Konfigurierbare Systemsoftware (KSS)

VL 4 – Aspect-Aware Development: The CiAO Approach

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About this Lecture

Problem Space

Domain Expert

Features and Dependencies

Solution Space

Architect / Developer

Architecture and Implementation

Configuration

Specific Problem

System User

intentional side

intended properties

Variant

Specific Solution

System User

extensional side

actual implementation

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Specific Solution

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actual implementation
### Decompositional Approaches
- Text-based filtering (untyped)
- Preprocessors

### Compositional Approaches
- Language-based composition mechanisms (typed)
- OOP, AOP, Templates

### Generative Approaches
- Metamodel-based generation of components (typed)
- MDD, C++ TMP, generators
Implementation Techniques: Goals

General
1. Separation of concerns (SoC)
2. Resource thriftiness

Operational
3. Granularity Components should be fine-grained. Each artifact should either be mandatory or dedicated to a single feature only.
4. Economy The use of memory/run-time expensive language features should be avoided as far as possible. Decide and bind as much as possible at generation time.
5. Pluggability Changing the set of optional features should not require modifications in any other part of the implementation. Feature implements should be able to “integrate themselves”.
6. Extensibility The same should hold for new optional features, which may be available in a future version of the product line.

How to achieve these with AOP?
4.1 AOP Mechanisms Under the Hood
4.2 Study: i4Weathermon AOP
4.3 CiAO
4.4 CiAO Results
4.5 Summary
4.6 References
4.1 AOP Mechanisms Under the Hood
   Diagram Notation
   Obliviousness & Quantification
   AOP Mechanisms: Summary

4.2 Study: i4Weathermon AOP

4.3 CiAO

4.4 CiAO Results

4.5 Summary

4.6 References
Szenario:
Optional feature component $F_1$ shall be integrated into SPL component $PL$.

With OOP:
- $PL$ has to call $F_1$  \(\leadsto\) $PL$ has to know $F_1$
- control flows can only be established in the direction of knowledge

With AOP:
- $F_1$ can give advice to $PL$  \(\leadsto\) $F_1$ has to may know $PL$
- control flow is established opposite to the direction of knowledge
- binding is inherently loose  \(\leadsto\) silently missed, if $PL$ does not exist
Szenario:
(Nonfunctional)
feature component $F_1$
shall be integrated into
(optional) SPL
components $PLC_1...n$

With AOP:
- binding is inherently loose $\leadsto$ may quantify over $n$ join points
- possible by delarative pointcut concept
  (here: wildcard in match expression)
Advice

inverses the direction in which control-flow relationships are established: \( C \text{ calls } A \implies A \text{ advises } C \)

- Aspects integrate themselves into the surrounding program
  \( \leadsto \) “I make you call me”

- Surrounding program can be kept oblivious of the aspects
  \( \leadsto \) advice-based binding as a means to integrate (optional) features

Pointcuts

provide for an implicit quantification of this integration

- Applies to \( 0 \ldots M \ldots n \) join points, depending on the pointcut expression
  \( \leadsto \) Aspects can be kept oblivious of the surrounding program

- Thereby, advice-based binding is inherently loose
  \( \leadsto \) advice-based binding as a means to integrate interacting features
Agenda

4.1 AOP Mechanisms Under the Hood
4.2 Study: i4Weathermon AOP
   Flashback: i4Weathermon
   i4WeatherMon with AOP
   i4WeatherMon with AOP: Results
4.3 CiAO
4.4 CiAO Results
4.5 Summary
4.6 References
How to achieve *Granularity, Economy, Pluggability, Extensibility*?

- Configuration-dependent sensor and actuator sets
  - initialization, integration, interaction of optional feature code
- Generic and nongeneric actuators
  - interacting optional feature code
I4WeatherMon: OOP Solution Space

Weather
registerSensor() measure() init()

Sensor
measure() name() unit() str_val() init()

Wind
id() measure() name() unit() str_val() init()

Pressure
id() measure() name() unit() str_val() init()

Sink
registerActuator() process() init()

Actuator
before_process() after_process() process() init()

ChainBase
_sensors
_init, measure

Display
#print()
before_process() process() init()

PCConnection
«alias»
before_process() after_process() process() init()

SNGConnection
#send()

registerSensor

registerActuator

_i4WeatherMon: OOP Solution Space

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#send()
I4WeatherMon: AOP Solution Space

**Basic structure**

- **Weather** and **Sink** are (almost) empty classes.
  - Provide a **lexical scope** for sensor / actuator introductions
  - Provide **explicit join points** (empty methods `measure()` / `process()` that are invoked by the main loop, when measuring / processing should take place
  - All further functionality is provided by the aspects!
**Sensor integration**

A *Sensor* is implemented as a class with an accompanying **Handling** aspect:

- Slices the sensor singleton instance into **Weather**
- Gives advice to **Weather::measure()** to invoke **Sensor::measure()**
- Slices an explicit join point **process_data(Sensor)** into **Sink**
- Gives advice to **Sink::process()** to invoke **process_data(Sensor)**
class Weather {
public:
    void measure() {} // empty implementation
};

class Sink {
public:
    void process() {} // empty implementation
};

aspect PressureHandling {
    // Weather integration
    advice "Weather" : slice struct{
        Pressure _pressure; // introduce sensor instance (singleton)
    };
    advice execution( "void Weather::measure()" ) : before() {
        theWeather._pressure.measure(); // invoke sensor’s measure()
    }
    // Sink integration
    advice "Sink" : slice struct {
        // introduce sensor-specific explicit join point for actuator aspects
        void process_data( const Pressure & ) {} 
    };
    advice execution( "void Sink::process()" ) : after() {
        theSink.process_data( theWeather._pressure ); // trigger it
    }
};
Generic actuator integration

A generic actuator (processes all sensors) is implemented by an aspect

- Gives advice to `Sink::process()` to execute processing pre-/post actions
- Gives generic advice to all overloads of `Sink::process_data()` to invoke each sensor (typed) in order to process its data via the generic `str_val()`

> Generic actuator does not know the available / possible sensor types
aspect Display {
    ...
    // display each element of the weather data
    advice execution("void Sink::process_data(%)") : before () {
        typedef JoinPoint::template Arg<0>::ReferredType Data;
        char val[5];
        tjp->arg<0>()->str_val( val );
        print( Data::name(), val, Data::unit() );
    }
};
Nongeneric actuator integration

A nongeneric actuator (processes some sensors) is implemented by an aspect

- Gives advice to `Sink::process()` to execute processing pre-/post actions
- Gives advice to selected overloads of `Sink::process_data()` to invoke them in order to process each sensors data via a sensor-specific interface

Nongeneric actuator has to know specific sensor types
**I4WeatherMon: AOP Generic Actuator Integration**

```cpp
aspect SNGConnection : protected PCConnection {
  UInt8 _p, _w, _t1, _t2;  // weather record
...
  // let this aspect take a higher precedence than <Sensor>Handling
  advice process () : order ("SNGConnection", "%Handling");
  advice execution("void Sink::process(const Weather&)")
    : before () { ... /* init record */ }
  advice execution("void Sink::process(const Weather&)")
    : after () { ... /* transmit record */ }

  // collect wind, pressure, temperature data by giving specific advice
  advice execution("void Sink::process_data(...)") && args (wind)
    : before (const Wind &wind) {
      _w = wind._w;
    }
  advice execution("void Sink::process_data(...)") && args (pressure)
    : before (const Pressure &pressure) {
      _p = pressure._p - 850;
    }
  advice execution("void Sink::process_data(...)") && args (temp)
    : before (const Temperature &temp) {
      _t1 = (UInt8)temp._t1;
      _t2 = temp._t2;
  }
};
```
AOP is as efficient as CPP-based configurability!
I4WeatherMon (AOP): Evaluation

General
1. Separation of concerns (SoC)
2. Resource thriftiness

Operational
3. Granularity
   - Every component implements functionality of a single feature only.
4. Economy
   - All control-flow bindings are established at compile time.
5. Pluggability
   - Sensors and actuators integrate themselves by aspects.
6. Extensibility
   - “Plug & Play” of sensor and actuator implementations.
Agenda

4.1 AOP Mechanisms Under the Hood
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4.3 CiAO
   - Motivation and Goals
   - Design Approach
   - Examples: Aspects in Action
   - Explicit Join Points
   - Further Examples
4.4 CiAO Results
4.5 Summary
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CiAO: Motivation and Goals

Throughout the entire operating-system design cycle, we must be careful to separate policy decisions from implementation details (mechanisms). This separation allows maximum flexibility if policy decisions are to be changed later.

Silberschatz, Gagne, and Galvin 2005: Operating System Concepts [8, p. 72]

Primary goal: architectural configurability
- configurability of even fundamental policies
  ⚫ synchronization, protection, interaction

Secondary goal: < the standards >
- efficiency, configurability in general, portability

Approach: aspect-aware operating system design
- strict decoupling of policies and mechanisms in the implementation
  ⚫ using aspects as the primary composition technique
CiAO ↔ CiAO is Aspect-Oriented

A product line of aspect-oriented operating systems
- Implements OSEK VDX / AUTOSAR OS [1, 7]
- Fine-grained configurability of all system policies and abstractions
- Developed from scratch with AOP
Layered Architecture
- Interface layer (as/ciao)
- System layer (os)
- Hardware layer (hw)

Layers $\mapsto$ C++ namespaces
- Potential join points for cross-layer transitions
- Further refined by sublayers (os::krn, hw::irq)
- Layers as a means of aspect-aware development

$\sim$ “visible transitions”

// yields all hardware invocations from the system layer
pointcut OStoHW() = call("% hw::....::%(...)")
&& within("% os::....::%(...)");
## Methodology: Principles of Aspect-Aware Development

### Design Principles:

<table>
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<tr>
<th>Design Principles</th>
<th>Development Idioms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. loose coupling</td>
<td>by advice-based binding</td>
</tr>
<tr>
<td>2. visible transitions</td>
<td>by explicit join points</td>
</tr>
<tr>
<td>3. minimal extensions</td>
<td>by extension slices</td>
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</table>
Methodology: Principles of Aspect-Aware Development

The principle of loose coupling. Make sure that aspects can hook into all facets of the static and dynamic integration of system components. The binding of components, but also their instantiation (e.g., placement in a certain memory region) and the time and order of their initialization should all be established (or at least be influenceable) by aspects.

The principle of visible transitions. Make sure that aspects can hook into all control flows that run through the system. All control-flow transitions into, out of, and within the system should be influenceable by aspects. For this they have to be represented on the join-point level as statically evaluable, unambiguous join points.

The principle of minimal extensions. Make sure that aspects can extend all features provided by the system on a fine granularity. System components and system abstractions should be fine-grained, sparse, and extensible by aspects.
What to model as a *class* and what as an *aspect*?

- `<Thing>` is a class if – and only if – it is a distinguishable, instantiable concept of CiAO:
  - A *system component*, instantiated internally on behalf of CiAO
    - The Scheduler, the Alarm Manager, the OS control facility, ...
    - Hold and manage kernel state, singletons by definition
  - A *system abstraction*, instantiated as objects on behalf of the user
    - Task, Event, Resource, ...
    - In AUTOSAR OS: instantiated at compile time
  - Both are *sparse* ~ provide a minimal implementation only

- Otherwise `<thing>` is an aspect!
Three idiomatic aspect roles

- **Extension aspects:** extend some system component or system abstraction by additional functionality.

- **Policy aspects:** “glue” otherwise unrelated system abstractions or components together to implement some CiAO kernel policy.

- **Upcall aspects:** bind behavior defined by higher layers to events produced in lower layers of the system.
visible transitions by explicit join points
**Example: Mechanism Integration**

**binding aspects**

Implement upcalls by advice-based bindings

```
Serial0
init()
sendBlock()
```

```
Serial0_Init
exec("init")
```

```
Sched_Init
exec("init")
```

```
Serial0Ext
task
init()
```

```
Serial0Ext_Task
init()
```

```
ready()
```

```
uses
ready
```

This might lead to additional functional dependencies

`os::krn`

`hw::hal`

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**Example: Mechanism Integration**

- **Serial0**
  - init()
  - sendBlock()

- **Sched**
  - init()
  - ready()

**Serial0Ext**
- «extension aspect»
- exec("init")

**Serial0Ext_Task**
- «slice»
- Task_task

**Serial0_Init**
- «binding aspect»
- exec("init")

**Sched_Init**
- «binding aspect»
- exec("init")

**uses**

- Serial0Ext_Task
  - init()

**ready**

- «extension aspect»

**extension aspects**
- add to mechanisms by extension slices

This might lead to additional functional dependencies.
Example: Mechanism Integration

```
aspect Serial0Ext {
    ...
    advice execution( "void hw::hal::init()" )
        : order( "Sched_Init", "Serial0_Init" );
    ...
};
```

This might lead to additional functional dependencies.

extension aspects
add to mechanisms by extension slices
Example: Policy Integration

Cooperative Scheduling:

```plaintext
Sched_LeaveBinding
  enterKernel()
  leaveKernel()

exec("leaveKernel")
```

Preemptive Scheduling:

```plaintext
Kernel_ASTSync
  enterKernel()
  leaveKernel()

exec("enterKernel()")
exec("leaveKernel()")
```

visible transitions
by explicit join points

```plaintext
Sched
  reschedule()
  setNeedReschedule()

Sched_ASTBinding
  exec("ast")
  exec("setNeedReschedule")

Kernel_ASTSync
  exec("enterKernel()")
  exec("leaveKernel()")
```

os::krn
hw::hal

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Example: Policy Integration

Cooperative Scheduling:

- `enterKernel()`
- `leaveKernel()`

**Sched_LeaveBinding**

- `exec("leaveKernel")`

- `reschedule()`
- `setNeedReschedule()`

**Sched**

Preemptive Scheduling:

- `enterKernel()`
- `leaveKernel()`

**Kernel_ASTSync**

- `exec("enterKernel()")`
- `exec("leaveKernel()")`

- `reschedule`
- `setNeedReschedule`

- `ast()`

**AST0**

- `trigger`
- `disable`
- `enable`

- `ast()`

**policy aspects**

Connect mechanisms to implement some CiAO kernel policy.

Os::krn

Ww::hal
Example: Policy Integration

Cooperative Scheduling:

- `enterKernel()`
- `leaveKernel()`

«policy aspect»

Sched_LeaveBinding

exec("leaveKernel")

reschedule()

Sched

reschedule()

setNeedReschedule()

Preemptive Scheduling:

- `enterKernel()`
- `leaveKernel()`

«policy aspect»

Kernel_ASTSync

exec("enterKernel()")

eexec("leaveKernel()")

reschedule

«policy aspect»

Sched_ASTBinding

exec("ast")

eexec("setNeedReschedule")

reschedule

Sched

reschedule()

setNeedReschedule()

os::krn

hw::hal

os::krn

4 The CiAO Approach | 4.3 CiAO
Methodology: Explicit Join Points

- Advice-based binding $\mapsto$ availability of the “right” join points
  - for all semantically important transitions in the system
  - statically evaluable

- Fine-grained component structure $\leadsto$ many implicit join points, but
  - amount and precise semantics often implementation dependent
  - aspects have to “know” $\leadsto$ no obliviousness

- Important transitions not available for technical reasons as JPs
  - target code may be fragile (e.g., context switch) $\leadsto$ must not be advised
  - target code may be written in assembly $\leadsto$ transitions not visible as JPs
Methodology: Explicit Join Points (Cont’d)

- **Solution:** explicit join points
  - empty inline methods for the sole purpose that aspects can bind to them
  - explicitly triggered by components or other aspects
  - well defined semantics

- **Upcall join points (U)** represent system-internal events that are to be processed on a higher layer
  - exceptions, such as signals or interrupts
  - internal events, such as system initialization or entering of the idle state

- **Transition join points (T)** represent semantically important control-flow transitions inside the kernel
  - level transitions: \( \text{user} \rightarrow \text{kernel}, \text{user} \rightarrow \text{interrupt} \)
  - context transitions: \( \text{threadA} \rightarrow \text{threadB} \)
Explicit join points for the support and binding of OSEK OS and AUTOSAR OS user-level hook functions, as specified in [36, p. 39] and [4, p. 46].

**Type** representing function or method | Description
--- | ---
`U internalErrorHook()` | Triggered in case of an error, a protection violation, before (pre) and after (post) at high-level task switch, and at operating-system startup and shutdown time.

**os::km**

- `U internalProtectionHook(StatusType error)`
- `U internalPreTaskHook()`
- `U internalPostTaskHook()`
- `U internalStartupHook()`
- `U internalShutdownHook()`

- `T enterKernel()`
- `T leaveKernel()`
- ...

**hw::hal**

- `T before_CPURelease(Continuation*& to)`
- `T before_LastCPURelease(Continuation*& to)`
- `T after_CPUReceive()`
- `T after_FirstCPUReceive()`

- `U AST<#>::ast()`
- `U init()`
- ...

- `U <IRQ_NAME>::handler()`

**hw::irq**

- Entry point of a new thread (continuation).

- Entry point of the respective AST.

- Entry point of the respective interrupt handler. (Interrupts are still disabled.)
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### Table 5. CiAO-AS kernel concern implemented as aspects with number of affected services

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<th>upcall advice</th>
<th>join points</th>
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<td>1</td>
<td>2 + m</td>
<td>2 + m API, OS control</td>
<td>m ISR bindings</td>
<td></td>
</tr>
<tr>
<td>ISR cat. 2 support</td>
<td>1</td>
<td>5 + n</td>
<td>5 + n API, OS control, scheduler</td>
<td>n ISR bindings</td>
<td></td>
</tr>
<tr>
<td>ISR abortion support</td>
<td>1</td>
<td></td>
<td>1 + m + n scheduler</td>
<td>m + n ISR functions</td>
<td></td>
</tr>
<tr>
<td>Resource support</td>
<td>1</td>
<td>3</td>
<td>5 scheduler, API, task</td>
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<tr>
<td>Resource tracking</td>
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<td>4 task, ISR</td>
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<td>5</td>
<td>5 scheduler, API, task, alarm</td>
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<td>3 points of rescheduling</td>
<td></td>
</tr>
<tr>
<td>Mixed preemption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple activation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stack monitoring</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>task</td>
<td>CPU-release JPs</td>
</tr>
<tr>
<td>Context check</td>
<td>1</td>
<td>1</td>
<td>s</td>
<td>s service calls</td>
<td></td>
</tr>
<tr>
<td>Disabled interrupts check</td>
<td>1</td>
<td>1</td>
<td>30</td>
<td>all services except interrupt services</td>
<td></td>
</tr>
<tr>
<td>Enable w/o disable check</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>enable services</td>
<td></td>
</tr>
<tr>
<td>Missing task end check</td>
<td>1</td>
<td>1</td>
<td>t</td>
<td>t task functions</td>
<td></td>
</tr>
<tr>
<td>Out of range check</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>alarm set and schedule table start services</td>
<td></td>
</tr>
<tr>
<td>Invalid object check</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>services with an OS object parameter</td>
<td></td>
</tr>
<tr>
<td>Error hook</td>
<td>1</td>
<td>2</td>
<td>30 scheduler</td>
<td>29 services</td>
<td></td>
</tr>
<tr>
<td>Protection hook</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>API</td>
<td>default policy implementation</td>
</tr>
<tr>
<td>Startup / shutdown hook</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>explicit hooks</td>
<td></td>
</tr>
<tr>
<td>Pre-task / post-task hook</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>explicit hooks</td>
<td></td>
</tr>
</tbody>
</table>

**Plug & Play of optional features and policies!**
## Kernel Latency Comparison with “OSEK”

<table>
<thead>
<tr>
<th>test scenario</th>
<th>CiAO min</th>
<th>CiAO full</th>
<th>OSEK min</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) voluntary task switch</td>
<td>160</td>
<td>178</td>
<td>218</td>
</tr>
<tr>
<td>(b) forced task switch</td>
<td>108</td>
<td>127</td>
<td>280</td>
</tr>
<tr>
<td>(c) preemptive task switch</td>
<td>192</td>
<td>219</td>
<td>274</td>
</tr>
<tr>
<td>(d) system startup</td>
<td>194</td>
<td>194</td>
<td>399</td>
</tr>
<tr>
<td>(e) resource acquisition</td>
<td>19</td>
<td>56</td>
<td>54</td>
</tr>
<tr>
<td>(f) resource release</td>
<td>14</td>
<td>52</td>
<td>41</td>
</tr>
<tr>
<td>(g) resource release with preemption</td>
<td>240</td>
<td>326</td>
<td>294</td>
</tr>
<tr>
<td>(h) category 2 ISR latency</td>
<td>47</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>(i) event blocking with task switch</td>
<td>141</td>
<td>172</td>
<td>224</td>
</tr>
<tr>
<td>(j) event setting with preemption</td>
<td>194</td>
<td>232</td>
<td>201</td>
</tr>
<tr>
<td>(k) comprehensive application</td>
<td>748</td>
<td>748</td>
<td>1216</td>
</tr>
</tbody>
</table>

Execution time [clock ticks] on TC1796@50 MHz

(ac++1.0pre3 with tricore-g++3.4.3 -O3 -fno-rtti -funit-at-a-time -ffunction-sections -Xlinker --gc-sections)
## Kernel Latency Comparison with “OSEK”

<table>
<thead>
<tr>
<th>test scenario</th>
<th>CiAO</th>
<th>OSEK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>full</td>
</tr>
<tr>
<td>(a) voluntary task switch</td>
<td>160</td>
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</tr>
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<td>(b) forced task switch</td>
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</tr>
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<td>194</td>
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<tr>
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<td>52</td>
</tr>
<tr>
<td>(g) resource release with preemption</td>
<td>240</td>
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<td>232</td>
</tr>
<tr>
<td>(k) comprehensive application</td>
<td>748</td>
<td>748</td>
</tr>
</tbody>
</table>

CiAO outperforms the marked leader in 11 out of 12 cases by up to **260 percent**.

Execution time [clock ticks] on TC1796@50 MHz

(ac++1.0pre3 with tricore-g++3.4.3 -O3 -fno-rtti -funit-at-a-time -ffunction-sections -Xlinker --gc-sections)
### Feature Granularity of CiAO

<table>
<thead>
<tr>
<th>feature</th>
<th>with feature or instance</th>
<th>text</th>
<th>data</th>
<th>bss</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base system (OS control and tasks)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>per task</td>
<td>+ func</td>
<td>+20</td>
<td>+16</td>
<td>+ stack</td>
</tr>
<tr>
<td>per application mode</td>
<td></td>
<td>0</td>
<td>+4</td>
<td>0</td>
</tr>
<tr>
<td>ISR cat. 1 support</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per ISR</td>
<td>+ func</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per disable–enable</td>
<td></td>
<td>+4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Resource support</td>
<td>+ 128</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per resource</td>
<td></td>
<td>0</td>
<td>+4</td>
<td>0</td>
</tr>
<tr>
<td><strong>CiAO achieves excellent granularity!</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>per task</td>
<td></td>
<td>0</td>
<td>+8</td>
<td>0</td>
</tr>
<tr>
<td>per alarm</td>
<td></td>
<td>0</td>
<td>+12</td>
<td>0</td>
</tr>
<tr>
<td>Full preemption</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per join point</td>
<td>+ 12</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mixed preemption</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per join point</td>
<td>+ 44</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per task</td>
<td></td>
<td>0</td>
<td>+4</td>
<td>0</td>
</tr>
<tr>
<td>Wrong context check</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per void join point</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per StatusType join point</td>
<td>+ 8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Interrupts disabled check</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>per join point</td>
<td>+ 64</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Invalid parameters check</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>per join point</td>
<td>+ 36</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Error hook</td>
<td></td>
<td>0</td>
<td>0</td>
<td>+4</td>
</tr>
<tr>
<td>per join point</td>
<td>+ 54</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Startup hook or shutdown hook</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pre-task hook or post-task hook</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Discussion: Aspect-Aware Development

By AAD CiAO achieves excellent properties [3–5]

- configurability and granularity even for fundamental kernel policies
- complete separation of concerns in the implementation

The approach has also been applied to other system software

- PUMA, the C/C++ transformation framework behind ac++ [9]
- CiAOIP, an aspect-oriented IP stack for embedded systems [2]

Issues: comprehensibility & tool support

- CiAO: aspect code/base code = 1/2.4
  \[ \sim \text{where the heck } xyz \text{ is implemented?} \]
- calls for additional tool support
- ac++ weaver implementation is stable, but not as mature as gcc
  - missing or confusing error messages
  - no support for weaving in template code
  - no C++0x support

<table>
<thead>
<tr>
<th></th>
<th>Base code</th>
<th>Aspect code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Files</td>
<td>LOC</td>
</tr>
<tr>
<td>CiAO kernel only</td>
<td>423</td>
<td>21,086</td>
</tr>
<tr>
<td>CiAO COM</td>
<td>112</td>
<td>8,689</td>
</tr>
<tr>
<td>CiAO IP stack</td>
<td>45</td>
<td>5,038</td>
</tr>
<tr>
<td>CiAO overall</td>
<td>580</td>
<td>34,813</td>
</tr>
</tbody>
</table>

This is research, after all :-)
4.1 AOP Mechanisms Under the Hood
4.2 Study: i4Weathermon AOP
4.3 CiAO
4.4 CiAO Results
4.5 Summary
4.6 References
Aspect-Aware Development exploits AOP mechanisms to achieve separation of concerns in configurable system software

- Advice inverses the direction in which control-flow relationships are established: $C \text{ calls } A \implies A \text{ advises } C$
- Advice-based binding as a means to integrate (optional) features
- Pointcuts provide for an implicit quantification of this integration
- Advice-based binding as a means to integrate interacting features

CiAO applies these concepts from the very beginning

- loose coupling by advice-based binding
- visible transitions by explicit join points
- minimal extensions by extension slices

The results are compelling

- configurability of even all fundamental system policies
- excellent granularity and footprint


