ON THE CORRECTNESS OF SOFTWARE ARCHITECTURES
Formal Specification of Correctness Properties using π-AAL

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Abstract: Software has become a critical part of a rapidly growing range of products and services. Key aspects of the development of such software-intensive systems are the description and analysis of their software architecture, encompassing both the formal model of the component-based architecture and the formal specification of the correctness properties that the modeled architecture must satisfy. Therefore, an Architecture Description Language (ADL) must be complemented by an Architecture Analysis Language (AAL) enabling the specification of architecture-related correctness properties. A major challenge for an AAL is to provide adequate expressive power to specify both structural and behavioral correctness properties, and to be well-suited for machine-automated processing for verification, at a time. This paper presents how π-AAL complements π-ADL (designed in the ArchWare European Project) for enabling the specification of architectural correctness properties based on the modal π-calculus. The toolset and its experimentation in industrial pilot projects are outlined.

1 INTRODUCTION

Software has become a critical part of a rapidly growing range of products and services. Key aspects of the development of such software-intensive systems are the description and analysis of their software architecture, i.e. the fundamental organization of the system embodied in its components, their relationships to each other and to the environment, and the principles guiding its design and evolution (IEEE Std 1471-2000).

From the perspective of the system design, an architecture description provides a formal model of a software architecture in terms of its structure and behavior:

- The structure may be specified in terms of: (i) components (units of computation of a system); (ii) connectors (interconnections among components supporting their interactions); (iii) configurations of components and connectors.
- The behavior may be specified in terms of: (i) actions a component or connector executes or participates in; (ii) relations among actions to specify behaviors; (iii) behaviors of components and connectors, and how they interact.

In the past decade, several Architecture Description Languages (ADLs) have been defined for modeling the structure and behavior of software architectures. However, describing the structure and behavior of an architecture is needed, but it is not enough. Indeed, in addition to describing software architectures, designers need to rigorously specify their correctness properties.

An architectural correctness property is a semantic property that specifies a constraint which an architecture must enforce to be correct with respect to defined requirements. Thereby, an architecture is correct when it, by its structure and behavior in terms of configurations of components and connectors, meets the functional and nonfunctional requirements as described by the correctness properties.

Before using an architecture description as a blueprint to implement a system, designers must be able to specify, validate and verify the correctness of the architecture, i.e., that the architecture model satisfies the specified correctness properties. In addition, as the cost of addressing correctness properties is a function of how late they are addressed (the later,

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the more costly) (Barber & Holt 2001), addressing them in the architectural phase leads to more cost-effective solutions.

Therefore, an Architecture Analysis Language (AAL) must complement (or be part of) an ADL in order to enable the specification and support the verification of architectural correctness properties. A major challenge for an AAL is to provide sufficient expressive power to specify both structural and behavioral correctness properties and to be well-suited for machine-automated processing for verification, at a time.

Formal methods are increasingly used for modeling software architectures (Marcos et al. 2007). Their potential advantages have been widely recognized (Oquendo 2007). Designing an AAL enabling the specification of structural and behavioral correctness properties of component-based architectures is a key research challenge.

π-AAL has been designed in the ArchWare[1] European Project to meet this challenge. It complements π-ADL and provides a uniform framework for specifying correctness properties of software architectures. These properties have different natures: they can be structural (e.g., cardinality of architectural elements, interconnection topology) or behavioral (e.g., safety and liveness properties defined on actions of the architectural elements' behaviors).

The remainder of this paper is organized as follows. Section 2 introduces π-AAL design principles and Section 3 the architecture description concepts underlying π-ADL. Section 4 presents π-AAL concepts and notation. Section 5 presents through a case study how π-AAL can be used for specifying structural and behavioral correctness properties. In Section 6, we compare π-AAL with related work and in Section 7, briefly outline the π-AAL toolset and its experimentation in pilot projects. To conclude we summarize, in Section 8, the main contributions of this paper and sketch future work.

2 DESIGN PRINCIPLES OF π-AAL

π-ADL (Oquendo 2004) and π-AAL (Alloui et al. 2003) are companion languages for architecture description and analysis, respectively. With π-ADL, architectures are described, expressing the structure and behavior of their components, connectors, and configurations. With π-AAL, correctness properties that the architecture must satisfy in terms of structure and behavior of components, connectors, and configurations are specified, enabling the analysis of architecture models.

The following principles guided the design of π-AAL:

- π-AAL is a formal language: it provides a formal system (at the mathematical sense) for specifying correctness properties and reasoning about them;
- π-AAL is defined in a layered approach, with a core canonical abstract syntax and formal semantics;
- π-AAL offers a user-friendly enhanced concrete syntax to be easily used by software system architects.

π-AAL has as formal foundation the modal μ-calculus (Kozen 1983), a calculus for expressing properties of labeled transition systems by using least and greatest fixed point operators. π-AAL is itself a formal language defined as an extension of the μ-calculus: it is a well-formed extension for defining a calculus for expressing structural and behavioral properties of dynamically communicating architectural elements.

π-AAL takes its roots in previous work concerning the extension of modal operators with data-handling constructs (Mateescu & Garavel 1998), the use of regular expressions as specification formalism for value-passing process algebras (Garavel 1989), and the extension of fixed point operators with typed parameters (Groote & Mateescu 1999).

Indeed, a natural candidate for "pure" behavioral properties would be the modal μ-calculus, which is a very expressive fixed point-based formalism subsuming virtually all temporal logics defined so far in the literature (Stirling 2001). However, since π-AAL must also provide features for expressing structural properties of architectures, the modal μ-calculus is not sufficient. Therefore, a formalism encompassing both the predicate calculus and the modal μ-calculus is needed. The π-AAL is, thereby, this encompassing formalism.

π-AAL combines predicate logic with temporal logic in order to allow the specification of both structural and behavioral properties. It enables automated verification of property satisfaction by model checking (through on-the-fly model checking) and theorem proving (through deductive verification).

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3 ARCHITECTURE DESCRIPTION WITH π-ADL

Software architectures can be described with π-ADL which is a formal language based on the typed π-calculus (Milner 1999; Sangiorgi 1992). One can mechanically check whether an architecture described in π-ADL satisfies a property expressed in π-AAL.

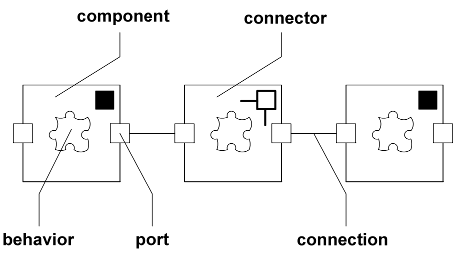


Figure 1: Architectural concepts in π-ADL.

In π-ADL, an architecture is described in terms of components, connectors, and their composition. Figure 1 depicts its main constituents.

Components are described in terms of external ports and an internal behavior. Their architectural role is to specify computational elements of a software-intensive system. The focus is on computation to deliver system functionalities.

Ports are described in terms of connections between a component and its environment. Their architectural role is to put together connections providing an interface between the component and its environment. Protocols may be enforced by ports and among ports.

Connections are basic interaction points. Their architectural role is to provide communication channels between two architectural elements.

A component can send or receive values via connections. They can be declared as output connections (values can only be sent), input connections (values can only be received), or input-output connections (values can be sent or received).

Connectors are special-purpose components. They are described as components in terms of external ports and an internal behavior. However, their architectural role is to connect together components. They specify interactions among components.

Therefore, components provide the locus of computation, while connectors manage interaction among components. A component cannot be directly connected to another component. In order to have actual communication between two components, there must be a connector between them.

Both components and connectors comprise ports and behavior. A connection provided by a port of a component is attached to a connection provided by a port of a connector by unification or value passing. Thereby, attached connections can transport values (that can be data or even connections).

Components and connectors can be composed to construct configured composite elements, which may themselves be components or connectors.

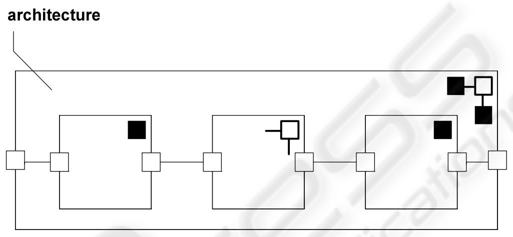


Figure 2: Architectural composition in π-ADL.

Architectures are composite elements representing systems (e.g., see Figure 2). An architecture can itself be a composite component in another architecture.

4 CORRECTNESS SPECIFICATION WITH π-AAL

π-AAL supports analysis of component-based software architectures, described with π-ADL. In π-AAL, an architectural correctness property is specified in terms of logical formulas comprising: predicate formulas, action formulas, regular formulas, state formulas, and connection formulas. When evaluated, a formula is checked against the architecture description, that provides the interpretation domain.

4.1 π-AAL Semantic Model

The formal foundation of π-AAL is the modal μ-calculus extended with the predicate calculus. As cited so far, π-AAL is itself a formal language defined as an extended calculus subsuming the modal μ-calculus and the predicate calculus for specifying correctness properties on component-based software architectures.

Formulas in π-AAL are formally interpreted relative to a predicate-extended labeled transition system.

Formally, a predicate-extended labeled transition system (*pLTS*) is of the form *pLTS* = (*StateSet*, *ActionSet*, *TransitionRelationSet*, *PredicateSetLabelling*, *state*$_0$), where:

- *StateSet* is a non-empty set of *states*;
- *ActionSet* is a set of *actions* (actions that label transitions);
- *TransitionRelationSet* is a set of transition relations, such that each transition relation *transition* $\in$ *TransitionRelationSet*, is of the form *transition* $\subseteq$ *StateSet* $\times$ *ActionSet* $\times$ *StateSet*;
- *PredicateSetLabelling* : *StateSet* $\to 2^{PredicateSet}$ is a function that labels each state with the set of atomic predicates true in that state (where *PredicateSet* is the set of atomic predicates and $2^{PredicateSet}$ the powerset of *PredicateSet*);
- *state*$_0$ $\in$ *StateSet* is the initial state.

All states of *StateSet* are assumed to be reachable from the initial state via sequences of (zero or more) transitions of the *TransitionRelationSet*.

The actions *action* of *ActionSet* are defined as:

- ***via*** *connection* ***send*** *value*$_1$,…, *value*$_n$
- ***via*** *connection* ***receive*** *value*$_1$,…, *value*$_n$

where *connection* is a connection and *value*$_1$,…, *value*$_n$ are data values (base values or constructed values).

In addition to communication actions, actions can be internal to a component or connector:

- the action ***unobservable***, where ***unobservable*** $\notin$ *ActionSet*, is used to model an internal "unobservable" action of a component or connector behavior,
- the match action ***if***, is used to express conditional behaviors of components or connectors.

The predicates *predicate* of *PredicateSet* are defined either as built-in predicates related to the architectural structure, or as user-defined predicates.

Finally we can define *BehaviorStateSet* as the set of states of a behavior in an architectural element (e.g., component or connector). Therefore for all s $\in$ *BehaviorStateSet, PredicateSet* contains all predicates related to types and data declared in an architectural element expressed with π-ADL.

For a complete definition of the π-AAL semantic model see (Alloui et al. 2003).

4.2 π-AAL Types

π-AAL is a typed language. It shares all base types and type constructors of π-ADL equipped with their operators. All types are value types. Value types are base types or constructed types. Type environments are expressed through declarations.

Typing

ValueType ::= BaseType | ConstructedType
BaseType ::= **Any** | **Natural** | **Integer** | **Real** | **Boolean** | **String** | **Behavior**
ConstructedType ::= **tuple [** ValueType$_1$, …, ValueType$_n$ **]**
| **view [** label$_1$ **:** ValueType$_1$, …, label$_n$ **:** ValueType$_n$ **]**
| **union [** ValueType$_1$, …, ValueType$_n$ **]** | **quote [** name **]**
| **variant [** label$_1$ **:** ValueType$_1$, …, label$_n$ **:** ValueType$_n$ **]**
| **location [** ValueType **]** | **sequence [** ValueType **]**
| **set [** ValueType **]** | **bag [** ValueType **]**
| **in [** ValueType **]** | **out [** ValueType **]**
| **inout [** ValueType **]**

4.3 π-AAL Formulas

π-AAL provides the formula constructs for specifying structural and behavioral properties to be satisfied by component-based software architectures.

The definition of π-AAL is structured in terms of kinds of formula constructs:

- *predicate formula constructs* for writing data predicate formulas over a set of data values using data variables, data operators and predicate operators;
- *action formula constructs* for writing action predicate formulas over a set of connection and data values;
- *regular formula constructs* for writing regular expressions (i.e., regular formulas) defined over action formulas using regular operators;
- *state formula constructs* for writing modal formulas defined over regular formulas and value variables using predicate, modal, and parameterized fixed point operators;
- *connection formula constructs* for writing formula on connections as first-class elements, taking into account connection mobility among architectural elements, i.e., components and connectors.

4.4 Relating Properties to Architectures

An architectural correctness property is specified by a formula that may be a data predicate formula, an action formula, a regular formula or a state formula.

Architectural properties are related to architecture descriptions for specifying their correctness. They are assumptions on the correctness of the architecture model and state proof obligations.

Relating architectural properties to architecture descriptions is defined as follows.

```
Relating Correctness Properties to Architectures
architecture { architectureDescription }
assuming {  architecturalCorrectnessProperties }
```

5 CASE STUDY: CORRECTNESS USING π-AAL

Instead of providing a formal description (Alloui et al. 2003), we will present hereafter the use of π-AAL for specifying correctness properties through a case study of a typical component-based software architecture, a pipe-and-filter architecture, described in π-ADL.

Pipe-and-filter architectures, e.g., pipelines, are used when a sequence of transformations is applied to a stream of data by a sequence of filters, producing a final output. Hence, pipelines are pipe-and-filter architectures composed of a single chain of pipes and filters.

A pipe transmits output of one filter to input of another filter. A filter transforms data received from its input and sends the transformed data to its output. Filters do not share state, i.e., they do not know about upstream or downstream filters.

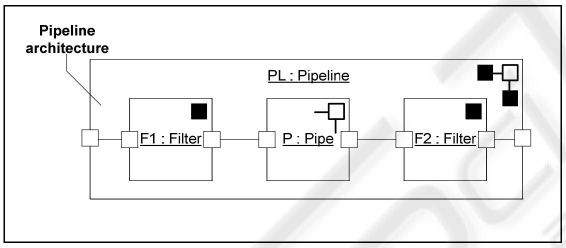


Figure 3: A simple pipeline architecture.

Figure 3 depicts a pipeline architecture comprising two components (that are filters) which exchange data through a connector (that is a pipe).

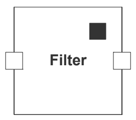
5.1 Architecture Description

In a pipeline architecture:

- the architecture is composed of filters and pipes;
- filters are components;
- a filter has a set of input and output connections and uses a function to transform data;
- pipes are connectors;
- a pipe has a set of input and output connections and transmits data from input to output as they are;
- a pipe connects two filters, it transmits an output of a filter to an input of another filter.

Using π-ADL, the *Filter* component abstraction can be formally described as follows.

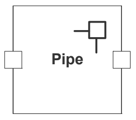
```
component Filter is abstraction() {
  type Data is Any.
  port is {
     connection input is in(Data).
     connection output is out(Data)
  } assuming {
     protocol is {
     ( via input receive any. true*. via output send any )* }
  }.
  behavior is {
     transform is function(d : Data) : Data {unobservable}.
     via input receive d : Data.
     via output send transform(d).
     behavior()
  }
}
```



The protocol is specified as a regular formula built upon action predicates (one-step sequences) by using the standard regular operators: '.' (concatenation), '|' (choice), and '*' (transitive reflexive closure). In these formulas 'true' means any action and 'false' no action.

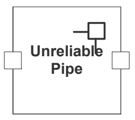
The *Pipe* connector abstraction can be formally described as follows.

```
connector Pipe is abstraction() {
  type Data is Any.
  port is {
     connection input is in(Data).
     connection output is out(Data)
  } assuming {
     protocol is {
     (via input receive d : Data. via output send d)* }
  }.
  behavior is {
     via input receive d : Data. via output send d.
     behavior() } }
```



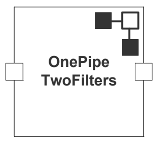
This pipe is reliable. Let us now describe a pipe that is unreliable, i.e., it can nondeterministically choose either to transmit data correctly, or to lose it.

```
connector UnreliablePipe is abstraction() {
  type Data is Any.
  port is {
     connection input is in(Data).
     connection output is out(Data)
  } assuming {
     protocol is {
     (via input receive d : Data. (via output send d | nil))* }
  }.
  behavior is {
     via input receive d : Data.
     choose {
          via output send d. behavior()
     or   unobservable. behavior()
```



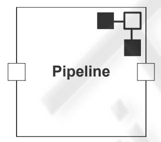
A simple pipeline architecture, with two filters connected by one pipe as the one shown in Figure 3, can be formally described as follows. It uses an unreliable pipe.

```
architecture OnePipeTwoFilters is
 abstraction() { behavior is compose {
          F1  is Filter()
    and   P   is UnreliablePipe()
    and   F2  is Filter()
 } where { F1::input    as i1
    and    P::input   unifies       F1::output    as o1
    and    P::output    unifies     F2::input     as i2
    and    F2::output                 as o2
    }
}
```



A general pipeline architecture, with at least one pipe and two filters, but with as many reliable pipes and filters as needed, can be formally described as follows.

```
architecture Pipeline is abstraction(n : Natural) {
 behavior is compose {
          F    issequence for i = 1 to n using Filter()
    and   P    issequence for i = 1 to n using Pipe()
 } where {
    iterate sequence(1..n) by i do {
          P::i::input   unifies        F::i::output
    and   P::i::output    unifies      F::(i+1)::input }
    }
}   assuming {
 parameter is { n >= 1 }
 and F –> size >= 2
 and P –> size >= 1
}
```



5.2 Specification of Correctness Properties

Let us now specify with π-AAL different kinds of architectural properties that must be analyzed in order to guarantee the correctness of the architecture, including architectural completeness and consistency.

Architectural completeness means that the architecture description does not lack components, connectors, connections or their parts or interrelationships with respect to architecture-specific, architect-defined, properties.

For instance, a pipeline architecture could be considered to be complete if all pipes have their input and output connections connected to filters and all filters, but the first and last one, have their input and output connections connected to pipes. Of course, input connections must be unified to output connections.

Regarding architectural consistency, it means that the architecture description makes sense; that different parts of the description do not contradict each other. For instance, protocols of ports of unified connections must be compatible.

Regarding correctness, in addition to completeness and consistency, it is defined with respect to the correctness of the system features, i.e., the conformity with correctness requirements. For instance, all filter transformations must be applied to all data.

Thereby, correctness (including completeness and consistency) are semantic properties, and as so are defined with respect to analysis of architecture-specific, architect-defined, properties.

For instance, an architect could specify architectural correctness properties for verifying that:

- protocols of ports are projections of behaviors of components or connectors;
- protocols of unified ports are compatible, with corresponding send-receive actions, and deadlock-free;
- components, connectors, and the architecture are deadlock-free;
- ports of components and connectors in the configuration are connected accordingly;
- configuration of components and connectors conform to the architectural style constraints.

More specifically, for the described pipeline architecture, an architect could specify and verify if:

- there is the right connectivity, in terms of the pipeline style, among pipes and filters;
- there is a safe alternation of send and receive actions in components, i.e., in filters;
- the pipeline is deadlock free;
- there is an inevitable reachability of the transform function after receive actions in the pipeline;
- all data received in components and connectors are transmitted.

Let us use the pipeline architecture and its components and connectors described so far in π-ADL to show how these properties could be specified using π-AAL.

The concrete syntax of π-AAL is based on the Object Constraint Language (OCL) and is part of a UML Profile for π-ADL. The **with** construct introduces the context for the **property**. The variable declared in the **with** construct is used to refer to the contextual instance. The "**.**", "**–>**", relational, logical and collection operators have their usual meaning as in OCL. Least and greatest fixed point operators have their usual meaning as in modal μ-calculus.

The structural property "there is the right connectivity, in terms of the pipeline style, among pipes and filters" can be formally specified as follows. It expresses that every pipe input port is connected to a filter output port and every pipe output port is connected to a filter input port in a pipeline architecture.

```
with { pl : Pipeline }
connectivityBetweenPipesAndFilters is property() {
-- every pipe input port is connected to a filter output port
-- and
-- every pipe output port is connected to a filter input port
pl.connectors –>
 forall { p | p.ports.connections –>
   forall { inp,outp |
       pl.components –>
       exists { fi, fo |
         (fi.ports.connections union
         fo.ports.connections) –>
           forall { infi, outfo |
             (p.ports.connections –> includes inp)
             and (inp.type = input)
             and (p.ports.connections –> includes outp)
             and (outp.type = output)
             and (fi.ports.connections –> includes infi)
             and (infi.type = input)
             and (fo.ports.connections –> includes
                   outfo)
             and (outfo.type = output)
             and (inp unifies outfo)
             and (outp unifies infi)
           }
       }
   }
 }
}
```

The behavioral property "there is a safe alternation of send and receive actions in filters" can be formally specified as follows. It expresses that there is no send before a receive initially, no two consecutive receives without a send in between, and no two consecutive sends without a receive in between.

```
with { c : Filter }
safetyAlternation is property() {
-- no send before a receive initially
-- no two consecutive receives without a send in between
-- no two consecutive sends without a receive in between
c.ports.inputPrefixes –>
 forall { r | c.ports.outputPrefixes –>
   forall { s |
     every sequence {
       (not via r receive any)* . via s send any }
     leads to state { false }
     and
     every sequence {
       true* . via r receive any . (not via s send any)* .
       via r receive any }
     leads to state { false }
     and
     every sequence {
       true* . via s send any . (not via r receive any)* .
       via s send any }
     leads to state { false }
   }
```

The behavioral property "the pipeline architecture is deadlock free" can be formally specified as follows. It expresses that at any moment, the pipeline system can execute an action. Thereby, it is never deadlocked.

```
with { pl : Pipeline }
deadlockFreedom is property() {
-- at any moment, the system can execute an action
pl.instances –>
 every sequence { true* }
   leads to state {
     some sequence { true } leads to state { true }
   }
}
```

The behavioral property "there is an inevitable reachability of the transform data function after receive actions in a pipeline architecture" can be formally specified as follows. It expresses that after a receive action in a filter, the function transform will always be carried out after a finite number of steps.

```
with { pl : Pipeline }
inevitableReachabilityOfTransformAfterReceive is
property() {
-- the inevitable reachability of a function transform data
-- after a receive
pl.components –>
 forall { f | f.functions –>
   forall { transf |
     transf.name = transform implies {
     f.ports.inputPrefixes –>
       exists { r |
         every sequence { true* . via r receive any }
         leads to state {
           finite tree Y given by {
             some sequence { true } leads to state
               {true}
             and
               every sequence { not via transf send any}
             leads to state { Y }
           }
         }
       }
   }
 }
}
```

The property "in a pipeline architecture, all data received in components and connectors are transmitted" can be formally specified as follows. It expresses that every data that is received will be eventually sent after a finite number of steps.

```
with { pl : Pipeline }
dataTransmission is property() {
-- every data that is received will be eventually sent
-- after a finite number of steps
pl.components –>
forall { f | f.ports.inputPrefixes –>
  forall { r | f.ports.outputPrefixes –>
     exists { s | r.data –>
        forall { d |
           every sequence { true* . via r receive d }
           leads to state {
              finite tree Y given by {
                 some sequence { true }
                 leads to state { true }
                 and
                    every sequence {not via s send d }
                 leads to state { Y }
              }
           }
        }
     }
  }
}
```

Now let us attach the architectural properties defined above to the pipeline architecture described so far.

```
architecture Pipeline is abstraction(n : Natural) {
  behavior is compose {
            F    issequence for i = 1 to n using Filter()
    and   P    issequence for i = 1 to n using Pipe()
  }  where { iterate sequence(1..n) by i do {
            P::i::input   unifies          F::i::output
    and   P::i::output   unifies       F::(i+1)::input }
    }
} assuming {
  components –> forall { f : Filter | f.safetyAlternation()}
  and connectivityBetweenPipesAndFilters()
  and deadlockFreedom()
  and inevitableReachabilityOfTransformAfterReceive()
  and dataTransmission()
}
```

6 RELATED WORK

Several Architecture Description Languages (ADLs) have been proposed in the literature (Medvidovic & Taylor 2000), including: ACME, AESOP, AML, CHAM-ADL, DARWIN, META-H, PADL, RAPIDE, SADL, UNICON-2, and WRIGHT.

Most of these ADLs integrate or are coupled with an Architecture Analysis Language (AAL), e.g., ARMANI (Monroe 2001) extends ACME (Garlan et al. 2000) for supporting the specification of design constraints on the architecture structure; and DARWIN (Kramer et al. 2003) embeds FSP for supporting the specification of safety and (a limited form of) liveness properties on the architecture behavior.

The main limitation of these AALs is that they address either structural or behavioral properties, but not both. Overall, they do not have the expressive power to specify architectural correctness properties such as those presented in this paper.

Indeed, π-AAL provides a novel language that on the one side has been specifically designed for architecture analysis taking into account the need to specify and verify properties on both structure and behavior from an architectural perspective and on the other side is highly expressive. It allows the specification of both structural properties and behavioral properties concerning architecture descriptions modeled in π-ADL.

Regarding behavioral properties, the choice of the modal μ-calculus as the underlying formalism provides a significant expressive power. Moreover, the extension of μ-calculus modalities with higher level constructs such as regular formulas inspired from early dynamic logics like PDL (Fischer & Ladner 1979) facilitates the specification task of the practitioners, by allowing a more natural and concise description of properties involving complex sequences of actions. The extension of fixed point operators with data parameters also provides a significant increase of the practical expressive power, and is naturally adapted for specifying behavioral properties of value-passing languages such as π-ADL.

In the context of software architectures, several attempts at using classical process algebras and generic model checking technology have been reported in the literature. In (Heisel & Levy 1997), various architectural styles (e.g., repository, pipe-and-filter, and event-action) are described in LOTOS, by using specific communication patterns and constraints on the form of components, and verified using the CADP toolbox (Fernandez et al. 1996; Garavel et al. 2002). In (Rongviriyapanish & Levy 2000), several variants of the pipe-and-filter style are described in LOTOS and analyzed using CADP. In (Kerschbaumer 2002), the transformation of software rchitecttures specified in LOTOS and their verification using the XTL model checker (Mateescu & Garavel 1998) of CADP are presented. Finally, an approach for checking deadlock freedom of software rchitecttures described using a variant of CCS is described in (Bernardo et al. 2001).

All these works provide rather ad-hoc solutions for a class of software architectures limited to static communication between architectural elements. None of them addresses dynamic architectures and they can be subsumed by the more general framework provided by π-AAL (with π-ADL) and its verification tools.

7 IMPLEMENTATION AND EXPERIMENTATION

A major impetus behind developing formal languages for architecture analysis is that their formality renders them suitable to be manipulated by software tools. The usefulness of an AAL is thereby directly related to the kinds of tools it provides to support automated verification. Indeed, π-AAL is supported by a comprehensive analytical toolset composed of:

- a model checking tool based on CADP;
- a theorem proving tool implemented in XSB.

π-AAL (jointly with π-ADL) has been applied in practice in several pilot projects in France, Italy, UK, Switzerland, and China for designing component-based software architectures. For instance, π-AAL and its supporting toolset have been applied at CERN (the European Organization for Nuclear Research, Switzerland) for enforcing the correctness of distributed control systems to restart particle accelerators.

Particle accelerators at CERN, as in many software-intensive systems, are composed of a large amount of distributed components, including numerous sensors, actuators, processing and storage devices. The CERN's Technical Control Room defined an architectural style with π-ADL and π-AAL by formalizing all the correctness properties of systems controlling the restart of a particle accelerator. These properties were embodied as a software environment integrating the π-AAL toolset, in order to guide the architectural design of such systems, analyze and generate the code of CERN's particle accelerator restart control systems.

This and other experimentations have shown that π-AAL and its toolset are suitable for formally specifying and verifying structural and behavioral correctness properties of component-based software architectures.

Furthermore, the ArchWare integrated development environment itself (Oquendo et al. 2004) that supports the architecture and development of software-intensive systems using π-ADL and π-AAL is itself a validation of π-ADL and π-AAL since it was designed based on a component-based software architecture and has been specified and developed using these languages.

8 CONCLUSIONS AND FUTURE WORK

This paper presented, in a nutshell, how π-AAL can be used for specifying correctness properties of component-based software architectures described in π-ADL. It complements other publications on π-AAL by providing a practical view on how to use its concepts and notation for specifying correctness instead of presenting its formal semantics.

π-AAL supports formal specification and corresponding verification of both structural and behavioral properties. This is a key factor in the architectural design phase in order to support semantic correctness.

Future work will mainly focus on specializing π-AAL for Service-Oriented Architecture (SOA) (OASIS 2008), a mainstream architectural style for developing software-intensive component-based systems based on the Web service technology stack, in particular by refining the level of description and analysis by providing service-oriented abstractions.

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