

MODEL DRIVEN DEVELOPMENT FOR MEDICAL DEVICES IN
AADL/BLESS AND SPARK ADA: PCA PUMP PROTOTYPE

by

Jakub Jedryszek

B.S., Wroclaw University of Technology, Poland, 2012

B.A., Wroclaw University of Economics, Poland, 2012

A THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Computing and Information Sciences
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2014

Approved by:

Major Professor
John Hatcliff

Copyright

Jakub Jedryszek

2014

Abstract

Ada programming language is targeted at embedded and real-time systems.

SPARK Ada is designed for the development of safety and security critical systems. It contains properties, which allows to prove correctness of program and its entities.

AADL (Architecture Analysis & Design Language) is modeling language for representing hardware and software. It is used for real-time, safety critical and embedded systems.

BLESS (Behavior Language for Embedded Systems with Software) is AADL annex sub-language defining behavior of components. The goal of BLESS is automatically-checked correctness proofs of AADL models of embedded electronic systems with software.

Nowadays, we have trend to generate code from models. The ultimate goal of research, which this thesis is part of, is to create AADL/BLESS to SPARK Ada translator. Ultimately there will be standardized AADL/BLESS models, which will be generating code base for developers extensions (like skeleton code for some Web Framework).

This thesis propose mapping from AADL/BLESS to SPARK Ada. As an example of Medical Device, PCA Pump (Patient Controlled Analgesia) is used. The foundation for this work is System Requirements for "Integrated Clinical Environment Patient-Controlled Analgesia Infusion Pump System Requirements" (DRAFT 0.10.1) [Lar14] and AADL Models with BLESS annexes created by Brian Larson. Additionally, there was a contribution made in clarifying the requirements document and extending AADL models.

Table of Contents

Table of Contents	viii
List of Figures	xi
List of Tables	xii
Acknowledgements	xii
Dedication	xiii
1 Introduction	1
1.1 Motivation	2
1.2 Goals	3
1.3 Contribution	4
1.4 Organization	4
1.5 Terms and Acronyms	4
2 Background	6
2.1 Integrated Clinical Environment	6
2.2 AADL	7
2.2.1 OSATE	9
2.3 BLESS	9
2.4 SPARK Ada	10
2.4.1 GNAT compiler and Programming Studio	15

2.4.2	Ravenscar Tasking Subset	15
2.4.3	AUnit	15
2.4.4	Sireum Bakar	16
2.4.5	GNAT Prove	16
2.5	AADL/BLESS to SPARK Ada code generation	16
2.5.1	Ocarina	16
2.5.2	Ramses	17
3	PCA Pump	18
3.1	PCA Pump Requirements Document	19
3.2	PCA Pump AADL/BLESS Models	19
3.3	BeagleBoard-XM	19
3.4	Interface for Integrated Clinical Environment	20
4	AADL/BLESS to SPARK Ada translation	21
4.1	AADL/BLESS to SPARK Ada mapping	21
4.1.1	Data types mapping	22
4.1.2	AADL ports mapping	22
4.1.3	Thread to task mapping	28
4.1.4	Subprograms mapping	31
4.1.5	Ports communication mapping	32
4.1.6	BLESS mapping	32
4.2	"DeusEx" translator	33
5	PCA Pump Prototype Implementation	34
5.1	Concurrency in SPARK Ada	34
5.2	Code generation from AADL models	35

5.3	Implementation for generated code	35
6	Verification	37
6.1	SPARK Examiner	37
6.2	AUnit tests	38
6.3	gnatPROVE?	38
7	Summary	39
8	Future work	40
	Bibliography	41
A	PCA Pump Prototype - simple, working example	44
B	PCA Pump Prototype - translated from AADL/BLESS	45

List of Figures

2.1	AADL model of simple thermometer	7
2.2	Developer responsibility in Ada ¹	10
3.1	Basic Process Control Loop ²	18

List of Tables

2.1	Sample SPARK 2005 to 2014 mapping.	13
4.1	AADL to SPARK ports mapping.	23
4.2	AADL threads to SPARK Ada subprograms(procedures/functions) mapping.	29
4.3	AADL threads to SPARK Ada tasks mapping.	30
4.4	AADL subprograms to SPARK Ada subprograms(procedures/functions) mapping.	32
4.5	BLESS to SPARK contractsmapping.	32

Acknowledgments

Say thank you for everybody involved directly and indirectly.

Dedication

For my family, mentors and all people who inspired me directly or indirectly in things I am doing.

I also dedicate this thesis to everyone who have supported me throughout the process.

Chapter 1

Introduction

The tale about software safety: why important, software everywhere, human life, etc. (info from 890).

Software Engineering for Real-Time and Safety-Critical systems is very different than creating Desktop applications. In both types of software we want to ensure correctness and security. In case of e.g. e-mail client software assurance is not critical. When something happens, we just restart the app. However, in case of e.g. Airplane, software cannot just crash. If it crashes, then people die. Behind these reasons, we need different properties of programming language and its tools. For Web or Mobile apps our priority is Rapid Development. For Safety-Critical systems, the security and correctness is crucial.

Most important in Safety-Critical Systems: Hazard analysis (avoid, recover)! Hazard can cause: * Incident * Accident Accident - event, which cause loss (undesired) Incident - event, which not cause loss (but undesired), and could lead to accident Hazard + Environmental Conditions = Accident (loss) Event - state change

Overview of Safety-Critical System loop.

1.1 Motivation

There are many accidents where Medical Devices are involved. Very often, the reason is the lack of communication between different Medical Devices. [EXAMPLE ACCIDENT] The solution for such a problem is to create "Integrated Clinical Environment" (ICE). SAnToS Lab at Kansas State University is working on Medical Device Coordination Framework (MDCF), which is prototype implementation of ICE.

Devices working under MDCF will need to satisfy some requirements. To make Developer's life easier, the requirements will be not only in documentation, but also in code. The code will be generated from models. Model Driven Development in this case means we will have some base models for medical devices development and developer will extend and customize them. The same like you do File > 'New Java project' in Eclipse, we want to be able to do the same in e.g. GNAT Programming Studio: File > 'New Medical device project'. Model as specification/requirements.

PCA Pump is as an example of Medical Device, which ultimately will work under Medical Device Coordination Framework (MDCF), an open source framework under development by SAnToS Lab at Kansas State University and University of Pennsylvania. Summarizing, we want to be able to have MDCF, which coordinates Medical Devices. Additionally we want set of AADL/BLESS models, which can be automatically translated to SPARK Ada. These models will be base for Medical Devices Developers, who can extend and adjust them to implement specific devices. Why AADL? Because it describes hardware and software. It allows to validate that the software will work on some device. Why SPARK? Because it contains set of verification tools. Testing vs Verification (form 721 slides): Testing starts with a set of possible test cases, simulates the system on each input, and observes the behavior. In general, testing does not cover all possible executions. On the other hand, verification establishes correctness for all possible execution sequences. Techniques for Verification:

- Formal verification: prove mathematically that the program is correct – this can be difficult for large programs.

- Correctness by construction: follow a well- defined methodology for constructing programs.
- Model checking: enumerate all possible executions and states, and check each state for correctness.

SPARK is a subset of Ada language, which is easy to deal with it. In the future, when everything will be done (in case of proving perspective) in SPARK, it will (probably) be extended. Maybe finally, there will be no SPARK, but only Ada. Thus for now, SPARK is temporary subset of Ada for reasoning and correctness proving.

1.2 Goals

- learn about PCA Pump Infusion pumps properties
- SPARK Ada cross-compilation for ARM-device (BeagleBoard-xM)
- implement PCA Pump based on Brian's Requirement Document (using Ravenscar profile)
- propose AADL/BLESS to SPARK Ada mapping
- mock PCA Pump AADL/BLESS models in SPARK Ada
- implement not generated part
- create AADL/BLESS to SPARK Ada translator
- Use SPARK toolset for software verification:
 - SPARK Examiner
 - SPARK Simplifier???
 - GNATprove
 - Sireum Kiasan

1.3 Contribution

Put all pieces together (SPARK, AADL, BLESS, ICE, PCA Pump) and analyze current state of target technologies. Review PCA Pump Requirements document Analyzed PCA Pump AADL models, then based on available resources proposed possible translation from AADL/BLESS to SPARK Ada. Created skeleton of generated SPARK code from AADL models. Implemented PCA Pump based on requirements document and skeleton code. Resolved some ambiguities and analyzed different implementation possibilities. Then the implementation is sort of proof that, this document and AADL models are base for future Infusion Pumps implementations. Presented SPARK 2005 Verification tools: its capabilities and issues. Created AADL/BLESS to SPARK Ada translator?

1.4 Organization

The thesis is organized in 8 chapters. Chapter 1 is the problem description and summary of contribution which was made. Chapter 2 is Background that gives details about Model Driven Development, SPARK Ada, AADL/BLESS, ICE and available tools for such environment. Chapter 3 describe patient-controlled analgesia (PCA) pump. Chapter 4 is about code generation from the model. Chapter 5 describes the implementation of PCA Pump Prototype. Faced issues and design decisions made. Chapter 6 describes verification of implemented PCA Pump Prototype. Chapter 7 summarizes all work which has been done in this thesis. Chapter 8 is the future work that can be done on this topic.

1.5 Terms and Acronyms

- **AADL** - Architecture Analysis & Design Language
- **BLESS** - Behavioral Language for Embedded Systems with Software

- **ICE** - Integrated Clinical Environment
- **MDCF** - Medical Device Coordination Framework
- **PCA** - Patient-Controlled Analgesia (pump)
- **AADL** - Architecture Analysis & Design Language
- **AADL** - Architecture Analysis & Design Language
- **AADL** - Architecture Analysis & Design Language
- **AADL** - Architecture Analysis & Design Language
- **AADL** - Architecture Analysis & Design Language

Chapter 2

Background

This chapter is brief introduction of all technologies and tools used in this thesis. It is SPARK Ada programming language and its tools (GNAT Programming Studio, Sireum Bakar, GNATprove), AADL modeling language, BLESS (AADL annex language). There is also overview of the context in which this work has been made: Integrated Clinical Environment standard (ICE) and PCA Pump (ICE compliant device). This is followed by main topic of the thesis: code generation from AADL and analysis of existing AADL translators (Ocarina, RAMSES).

2.1 Integrated Clinical Environment

Medical devices are safety-critical systems. Medical Devices Coordination Framework is an open, experimental ICE-compliant platform to bring together academic researchers, industry vendors, and government regulators. Medical Devices, which are ICE compliant can be connected to MDCF. It enables Medical Devices cooperation. [add some pictures etc.]

2.2 AADL

AADL stands for Architecture Analysis & Design Language. The aim of the AADL is to allow the description of Distributed Real-Time Embedded (DRE) systems by assembling separately developed blocks. Thus it focuses on the definition of clear block interfaces, and separates the implementations from those interfaces. AADL allows for the description of both software and hardware parts of a system ¹.

AADL has its roots in DARPA ² funded research. The first version (1.0) was approved in 2004 under technical leadership of Peter Feiler ³. AADL is develop by SAE AADL committee ⁴. AADL version 2.0 was published in January 2009. The most recent version (2.1) was published in September 2012 ⁵.

AADL is a language for Model-Based Engineering [FG13]. It can be represented in textual and graphical form. There are tools (like Osate 2.2.1), which transforms textual representation into graphical. There is also possibility to represent AADL in XML (using 3rd party tools). An example AADL model called Thermometer is shown in graphical representation in figure 2.2 and in textual representation in listing 2.1.

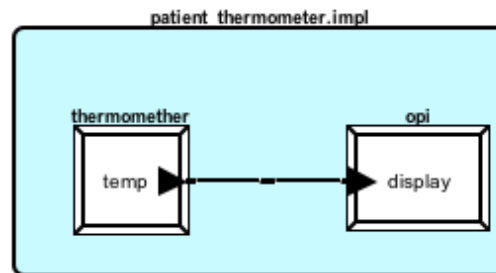


Figure 2.1: *AADL model of simple thermometer*

```
package Thermometer
```

¹<http://penelope.enst.fr/aadl>

²<http://www.darpa.mil>

³http://wiki.sei.cmu.edu/aadl/index.php/The_Story_of_AADL/

⁴https://wiki.sei.cmu.edu/aadl/index.php/Main_Page

⁵<https://wiki.sei.cmu.edu/aadl/index.php/Standardization>

```

public
with Base_Types;

  system patient_thermometer
  end patient_thermometer;

  system implementation patient_thermometer.impl
  subcomponents
    thermometer : device thermometer_device.impl;
    opi : device operator_interface.impl;
  connections
    tdn : port thermometer.temp -> opi.display;
  end patient_thermometer.impl;

  device operator_interface
  features
    display : in data port Base_Types::Integer;
  end operator_interface;

  device implementation operator_interface.impl
  end operator_interface.impl;

  device thermometer_device
  features
    temp : out data port Base_Types::Integer;
  end thermometer_device;

  device implementation thermometer_device.impl
  end thermometer_device.impl;
end Thermometer;

```

Listing 2.1: *AADL model of simple thermometer*

Recently AADL becomes a new market standard. There are lots of tools for AADL models analysis, such as: STOOD ⁶, ADELE ⁷, Cheddar ⁸, AADLInspector ⁹ or Ocarina ¹⁰.

What is important, AADL is for architectural description. It should not be compared with UML suites, which allows to link with source code.

2.2.1 OSATE

Open Source AADL Tool Environment (OSATE) is a set of plug-ins on top of the open-source Eclipse platform. It provides a toolset for front-end processing of AADL models. OSATE is developed mainly by SEI (Software Engineering Institute - CMU) ¹¹. Latest available version of OSATE in the time when this work was published is OSATE2 ¹².

2.3 BLESS

BLESS (Behavior Language for Embedded Systems with Software) is AADL annex sub-language defining behavior of components. The goal of BLESS is automatically-checked correctness proofs of AADL models of embedded electronic systems with software.

BLESS contains three AADL annex sublanguages:

- Assertion - it can be attached individually to AADL features (e.g. ports)
- subBLESS - can be attached only to subprograms; it has only value transformations and Assertions without time expressions
- BLESS - it can be attached to AADL thread, device or system components; it contains states, transitions, timeouts, actions, events and Assertions with time expressions...

⁶<http://www.ellidiss.com/products/stood>

⁷<https://wiki.sei.cmu.edu/aadl/index.php/Adele>

⁸<http://beru.univ-brest.fr/~singhoff/cheddar>

⁹<http://www.ellidiss.com/products/aadl-inspector>

¹⁰<http://www.openaadl.org>

¹¹<http://www.aadl.info/aadl/currentsite/tool/osate.html>

¹²https://wiki.sei.cmu.edu/aadl/index.php/Osate_2

How it fits into the picture. Why it was developed. Corectness prove in AADL + behavior [LCH13], from which we can generate SPARK Ada code.

2.4 SPARK Ada

First version of Ada programming language - Ada 83 - was designed to meet the US Department of Defence Requirements formalized in "Steelman" document ¹³. Since that time, Ada evolved. There were Ada 95, Ada 2005 and Ada 2012 (released in December 10, 2012) ¹⁴. Ada is actively used in many Real-World projects¹⁵, e.g. Aviation (Boeing ¹⁶), Railway Transportation, Commercial Rockets, Satellites and even Banking. One of the main goals of Ada is to ensure software correctness and safety.

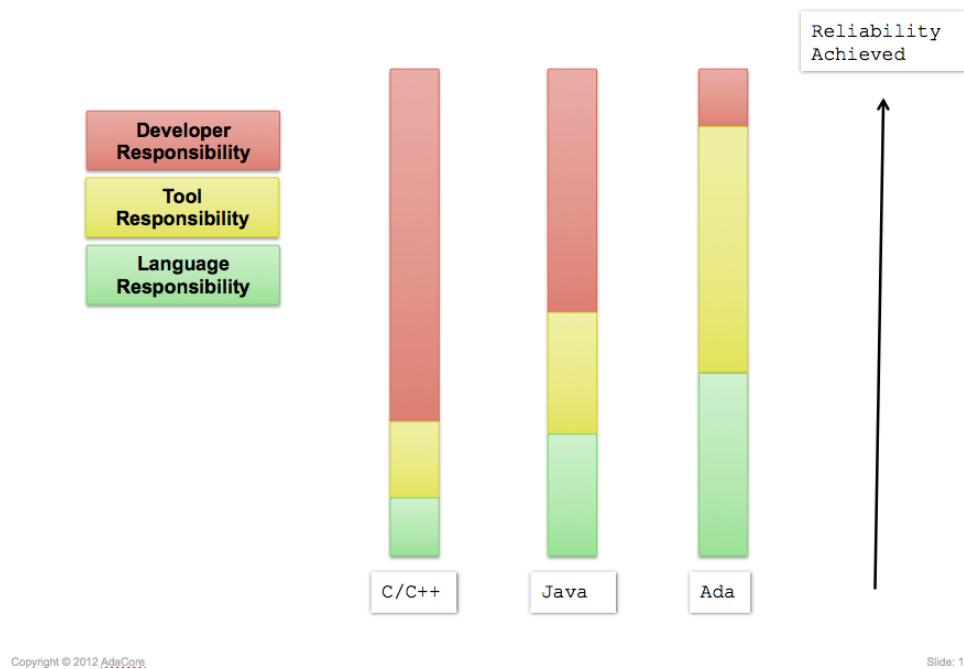


Figure 2.2: *Developer responsibility in Ada*¹⁷.

¹³<http://www.adahome.com/History/Steelman/steelman.htm>

¹⁴<http://www.ada2012.org>

¹⁵<http://www.seas.gwu.edu/~mfeldman/ada-project-summary.html>

¹⁶<http://archive.adaic.com/projects/atwork/boeing.html>

¹⁷<http://www.slideshare.net/AdaCore/ada-2012>

SPARK is a programming language and static verification technology designed specifically for the development of high integrity software. It is a ‘safe’ subset of Ada designed to be susceptible to formal methods, accompanied with a set of approaches and tools. Using SPARK, a developer takes a Z specification and performs a stepwise refinement from the specification to SPARK code. For each refinement step a tool is used to produce verification conditions (VC’s), which are mathematical theorems. If the VC’s can be proved then the refinement step will be known to be valid. However if the VC’s cannot be proved then the refinement step may be erroneous ¹⁸.

First version was designed over 20 years ago. SPARK has established a track record of use in embedded and critical systems across a diverse range of industrial domains where safety and security are paramount [Bar13].

SPARK provides a significant degree of automation in proving exception freedom [IEC⁺06]. SPARK excludes some Ada constructs to make static analysis feasible [IEC⁺06]. Additionally SPARK contains tool-set for Software Verification:

- Examiner - analyze code and ensures that it conforms to the SPARK language; also verify program to some extent using Verification Conditions (VC)
- Simplifier - simplify Verification Conditions generated by Examiner
- Proof Checker - prove the Verification Conditions

First version of SPARK was based on Ada 83. The second version (SPARK 95) - on Ada 95. SPARK 2005 is based on Ada 2005. It is a subset of Ada 2005 with annotations. The annotation language support flow analysis and formal verification. Annotations are encoded in Ada comments (via the prefix `--#`). It makes every SPARK 2005 program, valid Ada 2005 program. Figure 2.2 shows example SPARK 2005 package specification.

```
package Odometer
--# own Trip, Total : Integer;
is
```

¹⁸<http://www.dwheeler.com/lovelace/s17s4.htm>

```

procedure Zero_Trip;

--# global out Trip;
--# derives Trip from ;
--# post Trip = 0;

function Read_Trip return Integer;
--# global in Trip;

function Read_Total return Integer;
--# global in Total;

procedure Inc;
--# global in out Trip, Total;
--# derives Trip from Trip & Total from Total;
--# post Trip = Trip~ + 1 and Total = Total~ + 1;

end Odometer;

```

Listing 2.2: *SPARK 2005 code: Odometer* [[Bar13](#)]

SPARK 2005 does not include constructs such as pointers, dynamic memory allocation or recursion [[IEC+06](#)].

SPARK 2014 ¹⁹ is based on Ada 2012 programming language targeted at safety- and security-critical applications [[DEL+14](#)]. Since Ada 2012 contains contracts, there is no need to use annotations like in SPARK 2005. Thus SPARK 2014 is subset of Ada 2012. It contains all features of Ada 2012 except:

- Access types (pointers)
- Exceptions
- Aliasing between variables

¹⁹<http://www.spark-2014.org>

- Concurrency features of Ada (Tasking) - it's part of SPARK 2014 road-map to include support for tasking in the future, although likely not this year
- Side effects in expressions and functions

Sample mapping from SPARK 2005 to 2014 is shown on table 2.1. Complete mapping can be found in SPARK 2014 documentation²⁰ [AL14].

Table 2.1: *Sample SPARK 2005 to 2014 mapping.*

SPARK 2005	SPARK 2014
<code>--# global in out X, Y;</code>	<code>with Global => (In_Out => (X, Y));</code>
<code>--# derives X from Y & --# Y from X;</code>	<code>Depends => (X => Y, Y => X);</code>
<code>--# pre Y /= 0 and --# X > Integer'First;</code>	<code>with Pre => Y /= 0 and X > Integer'First;</code>
<code>--# post X = Y~ and Y = X~;</code>	<code>with Post => (X = Y'Old and Y = X'Old);</code>

SPARK 2014 does not contains Examiner. Instead, proofs are made by gnatPROVE. The notion of executable contracts in Ada 2012, was inspired by SPARK. The previous Odometer example in SPARK 2014 is shown in figure 2.3.

```
package Odometer
with SPARK_Mode
Abstract_State => (Trip, Total)
is
  procedure Zero_Trip
  with Global => (Output => (Trip)),
```

²⁰<http://docs.adacore.com/spark2014-docs/html/lrm/mapping-spec.html>

```

    Depends => (Trip => null),
    Post => (Trip = 0);

function Read_Trip return Integer
with Global => (Input => (Trip));

function Read_Total return Integer
with Global => (Input => (Total));

procedure Inc
with Global => (In_Out => (Trip, Total)),
    Depends => (Trip => Trip, Total => Total),
    Post => Trip = Trip'Old + 1 and Total = Total'Old + 1;

end Odometer;

```

Listing 2.3: *SPARK 2014 code: Odometer*

It is possible to mix SPARK 2014 with Ada 2012. However, only the part which is SPARK 2014 compliant will be verified. Usually SPARK is used in the most critical parts of Software Systems [Cha00]. It means, that some part is written in e.g. Ada or C++ and the rest in SPARK. The reason of that is the SPARK limitation and lack of necessity to verify some modules.

The most popular IDE for SPARK Ada is GNAT Programming Studio ²¹.

There is also plugin for Eclipse: GNATbench ²² created by AdaCore. Tools for correctness proving.

²¹<http://libre.adacore.com/tools/gps>

²²<https://www.adacore.com/gnatpro/toolsuite/gnatbench/>

2.4.1 GNAT compiler and Programming Studio

GNAT compiler is front end of gcc... IDE for SPARK Ada programs development. Includes proving tools. E.g. Sireum Bakar (developed by SAnToS lab) or GNATprove.

2.4.2 Ravenscar Tasking Subset

RavenSPARK is subset of the SPARK Ravenscar Profile (which is subset of Ada tasking). The Ravenscar Profile provides a subset of the tasking facilities of Ada95 and Ada 2005 suitable for the construction of high-integrity concurrent programs [Tea12].

The Ravenscar Profile is a subset of the tasking model, restricted to meet the real-time community requirements for determinism, schedulability analysis and memory-boundedness, as well as being suitable for mapping to a small and efficient run-time system that supports task synchronization and communication, and which could be certifiable to the highest integrity levels. The concurrency model promoted by the Ravenscar Profile is consistent with the use of tools that allow the static properties of programs to be verified. Potential verification techniques include information flow analysis, schedulability analysis, execution-order analysis and model checking. These techniques allow analysis of a system to be performed throughout its development life cycle, thus avoiding the common problem of finding only during system integration and testing that the design fails to meet its non-functional requirements. [AB04]

Concurrent programs require the use of different specification and verification techniques from sequential programs. For this reason, tasks, protected units and objects, and synchronization features are currently excluded from SPARK 2014²³ [AL14].

2.4.3 AUnit

Overview AUnit tutorials [Fal14] AUnit Cookbook [Ada14]

²³<http://docs.adacore.com/spark2014-docs/html/lrm/tasks-and-synchronization.html>

2.4.4 Sireum Bakar

Overview: symbolic execution, Pilar, Kiasan and Alir [Thi11]. Sireum Kiasan [BHR⁺11] is a tool, which use symbolic execution for finding possible paths in program. Plugin for GNAT Programming Studio (SPARK 2005 and 2014 under development). Plugin for Eclipse (only for SPARK 2005).

2.4.5 GNAT Prove

GNATprove²⁴ is a formal verification tool for SPARK 2014 programs. It interprets SPARK Ada annotations exactly like they are interpreted at run time during tests.

2.5 AADL/BLESS to SPARK Ada code generation

The ultimate goal of long term research, this thesis is part of, is AADL (with BLESS) to SPARK Ada translation.

2.5.1 Ocarina

Ocarina [LZPH09, LZPH09] generates code from an AADL architecture model to an Ada application running on top of PolyORB framework. In this context, PolyORB acts as both the distribution middleware and execution runtime on all targets supported by PolyORB. It generate Ada 2005 and C code. Since mid-2009, Telecom ParisTech is no longer involved in Ocarina, and is developing another AADL tool-chain, based on Eclipse, codenamed RAM-SES [Hug13].

examples on github

run: `ocarina -x scenario.aadl`

²⁴<http://www.open-do.org/projects/hi-lite/gnatprove/>

2.5.2 Ramses

RAMSES is a model transformation framework dedicated to the refinement of AADL models. It contains code generation plug-in.

Chapter 3

PCA Pump

Description of PCA Pump, its functions, problems and how ICE can solve them. Requirements document [Lar14]. Requirements document overview [LHC13].

In this thesis, only the operation module is implemented.

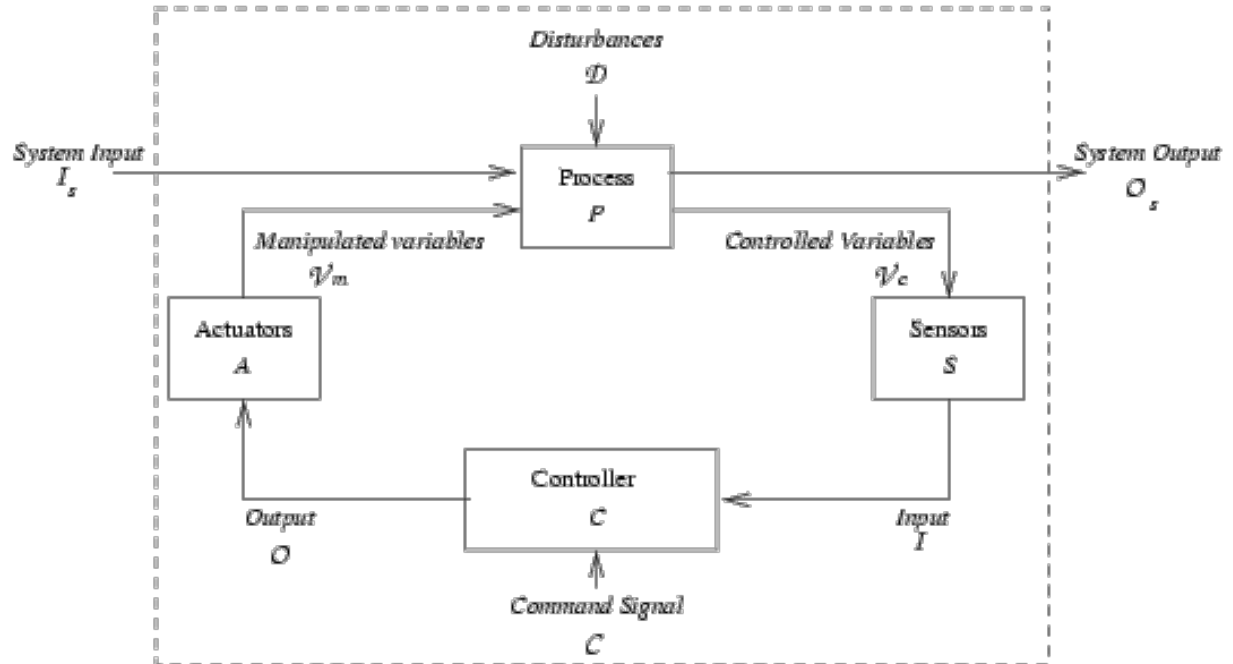


Figure 3.1: Basic Process Control Loop¹.

Pump internal implementation based on [Med10]. - basal dose deliver in increments - easier to track delivered amount (page 14)

3.1 PCA Pump Requirements Document

Selected use cases for implementation?

3.2 PCA Pump AADL/BLESS Models

Selected modules for implementation. Pictures etc.

3.3 BeagleBoard-XM

First step was create PCA Pump prototype on BeagleBoard-xM.

BeagleBoard-xM is Embedded device with AM37x 1GHz ARM processor (Cortex-A8 compatible). It has 512 MB RAM, 4 USB 2.0 ports, HDMI port, 28 General-purpose input/output (GPIO) ports and Linux Operating System (on microSD card). Moreover there is PWM support. All these properties makes this device good candidate for prototyping PCA Pump.

Pulse width modulation (PWM) is a technique for controlling analog circuits with a processor's digital outputs.

Expansion port 14(PWM) and 28(GND?) GPIO158 Java Program to Run the pump for 10 seconds

There is no existing SPARK Ada compiler running on ARM system. Hence, to compile SPARK Ada program for ARM device, we need to perform cross-compilation on other machine. There is GNAT compiler [Hor09] created by AdaCore, but there was no cross-

¹http://www.safeware-eng.com/system_and_software_safety_publications/Designing_Specification_Languages.htm

compiler for ARM. However AdaCore was working on it. They had working version in 2013, but tested only on their target, Android-based device. BeagleBoard-xM is coming with Linux Angstrom Operating System. There is possibility to install Android on BeagleBoard-xM, but still not warranty everything will be working. Cooperation with AdaCore allowed to cross-compile SPARK Ada program for BeagleBoard-xM.

Include source of simple program? GNAT cross-compiler only for Linux Platform (cross-compilation has to be done on Linux).

compilation+linking command: `arm-linux-gnueabi-gnatmake -d -Ppca_ravenscar.gpr.`

3.4 Interface for Integrated Clinical Environment

PCA Pump will be connected to ICE. It will allow to monitor and control device by MDCF (ICE implementation). Describe communication with MDCF/ICE. PCA Pump ports for that etc.

Chapter 4

AADL/BLESS to SPARK Ada translation

First step was to create mock (based on doc, aadl models and implemented PCA Pump). Prototyping Embedded Systems using AADL lasts for a few years [CB09].

4.1 AADL/BLESS to SPARK Ada mapping

Mapping is driven by "Architecture analysis & Design Language (AADL) V2 Programming Language Annex Document" [SCD14]. This document was discussed during AADL User Days in Valencia (February 2013)¹ and in Jacksonville, FL (April 2013)². Ocarina tool suite (based on older AADL annex documents [HZPK08]) and its examples³ was also helpful in understanding of AADL to Ada translation. Only high level mapping is done. No implementation (thread interactions) like Ocarina does.

¹http://www.aadl.info/aadl/downloads/committee/feb2013/presentations/13_02_04-AADL-Code%20Generation.pdf

²https://wiki.sei.cmu.edu/aadl/images/8/8a/Constraint_Annex_April22.v3.pdf

³<https://github.com/yoogx/polyorb-hi-ada/tree/master/examples/aadlv2>

4.1.1 Data types mapping

[TABLE WITH TYPES MAPPING - when types mapping will be done]

During AADL/BLESS to SPARK Ada types mapping, SPARK Examiner was helpful. It detected redundancy in enumerators. Both `Alarm_Type` and `Warning_Type` contained `No_Alarm` enumerators, which was a bug. `Warning_Type` should have `No_Warning` enumerator instead.

4.1.2 AADL ports mapping

Proposed ports mapping shown in table 4.1 is based on AADL runtime services from Annex 2 to "Programming Language Annex Document" [SCD14]. Additionally, the mapping contains SPARK 2005 contracts.

Table 4.1: AADL to SPARK ports mapping.

AADL/BLESS	SPARK Ada
<pre> Port_Name : in data port Port_Type; </pre>	<pre> -- spec (.ads): procedure Receive_Port_Name; --# global out Port_Name; -- body (.adb): Port_Name : Port_Type; procedure Receive_Port_Name is begin -- TODO: implement receiving Port_Name value -- e.g.: -- Port_Name := Some_Pkg.Get_Port_Name; null; end Receive_Port_Name; </pre>
Continued on next page	

Table 4.1 – continued from previous page

AADL/BLESS	SPARK Ada
<pre> Port_Name : out data port Port_Type; </pre>	<pre> -- spec (.ads) function Get_Port_Name return Port_Type; --# global in Port_Name; -- body (.adb): Port_Name : Port_Type; function Get_Port_Name return Port_Type is begin return Port_Name; end Get_Port_Name; </pre>
Continued on next page	

Table 4.1 – continued from previous page

AADL/BLESS	SPARK Ada
<pre>Port_Name : in event port;</pre>	<pre>-- spec (.ads) procedure Put_Port_Name; -- body (.adb): procedure Put_Port_Name is begin -- TODO: implement event handler null; end Put_Port_Name;</pre>
Continued on next page	

Table 4.1 – continued from previous page

AADL/BLESS	SPARK Ada
<pre>Port_Name : out event port;</pre>	<pre>-- spec (.ads) procedure Send_Port_Name; -- body (.adb): procedure Send_Port_Name is begin -- TODO: implement receiving Port_Name value -- e.g.: -- Some_Pkg.Put_Port_Name; null; end Send_Port_Name;</pre>
Continued on next page	

Table 4.1 – continued from previous page

AADL/BLESS	SPARK Ada
<pre> Port_Name : in event data port Port_Type; </pre>	<pre> -- spec (.ads) procedure Put_Port_Name(Port_Name_In : Port_Type); --# global out Port_Name; --# derives Port_Name from Port_Name_In; -- body (.adb): Port_Name : Port_Type; procedure Put_Port_Name (Port_Name_In : Port_Type) is begin Port_Name := Port_Name_In; end Put_Port_Name; </pre>
Continued on next page	

Table 4.1 – continued from previous page

AADL/BLESS	SPARK Ada
Port_Name : out event data port Port_Type;	<pre>-- spec (.ads) procedure Send_Port_Name; --# global in Port_Name; -- body (.adb): Port_Name : Port_Type; procedure Send_Port_Name is begin -- TODO: implement receiving Port_Name value -- e.g.: -- Some_Pkg.Put_Port_Name(Port_Name); null; end Send_Port_Name;</pre>

4.1.3 Thread to task mapping

Thread features are mapped into SPARK Ada tasks according to table 4.3. There is another proposition: map threads to subprograms (table 4.2) in case of single threaded programs. BOTH TABLES ARE INCOMPLETE!

AADL package, which contains threads is split into child packages with convention: AADL_Package_Name -> AADL_Package_Name.Thread_Name.

Table 4.2: *AADL threads to SPARK Ada subprograms(procedures/functions) mapping.*

AADL/BLESS	SPARK Ada
<pre> package Some_Pkg thread Some_Thread features Some_Port : out data port Port_Type; end Some_Thread; end Some_Pkg; </pre>	<pre> package Some_Pkg.Some_Thread is function Get_Some_Port return Port_Type; end Some_Pkg.Some_Thread; </pre>
<pre> package Some_Pkg thread Some_Thread features Some_Port : out data port Port_Type {Compute_Entrypoint_Source_Text => "Custom_Pkg.Custom_Subprogram";}; end Some_Thread; end Some_Pkg; </pre>	<pre> package Custom_Pkg is function Custom_Subprogram return Port_Type; end Custom_Pkg; </pre>

In SPARK Ada there are nested packages and child packages. Sample nested packages are shown in listing 4.1. Equivalent child packages are shown in listing 4.2. The name of a child package consists of the parent unit’s name followed by the child package’s identifier, separated by a period (dot) ‘.’. Calling convention is the same for child and nested packages (e.g. P.N in listings 4.1 and 4.2. However, there is a difference between nested packages and child packages. In nested package declarations become visible as they are introduced, in textual order. For example, in listing 4.1 spec N cannot refer to M in any way. In case of child packages, with certain exceptions, all the functionality of the parent is available to a child and parent can access all its child packages. More precisely: all public and private declarations of the parent package are visible to all child packages. Private child package can be accessed only from parent’s body.

```

package P is
  D: Integer;

```

Table 4.3: *AADL threads to SPARK Ada tasks mapping.*

AADL/BLESS	SPARK Ada
<pre> package Some_Pkg thread Some_Thread features Some_Port : out data port Port_Type; end Some_Thread; end Some_Pkg; </pre>	<pre> package Some_Pkg.Some_Thread is task type Some_Thread --# global out Some_Port; is pragma Priority(10); end Some_Thread; end Some_Pkg.Some_Thread; </pre>
<pre> package Some_Pkg thread Some_Thread.imp end Some_Thread; end Some_Pkg; </pre>	<pre> st : Some_Thread; package body Custom_Pkg is task body Some_Thread is begin null; end Some_Thread; end Custom_Pkg; </pre>

```

-- a nested package:

package N is
  X: Integer;

private
  Foo: Integer;
end N;

E: Integer;
private
  -- nested package in private section:
  package M is
    Y: Integer;

  private
    Bar: Integer;

```



```
    end M;  
  
end P;
```

Listing 4.1: *Nested packages in SPARK Ada*

```
package P is  
    D: Integer;  
    E: Integer;  
end P;  
  
-- a child package:  
package P.N is  
    X: Integer;  
    private  
        Foo: Integer;  
end P.N;  
  
-- a child private package:  
private package M is  
    Y: Integer;  
    private  
        Bar: Integer;  
end M;
```

Listing 4.2: *Child packages in SPARK Ada*

4.1.4 Subprograms mapping

I added Subprograms to existing PCA Pump AADL models (???) etc. How I did it. Code examples.

Table 4.4: *AADL subprograms to SPARK Ada subprograms(procedures/functions) mapping.*

AADL/BLESS	SPARK Ada
<pre>subprogram sp features e : in parameter T; s : out parameter T; end sp;</pre>	<pre>procedure sp(e : in T; s : out T) is begin null; end sp;</pre>
<pre>data Flow_Rate --dose rate properties BLESS::Typed=>"integer"; Data_Model::Base_Type => (classifier(Base_Types::Integer_16)); Data_Model::Measurement_Unit => "ml /hr"; end Flow_Rate;</pre>	<pre>subtype Flow_Rate is Integer range 0 .. Integer'Last;</pre>

4.1.5 Ports communication mapping

This is a problem: "consumer.ads:1:13: Semantic Error 135 - The package Producer is undeclared or not visible, or there is a circularity in the list of inherited packages."

4.1.6 BLESS mapping

Table 4.5: *BLESS to SPARK contractsmapping.*

AADL/BLESS	SPARK Ada
<pre>BLESS::Assertion=>"<<VP()>>"</pre>	<pre>--# pre VP; --# post VP;</pre>
<pre><<Pre()>>Action()<<Post()>></pre>	<pre>procedure Action; --# pre Pre; --# post Post;</pre>

4.2 "DeusEx" translator

AADL/BLESS to SPARK Ada translator in Scala. Main idea. Maybe at least create base: AADL to AST conversion? Maybe create only types conversion? Maybe create only types thread2tasks? No conversion of entire programs. Talk to Sam.

Chapter 5

PCA Pump Prototype Implementation

Currently SPARK 2014 does not support tasking [AL14]. For SPARK 2005, GNAT compiler provides Ravenscar Profile [Tea12]. It provides a subset of the tasking facilities of Ada95 and Ada 2005 suitable for the construction of high-integrity concurrent programs.

In real-world applications, the embedded critical components are written in SPARK while the non-critical components are written in Ada. Components written in Ada should be hidden for SPARK Examiner with `--# hide` annotation.

The biggest challenge during PCA Pump development was the SPARK limitations. There are many common libraries, which cannot be verified by SPARK tools. Thus it required to isolate some functionalities or implement them in different way. An example might be reading and writing numbers to standard input.

5.1 Concurrency in SPARK Ada

Based on AADL models, PCA Pump has to be multitasking device. Thus, concurrency features are needed. In SPARK 2005, concurrency is enable with Ravenscar profile [Tea12]. For now, concurrency is not allowed in SPARK 2014.

Ravenscar does not allow dynamic task creation. Thus, all tasks have to exists for the

full lifetime of the program. [AW01]

There are two ways to access protected variable in task body:

- It has to be protected object
- It has to be atomic type

Protected variables may not be used in proof contexts. Thus, if we try to use protected variable in proofs (pre- or postcondition), then SPARK Examiner returns **Semantic Error 940 - Variable is a protected own variable**. To preserve opportunity to use pre- and postconditions, atomic types have to be used.

5.2 Code generation from AADL models

Skeleton code generated from AADL models. Then implemented.

Show generated code.

5.3 Implementation for generated code

Overview of issues solved: * Bolus options: FBasal + FPatient or FPatient => implemented: FBasal + FPatient (consistent in doc) 5 modes: * Stopped: F=0 * KVO: F=0.1 * Basal: F=FBasal * Patient: F = FBasal + Fbolus (for vtbi/Fbolus) * Clinician: F = Fbasal + Fbolus (for specified time)

Most common Examiner[Tea11] erroes/warnings: *** Warning :302: This expression may be *** Semantic Error :725: Protected function or variable XXX may only appear directly in an assignment or return statement.

Discuss implementation of basal infusion: 0.1 ml pulses timed according to the desired rate. (based on CADD-Prizm page 14). Easier bolus monitoring/calculations. Possibility to separate pulse from engine logic. Just array with time stamps(?) or array with size

= (60 * 60 / min_possible_time_between_activations) and set 1 if activation occurred. In every second, update array: array[i]=array[i+1]. Array is protected object, so bolus thread cannot access it in the same time, when update thread. Another option: constant speed of engine and speed-up on boluses. Harder bolus monitoring/calculations?

Internal calculations are in micro liters 1 micro liters (μl) = 0.001 ml thus 1 ml = 1000 μl .

Chapter 6

Verification

Verification

6.1 SPARK Examiner

The Examiner supports several levels of analysis. The Examiner supports:

- checking of SPARK language syntactic and static semantic rules
- data flow analysis
- data and information flow analysis
- formal program verification via generation of verification conditions
- proof of absence of run-time errors
- dead path analysis

There is also an option to make the Examiner perform syntax checks only. Using this option on a source file does not require access to any other units on which the file depends, so files can be syntax checked on an individual basis. This allows any syntax errors to be

corrected before the file is included in a complex examination. This option must only be used as a pre-processor: the absence of syntax errors does NOT indicate that the source text is a legal SPARK program. [Tea11] (THIS PART IS COPY AND PASTE FROM Examiner doc - is it ok?)

During implementation, code was regularly checked using SPARK Examiner.

What is very important, Examiner can perform data and information analysis of Ravenscar programs in exactly the same manner as for sequential programs [Tea12]. Unfortunately it does not allow protected objects in proof annotations (pre- and post-conditions).

6.2 AUnit tests

- test incrementing array - test moving array - test prescription setters and getters - test state machine * change to bolus mode * change to KVO rate * etc.

6.3 gnatPROVE?

There is a new tool set "gnatPROVE" for SPARK 2014. It was not used because PCA Pump was developed in SPARK 2005. I CAN TRANSLATE SOME SINGLE FUNCTIONS AND USE GNAT PROVE TO VERIFY?

Chapter 7

Summary

What I have done.

The work is done for SPARK 2005. SPARK 2014 (especially taking) and its tools (such as gnatPROVE) were not ready at the time, when this thesis was written.

Issues:

- not many online resources - no access to industry code - everything (AADL, SPARK2014, BLESS, tools) is under development - hard to create running application - need to rely on some resources, which are not necessarily up to date

Chapter 8

Future work

What has to be done now.

- translation of BLESS state machine

- The semantics of BLESS contain notions of time that make translation to SPARK difficult.

Bibliography

- [AB04] Tullio Vardanega Alan Burns, Brian Dobbing. Guide for the use of the ada ravenstar profile in high integrity systems. *ACM SIGAda Ada Letters*, 24(2):1–74, Juin 2004.
- [Ada14] AdaCore. Aunit cookbook. URL: <http://docs.adacore.com/aunit-docs/aunit.html>, Mars 2014.
- [AL14] AdaCore and Altran UK Ltd. Spark 2014 reference manual. URL: <http://docs.adacore.com/spark2014-docs/html/lrm>, 2011-2014.
- [AW01] Neil Audsley and Andy Wellings. Issues with using ravenstar and the ada distributed systems annex for high-integrity systems. In *IRTAW '00 Proceedings of the 10th international workshop on Real-time Ada workshop*, pages 33 – 39. ACM New York, NY, USA, 2001.
- [Bar13] John Barnes. *SPARK - The Proven Approach to High Integrity Software*. Altran, 2013.
- [BHR⁺11] Jason Belt, John Hatcliff, Robby, Patrice Chalin, David Hardin, and Xianghua Deng. Bakar kiasan: Flexibe contract checking for critical systems using symbolic execution. In *NASA Formal Methods*, pages 58–72. Springer Berlin Heidelberg, 2011.
- [CB09] Mohamed Yassin Chkouri and Marius Bozga. Prototyping of distributed embedded systems using aadl. In *ACESMB 2009, Second International Workshop on Model Based Architecting and Construction of Embedded Systems*, pages 65–79. Springer Berlin Heidelberg, 2009.

- [Cha00] Roderick Chapman. Industrial experience with spark. *ACM SIGAda Ada Letters* - special issue on presentations from SIGAda 2000, XX(4):64–68, Décembre 2000.
- [DEL⁺14] Claire Dross, Pavlos Efstathopoulos, David Lesens, David Mentre, and Yannick Moy. Rail, space security: Three case studies for spark 2014. In *ERTS 2014: Embedded Real Time Software and Systems*, 2014.
- [Fal14] Ed Falis. Aunit tutorials. URL: <http://libre.adacore.com/tools/aunit>, Mars 2014.
- [FG13] Peter H. Feiler and David P. Gluch. *Model-Based Engineering with AADL*. Addison-Wesley, 2013.
- [Hor09] Bartłomiej Horn. Ada’05 compiler for arm based systems. thesis, Technical University of Lodz, Poland, 2009.
- [Hug13] Jérôme Hugues. About ocarina. URL: <http://www.openaadl.org/ocarina.html>, 2013.
- [HZPK08] Jérôme Hugues, Bechir Zalila, Laurent Pautet, and Fabrice Kordon. From the prototype to the final embedded system using the ocarina aadl tool suite. *ACM Transactions on Embedded Computing Systems*, 7(4):237–250, Juillet 2008.
- [IEC⁺06] Andrew Ireland, Bill J. Ellis, Andrew Cook, Roderick Chapman, and Janet Barnes. An integrated approach to high integrity software verification. *Journal of Automated Reasoning*, 36(4):379–410, Avril 2006.
- [Lar14] Brian R. Larson. Integrated clinical environment patient-controlled analgesia infusion pump system requirements draft 0.10.1, Février 2014.
- [LCH13] Brian R. Larson, Patrice Chalin, and John Hatcliff. Bless: Formal specification and verification of behaviors for embedded systems with software. In *NASA Formal Methods*, pages 276–290. Springer Berlin Heidelberg, 2013.

- [LHC13] Brian R. Larson, John Hatchiff, and Patrice Chalin. Open source patient-controlled analgesic pump requirements documentation. In *Software Engineering in Health Care (SEHC), 2013 5th International Workshop*, pages 28–34. Institute of Electrical and Electronics Engineers (IEEE), 2013.
- [LZPH09] Gilles Lasnier, Bechir Zalila, Laurent Pautet, and Jérôme Hugues. Ocarina : An environment for aadl models analysis and automatic code generation for high integrity applications. In *Reliable Software Technologies – Ada-Europe 2009*, pages 237–250. Springer Berlin Heidelberg, 2009.
- [Med10] Smiths Medical. Cadd-prizm ambulatory infusion pump model 6100 and model 6101 - technical manual. URL: http://www.smiths-medical.com/upload/products/pdf/cadd_prizm_vip_system/in19824.pdf, Novembre 2010.
- [SCD14] SAE AS-2C Architecture Description Language Subcommittee, Embedded Computing Systems Committee, and Aerospace Avionics Systems Division. Aerospace standard - architecture analysis & design language (aadl) v2 programming language annex document draft 0.9, Avril 2014.
- [Tea11] SPARK Team. Spark examiner user manual. URL: http://docs.adacore.com/sparkdocs-docs/Examiner_UM.htm, Décembre 2011.
- [Tea12] SPARK Team. The spark ravenscar profile. URL: http://docs.adacore.com/sparkdocs-docs/Examiner_Ravenscar.htm, 2012.
- [Thi11] Hariharan Thiagarajan. Dependence analysis for inferring information flow properties in spark ada programs. thesis, Kansas State University, 2011.

Appendix A

PCA Pump Prototype - simple, working example

Content of this appendix.

Appendix B

PCA Pump Prototype - translated from AADL/BLESS