AADS+: AADL Simulation including the Behavioral Annex [1]

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Abstract

AADL has been proposed for designing and analyzing SW and HW architectures for real-time mission-critical embedded systems. However, it does not support the expression of the behavior of a system in detail, so a behavioral annex has been defined.

In this paper we propose AADS+, an AADL simulation tool that supports the performance analysis of the AADL specification, enriched with behavior specifications, throughout the refinement process from the initial system architecture until the complete, detailed application and execution platform are developed. In this way, AADS+ enables the verification of the initial timing constraints during the complete design process.

1. Introduction

AADL [1-3] was developed as a standard of the SAE to enable the description of task and communication architectures of real-time, embedded, fault-tolerant, secure, safety-critical, SW-intensive systems. It is used to describe the software and hardware components of a system and the interfaces between them. However, AADL does not support the expression of behavior in detail. At most, it is possible to specify the non-deterministic behavior of a thread as a set of subprogram calls, and application behavior relies mainly on source code written in source languages. The behavioral annex [4] has introduced high-level composition concepts and a richer state representation than the standard AADL mode automata. The behavior is specified using extended automata that may trigger a transition by an event, a Boolean expression, etc. A transition may trigger one or more actions such as assignment of values to variables, sending data, events, etc. The annex mainly declares states and transitions with guards and an action part. Guards and actions can access ports and data subcomponents declared in the AADL component to which they are attached.

There is a commonly recognized need for new development frameworks that enable designers to perform efficient exploration of design alternatives and analyze system properties throughout the design cycle. Some system properties can be obtained by static analysis. Many other properties can only be obtained through simulation. In any case, system simulation is necessary for performance analysis under real execution conditions. System simulation validates the correct dimensioning of the system, detection of locks, missed deadlines and other potential problems caused by the complex interaction among components that can be found in a real system. The earlier all those problems are detected, the less the associated cost of correcting them [5].

Evolutionary prototyping is becoming a well-accepted development approach in Model-Driven Engineering (MDE) [6]. The design flow is based on a central model that is refined unless it is satisfactory. Programs can be generated from this model and constitute intermediate versions of the product. The last refined model corresponds to the final system. A prototyping-based design process is of interest to verify as early as possible, the impact of deployment decisions, or the use of a particular HW/SW component in the system.

In this paper, a complete AADL simulation methodology including the behavioral annex is presented. This methodology has been implemented in the tool AADS [7]. AADS is a simulation framework that can support prototype-based design allowing the functional and non-functional (execution times, power consumption, etc.) verification of the system while it is being refined right through to the final implementation. AADS is based on SystemC that has become the standard language for modeling and simulation of HW/SW embedded systems [8]. The SystemC framework supports the seamless integration of any HW component and an easy optimization of the executive platform.

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The contents of the paper are as follows. The following section analyzes the state of the art. In Section 3, the previous work carried out with AADS is summarized. Then, the SystemC model generation methodology from AADL behavioral annex is explained. Next, a case study is presented and finally conclusions are stated.

2. State of the art

Several authors have considered the behavioral annex in their research on AADL. Some of their papers were written in the initial stage of the behavioral annex so they were intended to evaluate, promote and disseminate it. P. Dissaux et al. [9] present a proposal for a behavioral annex to the AADL standard. They explain how to implement the behavioral annex with the Stood tool, a graphical AADL editor that can import and export AADL textual specifications. R. Bedin et al. [10] evaluate the behavioral annex through a flight software design in the ArchiDyn project. They require new synchronization primitives for AADL runtime and support using edition and analysis tools for the behavioral annex. J. P. Bodeveix et al. [11] propose an AADL behavioral annex and a technique to perform compositional real-time verification of AADL models through the use of a method which translates environmental constraints into behavior.

Other papers, such as the latter one, include the behavioral annex in their verification process of AADL models. B. Berthomieu et al. describe in [12] a formal verification tool chain for AADL with its behavioral annex available in the Topcased environment. They translate the AADL model to Fiacre and verify the behavior with a Time Petri Net Analyzer (Tina).

C. Ponsard et al. explore in [13] the interplay of requirements and architecture in a model-based perspective by defining a mapping and a constructive process taking into account specificities of embedded systems, especially the importance of non functional requirements. To generate the behavioral part of a system they first generate a finite state machine and then an AADL mode-transition.

A way to tackle AADL and its behavioral annex is translation to another language. To allow simulation M. Yassin Chkouri et al. propose in [14] a translation from AADL models into BIP models. They take into account behavior specifications allowing state variables, initialization, states and transitions sections to be defined and translating them into BIP. DUALLY [15] is an automated framework that allows architectural language interoperability through automated model transformation techniques. I. Malavolta et al. analyze the feasibility of integrating AADL and OSATE in DUALLY. They map AADL behavioral annex sections of states, composite states and transitions.

After analyzing the state of the art, a behavioral annex to the AADL standard appears to be necessary, which could be included in an AADL model in order to express the behavior of the components.

However, no approach uses SystemC [16], which is the recognized standard for modeling HW/SW platforms, with its great potential for integration of processors, buses, memories and specific platform HW. Our solution makes HW/SW co-design easier because of the use of SystemC.

SCoPE [17-18] is a C++ library that extends the standard language SystemC without modifying it. It simulates C/C++ SW code based on two different operating system interfaces (POSIX [19-20] and MicroC/OS). Moreover, it co-simulates these pieces of code with HW described in SystemC.

In a previous work [21], a preliminary version of AADS supporting a part of the AADL standard was developed. Now we have improved AADS to take into account the most important issues of the AADL behavioral annex (states, transitions, sending and receiving messages, etc.). AADS+ supports AADL behavioral annex simulation in SystemC, thus enabling the HW platform to be modeled and permitting HW/SW codesign. The AADL model is based on POSIX, so it supports many different RTOSs.

3. Previous work

AADS is written in Java and was developed as a plug-in [22] of Eclipse [23]. AADS enables the modeling of a subset of AADL for purposes of implementation and simulation. The starting point of the simulator is a functional AADL specification without detailed code. For each component, the corresponding timing constraints are defined. This initial AADL specification supports the verification of the global performance constraints of the system based on the specific timing constraints of the different components. The AADL model is parsed using AADS and a model suitable for simulation with SCoPE is produced, in order to check whether the AADL constraints are fulfilled. As the design process advances and, on the one hand, the actual functionality is attached to the SW components using the corresponding source code and, on the other, the functionality is mapped onto specific platform resources, a more accurate performance estimation is performed. These refined properties can be added to the AADL model and a new model can be generated by

AADS. By comparing the initial timing constraints with these refined, timing estimations, it is possible to verify the non functional correctness of the design process at any refinement step.

AADL enables the specification of both the architecture and functionality of an embedded real-time system. AADS translates both to SystemC (see Figure 1). It parses the AADL model so the functionality is translated to an equivalent POSIX model and the architecture is represented in XML [24].

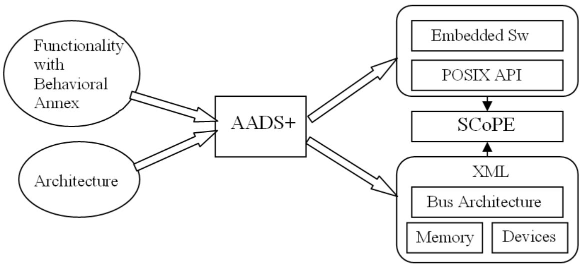


Figure 1: Translation process.

4. Translation of the behavioral annex

The AADL behavioral annex improves the specification of a component's behavior. AADS+ parses the AADL model so the *annex behavior_specification* sections are translated to an equivalent POSIX model.

The behavioral annex describes a *transition* system (an extended automaton) using optional sections:

State variables. The *state variables* section declares typed identifiers. Types are data classifiers of the AADL model. AADS+ translates these *state variables* declaring variables with their corresponding type in the C++ source code of the thread or subprogram itself.

Initialization. The *state variables* must be initialized in the *initialization* section using a sequence of assignments. AADS+ translates this *initialization* initializing the variables with their corresponding value where they were declared.

States. The *states* section declares automaton *states* which can be qualified as *initial, complete, return, urgent* or *composite*. AADS+ uses this section to know which *states* have been defined.

Transitions. The *transitions* section defines system *transitions* from a source *state* to a destination *state*. The *transition* can be guarded with events or Boolean conditions. An *action* part can be attached to the *transition*. It can perform subprogram calls, message sending or assignments. AADS+ translates the *transitions* section into *switch* and *case* statements to transit from one *state* to another. It starts in the initial *state* and moves to the next *state* when the *guard* of the *transition* is true. So the *guard* of the *transition* translated by AADS+ acts as a condition to execute the sentence/s of the *state* and to change the *state*. This sentence/s is the *action* of the *transition* translated by AADS+. If there is no *guard* there is no condition to check. The *guard* can be an expression as simple as *on* $i < 5$, so AADS+ will translate it directly.

Depending on the content of the *guard* and the *action* of the *transition*, AADS+ translates them into the corresponding sentences of source code:

Sending / receiving messages. Messages are sent / received through *event* or *event data ports*. If *p* is an input *port*: *p?* de-queues an *event port* variable, *p?x* de-queues a datum on an *event data port* in the variable *x*. If *p* is an output *port*: *p!* calls *Raise_Event* on an *event port*, *p!d* writes data *d* in the *event data port* and calls *Raise_Event*.

In the first case the *guard* of a *transition* is *p1?x* (where *p1* is an *in event data port*) and the *action* of that *transition* is *p2!(x+1)* (where *p2* is an *out event data port*). AADS+ translates this case, checking whether a variable arrives at the POSIX message queue associated with the *port p1*. Then the variable is sent through the POSIX message queue associated with the *port p2*, in this case after adding 1 to it.

In the second case the *guard* of a *transition* is *p1?* (*p1* is an *in event port*) and the *action* of that *transition* is *p2!* (*p2* is an *out event port*). AADS+ translates this case, checking whether the corresponding POSIX signal associated with the *port p1* has been received. Then the corresponding POSIX signal associated with the *port p2* is sent.

Subprograms. A behavior expressed by the annex can be attached to a subprogram implementation. The behavior can refer to the subprogram parameters and to variables. The automaton specifying the subprogram implementation has one or more return *states* indicating the return to the caller. While the AADL control flows define the call sequences produced by a subprogram, the annex enables the expression of dependencies between the control flows and *state variables* or parameters. A subprogram specification can express other calls or notification of events.

In the first case the *guard* of a *transition* is *p1?* (*p1* is an *in event port*) and the *action* of that *transition* is *subp!* (*subp* is a subprogram). AADS+ translates this case checking whether the corresponding POSIX signal associated with the *port p1* has been received. If the signal has been received then the corresponding previously defined subprogram is called.

Parameters can be passed to called subprograms. The *action* of that *transition* could be *subp!(5->x,2->y)* where *x* and *y* are two in parameters of the subprogram *subp*. Then AADS+ translates it into a call to the subprogram with those two parameters as *subp(5,2).*

Using the AADL behavioral annex, it is possible to indicate in the *action* of a *transition* that the *out* parameter of a subprogram is the *in* parameter modified in some way. It could be *po!(pi+1),* where *po* is the *out* parameter and *pi* the *in* parameter. AADS+ translates this case, creating the source code in the subprogram that sums one to the *in* parameter and assigns the result to the *out* parameter.

In the last case the *guard* of a *transition* is *on pi* (*pi* is an in parameter of a subprogram) and the *action* of that *transition* is a call to a standard function like *std::cout!*. To translate this *transition* AADS+ generates the C++ source code that checks whether the in parameter is true and, if it is, calls the standard function *cout*.

Control structures. Control structures support conditional execution of alternative actions (*if, else, end if*), conditional repetition of actions (*while*), and application of actions over all elements of a data component array, *port* queue content, or integer range (*for*). The *For* structure represents an ordered iteration over all elements. Within the *for* structure the element can be referenced by *element_variable_identifier*, which acts as a local variable with the name scope of *for* structure.

In the case that the *action* of a *transition* contains a conditional structure of the type: *if (logical value expression) behavior_actions [else behavior_actions] end if*, AADS+ translates it producing the source code with the analogous *if else* structure in C++, adapting the differences between them.

The same can be said about *for* and *while* structures of the type: *for (element variable identifier in values) {behavior_actions}* and *while (logical value expression) {behavior_actions}*. AADS+ translates them producing the source code with the analogous *for* and *while* structure in C++, adapting the differences between them.

Arrays. To declare collections of data which are considered to be ordered the notion of *multiplicity* is used. AADS+ translates *multiplicity* into a C++ *array* of data. The type of the *array* is the same in both AADL and C++.

5. Case study

The proposed method implemented in AADS+ has been tested in a typical case study, the cruise control presented in Figure 2, to assure the feasibility of the translation. Cruise control is a system that automatically controls the velocity of a motor vehicle. The driver sets a speed and the system will take over the throttle to maintain it.

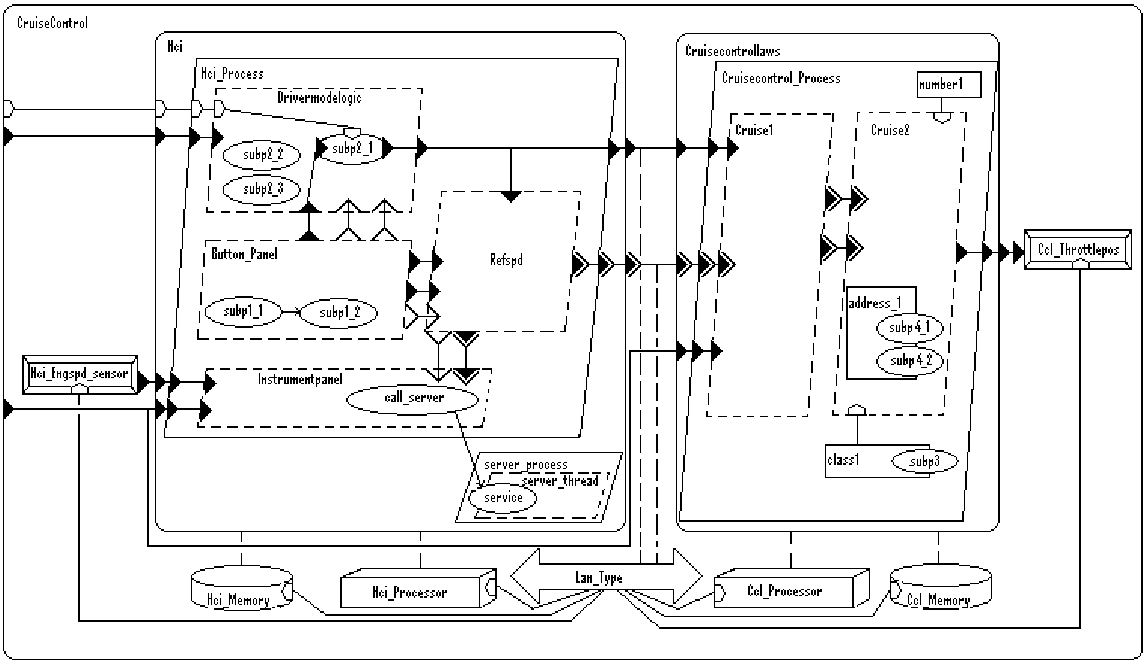


Figure 2. Refined cruise control architecture.

The use of the AADL behavioral annex with AADS+ has been validated through the refinement of the original cruise control design. As the original model was developed without using the behavioral annex, the model lacked relevant behavioral information. The annex overcomes these problems and enables the development of a more detailed architecture.

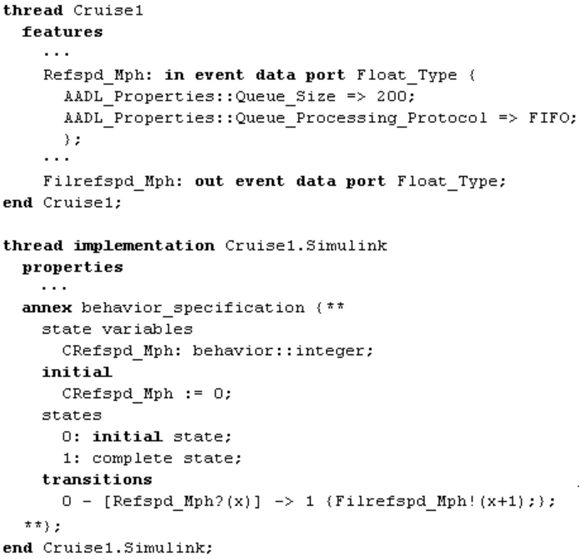
The figure shows an AADL model with its behavioral annex of a cruise control system, taken from the collection of AADL examples in the OSATE release, but modified to add some subcomponents. The system component contains two processors, two memories and two devices connected by a bus, and two SW subsystems. Each of the subsystems is bound to a separate processor and to a separate memory. Threads communicate via data ports, event ports and event data ports. Some data access connections can be seen too. There are some subprograms within threads and within data subcomponents and the call sequences (local and remote) between them are shown. The parameter connections between subprograms are shown too. One subsystem has two processes, one with four threads and the other with one. The other subsystem contains one process, with two threads.

The files produced by AADS+ are compiled with SCoPE to simulate the model. The results obtained in the simulation are used to refine the model of the cruise control as needed.

Figures 3 and 4 are an example of the translation performed by AADS+ of the behavior specification of a thread. Messages are sent and received through *event data ports*. In this case the *guard* of a *transition* is *Refspd_Mph?x* and the *action* of that *transition* is *Filrefspd_Mph!(x+1)* (*Refspd_Mph* / *Filrefspd_Mph* are *in / out event data ports*). AADS+ translates it checking whether a variable arrives at the POSIX message queue associated with the *port Refspd_Mph*. Then the variable is sent through the POSIX message queue associated with the *port Filrefspd_Mph*, after adding 1 to it.

Subprograms with their behavior specifications have been added to the AADL model of the cruise control to obtain the desired system performance. For example, to detect if a button has been pushed by the driver the corresponding behavior was added to a *subprogram* in *Button_panel thread* and refined through simulation.

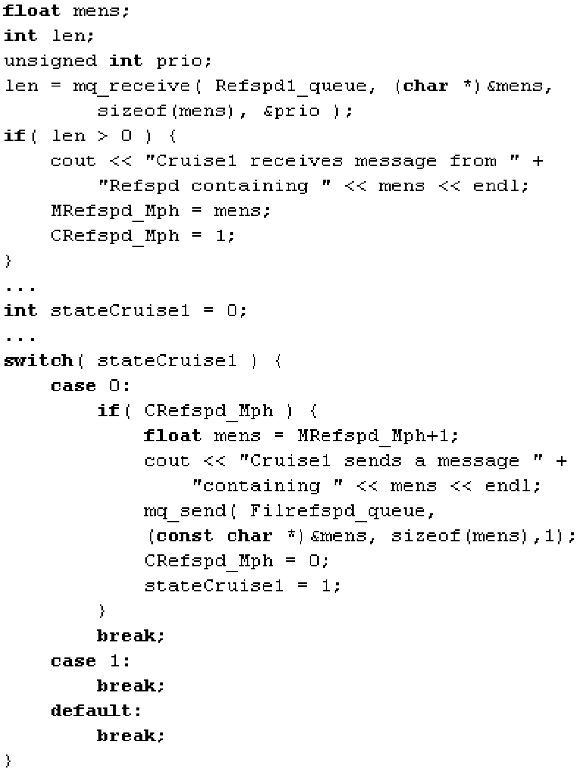
When the driver activates the cruise control, an event is sent to the *Refspd thread* that sends another event to the *Instrumentpanel thread* to show the activation; this behavior has been implemented in the *thread Refspd*.



```
thread Cruise1
  features
    ...
    Refspd_Mph: in event data port Float_Type {
      AADL_Properties::Queue_Size => 200;
      AADL_Properties::Queue_Processing_Protocol => FIFO;
      };
    ...
    Filrefspd_Mph: out event data port Float_Type;
end Cruise1;

thread implementation Cruise1.Simulink
  properties
    ...
  annex behavior_specification {**
    state variables
      CRefspd_Mph: behavior::integer;
    initial
      CRefspd_Mph := 0;
    states
      0: initial state;
      1: complete state;
    transitions
      0 - [Refspd_Mph?(x)] -> 1 {Filrefspd_Mph!(x+1);};
  **};
end Cruise1.Simulink;
```

Figure 3. A behavior specification of a thread.



```
float mens;
int len;
unsigned int prio;
len = mq_receive( Refspd1_queue, (char *)&mens,
        sizeof(mens), &prio );
if( len > 0 ) {
    cout << "Cruise1 receives message from " +
        "Refspd containing " << mens << endl;
    MRefspd_Mph = mens;
    CRefspd_Mph = 1;
}
...
int stateCruise1 = 0;
...
switch( stateCruise1 ) {
    case 0:
        if( CRefspd_Mph ) {
            float mens = MRefspd_Mph+1;
            cout << "Cruise1 sends a message " +
                "containing " << mens << endl;
            mq_send( Filrefspd_queue,
            (const char *)&mens, sizeof(mens),1);
            CRefspd_Mph = 0;
            stateCruise1 = 1;
        }
        break;
    case 1:
        break;
    default:
        break;
}
```

Figure 4. C++ code translated by AADS+.

The correct operation of the behavior specification created to know whether the *Drivermodelogic* is activated or disactivated was refined by simulating the model.

Another example of behavior specification is in the *thread Instrumentpanel,* which provides information about the actuation zone depending on the speed of the vehicle (see Figure 5). All these examples were translated by AADS+ in an analogous way as can be seen in the previous figures.

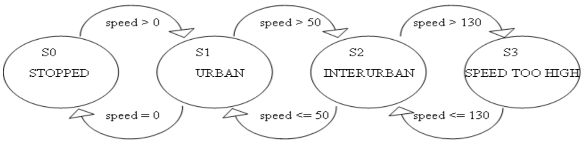


Figure 5. State diagram of one *Instrumentpanel's* behavior.

Refinement of the original cruise control model with behavior specifications does not require a large number of AADL code lines, AADS+ does not produce so many C++ code lines as one might fear (see Figure 6) and the gain in expressiveness of the model's behavior is great. Furthermore, the cost in terms of use of CPU, core energy/power, bus access time, etc is slight.

	AADL model without behavioral annex	AADL model refined with behavioral annex
AADL lines	560	682
C++ & XML lines	1954	2207
Number of thread switches	6936	6567
Running time	3,927344674 s	3,942027992 s
Use of CPU	98,1836 %	98,5507 %
Instructions executed	330919376	332182295
Instruction cache misses	15340	16900
Core Energy	66,18386e+07 nJ	66,43646e+07 nJ
Core Power	165,4594 mW	166,0914 mW
Instruction cache energy	9,93372e+08 nJ	9,97223e+08 nJ
Instruction cache power	248,343 mW	249,3058 mW
Bus access time	5830500 ns	6636280 ns
Idle time	4057597179 ns	4046782848 ns
Number of interrupts	4855	4575

Figure 6. Comparison between the two models' metrics.

6. Conclusions and further work

This paper presents the simulation of the AADL behavioral annex using the AADS+ simulation tool. AADS+ supports the refinement of AADL models, including the behavioral annex, through performance analysis done with SCoPE, after translating those models.

The generation of the SystemC model from the AADL specification and its behavioral annex is not straightforward. Nevertheless, the SystemC model generated by AADS+ is able to capture the fundamental dynamic properties of the initial system specification. In this way, AADS+ supports design space exploration by refinement of the AADL functionality and its implementation on an optimized platform.

Future work includes incorporation of AADS+ features that appear in V2.0 of the AADL standard. Furthermore, the source code produced by AADS+ for the software components will be made compatible with the ASSERT Ravenscar Computational Model (RCM).

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