule Tables allow similar time-triggered task activation
For temporal separation, optional timing protection facilities are available

ARINC 653 Time Partitioning

Major Time Frame

Activation

Partition 1
Part. 2
Part. 3
Partition 1
Partition 4
Idle

Duration

Time

Time partitioning separates partitions and drives time-triggered tasks
Differences

AUTOSAR

• Construction kit
• Task classes
• Scalability classes
• Isolation is an add-on
• Goals:
  – reduce resource usage
  – *keep it simple*
Differences

AUTOSAR
- Construction kit
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ARINC 653
- General purpose API
- No configuration options
- Certification
- Decoupling of partitions
- Goals:
  - fault mitigation
  - *safety first*
Challenges

- Support both AUTOSAR and ARINC 653 APIs
- Full ARINC 653 partitioning at minimal resource costs
- Performance comparable to other AUTOSAR implementations
- Keep system easy to (re-)certify
AUTOBEST
Statically configured microkernel

Partitions
- Space partitioning
- Time partitioning
- Driven by ARINC 653

Tasks
- Superset of AUTOSAR & ARINC 653 task API
- Keep OS specific differences out of the kernel
- User space libraries provide full AUTOSAR or ARINC 653 API
Scheduling

- Two-level scheduler
- Time-Partition Scheduling
  - One ready queue per time partition
  - Multiple space partitions can share one time partition
- Task Scheduling
  - Priority Scheduling with FIFO order on tie
- Fast critical sections using priority ceiling protocols
- Futex wait queues
Special Requirements of AUTOSAR

- Counters, Alarms, and Schedule Tables
  → difficult to implement in user space

- Interrupt Handling
  • Allow ISRs in both kernel and user space
    - ISR cat 1 → kernel domain (no interaction with OS)
    - ISR cat 2a → kernel domain
    - ISR cat 2b → partition domain
  • Partitioned ISRs are mapped to high priority tasks
  • DisableInterrupts() → raise priority to partition maximum
- “hooks” (high priority pseudo tasks) for error handling
Special Requirements of ARINC 653

- Futex wait queues for ARINC sync objects
- 64-bit Nanosecond Timeout API
- Health Monitoring
  - Strict error handling using HM tables
  - Error process is mapped to a hook (like for AUTOSAR)
- Partitioning API
  - Start & Shutdown of other partitions
  - Privileged system calls
- Task deadline monitoring
 Component Architecture

- Generic code
- Architecture code
- Board code
  - Boot, Interrupt Handling, ...
  - Kernel device drivers
- Configuration data
- OS specific libraries
- Kernel and partition code kept in dedicated binary images

System Configuration

- XML config → C language data structs (no C code, no #ifdefs)
- Binary reuse possible + reduces testing efforts
Resource Efficiency: **RAM is precious!**

- **Split data model:**
  - keep config in flash
  - keep data in RAM

- **Most expensive:**
  - task data (64 bytes)
  - register contexts
  - kernel stacks
  - ready queue per time partition (2 KiB / 256 priority levels)

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**Task Data**

Queues use doubly-linked lists:
- either ready queue or timeout queue
- sync object's wait queue
- deadline monitoring queue

Time tracking in 64-bit nanoseconds:
- timeout expiry time
- phase shift of task activation
- deadline timeout

House keeping:
- task state, priorities,
- pending events and task activations
- etc
Resource Efficiency: And flash as well!

• Example Configuration:
  – 5 resource partitions, 1 time partition
  – 29 tasks, 10 hooks, 1 ISR
  – 4 schedule tables, 2 alarms

• Kernel memory usage on TMS570:
  – 13.5 KiB code (ARM thumb code, gcc -O2)
  – 7.5 KiB config
  – 17 KiB data (8 KiB stacks, 3.5 KiB registers, 2 KiB ready queues)
Lazy Priority Switching
Typical critical section

(using the AUTOSAR priority ceiling protocol)
Lazy Priority Switching

Typical critical section
(using the AUTOSAR priority ceiling protocol)

If critical sections are short and frequent, the overhead to change the caller's scheduling priority dominates runtime costs!
Lazy Priority Switching

Change scheduling priority:
- System call overhead
- Raising priority: check & update some values
- Lowering priority: same + check for rescheduling
Lazy Priority Switching

Change scheduling priority:
- System call overhead
- Raising priority: check & update some values
- Lowering priority: same + check for rescheduling

Idea for Optimization:
- Get rid of system call to set some values
- Kernel and user share variables to set priority
- Move rescheduling check into user space (checked when leaving a critical section)
Lazy Priority Switching

Optimized critical section:
One system call in the worst case (preemption)

Frequently used pattern, esp. in OS libraries!

Best case / no preemption:
MPC5646C: 688 → 31
TMS570: 843 → 94
(CPU cycles)
Futex Wait Queues
All ARINC 653 synchronization objects behave similar:

- Some tasks **wait** for something to happen
- Other tasks **wake** one or all waiters
- Each sync object has a wait queue
- Queue discipline: FIFO or priority-sorted (configured at partition start)
- Optional timeout
- **Provide an API for wait queue operations**
Futex Wait Queues

Example: Queuing port communication
- Shared memory for message buffers in queuing port channel
- One atomic Futex variable encodes read and write positions
- Two cross-connected wait queues

receiver side \textit{wakes one} after message was consumed

\begin{itemize}
  \item sender side \textit{waits} if message queue is \textit{full}
  \item receiver side \textit{waits} if message queue is \textit{empty}
\end{itemize}

\begin{itemize}
  \item sender side \textit{wakes one} after message was sent
\end{itemize}
The kernel needs to manage wait queues only:

- Abstract \textit{wait} and \textit{wake} operations like in Linux Futexes
- \textit{Wait} and \textit{wake} sides can reside in different partitions

All ARINC 653 synchronization objects can be built upon Futexes and wait queues

Bonus: all copy operations done in user space (copy messages in user space at highest priority)
Conclusion
Conclusion

- Possible: unified kernel for AUTOSAR and ARINC
- Lazy priority switching improves performance
- Futex wait queues for ARINC 653 synchronization means keep complexity out of the kernel

Lessons learned

- Statically tailored kernels: good choice for safety-critical systems (much simpler than using runtime configuration)
- AUTOSAR nowadays provides similar functionality as ARINC 653
Outline

Status

- Single core: PPC (e200) and ARM (Cortex R4)
- AUTOSAR OS 4.1 rev 3
- ARINC 653 part 1 suppl 3
- Pthread subset as additional OS environment

Future work

- Multi core: Infineon AURIX
- Real-world benchmarks
- Interrupts do not fit well to a time partitioned world
- Problem: Lock step not available for all cores
Thank you for your attention!
Backup Slides
Subset of POSIX PSE5.1

- Pthread API
  - Pthreads
  - Mutexes
  - Condition Variables
- Minimal C-library
- Dynamic memory allocation
- Scheduling
  - SCHED_FIFO supported
  - SCHED_RR not supported
- No Signal Handling
- No Thread Cancellation

No additional efforts in the kernel!
Performance (Nov 2014)

- Freescale MPC5646C *Bolero* @120 MHz
  - Syscall: 87 cycles / 0.73 µs
  - OSEK resource fast: 29 cycles / 0.24 µs
  - OSEK resource slow: 300 cycles / 2.50 µs
  - Task switch: 390 cycles / 3.25 µs

- Texas Instruments TMS570LS3137 @180 MHz
  - Syscall: 151 cycles / 0.83 µs
  - OSEK resource fast: 70 cycles / 0.38 µs
  - OSEK resource slow: 431 cycles / 2.39 µs
  - Partition switch overhead: 659 cycles / 3.66 µs
# AUTOBEST Architecture

**Considered alternative: Hypervisor design**

<table>
<thead>
<tr>
<th>Microkernel</th>
<th>Hypervisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernel knows all OS tasks</td>
<td>HV knows only partitions</td>
</tr>
<tr>
<td>Kernel schedules tasks and partitions</td>
<td>HV schedules partitions, delegates task scheduling to partition</td>
</tr>
<tr>
<td>API: OSEK + Partitioning API</td>
<td>API: Virtual CPU + virtual interrupt controller programming interface</td>
</tr>
<tr>
<td>ISRs: - Cat 2 ISRs → partitioned</td>
<td>ISRs: similar</td>
</tr>
<tr>
<td>- Cat 1 ISRs → global</td>
<td></td>
</tr>
<tr>
<td>Cat 2 ISRs are scheduled like tasks</td>
<td>How to inject interrupts with priority?</td>
</tr>
</tbody>
</table>
The End