Exploiting Static Application Knowledge in a Java Compiler for Embedded Systems

A Case Study

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Motivation

Automotive industry

- High robustness requirements
- But: mass production, immense cost pressure
- {Computational, memory} efficiency is key!

Challenge for the deployment of Java applications

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Challenge for the deployment of Java applications

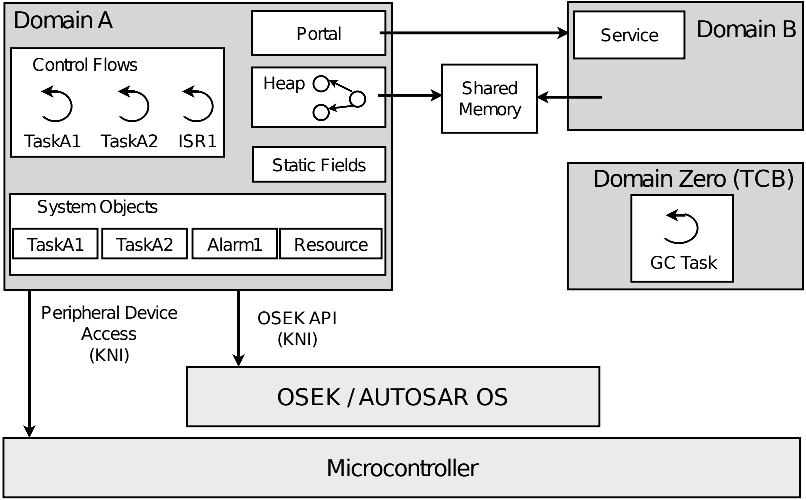
System model of the OSEK/AUTOSAR OS

- OS tailoring: only enable features needed by the application
- Completely static configuration of the application world:
  - Fixed number of tasks
  - No dynamic code loading
  - Fixed-priority scheduling

Let's build a Java VM for this system model!

The KESO Multi-JVM

- Java-to-C ahead-of-time compiler
- VM tailoring, static configuration



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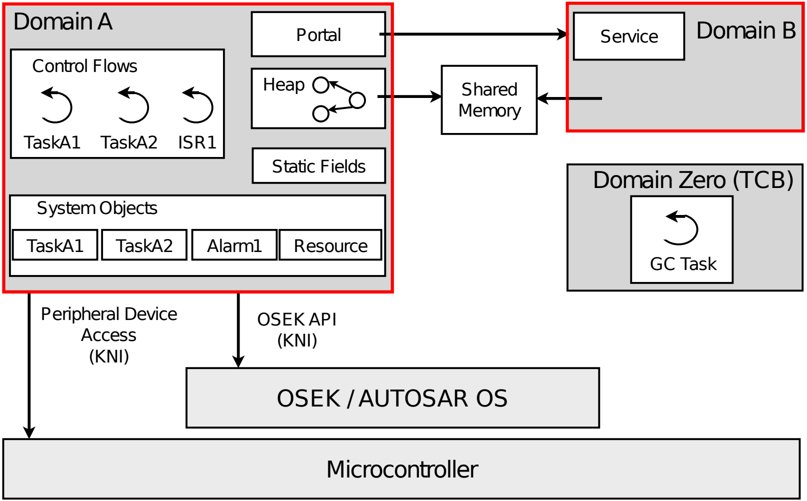

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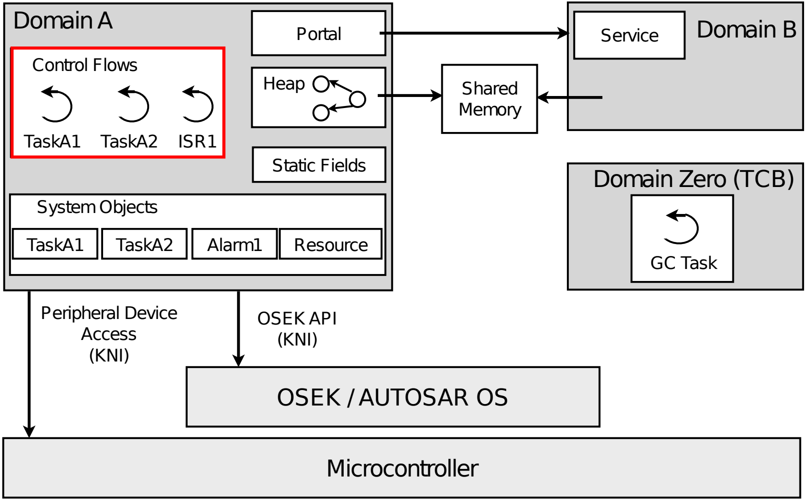

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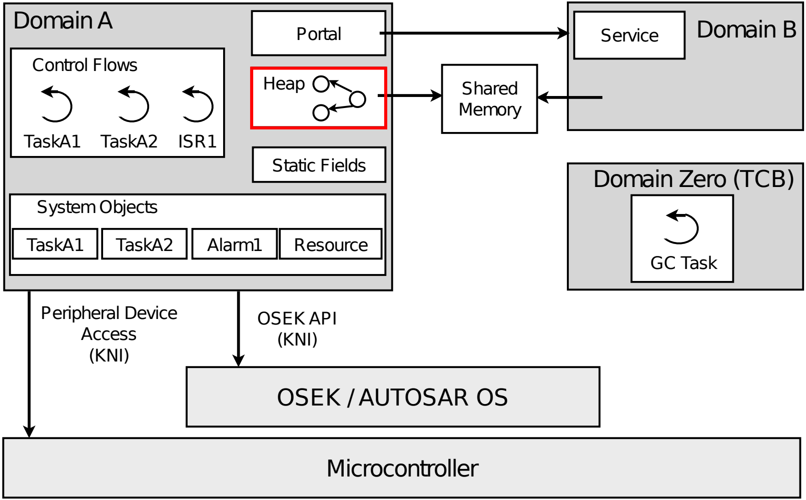

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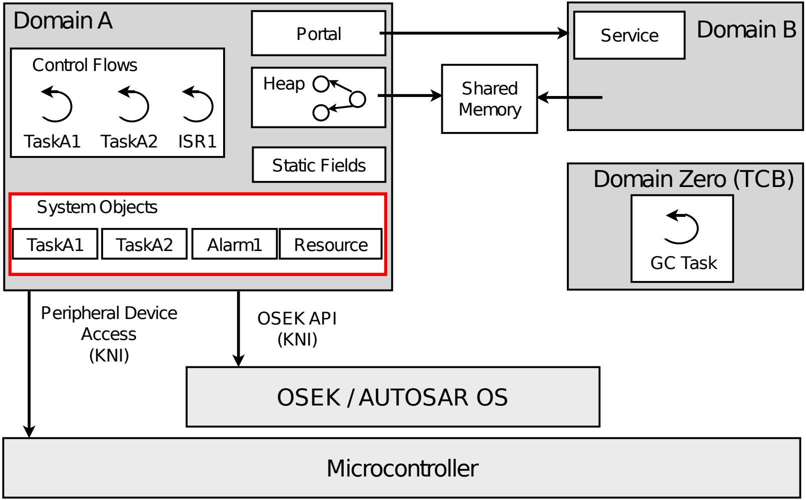

Static knowledge

KESO relies upon the availability of extensive application knowledge at compile-time.

Sources of knowledge

1. System model
   - Abandon the aspects of the Java programming model that don't fit the OSEK/AUTOSAR system model!
   - "Everything is static"

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   - Entry points
   - System objects

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3. Application bytecode
   - Analyze to gain additional knowledge
   - Optimize aggressively using the aggregated knowledge

Optimizations

Static whole-program (or rather: whole-domain) analysis

- Starting at each domain's entry points
- Combined control flow, data flow and class hierarchy analysis

Since the application's static nature enables us to collect extensive information ahead of time, we can apply aggressive optimizations.

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Improved standard optimizations

- Method inlining
- Constant propagation & folding
- Escape analysis & stack allocation
- Runtime check elimination (`null`-, bounds checks)
- Dead-code elimination
- Devirtualization

Selective use of linked stack frames

- Local references stored as compounds, stack frames linked in order to enable GC scanning
- Induces significant overhead!
- But: GC will only run in slack time

Optimization: Only enable Henderson frames in methods that can possibly block – i.e., methods directly or indirectly invoking the `WaitEvent()` OS function

Variant-specific constants

- The `final` qualifier for field variables allows better optimizations
- However...
  - ... programmers may be lazy or unaware
  - ... declaring a field as `final` is impossible in some cases:

```
public final class Constants {
    public static int MAX_FRAMES = 1000;
    // ... more similar constants...
}

public class Main {
    private static void parse(final String[] v) {
        // ...
        if (v[i].equals("MAX_FRAMES"))
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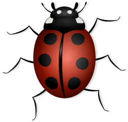
Idea: deduce `final` qualifiers where possible and legal

Bug detection at compile-time

System configuration



- Does a task have run-to-completion semantics according to the configuration, but invokes `WaitEvent()` anyway?
- Service protection: Does a task or ISR access system objects other than those specified in the configuration?

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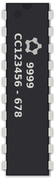
Used raw-memory areas



- Which address ranges are accessed from a specific domain?
- Would a raw-memory area intersect with the regular application memory?
- Which memory-mapped I/O ports are used by which domains?

Results

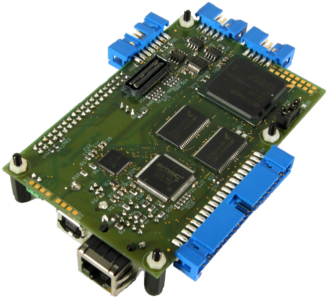
Test system

Software

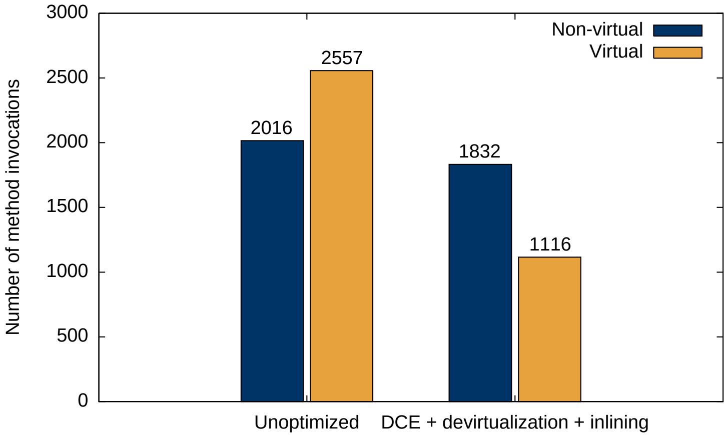
- CD_j 1.2, ported to KESO:
  - Real-time air traffic simulator and collision detector
  - Community-accepted benchmark
- CiAO OS (AUTOSAR programming interface)

Hardware

- TriCore TC1796 @ 150 MHz
- 2 MiB ROM
- 1 MiB SRAM



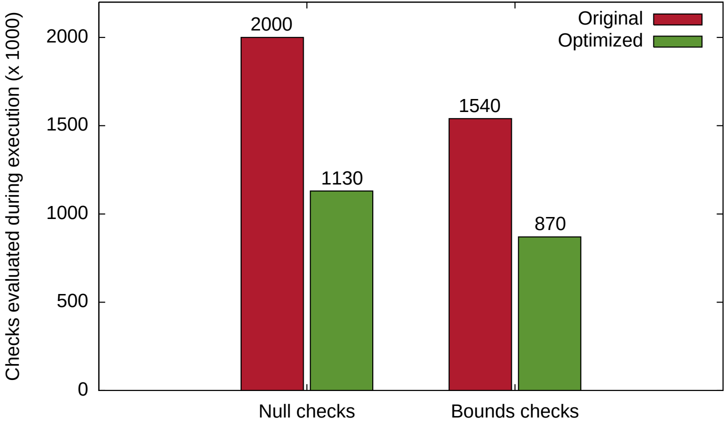
Dead code elimination & devirtualization



More than half of all virtual method invocations are either removed or bound statically.

How many checks are performed during execution?

CD_j detector, 10,000 radar frames:



Over 40 % of all runtime checks are elided.

Effectiveness of advanced optimizations

	Default	+ Optimized frames[1]	+ Variant-specific constants
Exec. time[2]	23.9 ms	15.9 ms (−33.5 %)	15.8 ms (−33.9 %)
Code size	67.8 KiB	55.2 KiB (−18.6 %)	46.5 KiB (−31.4 %)
Data size	4.86 KiB	4.86 KiB (±0 %)	3.08 KiB (−36.6 %)

- Using Henderson frames selectively improves both execution time and code size significantly
- Inferring the `final` qualifier for CD_j's `Configuration` fields would drastically reduce the memory footprint

[1] Use of Henderson frames only where necessary
[2] For detector run with 10,000 radar frames; median

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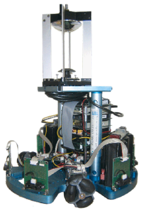
  - ... permitting aggressive whole-program optimizations
  - ... bringing the benefits of Java to deeply embedded systems
- Our smallest system to date: Robertino
  - Autonomous robot navigating around obstacles
  - Control software running on ATmega8535 (8-bit AVR, 8 KiB Flash, 512 B SRAM)



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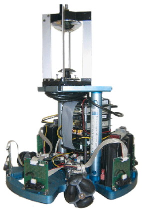

Future work

- Implementation of more advanced optimizations
- Extensive evaluation of real-life embedded applications