

A MODEL-DRIVEN DEVELOPMENT AND VERIFICATION APPROACH  
FOR MEDICAL DEVICES

by

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# Abstract

Medical devices are safety-critical systems whose failure may put human life in danger. They are becoming more advanced and thus more complex. This leads to bigger and more complicated code-bases that are hard to maintain and verify. Model-driven development provides high-level and abstract description of the system in the form of models that omit details, which are not relevant during the design phase. This allows for certain types of verification and hazard analysis to be performed on the models. These models can then be translated into code. However, errors that do not exist in the models may be introduced during the implementation phase. Automated translation from verified models to code may prevent to some extent.

This thesis proposes approach for model-driven development and verification of medical devices. Models are created in AADL (Architecture Analysis & Design Language), a language for software and hardware architecture modeling. AADL models are translated to SPARK Ada, contract-based programming language, which is suitable for software verification. Generated code base is further extended by developers to implement internals of specific devices. Created programs can be verified using SPARK tools.

A PCA (Patient Controlled Analgesia) pump medical device is used to illustrate the primary artifacts and process steps. The foundation for this work is "Integrated Clinical Environment Patient-Controlled Analgesia Infusion Pump System Requirements" document and AADL Models created by Brian Larson. In addition to proposed model-driven development approach, a PCA pump prototype was created using the BeagleBoard-xM device as a platform. Some components of PCA pump prototype were verified by SPARK tools and Bakar Kiasan.

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*"Showing gratitude is one of the simplest yet most powerful things humans can do for each other."*

— Randy Pausch, *Last Lecture*

Say thank you to: Andrew Rys, John Hatcliff, Robby, Jason, Brian, Eugene, Venkatesh.

# Dedication

*For my family, mentors, friends and all people  
who inspired me directly or indirectly  
in things I do.*

# Chapter 1

## Introduction

Software is present in all aspects of our lives, from the simple program in alarm clocks to iPads, through cars, refrigerators and computers. Furthermore, our lives are getting more and more dependent on software. Usually when we think about software, we think about applications for PC or smart phone, e.g. calculator, word processor or stock market application. In this case, rapid development and smooth operation is a key. However, there is also another, very important class of software: safety-critical systems. This class comprised of software for airplanes, medical devices, satellites, and rockets. Safety-critical systems are usually real-time - their correctness depends not only on logic, but also upon the time constraints (hard and soft deadlines in which operations has to be accomplished).

Software Engineering for real-time safety-critical systems is very different than creating business applications. In both types of software we want to ensure correctness and security. However, in each of them, to a different extent. In the case of the aforementioned word processor, software assurance is not critical. When it crashes, it can be restarted. In worst case scenario, some work might be lost. Airplane software errors may put human lives in danger or even cause death. Thus for safety-critical systems, the security and correctness are crucial. Behind these reasons, different software design methodology, different properties of programming languages and verification tools are needed.

Part of safety-critical systems design and development is their verification. The goal of software verification is to assure that software satisfies requirements. Furthermore, during verification process some potential issues might be detected by discovering possible program states and execution paths.

## 1.1 Motivation

Nowadays, medical devices work rather independently. This leads to many accidents, which could have been avoided by their interoperability. For example, over-dose of a drug (e.g. morphine) delivered by the patient-controlled analgesia (PCA) pump after surgery can lead to low blood oxygenation or even lack of pulse [OG11]. That can lead to patient's death. The PCA pump does not monitor an oxygen level, but oxygen monitoring device does. If these two devices are organized in centralized system, which implements safety interlock mechanism to shutdown the pump when low blood oxygenation<sup>1</sup> is detected, accident can be avoided.

In order to communicate, devices have to use compatible interfaces and protocols. There is a concept of "Integrated Clinical Environment" (ICE). It is captured in the standard ASTM F2761, which describes a functional architecture for inter operable systems [HKL<sup>+</sup>12]. The "Laboratory for Specification, Analysis, and Transformation of Software" (SAnToS Laboratory) created "Medical Device Coordination Framework" (MDCF) [HKL<sup>+</sup>12], which is prototype implementation of ICE. The MDCF vision for ICE is to have requirements documents and conforming software and hardware models. This will enable different medical devices, created by different vendors, to be connected and work under supervision of a centralized system.

In last decades, model-driven development [SVC06] became standard for safety critical systems design. It provides higher level of abstraction, which enables to focus on business

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<sup>1</sup>Blood oxygenation is also referred as  $SpO_2$

problems instead of technology. Models captures domain knowledge and systems analysis, disregarding implementation details, is possible. Additionally, software validation and verification can be executed at design-time. The model-driven development approach proposed in this thesis is a response for the need to create code from models. The PCA pump prototype created in this thesis is as an example of a medical device, which ultimately will work under MDCF.

## 1.2 Technologies

AADL (Architecture Analysis & Design Language) [FG13] is a modeling language for representing hardware and software. It is used for real-time, safety critical and embedded systems [FWH]. AADL allows for the description of both software and hardware parts of a system. It is used to describe architecture, but AADL allows to add behavioral extensions through annex languages. BLESS (Behavior Language for Embedded Systems with Software) [LCH13] is an AADL annex sub language defining behavior of components. The goal of BLESS is to automatically check the correctness of AADL models.

Ada is one of the most popular programming languages (along with C/C++) targeted at embedded and real-time systems. SPARK Ada [Bar13] is a subset of Ada, designed for the development of safety and security critical systems. This subset is designed to facilitate static analysis and program verification, which allows to reason about and prove correctness of programs and their entities. There are also SPARK tools for software verification, including tools provided by Altran UK and AdaCore (the developers of SPARK) as well as research groups such as SAnToS Laboratory at Kansas State University.

## 1.3 Contribution

This thesis demonstrates mapping of AADL/BLESS models to code in SPARK Ada. Additionally it presents current possibilities and limitations of SPARK Ada language, Ravenscar



profile and SPARK verification tools. The main contributions of this thesis are as follows:

- Review of "Open Patient-Controlled Analgesia Infusion Pump System Requirements" [LH14, LHC13].
- Identification and analysis of PCA pump and Infusion pumps properties and internals required for implementation.
- Cross-compilation and testing of SPARK Ada 2005 and 2014 programs on BeagleBoard-xM platform.
- Implementation of PCA pump based on [LH14] and AADL/BLESS models.
- AADL/BLESS to SPARK Ada translation schemes.
- Translation of simplified PCA Pump models (based on created translation schemes).
- Design requirements for AADL/BLESS to SPARK Ada translator.
- Practical demonstration of SPARK 2005 and SPARK 2014 verification tools: its capabilities and limitations:
  - SPARK Examiner
  - SPARKSimp
  - Proof Obligation Summarizer (POGS)
  - Bakar Kiasan
  - GNATprove

## 1.4 Organization

This thesis is organized as follows:

- Chapter 2 is background that gives details about ICE, MDCF, Model-Driven Development, AADL, BLESS, SPARK Ada and its verification tools.
- Chapter 3 describes Patient-Controlled Analgesia (PCA) pump.
- Chapter 4 presents mappings from AADL/BLESS to SPARK Ada.
- Chapter 5 describes the implementation of PCA Pump Prototype. Faced issues and design decisions made.
- Chapter 6 describes verification of implemented PCA Pump Prototype and code translated from simplified version of AADL models.
- Chapter 7 summarizes all work which has been done in this thesis.
- Chapter 8 is the future work that can be done in this topic.

# Chapter 2

## Background

This chapter is a brief introduction of all technologies and tools used in this thesis. They are: AADL modeling language, BLESS (AADL annex language), SPARK Ada programming language and its verification tools. There is also an overview of the context in which this work has been done: Integrated Clinical Environment (ICE) standard 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

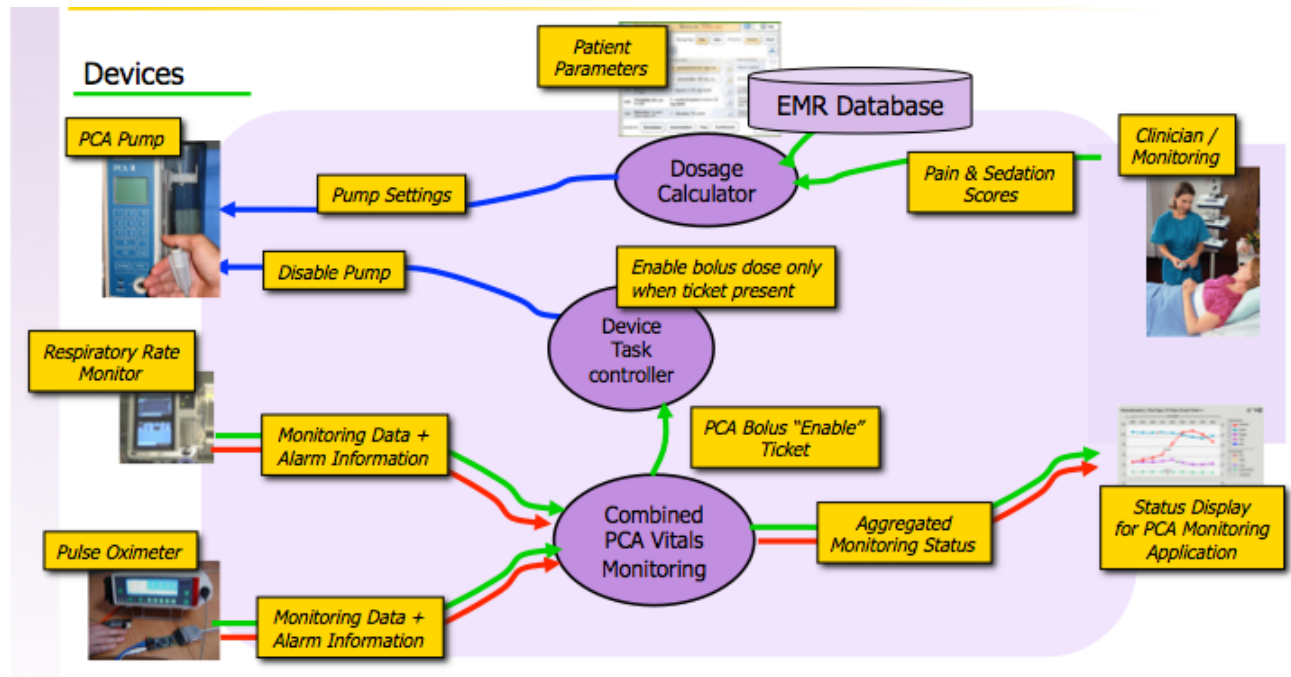
The concept of the "Integrated Clinical Environment" (ICE) was initiated and championed by Dr. Julian Goldman from Center for Integration of Medicine & Innovative Technology.<sup>1</sup> The main idea is to create a platform for integrating medical devices in a local area network. ICE will enable clinicians and software system to make decisions based not only on output from one device, but from different devices working together in network. Moreover, ICE comprises components that may be implemented by different vendors. Such components are medical devices and applications to supervise them. The purpose of ICE is to solve current

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<sup>1</sup><http://www.cimit.org/>

issues with medical devices, which usually operate independently and requires more human attention and control through checking output of every device manually and then making decisions. ICE propose a concept of Medical Application Platform [HKL<sup>+</sup>12] that assure medical devices interoperability and provides execution environment for clinical applications. Different devices can exchange data and centralized system can make decisions (based on this data) automatically. For example when PCA pump infuse some drug to patient's vein and Pulse Oximeter detects low oxygen level, ICE can coordinate PCA pump shutdown.

Figure 2.1 presents high-level overview of one particular application of an ICE system. Medical devices (PCA Pump, Respiratory Rate Monitor and Pulse Oximeter) are connected to the system, which monitors or controls them. There is communication between devices and ICE in order to exchange data. ICE can make decisions (such as PCA Pump shutdown) based on them.



**Figure 2.1:** ICE Closed Loop Control

## 2.2 Medical Device Coordination Framework

Medical Device Coordination Framework (MDCF) [HKL<sup>+</sup>12], jointly developed by SAnToS Laboratory (Kansas State University) and University of Pennsylvania is prototype implementation of ICE. It is an open, experimental platform to bring together academic researchers, industry vendors, and government regulators. This project is a response to a request from Food and Drug Administration (FDA) to build a prototype of ICE. There is a vision of different medical devices, created by different vendors, connected and working under centralized system. MDCF is designed to illustrate by example issues related to functional concepts, safety, security, verification and certification.

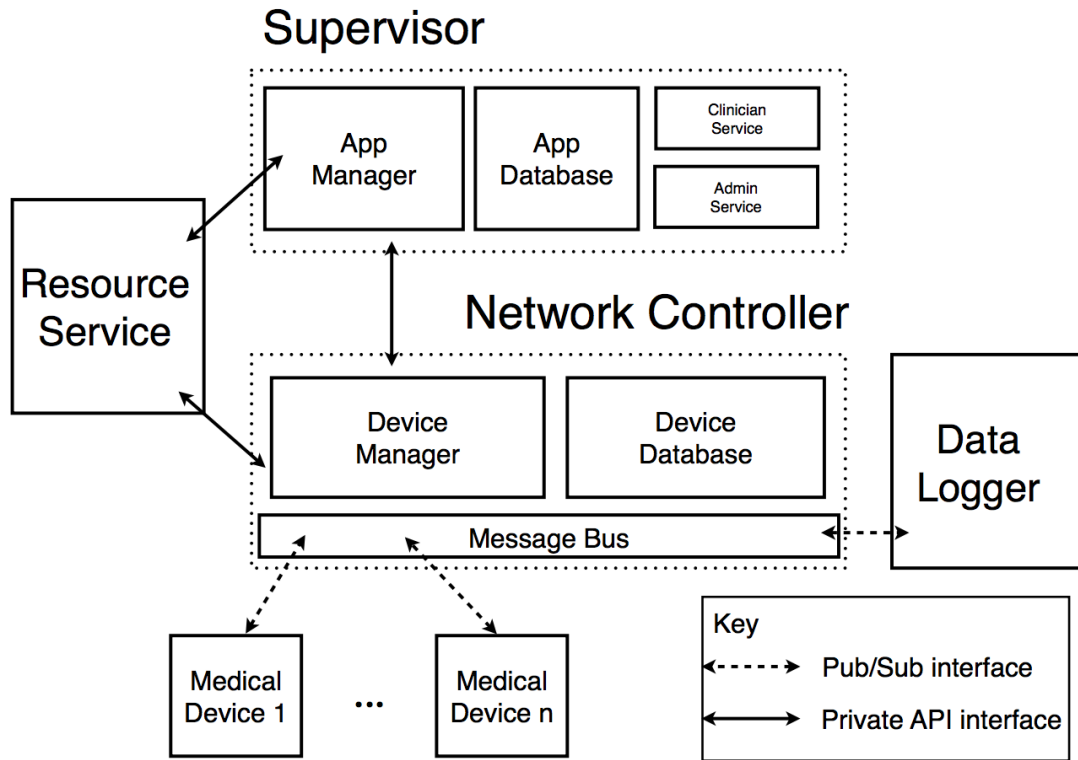
The following comprise the goals of the MDCF project:

- Open source infrastructure
- Meet performance requirements of realistic clinical scenarios
- Provide middleware with reliability, real-time, security
- Provide an effective app programming model and development environment with integrated verification/validation support and construction of regulatory artifacts
- Support evaluation of device interfacing concepts
- Illustrate how to support real and mock devices
- Illustrate envisioned regulatory oversight and 3rd party certification

Currently, MDCF use only mock devices, which are Java desktop applications. PCA Pump Prototype, developed in this thesis, aims to be the realistic hardware device targeted specifically for the MDCF.

MDCF uses a publish-subscribe architecture for communication between components: apps and devices. Figure 2.2 presents MDCF structure. Devices, such as PCA pump, are

connected to Message Bus, which along with Device Manager and Device Database ensures communication with Application Manager [HKL<sup>+</sup>12].



**Figure 2.2:** MDCF architecture and example app virtual machine (lower right)

## 2.3 AADL

AADL stands for Architecture Analysis & Design Language. It is used to model embedded and real-time systems. AADL allows for description of both software and hardware parts of a system. It can be used not only for design phase of software development process, but also for analysis, verification, and code generation.

AADL has its roots in DARPA<sup>2</sup> funded research. The first version (1.0) was approved in

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<sup>2</sup><http://www.darpa.mil>

2004 under technical leadership of Peter Feiler.<sup>3</sup> AADL is develop by SAE AADL standard committee.<sup>4</sup> AADL version 2.0 was published in January 2009. The most recent version (2.1) was published in September 2012.<sup>5</sup>

AADL is a language for Model-Based Engineering [FG13]. It can be represented in textual and graphical form. There are tools, like plug-in for OSATE (see Section 2.3.1) that enable transformation of textual representation into graphical or XML.

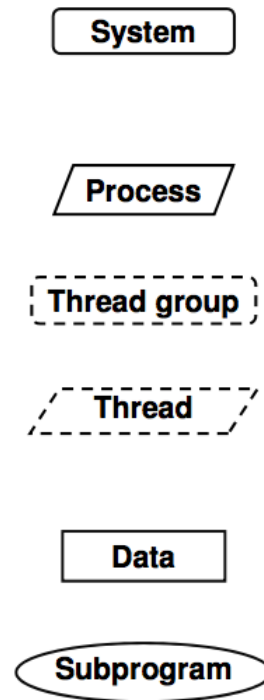
AADL contains entities for modeling software and hardware components, and allows to create interactions and dependencies between them.

AADL Execution Platform Components and Devices:

- Processor / Virtual Processor - Provides thread scheduling and execution services
- Memory - provides storage for data and source code
- Bus / Virtual Bus - provides physical/logical connectivity between execution platform components
- Device - interface to external environment

Application Software Components of AADL (Figure 2.3):

- System - hierarchical organization of components
- Process - protected address space
- Thread group - logical organization of threads
- Thread - a schedulable unit of concurrent execution
- Data - potentially sharable data
- Subprogram - callable unit of sequential code

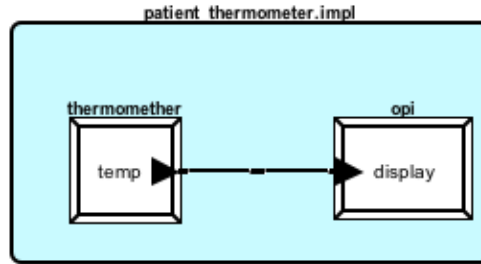


**Figure 2.3:** AADL Application Software Components

<sup>3</sup>[http://wiki.sei.cmu.edu/aadl/index.php/The\\_Story\\_of\\_AADL/](http://wiki.sei.cmu.edu/aadl/index.php/The_Story_of_AADL/)

<sup>4</sup>[https://wiki.sei.cmu.edu/aadl/index.php/Main\\_Page](https://wiki.sei.cmu.edu/aadl/index.php/Main_Page)

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



**Figure 2.4:** AADL model of simple thermometer

An example AADL model is shown in graphical representation, in the Figure 2.4. Its textual representation is presented in the Figure 2.5.

```
package Thermometer
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;
```

**Figure 2.5:** AADL model of simple thermometer

There are several tools for AADL model support, such as: OSATE (see Section 2.3.1), STOOD (AADL design tool),<sup>6</sup> ADELE (graphical editor),<sup>7</sup> Cheddar (real time scheduling

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

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



tool),<sup>8</sup> AADLInspector (model processing framework),<sup>9</sup> or Ocarina (see Section 2.7.1).

AADL focuses on architectural modeling, but it can be extended via the following methods:

- user-defined properties: user can extend the set of applicable properties and add their own to specify their own requirements
- language annexes (the core language is enhanced by annex languages that enrich the architecture description. For now, the following annexes have been defined):
  - Behavior annex: add components behavior with state machines (e.g. BLESS, see Section 2.4)
  - Error-model annex: specifies fault and propagation concerns
  - ARINC653 annex: defines modeling patterns for modeling avionics systems
  - Data-Model annex: describes the modeling of specific data types and structures with AADL

More details about AADL can be found in Peter Feiler's book "Model-Based Engineering with AADL" [FG13].

AADL is used as a modeling language in this thesis.

### 2.3.1 OSATE

Open Source AADL Tool Environment (OSATE) is a set of plug-ins on top of the Eclipse platform. It provides a tool set for front-end processing of AADL models. OSATE is developed mainly by SEI (Software Engineering Institute - Carnegie Mellon University).<sup>10</sup> The latest available version of OSATE at the time when this thesis was published is OSATE2.<sup>11</sup>

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

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

<sup>10</sup><http://www.aadl.info/aadl/currentsite/tool/osate.html>

<sup>11</sup>[https://wiki.sei.cmu.edu/aadl/index.php/Osate\\_2](https://wiki.sei.cmu.edu/aadl/index.php/Osate_2)

OSATE relies on EMF,<sup>12</sup> UML2 and Xtext.<sup>13</sup> It comprises, e.g., an AADL project wizard, AADL Navigator, and AADL syntax analyzer. OSATE enables the conversion of AADL in textual representation into its standardized graphical representation. There are also plug-ins for OSATE, such as the BLESS<sup>14</sup> and OCARINA<sup>15</sup> plug-ins.

OSATE has been used to develop AADL models for this thesis and work with already existing models.

## 2.4 BLESS

BLESS (Behavior Language for Embedded Systems with Software) is AADL annex sub-language defining behavior of components for AADL [LCH13]. BLESS comes with a verification framework that enables a developer to build proofs of AADL models of embedded electronic systems with software.

BLESS annex subclauses can be added to AADL models transparently without interfering with other uses of AADL. It includes a verification-condition (VC) generation framework and an accompanying proof tool that enables engineers to prove VCs via proof scripts build from system axioms and rules from a user-customizable rule library [LCH13].

BLESS contains three AADL annex sub-languages:

- Assertion - assertions 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

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<sup>12</sup><http://www.eclipse.org/modeling/emf/>

<sup>13</sup><http://www.eclipse.org/Xtext/>

<sup>14</sup><http://bless.santoslab.org/node/5>

<sup>15</sup><http://libre.adacore.com/tools/ocarina/>

The BLESS tool framework is implemented as a publicly available open source plug-in for OSATE (mentioned in Section 2.3.1). It includes an editor for BLESS specifications and an environment operating the BLESS proof engine [LCH13].

In the work for this thesis, subset of BLESS is translated into SPARK contracts and assertions. Detailed overview of supported features can be found in Section 4.1.8.

## 2.5 SPARK Ada

The Ada programming language was originally designed to meet the US Department of Defense Requirements for programming military applications. Since its first version (Ada 83) it has evolved through multiple versions: Ada 95, Ada 2005 and Ada 2012 (released in December 10, 2012).<sup>16</sup> Ada is actively used in many real-world projects in critical application domains,<sup>17</sup> e.g. Aviation (Boeing<sup>18</sup>), Railway Transportation, Commercial Rockets, Satellites and even Banking. One of the main goals of Ada is to ensure software correctness and safety. Ada includes features that eliminate common errors involving pointers, array bounds violations and unprincipled control flow, in comparison to other programming languages (see Figure 2.6). This is achieved not only by language capabilities, but also by tools for testing and verification.

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 amenable to state analysis and formal methods, by collection of analysis and verification tools. Some Ada constructs are excluded from SPARK to make static analysis feasible [IEC<sup>+</sup>06]. SPARK 2005 does not include constructs such as pointers, dynamic memory allocation or recursion [IEC<sup>+</sup>06]. Verification tools (see Section 2.6) produce Verification

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<sup>16</sup><http://www.ada2012.org>

<sup>17</sup><http://www.seas.gwu.edu/~mfeldman/ada-project-summary.html>

<sup>18</sup><http://archive.adaic.com/projects/atwork/boeing.html>

Conditions (VCs) to check program correctness. Sample Verification Condition contains checks for:

- array index out of range
- type range violation
- division by zero
- numerical overflow



Copyright © 2012 AdaCore

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**Figure 2.6:** Developer responsibility in Ada.<sup>19</sup>

SPARK is used not only for research, but also in industry: aerospace (e.g., EuroFighter Typhoon aircraft,<sup>20</sup> The Lockheed Martin C130J<sup>21</sup> and standard DO-178B<sup>22</sup>), security (e.g.,

<sup>19</sup><http://www.slideshare.net/AdaCore/ada-2012>

<sup>20</sup><http://www.eurofighter.com/>

<sup>21</sup><http://www.lockheedmartin.com/us/products/c130/c-130j-variants/c-130j-30.html>

<sup>22</sup><http://www.adacore.com/gnatpro-safety-critical/avionics/do178b/>

MULTi-application Operating System<sup>23</sup>), air traffic management (e.g., iFACTS system<sup>24</sup>) [Bar13]. In practice, because the features of SPARK are limited and because the use of SPARK can be labor intensive, the embedded critical components are written in SPARK while the non-critical components are written in Ada [Cha00].

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 `--#`). This approach allows every SPARK 2005 program to be a valid Ada 2005 program. SPARK annotations contains code contracts (see Table 2.1), which are analyzed by verification tools, but ignored by Ada compiler.

```

procedure Increment (X : in out Integer);
--# derives X from X;
--# pre X < Integer'Last;
--# post X = X~ + 1;

```

**Figure 2.7:** Sample SPARK procedure with code contracts

Figure 2.7 presents simple procedure with code contracts. It increments variable given as parameter by 1. The `derives` clause specify variable dependency. Its future value depends on its current value. There is precondition saying that the value has to be lower than maximum value of `Integer` type, to avoid overflow. There is also post condition, which states that the value of variable (given as parameter) after the procedure execution has to be equal to its previous value incremented by 1 (`'~` attached to variable means value of this variable, before procedure execution).

SPARK 2014<sup>25</sup> (based on Ada 2012) is under development. There is partial tool support (in GNAT Programming Studio), but some language features (such as tasking) are still not

<sup>23</sup><http://www.cardwerk.com/smartcards/MULTOS/>

<sup>24</sup><http://www.adacore.com/customers/uks-next-generation-atc-system/>

<sup>25</sup><http://www.spark-2014.org>

supported. Ada 2012 contains code contracts, which was inspired by previous versions of SPARK. Thus SPARK 2014 is just a subset of Ada 2012 [DEL<sup>+</sup>14]. Some of Ada 2012 features are not allowed in SPARK, e.g.:

- Access types (pointers)
- Exceptions
- Aliasing between variables
- The goto statement
- 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

Table 2.1 presents fundamental SPARK 2005 annotations and their equivalents in SPARK 2014 (Ada 2012).

**Table 2.1:** Fundamental SPARK annotations

SPARK 2005	SPARK 2014	Description
<code>--# global</code>	Global	list of used global variables within subprogram
<code>--# derives</code>	Depends	describe dependencies between variables
<code>--# own</code>	Abstract_State	declare variables defined in package body
<code>--# initializes</code>	initializes	indicates variables, which are initialized
Continued on next page		

Table 2.1 – continued from previous page

SPARK 2005	SPARK 2014	Description
<code>--# inherit</code>	not needed	allows to access entities of other packages
<code>--# pre</code>	Pre	pre condition
<code>--# post</code>	Post	post condition
<code>--# assert</code>	Assert	assertion

A sample mapping from SPARK 2005 to 2014 is shown in the Table 2.2. A complete mapping can be found in SPARK 2014 documentation<sup>26</sup> [AL14a].

The previous example (Figure 2.7), translated to SPARK 2014 syntax, is presented in the Figure 2.8.

```

procedure Increment (X : in out Integer)
with Depends => (X => X),
    Pre => (X < Integer'Last),
    Post => (X = X'Old + 1);

```

Figure 2.8: Sample SPARK 2014 procedure and Code Contracts

It is possible to mix SPARK 2014 with Ada 2012. However, only the part which is SPARK 2014 compliant can be verified by SPARK 2014 tools. SPARK 2014 does not contains Examiner like SPARK 2005. Instead, proofs are made by GNATprove (see Section 6.5).

<sup>26</sup><http://docs.adacore.com/spark2014-docs/html/lrm/mapping-spec.html>

**Table 2.2:** Sample SPARK 2005 to 2014 mapping.

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

The most popular IDE for SPARK Ada is GNAT Programming Studio<sup>27</sup> (see Section 2.5.2). There is also Ada plug-in for Eclipse - GNATbench<sup>28</sup> created by AdaCore.

SPARK Ada is target language for code generation from AADL/BLESS models in this thesis.

### 2.5.1 GNAT Compiler

The GNAT compiler is an Ada compiler created by AdaCore<sup>29</sup>. It is part of GNU Compiler Collection (GCC). The GNU Compiler Collection includes front ends for C, C++, Objective-C, Fortran, Java, Ada, and Go. It is one of the most popular compiler systems and is included in all Linux distributions. GCC is open source, published on GNU General Public License. GCC is divided into a front end and a back end. This architecture enables compiler developers to create new front ends for some language and reuse existing back ends (or vice versa).

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<sup>27</sup><http://libre.adacore.com/tools/gps>

<sup>28</sup><https://www.adacore.com/gnatpro/toolsuite/gnatbench/>

<sup>29</sup><http://www.adacore.com>



GNAT supports Ada 2012, Ada 2005, Ada 95 and Ada 83. The front-end and run-time are written in Ada. To make compilation easier, GNAT provides `gnatmake` tool. It takes as an argument project file (`.gpr`) or main program file (file, which contains main procedure) and builds entire program automatically. `gnatmake` invokes GCC to perform the actual compilation. It check all dependencies contained in `.ali` files. Each invocation of GCC produces object files (`.o`) and Ada Library Information files (`.ali`). Once compilation is done, `gnatmake` invokes `gnatbind` tool to check consistency and generate a main program. Then `gnatlink` performs linking using binding output and all object files.

GNAT compiler is available for all most popular platforms: Windows, Linux and MacOS. AdaCore, released also GNAT cross-compiler for ARM devices. Currently, cross-compilation can only be performed on a 32-bit Linux platform.

GNAT compiler and GNAT cross-compiler has been used to compile SPARK Ada programs created for this thesis.

## 2.5.2 GNAT Programming Studio (GPS)

GNAT Programming Studio (GPS) is an Integrated Development Environment (IDE) for Ada. It allows to easily manage and compile Ada projects, providing Graphical User Interface as front end for underlying tools, which have command line interface. Additionally, it enables to create plug-ins using Python and PyGTK.<sup>30</sup> GPS has a plug-ins for SPARK Ada. There is also Sireum Bakar (see Section 2.6.9) plug-in for GPS (developed by SAnToS Laboratory).

There are two versions of GPS: free (GPL) and commercial (Pro). There are version for all most popular platforms: Windows, Linux and MacOS.

GPS has been used for creating and editing all SPARK Ada programs created in this thesis.

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<sup>30</sup>[http://docs.adacore.com/gps-docs/users\\_guide/\\_build/html/extending.html](http://docs.adacore.com/gps-docs/users_guide/_build/html/extending.html)

### 2.5.3 Ravenscar Tasking Subset

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]. RavenSPARK is SPARK subset of the Ravenscar Profile. Burns, Dobbing, and Vardanega gives the following Ravenscar profile description:

The Ravenscar Profile is a subset of Ada tasking model, restricted to meet the real-time requirements for safety critical applications such as 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. 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 [BDV04].

Ravenscar profile is available in SPARK 2005, but not yet in SPARK 2014<sup>31</sup> [AL14a]. The default SPARK 2005 profile (sequential) does not enable tasking. In other words, SPARK 2005 tools cannot analyze and reason about concurrent programs if Ravenscar profile flag (`-profile=ravenscar`) is not provided.

To create a task, the task type has to be declared and task variable of this type has to be defined. Ravenscar does not allow dynamic task creation. Thus, all tasks have to exist for the full lifetime of the program [AW01]. Tasks can be declared only in packages, not

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<sup>31</sup><http://docs.adacore.com/spark2014-docs/html/lrm/tasks-and-synchronization.html>

in subprograms or in other tasks [Bar13]. The priority of each task has to be specified by `pragma Priority`. The range of available priority values is specified in the `system` package. The default range is 1 to 63. A lower value indicates lower priority. Figure 2.9 shows sample package with two tasks. Declared tasks have to be implemented in the package body.

```
package Some_Pkg
--# own task t1 : Task1;
--#   task t2 : Task2;
is
  task type Task1
  is
    pragma Priority(10);
  end Task1;

  task type Task2
  is
    pragma Priority(9);
  end Task2;
end Some_Pkg;

package body Some_Pkg
is
  t1 : Task1;
  t2 : Task2;

  task body Task1
  is
    begin
      loop
        -- implementation;
      end loop;
    end Task1;

  task body Task2
  is
    begin
      loop
        -- implementation;
      end loop;
    end Task2;
end Some_Pkg;
```

**Figure 2.9:** Sample tasks

There are two ways to access a variable in different tasks:

- The variable has to be a protected object.
- The variable has to be an atomic type.

A protected object encapsulates a variable in such a way that it is accessible only through protected subprograms. This mechanism uses locking to ensure atomicity. Protected type declaration is similar to task: both a specification and a body has to be defined. Figure 2.10 shows sample tasks with protected type `Integer_Store`, which enables to share an Integer variable between tasks. A protected type has to be declared before tasks that will use it. Otherwise, it will be not visible for them. A protected type body also has to be defined in package body (Figure 2.11).

```
package Some_Pkg
--# own protected Shared_Var : Integer_Store (Priority => 11);
--#   task t1 : Task1;
--#   task t2 : Task2;
is
  protected type Integer_Store
  is
    pragma Priority (11);

    function Get return Integer;
    --# global in Integer_Store;

    procedure Put(X : in Integer);
    --# global out Integer_Store;
    --# derives Integer_Store from X;
  private
    TheStoredData : Integer := 0;
  end Integer_Store;

  task type Task1
    --# global out Shared_Var;
  is
    pragma Priority(10);
  end Task1;

  task type Task2
    --# global in Shared_Var;
  is
    pragma Priority(9);
  end Task2;
end Some_Pkg;
```

**Figure 2.10:** Sample tasks with protected object

In example given in figures 2.10 and 2.11, `Task1` is writing to `Shared_Var` and `Task2` is reading `shared_Var`. The highest priority is assigned to the protected object to ensure atomicity during operations on it. The lowest priority is assigned to `Task2`, which is reading `shared_Var`. Reading

```

package body Some_Pkg
is
  Shared_Var : Integer_Store;
  t1 : Task1;
  t2 : Task2;

  protected body Integer_Store is
    function Get return Integer
      --# global in TheStoredData;
    is
    begin
      return TheStoredData;
    end Get;

    procedure Put(X : in Integer)
      --# global out TheStoredData;
      --# derives TheStoredData from X;
    is
    begin
      TheStoredData := X;
    end Put;
  end Integer_Store;

  task body Task1
  is
  begin
    loop
      Shared_Var.Put(5);
    end loop;
  end Task1;

  task body Task2
  is
    Local_Var : Integer;
  begin
    loop
      Local_Var := Shared_Var.Get;
    end loop;
  end Task2;

end Some_Pkg;

```

**Figure 2.11:** Sample tasks with protected object body

is usually less expensive operation than writing. Thus, to avoid starvation, `Task1` has higher priority than `Task2`. Notice, that `Shared_Var` is declared in the package body, but refined in package specification.

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: Semantic Error 940 - Variable is a **protected** own variable. **Protected** variables may not be used in proof contexts. Formal reasoning about interactions and especially temporal properties requires

other techniques such as model checking and lies outside the scope of SPARK [Bar13]. To preserve the opportunity to use pre- and postconditions, atomic types have to be used.

To declare atomic type, `pragma Atomic` has to be used. However, there is restriction that `pragma Atomic` cannot be applied to a predefined type such as `Integer`. Thus, a custom type has to be defined. It can be just rename of `Integer` (e.g., `Int32` in the Figure 2.12). Then `pragma Atomic` can be applied on this type. Figure 2.12 presents the previous example using atomic types instead of protected objects.

It is important to mention, that `pragma Atomic` does not guaranty atomicity. In most cases, atomic types should not be used for tasking. Instead, protected types should be used. When an object is declared as atomic, it just means that it will be read from or written to memory atomically. The compiler will not generate atomic instructions or memory barriers when accessing to that object. `pragma Atomic` force compiler only to:

- check if architecture guarantees atomic memory loads and stores,
- disallow some compiler optimizations, like reordering or suppressing redundant accesses to the object

Another important thing in tasking is Time library: `Ada.Real_Time`. It allows to run task periodically, using `delay until` statement, which suspends task until specified time. To use `delay` in the task, it has to be declared in `declare` annotation: `--# declare delay;` [Bar13].

Details about tasking in SPARK are well described in Chapter 8 of [Bar13]. The "Guide for the use of the Ada Ravenscar profile in high integrity systems" [BDV04] and the official Ravenscar Profile documentation (which includes examples) [Tea12] is another good source. The limitations of Tasking in SPARK are reviewed in [AW01].

Ravenscar profile has been used for multitasking applications (including PCA Pump Prototype) created in this thesis.

```

package Some_Pkg
--# own Shared_Var;
--#   task t1 : Task1;
--#   task t2 : Task2;
--# initializes Shared_Var;
is
    type Int32 is new Integer;

    task type Task1
        --# global out Shared_Var;
    is
        pragma Priority(10);
    end Task1;

    task type Task2
        --# global in Shared_Var;
    is
        pragma Priority(9);
    end Task2;

end Some_Pkg;

package body Some_Pkg
is
    Shared_Var : Int32 := 0;
    t1 : Task1;
    t2 : Task2;

    task body Task1
    is
        begin
            loop
                Shared_Var := 5;
            end loop;
        end Task1;

    task body Task2
    is
        Local_Var : Integer;
        begin
            loop
                Local_Var := Integer(Shared_Var);
            end loop;
        end Task2;

end Some_Pkg;

```

**Figure 2.12:** Sample tasks with atomic type

## 2.6 SPARK Ada Verification

The goal of software verification is to assure that software satisfies specification and requirements, and to prove the lack of errors. There are two primary types of verification:

- dynamic - performed during the execution of software, e.g. unit tests (by comparison of expected and actual states)
- static - achieved by formal methods, flow analysis, mathematical calculations and logical evaluations (based on formal rendering of specification)

Dynamic verification starts with a set of possible test cases, simulates the system on each input, and observes the behavior. In general, it does not cover all possible executions. On the other hand, static verification establishes that program conforms to a particular class of properties for all possible execution sequences. Static and dynamic verification can be mixed, e.g. by generating test cases with static verification tools and then proving correctness with unit tests during runtime [DRH07].

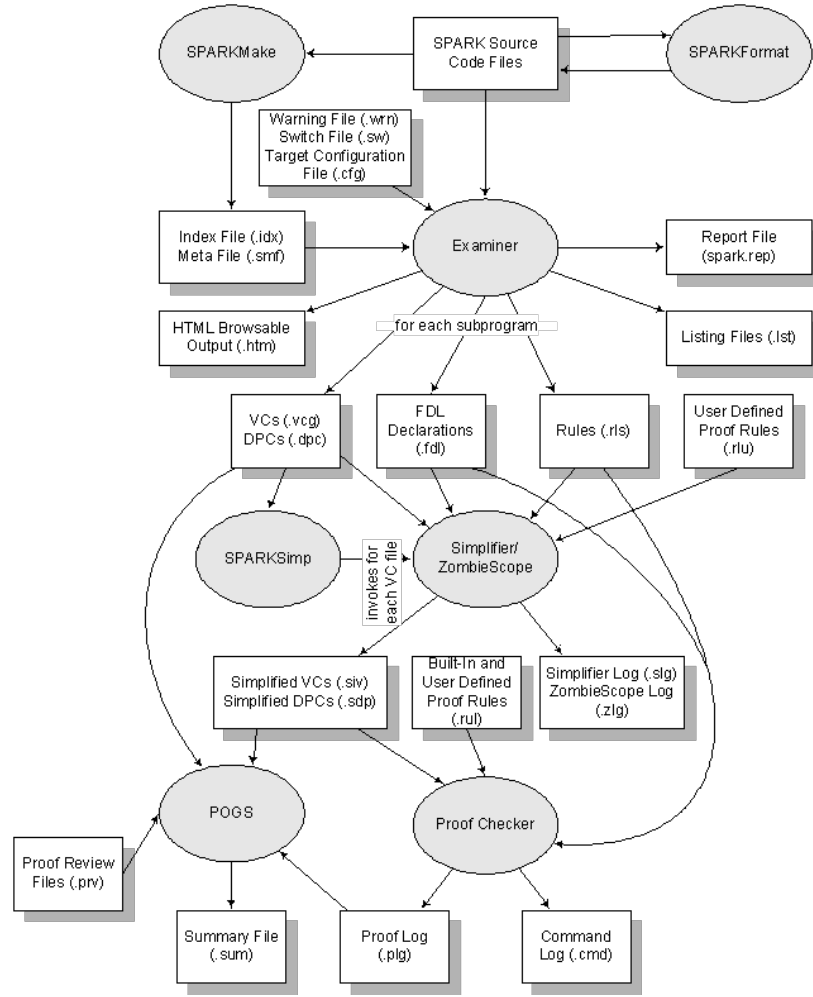
Techniques for Static Verification:

- 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 via formal refinement of code from specifications.
- Model checking: enumerate all possible executions and states, and check each state for correctness.

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<sup>32</sup>[http://docs.adacore.com/sparkdocsdocs/Examiner\\_UM.htm](http://docs.adacore.com/sparkdocsdocs/Examiner_UM.htm)





**Figure 2.13:** Relationship of the Examiner and Proof Tools.<sup>32</sup>

SPARK includes a development and verification tool-set with the following components:

- SPARKMake - generates index file (.idx) and meta file (.smf)
- Examiner - checks syntax, generates Verification Conditions (VCs) and Dead Path Conjectures (DPCs), and discharges (proves) some of them (some might be impossible to discharge)
- Simplifier - simplifies VCs (not discharged by Examiner) and tries to discharge them after simplification process in similar fashion like Examiner

- ZombieScope - finds dead paths
- ViCToR - translates VCs and DPCs to format acceptable by SMT solver and proves correctness using specified SMT solver
- SPARKSimp - runs Simplifier or/and ZombieScope
- POGS - produces verification report
- Proof Checker - discharges VCs or DPCs not discharged by Examiner and Simplifier by carrying out tool-assisted manual proof steps

Relationships between tools and verification flow is presented in the Figure 2.13. SPARK proof tools use FDL as the modeling language.

### 2.6.1 SPARK Examiner

The main SPARK verification tool is Examiner. It supports several levels of analysis:

- 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 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 [Tea11b].

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) as mentioned in Section 2.5.3.

When some parts of the system are written in full Ada (with non-valid SPARK constructs), then Examiner returns error. Ada parts can be excluded from Examiner analysis using `--# hide` annotation. Then, only a warning is returned by Examiner: 10 - The body of subprogram Main is hidden - hidden text is ignored by the Examiner.

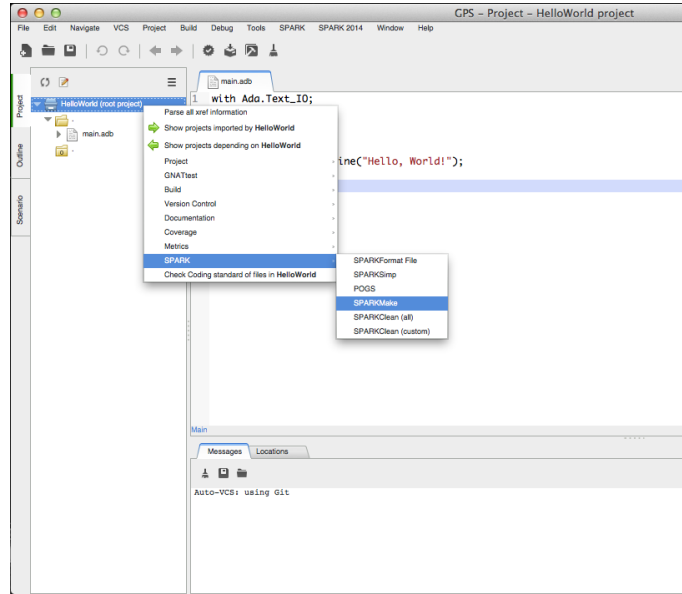
Examiner use SPARK index file (.idx) - generated by SPARKMake tool - to locate files necessary for verification [Bar13].

Examiner can be used with the `spark` command and appropriate flags described in Examiner Manual [Tea11b].

To use Examiner in GNAT Programming Studio:

- Run SPARK Make: right click on project / SPARK / SPARK Make (Figure 2.14)
- Set SPARK index file (to `spark.idx` generated by SPARKMake) (Figure 2.15)
- (optionally) set configuration file (e.g. `Standard.ads`)
- Choose appropriate version of SPARK (95 or 2005)
- Choose mode: Sequential (for single tasking programs) or Ravenscar (for multitasking programs)

To generate verification conditions (VCs), the `-vcg` switch has to be used. It can be set in GNAT Programming Studio (Project / Edit project properties / Switches / Examiner / Generate VCs). In addition to verification conditions, Examiner can check dead path conjectures (DPCs), i.e. paths through the code that can never be executed regardless of



**Figure 2.14:** Run SPARK Make

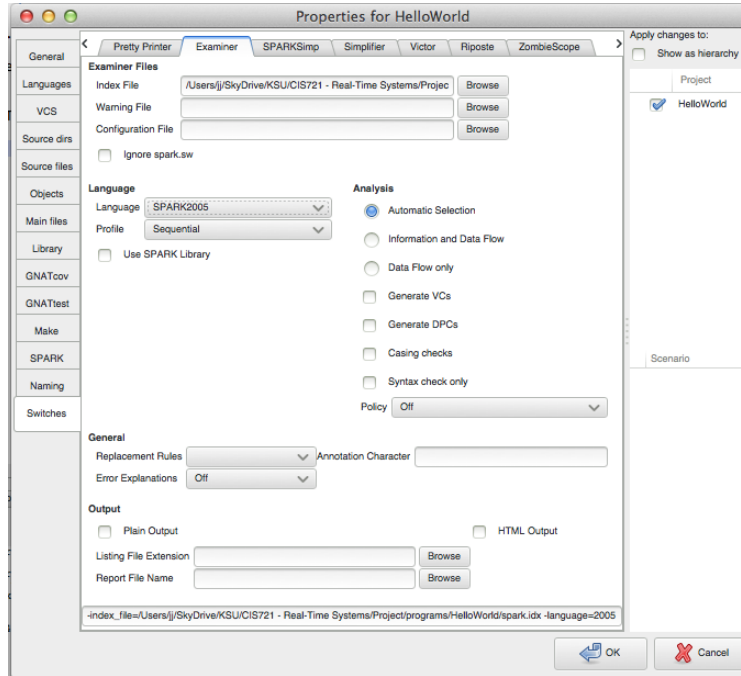
input. To generate dead path conjectures, the `-dpc` switch has to be used. It can be also set in GNAT Programming Studio (Project / Edit project properties / Switches / Examiner / Generate DPCs).

Examiner has been used to check syntax and semantics during PCA Pump Prototype development and in verification process described in Chapter 6.

## Flow analysis

There are two types of flow analysis:

- Data flow analysis:
  - Checks input/output behavior of parameters and variables.
  - Checks initialization of variables.
  - Checks that changed and imported variables are used later (possibly as output variables).
- Information flow analysis - verifies interdependencies between variables.



**Figure 2.15:** Examiner Properties

In data flow analysis, Examiner checks if input parameters are not modified, but used at least once (in at least one branch of program). In the same factor, output parameters cannot be read (before initialization) and has to be initialized (in all branches of program). Input/output parameters has to be both read and write (changed). In similar way, Examiner verify the global variables (specified in annotations). Functions can use only input parameters and can only read global variables. Therefore functions do not have side effects.

Global variables defined in package body (thus private) has to be declared by `--# own` annotation in package specification. If variable is also initialized, `--# initializes` annotation has to be used. In Ada, to use package in another package, `with` clause has to be used. In SPARK Ada, additionally `--# inherits` annotation has to be specified.

In information flow analysis, dependencies between variables are analyzed. These dependencies are specified by `--# derives` annotation.

## Verification conditions

Verification conditions is a set of generated hypothesis, if proven to be true can be concluded that they hold. To generate verification conditions, two kinds of annotations are relevant for Examiner:

- preconditions: `--# pre`
- postconditions: `--# post`

The notions of pre- and postconditions are based on Hoare logic [HLL<sup>+</sup>]. More precisely, in the Hoare triple below:

$$\{P\}C\{Q\} \tag{2.1}$$

`c` is a program that starts in a state satisfying precondition `p`. Program terminates in state satisfying postcondition `q`. Thus `p` and `q` are assertions, and `c` is a command (action) performed between them.

Additionally, assertions (`--# assert`) and checks (`--# check`) can be specified in procedure body. Then additional verification conditions are generated.

SPARK functions do not have side effects (as stated in 2.6.1), thus only preconditions are relevant. However, there is annotation `--# return`, which specifies function return value.

Verification Conditions (VCs) are generated depending on commands appearing in the subprogram along path segments. VC generation is performed backwards, in other words: we start from post-conditions and consider what must hold before. Flow analysis is well described in chapter 11 of [Bar13].

If preconditions are not present, then the formula expresses that the post-condition holds always.

## 2.6.2 SPARK Simplifier

Simplifier, simplifies Verification Conditions (VCs) generated by Examiner. It can also discharge (prove correctness) of those VCs, which are not proved by Examiner [Tea11c]. It takes as input `.vcg` files, `.fat` files for its data declarations and - if available - proof-rule files (`.rls`, `.rlu`). Then it generates `.siv` files (simplified VCs) and `.slg` files (which contain details about simplification that has been made).

SPARK Simplifier has been used in verification process described in Chapter 6.

## 2.6.3 ZombieScope

ZombieScope is a SPARK tool that analyze SPARK code to find dead paths, i.e. paths through the code that can never be executed. A program that contains dead paths may not necessarily be incorrect, but a dead path is an indication of a potential code issue.

ZombieScope reads `.dpc` files generated by the Examiner. In order to generate dead path conjectures, `-dpc` flag has to be used or 'Generate DPCs' option has to be checked in Examiner options, in GPS. It reads also `.fat` files for its data declarations and the `.rls` file for proof-rules if present. ZombieScope generates two output files: `.sdp` file (dead path summary) and `.zlg` file (details about underlying contradiction search performed). ZombieScope is invoked by SPARKSimp by default and the summary file generated by POGS includes information about the dead path analysis.

ZombieScope has been used for dead paths analysis in verification process described in Chapter 6.

## 2.6.4 ViCToR

ViCToR is a tool to translate Verification Conditions (VCs), generated by the Examiner, into SMT-LIB (file format used to communicate with SMT solvers) [Tea]. SMT (Satisfiability

Modulo Theories) solver is a tool for verification and proving the correctness of programs. ViCToR is integrated with SPARKSimp and POGS. To invoke ViCToR from SPARKSimp, flag `-victor` has to be used.

ViCToR has been used in verification process described in Chapter 6.

### 2.6.5 Proof Checker

Proof Checker is advanced verification tool, which require considerable experience in verification of SPARK programs. It is interactive program, which enables the user to direct the Checker to explore the use of various strategies and rules on the condition to be proved. Proof Checker can keep a log of the progress of a proof in `p1g` file. It also records the proof steps applied in a `.cmd` file. More details about Proof Checker can be found in chapter 12 of [Bar13].

Proof Checker was not used in this thesis. Instead Bakar Kiasan (see section 2.6.9) has been used.

### 2.6.6 SPARKSimp Utility

SPARKSimp is a simple "make" style tool for the SPARK analysis tools. Currently, it supports the Simplifier, ZombieScope and ViCToR. It applies the Simplifier (and ViCToR, if requested) to all `.vcg` files and ZombieScope to all `.dpc` files that it finds in a directory tree [Tea10].

SPARKSimp has been used to invoke Simplifier, ZombieScope and ViCToR in verification performed in this thesis (see Chapter 6).



### 2.6.7 Proof Obligation Summarizer (POGS)

The Proof Obligation Summarizer tool (POGS) reads and understands the structure of the verification conditions (`.vcg` files), their simplified version (`.siv` files), and dead path conjectures (`.dpc` files). It reports the status of proofs and dead path analyses in a human-readable, text form [Tea11a].

POGS has been used to generate reports for verification performed in this thesis (see Chapter 6).

### 2.6.8 AUnit

AUnit is a unit test framework for the Ada language. It can be also applied to test SPARK Ada programs. It was inspired by Java JUnit (created by Kent Beck, Erich Gamma) and C++ CppUnit (created by M. Feathers, J. Lacoste, E. Sommerlade, B. Lepilleur, B. Bakker, S. Robbins) unit test frameworks [Ada14]. Similar to these related frameworks, it enables simple test cases execution, fixtures, suites, and provides reporting [Fal14].

GNAT Programming Studio can generate test cases skeleton for all subprograms. It can be generated using Tools -> GNATtest -> Generate unit test setup. This generator creates a new project with AUnit tests. The project for which tests are generated is referenced in new generated test project. In order to run tests, the test project has to be opened in GNAT Programming Studio. The project is created in `[project_dir]/gnattest/harness/test_[proj_name].gpr`. It generates an empty (not implemented) test for each subprogram in project. To add/edit/remove tests or rename names, three files have to be edited:

- `[some_package]-test_data-tests.ads`
- `[some_package]-test_data-tests.adb`
- `[some_package]-test_data-tests-suite.adb`

Each test has to be declared in `[some_package]-test_data-tests.ads` and implemented in `[some_package]-test_data-tests.adb`. Then, it has to be added to test suite in `[some_package]-test_data-tests-suite.adb` file.

Tests can be also created manually. Then, the AUnit distribution has to be referenced in project file, and all test cases (and suits) have to be implemented by hand.

AUnit has been used to create unit test for isolated module of created PCA Pump Prototype (see Section 6.4).

## 2.6.9 Sireum Bakar

Sireum<sup>33</sup> is a long-term research project conducted by SAnToS Laboratory at Kansas State University. Its goal is to develop an over-arching software analysis platform that incorporates various static analysis techniques such as a data-flow framework, model checking, symbolic execution, abstract interpretation, and deductive reasoning techniques (e.g., using weakest precondition calculation). It can be used to build various kinds of software static analyzers for different kinds of properties.

It uses the Pilar language [SC12] as an intermediate representation. Any language which can be translated to Pilar can be analyzed by Sireum. For now, there are translators for SPARK and Java.

Bakar is a toolset for analyzing SPARK Ada programs (Bakar means "spark" in Indonesian). Sireum Bakar currently includes:

- Kiasan - functional behaviors verification tool
- Alir - information flow analysis tool

The Sireum distribution is available for Windows (32-bit, 64-bit), Linux (32-bit, 64-bit) and MacOS (64-bit). It can be downloaded from <http://www.sireum.org/>.

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<sup>33</sup><http://www.sireum.org/>

## Bakar Kiasan

Bakar Kiasan [BHR<sup>+</sup>11] is a fully automated tool for verifying functional behaviors of SPARK programs specified as software contracts. Kiasan use symbolic execution technique (Kiasan means "symbolic" in Indonesian). It provides various helpful feedback including generation of counter example for contract refutation, test cases for an evidence of contract satisfaction, verification reports, visual graphs illustrating pre/post states of SPARK procedures/functions, etc. It is much easier to understand than, e.g., analysis of `.vcg` files generated by SPARK Examiner.

There exists a Kiasan Plug-in for GNAT Programming Studio (GPS). Version 1, for GPS 5, supports SPARK 2005. Version 2, for GPS 6, which supports SPARK 2014, is under development. Both plug-ins are created by author of this thesis in Python and PyGTK. There is also plug-in for Eclipse, but only for SPARK 2005 programs.

Bakar Kiasan does not support the Ravenscar profile. Thus, it can be used only for sequential programs verification. Figure 2.16 presents sample Kiasan analysis result. The Kiasan window in GPS has two parts: (i) a list of units (packages and subprograms), and (ii) analysis cases with pre- and post states. Every unit has the following associated statistics:

- T# - Test cases (expected behavior),
- E# - Exception cases (unexpected behavior),
- Instruction coverage - amount of code that will be executed in execution paths generated by Kiasan analysis,
- Branch coverage - number of branches discovered by Kiasan analysis (0% branch coverage in the case of 100% instruction coverage means that there are no branches in the analyzed unit), and
- Time in which analysis was performed.

After double clicking on some unit, code that is executed during execution of this unit is highlighted. Additionally below the list of units, there is a combo box which contains all test cases associated with the selected (by double clicking) unit. Once some case is selected, code coverage equivalent to this test case is highlighted. Additionally, below the combo box, there are generated execution cases - one for each execution path. The pre-state is listed on the left hand side while the post state is listed on the right hand side. Variables with red font color, in the post-state, are those that are changed as the result of unit execution. Newly created variables (during unit execution) are marked in blue, but there are no such variables in the example presented in Figure 2.16.

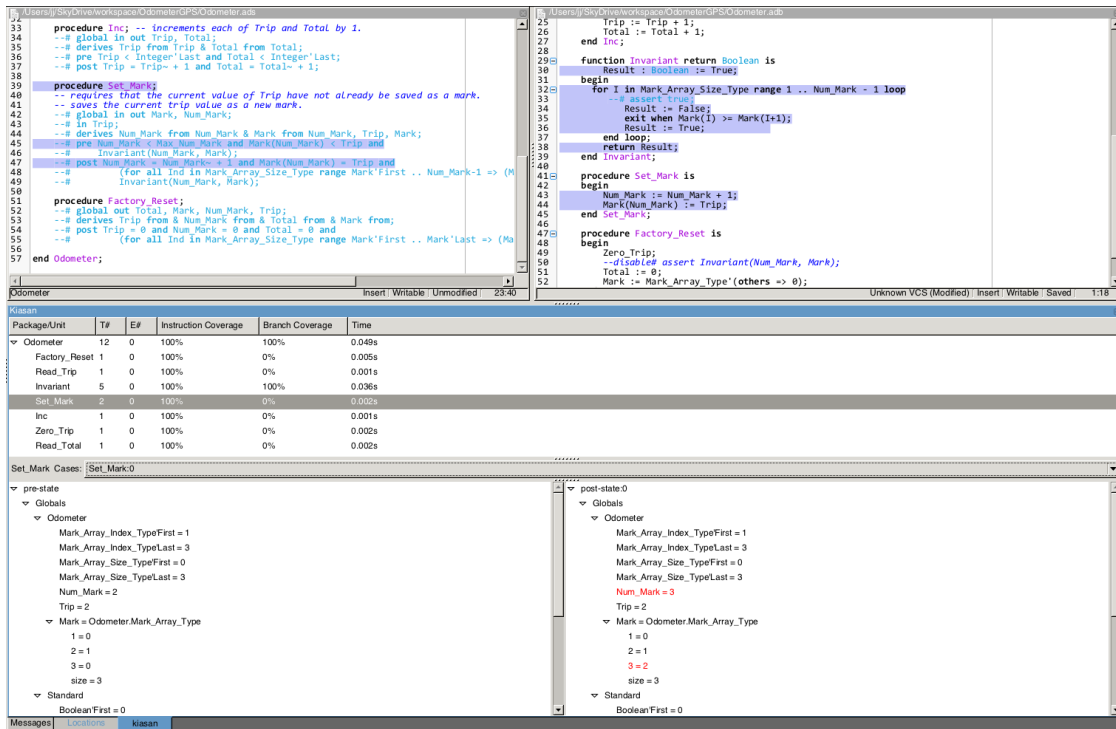


Figure 2.16: Bakar Kiasan report

Bakar Kiasan is useful especially for solving verification issues. It can generate counter examples that give developers greater intuition about problems in the code.

Bakar Kiasan has been used in verification of PCA Pump module (see Section 6.2).

## Bakar Alir

Alir is an information flow analysis tool for reasoning about SPARK's derive clauses/information flow (Alir means "flow" in Indonesian). Alir visualizes information flows to ease engineers in understanding information dependencies crucial for specifying and verifying SPARK's derive clauses. It provides various configurable intra-procedural and inter-procedural analyses. The inter-procedural analyses are control flow analysis, reaching definition analysis and data dependence analysis. The inter-procedural analyses in Alir include building the System Dependence Graph (SDG), slicing and chopping on SDG [Thi11].

Bakar Alir has not been used in this thesis, but can potentially be used in the future, to enrich verification process.

### 2.6.10 GNATprove

GNATprove<sup>34</sup> is a formal verification tool for SPARK 2014 programs, whose input is automatically constructed using GNAT compiler as a front-end. GNATprove interprets SPARK Ada annotations exactly like they are interpreted at run time during tests. It can prove that subprograms respect their contracts, expressed as preconditions and postconditions in the syntax of Ada 2012. The tool automatically discovers the subset of subprograms which can be formally analyzed. GNATprove is currently available for Linux x86, Windows x86 and Linux x86-64.

GNATprove consists of two distinct analyses, flow analysis and proof. Flow analysis checks the correctness of aspects related to data flow (`Global`, `Depends`, `Abstract_State`, `Initializes`, and refinement versions of these), and verifies the initialization of variables. Proof verifies the absence of runtime errors and the correctness of assertions such as `Pre` and `Post` aspects. Using the switch `--mode=<mode>`, whose possible values are `flow`, `prove` and `all`, only one or both

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<sup>34</sup><http://www.open-do.org/projects/hi-lite/gnatprove/>

of these analyses can be performed (`all` is the default) [AL14b]. GNATprove use Alt-Ergo prover for verification.

GNATprove has been used to verify isolated module of created PCA Pump Prototype, which has been translated to SPARK 2014 (see Section 6.5).

## 2.7 AADL/BLESS to SPARK Ada code generation

The ultimate goal of the long term research of which this thesis is part is to build an AADL (with BLESS) to SPARK Ada translation. AADL has been used to prototype and fully develop embedded systems for the past 5-7 years [CB09]. Related work in code generation from AADL, but for Java programming language has been done in [PHR]. There are also already existing tools, which performs code generation based on AADL:

- Ocarina
- Ramses

### 2.7.1 Ocarina

Ocarina [LZPH09] is a tool suite that contains plug-ins for code generation, model checking and analysis. The code generation plug-in generates code from an AADL architecture model to an Ada or C 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. Ocarina is written in Ada.

There is plug-in for OSATE (see Section 2.3.1) that supports code generation. Example AADL models, suitable for being an input of Ocarina are available on github repository:

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

Since mid-2009, Telecom ParisTech is no longer involved in Ocarina, and is developing another AADL tool-chain, based on Eclipse, codenamed RAMSES [CBGP12].

Ocarina has been used as inspirational tool for code generation from AADL models.

### 2.7.2 RAMSES

RAMSES (Refinement of AADL Models for Synthesis of Embedded Systems) [CBGP12] is a model transformation and code generation tool written in Java. Code generation module produces C code, but does not generate Ada. The approach for code generation is to transform AADL models using a rule-based transformation framework and generate code from transformed (simplified) models. Simplified AADL models contain behavior annex subclauses. RAMSES can be used as OSATE plug-in or standalone application.

RAMSES was initial point of interest, because of its code generation module. However, it has not been used due to its limitation to generate C code only.

# Chapter 3

## PCA Pump

A Patient Controlled Analgesia (PCA) pump<sup>1</sup> is a medical device that allows a patient to self-administer small doses of narcotics (usually Morphine, Dilaudid, Demerol, or Fentanyl). PCA pumps are commonly used after surgery to provide a more effective method of pain control than periodic injections of narcotics administered by a clinician. A continuous infusion mode of the pump (called a basal rate) permits the patient to receive a continuous infusion of pain medication. There is no need for a clinician to administer it. A patient can also request additional boluses, but only in spec-



**Figure 3.1:** Patient Controlled Analgesia (PCA) pump

ified intervals to avoid infusion. In addition to basal and patient bolus, clinician can also

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<sup>1</sup><http://ppahs.org/2012/05/30/patient-controlled-analgesia-pca-pumps-the-basics/>



request a bolus called clinician bolus or square bolus.

Figure 3.1 shows LifeCare PCA pump. On the left hand side, there is drug reservoir. On the right - clinician panel, which allows to control the pump. Figure 3.2 shows PCA Pump, made by company Alaris.

A PCA pump is safety-critical device which works in standard process control loop, proposed by Leveson in [Lev12], depicted in the Figure 3.3. The controller obtains information about (observes) the process state from measured variables (feedback) and uses this information to initiate action by manipulating controlled variables to keep the process operating within predefined limits or set points (the goal) despite disturbances to the process, such as different

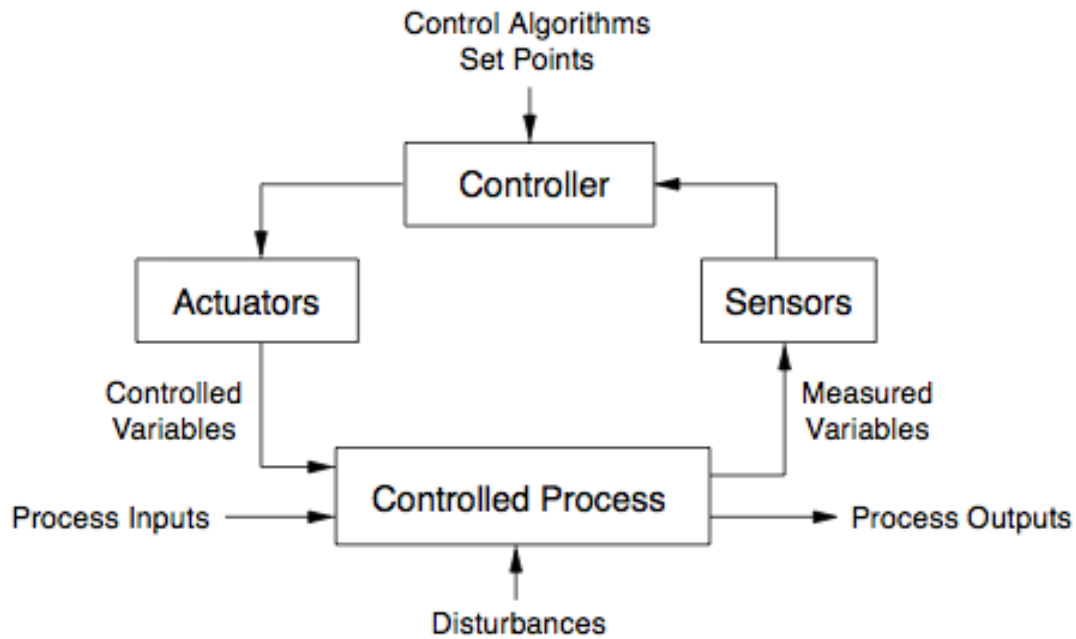


**Figure 3.2:** Alaris Pump

air pressure or device position (gravity impact). In general, the maintenance of any open-system hierarchy (either biological or man-made) will require a set of processes in which there is communication of information for regulation or control [Lev12].

The PCA pump actuator is a motor that pumps a drug to the patient's vein. The controlled process is dosing the drug. Sensors measure amount of dosed drug. They might be used to double-check if ordered (by controller) that the amount of drug was appropriately delivered. Sometimes there might be some disturbances caused by mechanical issues and environmental conditions. The controller issues appropriate actions based on information from sensors and clinician or patient's commands. A high level overview of PCA Pump is depicted in the Figure 3.4.

One of the problems of using PCA pumps, is that there is inadequate monitoring of patient's blood oxygenation. Nursing staff on general medical units typically track blood oxygenation ( $SpO_2$ ), heart rate and other vital signs every four hours, which is not enough



**Figure 3.3:** Standard Process Control Loop.

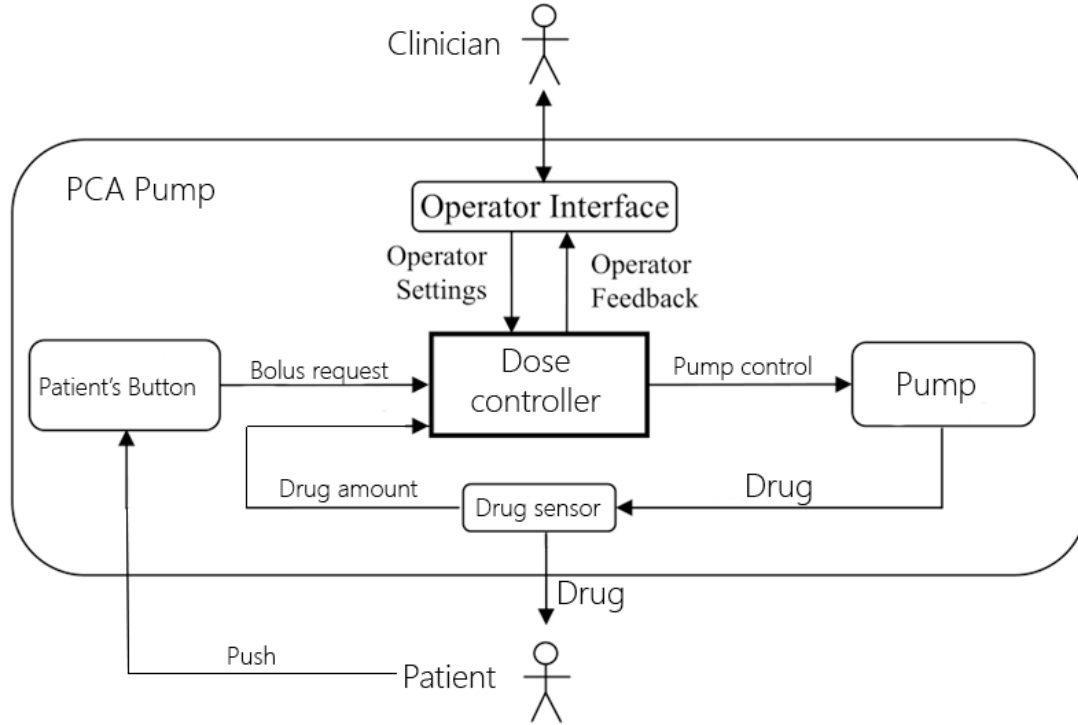
[OG11]. There should be a way to monitor levels continuously. Additionally, it can be hard to tell if a person’s breathing rate is dangerously low in certain circumstances. There are cases where lack of monitoring carbon dioxide level caused death.<sup>2</sup>

Another problem is not adequate resistance to human errors. For example, there is a case when nurse used a 5 mg/mL morphine cassette because a 1 mg/mL cassette was not available, but she programmed PCA Pump like for 1 mg/mL concentration. This caused over infusion that in addition to lack of pulse monitoring resulted in patient’s death.<sup>3</sup>

As mentioned in chapter 2, one way to address these problems is through medical devices interoperability. An integrated system can receive input from monitoring devices and disable the pump. In addition, less human error-prone device is needed. It can be assured by using more than one system for their detection.

<sup>2</sup><http://abcnews.go.com/Health/parents-warn-pca-pumps-daughters-death/story?id=16796805>

<sup>3</sup><http://webmm.ahrq.gov/case.aspx?caseID=291>



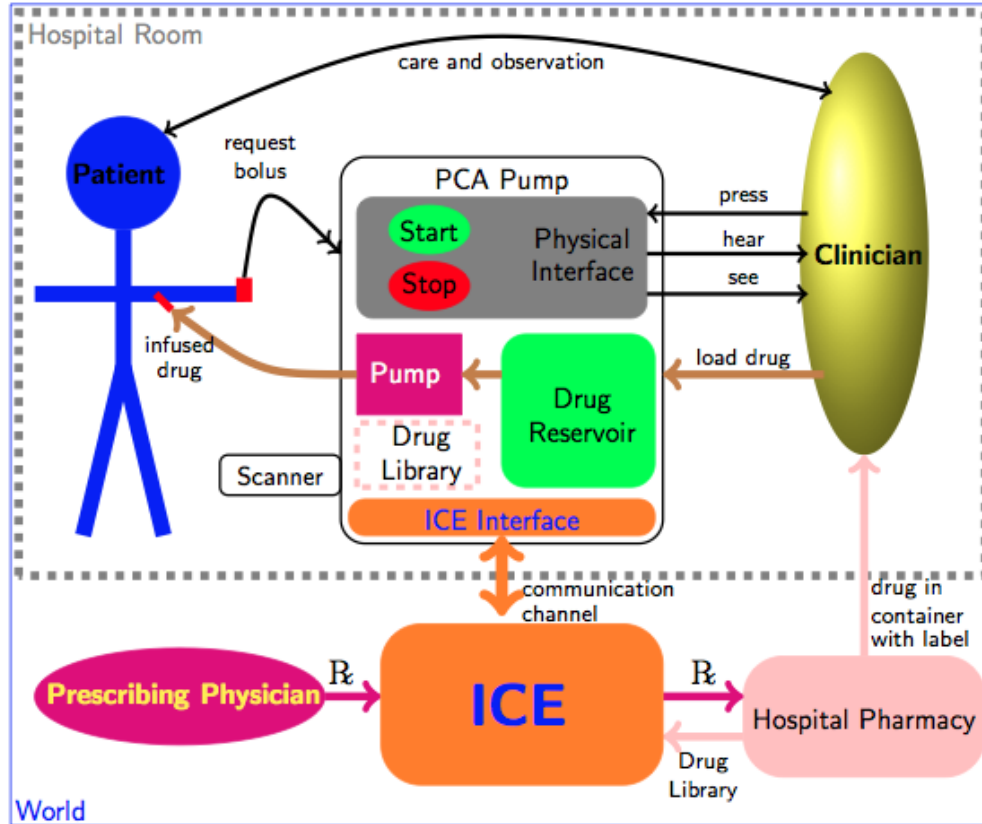
**Figure 3.4:** PCA Pump system

### 3.1 PCA Pump Requirements Document

Requirements of "Open Source PCA Pump" [LHC13], on which the work in this thesis is based, are captured in "Open Patient-Controlled Analgesia Infusion Pump System Requirements" document [LH14] created by Brian Larson. The requirements are a rigorously defined set of capabilities, which Open PCA Pump should have, based on consultations with domain experts, FDA, and Brian Larson's expertise gained while he was working in the medical device industry.

The conceptual model of Open PCA pump is depicted in the Figure 3.5. As mentioned earlier, the pump is connected to ICE so it may be integrated with ICE apps and displays. The interface must provide prescription and patient information, current status to be displayed remotely on a supervisor user interface, and a means to stop infusing upon human

command, or request from ICE app (based on data from monitoring devices). Such an ICE app could monitor a patient's blood oxygenation and pulse rate, stopping the pump if depressed respiratory function is indicated [LH14].



**Figure 3.5:** Open PCA Pump concept

Additionally, it cooperates with Drug Library, which contains information about drugs and their properties (like concentration). Data needed for pump operation, are captured on electronic prescription, which contains:

- Patient's name
- Drug name
- Drug code
- Drug concentration

- Initial volume of drug in the vial
- Basal flow rate - the rate of continuous infusion
- Volume to be infused (VTBI) on patient's request
- Maximum amount of drug allowed per hour
- Minimum time between patient boluses
- Date, in which prescription has been filled
- Prescribing physician's name
- Pharmacist name

Pain medication is prescribed by a licensed physician, which is dispensed by the hospital's pharmacy. The drug is placed into a vial labeled with the name of the drug, its concentration, the prescription, and the intended patient. A clinician loads the drug into the pump, and attaches it to the patient. The pump infuses a prescribed basal flow rate which may be augmented by a patient-requested bolus or a clinician-requested bolus. This allows additional pain medication in response to patient need within safe limits [LH14].

The prescription captures all data needed for basal infusion and patient requested boluses (referred as bolus). In addition to that, Open PCA Pump allows Clinician Requested Bolus (referred as square bolus). In order to do that, clinician has to enter the time (through PCA Pump panel) in which additional dose, equal to VTBI (Volume To Be Infused) specified in prescription, will be infused.

There can occur situations in which the maximum drug amount infused may exceed the allowed limit. E.g. when clinician issues too many square boluses. In such case, pump is switched to Keep Vein Open (KVO) mode, which has 1 ml/hr drug rate. KVO is standard mode used in infusion pumps to prevent the vein from closing. Pump switches to KVO rate also when ICE interface requests it. It may happen e.g. if patient's oxygen level is low. To recover from KVO state, pump has to be restarted by clinician in order to continue

operation. In Summary, Open PCA Pump has following modes:

- Stopped
- Basal rate
- Patient’s bolus (bolus)
- Clinician bolus (square bolus)
- Keep Vein Open (KVO)

There are also other scenarios, which are captured by Requirements Document [LH14], like scanner to enable automatic entry of patient’s and prescription data, occlusion detection, hardware errors alarms etc. Detailed overview of Open PCA Pump Requirements can be found in [LH14].

## 3.2 PCA Pump AADL/BLESS Models

In addition to PCA Pump Requirements Document [LH14], Brian Larson created an AADL model with formal behavioral specifications written in his BLESS framework. The graphical representation of the AADL model is depicted in the Figure 3.6.

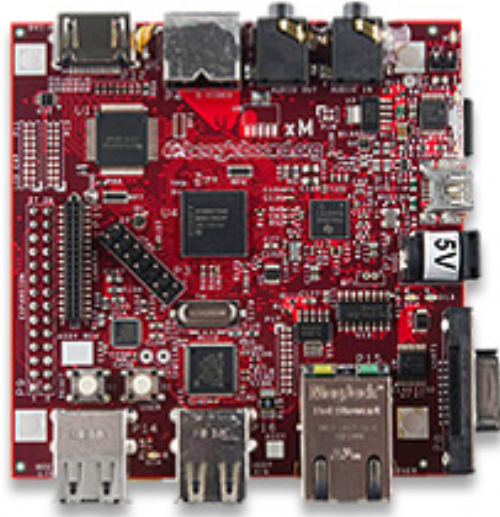
The AADL model captures the internal architecture of the device, while BLESS specifications capture its behavior. In Appendix D, thread `Rate_Controller` from the `PCA_Operation` component with BLESS assertions in thread declaration and BLESS behavioral description in thread implementation, is presented. The thread declaration contains input and output ports. Some of them have BLESS assertions attached. These assertions are defined using the BLESS annex in the thread implementation. In addition to assertions, states and transitions defined in thread implementation can potentially be translated into a working SPARK Ada program. Presence of timing properties in states and transitions makes translation extremely difficult, thus there are omitted in this thesis and only assertions are considered.



### 3.3 BeagleBoard-xM

For research on the MDCF project, BeagleBoard-xM (an open-source hardware single-board computer produced by Texas Instruments), has been chosen as hardware platform for PCA pump prototyping.

BeagleBoard-xM (presented in the Figure 3.7) is an embedded device with an 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, which enables control of pump actuator.

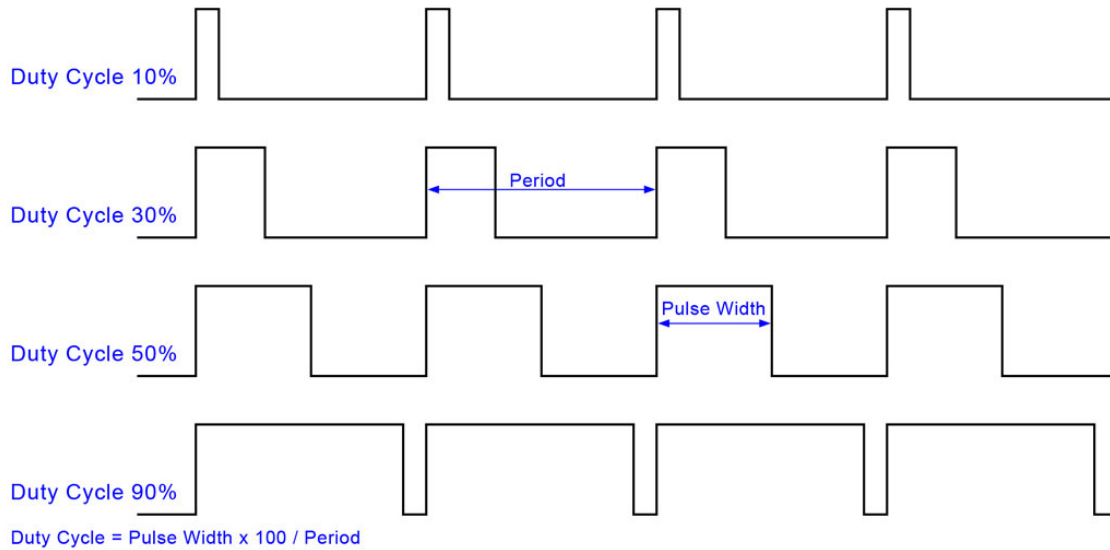


**Figure 3.7:** BeagleBoard-xM

Pulse-width modulation (PWM) is a technique for controlling analog circuits with a processor's digital outputs. The average value of voltage (and current) fed to the electrical load is controlled by turning the switch between supply and load on and off at a fast pace. The longer the switch is on compared to the off periods, the higher the power supplied to the load. Proportion of on and off periods is called the duty cycle and is expressed in percent. 100% means all the time on, 0% - all the time off. Figure 3.8 shows 10%, 30%, 50% and 90% duty cycles.

There is no existing SPARK Ada compiler running on ARM system. Hence, to compile SPARK Ada program for ARM device, cross-compiler is needed. There is GNAT compiler [Hor09] created by AdaCore, but there was no cross-compiler for ARM. However, AdaCore





**Figure 3.8:** An example of PWM duty cycles

was actively developing cross-compiler. They had a working version in 2013, but tested only on their target Android-based device. This version was not working on BeagleBoard-xM platform with Angstrom Linux (configuration used in this thesis). Cooperation with AdaCore, involved bundling and testing a cross-compiler for ARM to produce code for the BeagleBoard-xM, resulted in working cross-compiler. For now, the GNAT cross-compiler works only on Linux 32-bit operating system (as a platform in which cross-compilation has to be performed).

In addition to USB ports, BeagleBoard-xM has also a serial port and an Ethernet port. It allows to copy programs compiled on Linux, using all three types of ports.

# Chapter 4

## AADL/BLESS to SPARK Ada Translation

This chapter presents created AADL/BLESS to SPARK Ada translation schemes (4.1), proposed port communication (4.2) and discusses design of an automatic translator, which can be created based on translation schemes (4.3).

### 4.1 AADL/BLESS to SPARK Ada mapping

Mapping of AADL models to SPARK Ada 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)<sup>1</sup> and in Jacksonville, FL (April 2013).<sup>2</sup> Ocarina tool suite (based on older AADL annex documents [HZPK08]) and its examples<sup>3</sup> were also helpful in understanding of AADL to Ada translation. Mapping of BLESS assertions was created in consultation with Brian Larson (BLESS creator).

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<sup>1</sup>[http://www.aadl.info/aadl/downloads/committee/feb2013/presentations/13\\_02\\_04-AADL-Code%20Generation.pdf](http://www.aadl.info/aadl/downloads/committee/feb2013/presentations/13_02_04-AADL-Code%20Generation.pdf)

<sup>2</sup>[https://wiki.sei.cmu.edu/aadl/images/8/8a/Constraint\\_Annex\\_April22.v3.pdf](https://wiki.sei.cmu.edu/aadl/images/8/8a/Constraint_Annex_April22.v3.pdf)

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

### 4.1.1 Data Types Mapping

One of core AADL packages is `Base_Types`. It defines fundamental data types for AADL. Its definition, without floating and text types, is shown in the Figure 4.1.

In Ada 2012, and thus SPARK 2014, there is package `Interfaces`, which allows for easy mapping of AADL `Base_Types` package. The mapping proposed in Annex Document [SCD14] is presented in the Figure 4.2.

The target language for this thesis is SPARK 2005. We evaluated SPARK 2014, but determined that, at the time when this thesis was written SPARK 2014 tools were not mature enough and multitasking facilities were not yet included in the language. Types: `Float`, `Character` and `String` are also not part of this thesis, because of the limitations of SPARK 2005 verification tools limitation. Thus, only `Integer`, `Enumeration`, `Boolean` and `Record` types are taken into account in mappings.

Each type is translated into simple type definition and protected type. Then it can be used in multitasking programs with the Ravenscar Profile. For every protected type only setter (`Put`) and getter (`Get`) subprograms are defined. The type can be extended by the developer during the development phase. Protected objects can be also removed if they are not needed. The default value for priority, for each generated type is 10. It can be changed during development phase to align with system goals. Types: `Integer`, `Boolean` and `Natural` are already defined in SPARK Ada, thus only protected objects are generated for them. AADL `Base_Types` mapping to SPARK 2005 is presented in the Table 4.1.

Table 4.1: Base AADL types to SPARK mapping.

AADL	SPARK Ada
<pre> data Integer properties   Data_Model::Data_Representation     =&gt; Integer; end Integer; </pre>	<pre> protected type Integer_Store is   pragma Priority (10);    function Get return Integer;   --# global in Integer_Store;    procedure Put(X : in Integer);   --# global out Integer_Store;   --# derives Integer_Store from X; private   TheStoredData : Integer := 0; end Integer_Store; </pre>
<pre> data Integer_16 extends Integer properties   Data_Model::     Number_Representation =&gt;       Signed;     Source_Data_Size =&gt; 2 Bytes; end Integer_16; </pre>	<pre> type Integer_16 is new Integer range -2**(2*8-1) .. 2**(2*8-1-1);  protected type Integer_16_Store is   pragma Priority (10);    function Get return Integer_16;   --# global in Integer_16_Store;    procedure Put(X : in Integer_16);   --# global out Integer_16_Store;   --# derives Integer_16_Store from X; private   TheStoredData : Integer_16 := 0; end Integer_16_Store;  protected body Integer_16_Store is   function Get return Integer_16   --# global in TheStoredData;   is   begin     return TheStoredData;   end Get;    procedure Put(X : in Integer_16)   --# global out TheStoredData;   --# derives TheStoredData from X;   is   begin     TheStoredData := X;   end Put; end Integer_16_Store; </pre>
Continued on next page	

Table 4.1 – continued from previous page

AADL	SPARK Ada
<pre> data Unsigned_16 extends Integer properties   Data_Model::     Number_Representation =&gt;       Unsigned;     Source_Data_Size =&gt; 2 Bytes; end Unsigned_16; </pre>	<pre> type Unsigned_16 is new Integer range 0 .. 2**(2*8-1);  protected type Unsigned_16_Store is   pragma Priority (10);    function Get return Unsigned_16;   --# global in Unsigned_16_Store;    procedure Put(X : in Unsigned_16);   --# global out Unsigned_16_Store;   --# derives Unsigned_16_Store from X; private   TheStoredData : Unsigned_16 := 0; end Unsigned_16_Store;  protected body Unsigned_16_Store is   function Get return Unsigned_16   --# global in TheStoredData;   is   begin     return TheStoredData;   end Get;    procedure Put(X : in Unsigned_16)   --# global out TheStoredData;   --# derives TheStoredData from X;   is   begin     TheStoredData := X;   end Put; end Unsigned_16_Store; </pre>
	Continued on next page

Table 4.1 – continued from previous page

AADL	SPARK Ada
<pre> data Type_With_Range properties   Data_Model::     Data_Representation =&gt;       Integer;   Data_Model::Base_Type =&gt; (     classifier (Base_Types::       Unsigned_16));   Data_Model::Integer_Range =&gt; 0     .. 1000; end Type_With_Range; </pre>	<pre> type Type_With_Range is new Integer range 0 .. 1000;  protected type Type_With_Range_Store is   pragma Priority (10);    function Get return Type_With_Range;   --# global in Type_With_Range_Store;    procedure Put(X : in Type_With_Range);   --# global out Type_With_Range_Store;   --# derives Type_With_Range_Store from X; private   TheStoredData : Type_With_Range := 0; end Unsigned_16_Store;  protected body Type_With_Range_Store is   function Get return Type_With_Range   --# global in TheStoredData;   is   begin     return TheStoredData;   end Get;    procedure Put(X : in Type_With_Range)   --# global out TheStoredData;   --# derives TheStoredData from X;   is   begin     TheStoredData := X;   end Put; end Type_With_Range_Store; </pre>

Type range is defined using AADL properties: `Data_Model::Number_Representation`, `Source_Data_Size` and `Data_Model::Integer_Range`. When `Data_Model::Integer_Range` property is not specified, then range is calculated. In case of `Integer` representation, the range starts from negative value, for `Unsigned` - from 0. The maximum value for `Integer` is calculated using the formula 4.1.

$$\text{Integer\_}[\text{Number\_Of\_Bytes} * 8]\_\text{Max} = 2^{\text{Number\_Of\_Bytes} * 8 - 1} - 1 \quad (4.1)$$

The minimum value formula for `Integer` (4.2) and maximum value for `Unsigned` (4.3) use similar strategy.

$$\text{Integer\_}[Number\_Of\_Bytes * 8]\_Min = -2^{Number\_Of\_Bytes*8-1} \quad (4.2)$$

$$\text{Unsigned\_}[Number\_Of\_Bytes * 8]\_Max = 2^{Number\_Of\_Bytes*8} - 1 \quad (4.3)$$

Mapping for enumeration types, presented in the Table 4.2, is straightforward. BLESS properties are ignored in translation. In addition to simple types, protected types are generated.

**Table 4.2:** AADL/BLESS enumeration types to SPARK mapping.

AADL	SPARK Ada
<pre> data Enum_Type   properties     BLESS::Typed=&gt;"enumeration (Enumerator1,       Enumerator2, Enumerator3)";     Data_Model::Data_Representation =&gt; Enum;     Data_Model::Enumerators =&gt; ("Enumerator1", "       Enumerator2", "Enumerator3"); end Enum_Type; </pre>	<pre> type Enum_Type is (Enumerator1, Enumerator2,   Enumerator3);  protected type Enum_Type_Store   is     pragma Priority (10);      function Get return Enum_Type;     --# global in Enum_Type_Store;      procedure Put(X : in Enum_Type);     --# global out Enum_Type_Store;     --# derives Enum_Type_Store from X;   private     TheStoredData : Enum_Type := Enum_Type'First;   end Enum_Type_Store;  protected body Enum_Type_Store is   function Get return Enum_Type     --# global in TheStoredData;   is   begin     return TheStoredData;   end Get;    procedure Put(X : in Enum_Type)     --# global out TheStoredData;     --# derives TheStoredData from X;   is   begin     TheStoredData := X;   end Put; end Enum_Type_Store; </pre>

Sometimes it is pragmatic to define a type that has exactly the same range as an already existing type, especially when it is used for some specific calculations, e.g., measuring speed. Let's say, that `Unsigned_16` was used. Then, during development of next car model, when a larger number of bits are required to hold anticipated values, it becomes not enough. In case when e.g., `Speed_Type` is not defined, there are two possible resolutions. First: change definition (range) of `Unsigned_16`. That is bad choice, especially because its name specifies the range. Another reason: it might be used not only for measuring the Speed, but maybe also for fuel level, which range is still fine. Second option is to change `Unsigned_16` to e.g. `Unsigned_32` everywhere in Speed Control Module (and maybe also in some external modules). When `Speed_Type` is defined and used everywhere for speed units, then only definition of `Speed_Type` has to be changed. To define type, using existing type in AADL, derived type (defined with `extends` keyword) or `Data_Model::Base_Type` property can be used. Translation to SPARK Ada is shown in the Table 4.3. There are two ways to define type based on some other type in SPARK Ada:

- subtype - it is compatible with its parent, in other words: parent type variable can be assigned to it, if its value is in the subtype range
- derived type - it is incompatible with its parent (parent type variable cannot be assigned to it), but inherits its primitive operations



**Table 4.3:** AADL types to SPARK mapping: Subtypes.

AADL	SPARK Ada
<pre>data Speed_Type extends Base_Types::Integer end Speed_Type;</pre>	<pre>subtype Speed_Type is Base_Types.Integer;</pre>
<pre>data Speed_Type properties   BLESS::Typed=&gt;"integer";   Data_Model::Base_Type =&gt; (classifier(     Base_Types::Unsigned_16)); end Speed_Type;</pre>	<pre>type Speed_Type is new Base_Types.Unsigned_16;</pre>

AADL array type can be defined using property `Data_Model::Data_Representation`. In addition to that, size for array has to be specified by `Data_Model::Dimension` property. Sample mapping of array of 10 integers is shown in the Table 4.4.

Table 4.4: AADL arrays to SPARK Ada mapping

AADL	SPARK Ada
<pre> data Some_Array   properties     BLESS::Typed =&gt; "array [10] of Base_Types:: Integer_32";     Data_Model::Data_Representation =&gt; Array;     Data_Model::Base_Type =&gt; (classifier( Base_Types::Integer_32));     Data_Model::Dimension =&gt; (10); end Some_Array; </pre>	<pre> subtype Some_Array_Index is Integer range 1 .. 10; type Some_Array is array (Some_Array_Index) of Base_Types.Integer_32;  protected type Some_Array_Store is   pragma Priority (10);    function Get(Ind : in Integer) return Base_Types.Integer_32;   --# global in Some_Array_Store;    procedure Put(Ind : in Integer; Val : in Base_Types.Integer_32);   --# global in out Some_Array_Store;   --# derives Some_Array_Store from Some_Array_Store, Ind, Val; private   TheStoredData : Some_Array := Some_Array'( others =&gt; 0); end Some_Array_Store;  protected body Some_Array_Store is   function Get(Ind : in Integer) return Base_Types.Integer_32   --# global in TheStoredData;   is   begin     return TheStoredData(Ind);   end Get;    procedure Put(Ind : in Integer; Val : in Base_Types.Integer_32)   --# global in out TheStoredData;   --# derives TheStoredData from TheStoredData, Ind, Val;   is   begin     TheStoredData(Ind) := Val;   end Put; end Some_Array_Store; </pre>

AADL v2 allows to create struct data types, using `Data_Model::Data_Representation => Struct`. AADL Struct is mapped to SPARK Ada record type. The mapping is presented in the Table 4.5.

**Table 4.5:** AADL struct to SPARK Ada record mapping

AADL	SPARK Ada
<pre> data Some_Record_Type properties   BLESS::Typed =&gt; "record (     Field1 : Base_Types::Integer_32;     Field2 : Base_Types::Boolean;     Field3 : Base_Types::Unsigned_32;   );   Data_Model::Data_Representation =&gt; Struct;   Data_Model::Element_Names =&gt; ("Field1", "Field2", "Field3");   Data_Model::Base_Type =&gt;   (     classifier(Base_Types::Integer_32),     classifier(Base_Types::Boolean),     classifier(Base_Types::Unsigned_32)   ); end Some_Record_Type; </pre>	<pre> type Some_Record_Type is record   Field1 : Integer_32;   Field2 : Boolean;   Field3 : Unsigned_32; end record; </pre>

Data types translations are created based on Brian Larson’s AADL/BLESS models of PCA Pump. They are syntactically verified with SPARK Examiner. During development of types mapping, SPARK Examiner was helpful also for detecting inconsistencies in AADL models. Eg. it detected redundancy in enumerators. Both `Alarm_Type` and `Warning_Type` contained `No_Alarm` enumerator, which was a bug. All enumerators, for all types have to be unique. Thus `Warning_Type` should have `No_Warning` enumerator instead.

### 4.1.2 AADL Ports Mapping

Proposed ports mapping shown in the Table 4.6 is based on AADL runtime services from Annex 2 to "Programming Language Annex Document" [SCD14]. Additionally, the mapping contains SPARK 2005 contracts. Data types used by ports has to be defined earlier, to be visible. Moreover, for port communication, protected types are used, to enable concurrency.

Table 4.6: AADL to SPARK ports mapping.

AADL/BLESS	SPARK Ada
<pre>Port_Name :   in data port Port_Type;</pre>	<pre>-- spec (.ads): --# own protected Port_Name : Port_Type_Store(Priority =&gt; 10)  procedure Receive_Port_Name; --# global out Port_Name;  -- body (.adb): Port_Name : Port_Type_Store;  procedure Receive_Port_Name is begin   -- TODO: implement receiving Port_Name value   -- e.g.:   -- Port_Name.Put(Some_Pkg.Get_Port_Name); end Receive_Port_Name;</pre>
<pre>Port_Name :   out data port Port_Type;</pre>	<pre>-- spec (.ads) --# own protected Port_Name : Port_Type_Store(Priority =&gt; 10)  procedure Get_Port_Name(Port_Name_Out : out Port_Type); --# global in Port_Name; --# derives Port_Name_Out from Port_Name;  -- body (.adb): Port_Name : Port_Type_Store;  procedure Get_Port_Name(Port_Name_Out : out Port_Type) is begin   Port_Name_Out := Port_Name.Get; end Get_Port_Name;</pre>
<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 end Put_Port_Name;</pre>
Continued on next page	

Table 4.6 – 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; end Send_Port_Name;</pre>
<pre>Port_Name :   in event data port Port_Type;</pre>	<pre>-- spec (.ads) --# own protected Port_Name : Port_Type_Store(Priority =&gt; 10);  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_Store;  procedure Put_Port_Name (Port_Name_In : Port_Type) is begin   Port_Name.Put(Port_Name_In); end Put_Port_Name;</pre>
<pre>Port_Name :   out event data port Port_Type;</pre>	<pre>-- spec (.ads) --# own protected Port_Name : Port_Type_Store(Priority =&gt; 10);  procedure Send_Port_Name; --# global in Port_Name;  -- body (.adb): Port_Name : Port_Type_Store;  procedure Send_Port_Name is begin   -- TODO: implement receiving Port_Name value   -- e.g.:   -- Some_Pkg.Put_Port_Name(Port_Name); end Send_Port_Name;</pre>

### 4.1.3 Thread to Task Mapping

AADL Threads are mapped into SPARK Ada tasks as presented in the Table 4.7. Communication between threads is described in Section 4.2.1.

**Table 4.7:** 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;    thread implementation Some_Thread.imp   end Some_Thread.imp; end Some_Pkg; </pre>	<pre> package Some_Pkg is   task type Some_Thread     --# global out Some_Port;   is     pragma Priority(10);   end Some_Thread; end Some_Pkg;  package body Some_Pkg is   st : Some_Thread;    task body Some_Thread   is   begin     loop       -- implementation     end loop;   end Some_Thread; end Some_Pkg; </pre>

### 4.1.4 Subprograms Mapping

Mappings of subprograms is also straightforward. However, it is different than mapping proposed in "AADL Code Generation Annex" [SCD14]. It does not use **renames** clause, but mapping directly to subprogram specification and body. For now, body is empty, because behavior (implementation) is not captured. Subprogram mapping should be revised and consulted with AADL committee members, in order to understand their design decisions.

**Table 4.8:** AADL subprograms to SPARK Ada subprograms 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);  procedure sp(e : in T; s : out T) is begin   --# implementation end sp; </pre>

### 4.1.5 Feature Groups Mapping

In SPARK Ada there are nested packages and child packages. Sample nested packages are shown in the Figure 4.3. Equivalent child packages are shown in the Figure 4.4. 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 figures 4.3 and 4.4). 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 the Figure 4.3 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.

There was an idea to create child package to encapsulate one feature group in it. However, SPARK Ada does not allow to access child packages private part from parent. Thus, it will require to expose feature group internal variable as public. It is definitely not good solution. Thus, feature group is translated with prefix `Feature_Group_Name_*`. Feature group mapping is presented in Section 4.1.6, in figures 4.5, 4.6 and 4.7.

### 4.1.6 AADL Package to SPARK Ada Package Mapping

Figure 4.5 presents sample AADL package with `system` entity. It contains all types of ports described in Section 4.1.2 and one feature group with two ports as example of feature group mapping.

For now, only single process SPARK Ada application is considered. Thus, ports are exposed only on system level. Communication between threads in process will be realized by protected objects and only SPARK annotations and data types will be needed as described in Section 4.1.3. Based on ports mapping, presented in Section 4.1.2, translation to SPARK Ada package is shown in the Figure 4.6 and Figure 4.7.

### 4.1.7 AADL Property Set to SPARK Ada Package Mapping

There is no equivalent construct for AADL property set in SPARK Ada. Thus property set is mapped to SPARK Ada package. In this thesis, only properties of type `constant aadlinteger` are considered. There are issues with using non-constant types in SPARK Ada package (e.g. when using them in some type definition). Table 4.9 shows sample property set mapping to SPARK Ada package.

**Table 4.9:** AADL property set to SPARK Ada package mapping

AADL	SPARK Ada
<pre>property set Some_Properties is   Some_Property1 : constant aadlinteger =&gt; 10;   Some_Property2 : constant aadlinteger =&gt; 27     applies to (all);   Some_Property3 : constant aadlinteger =&gt;     Some_Properties::Some_Property1 applies to (       all); end Some_Properties;</pre>	<pre>package Some_Properties is   Some_Property1 : constant Integer := 10;   Some_Property2 : constant Integer := 27;   Some_Property3 : constant Integer :=     Some_Property1; end Some_Properties;</pre>

In AADL, all declarations must have an `applies to` clause. It is ignored in resulted SPARK



Ada translation. However, it can be used in the future e.g. for automatic generation of **with** clauses.

#### 4.1.8 BLESS Mapping

In cooperation with Brian Larson, translations for BLESS assertions, invariant, pre- and postconditions were created. Table 4.10 presents their mapping to SPARK Ada. Generated (translated) code may not be complete. Then developer's effort to implement missing parts will be required. E.g. when assertion is specified in AADL/BLESS model, but not defined, it has to be implemented.

**Table 4.10:** BLESS to SPARK contracts mapping

AADL/BLESS	SPARK Ada
<code>BLESS::Assertion=&gt;"&lt;&lt;COND1()&gt;&gt;"</code>	<code>--# assert COND1;</code>
<pre>thread Some_Thread features   Some_Port : out event port   {BLESS::Assertion =&gt; "&lt;&lt;(Var1 &lt; Var2 and COND2()     )&gt;&gt;"}; end Some_Thread;</pre>	<pre>task body Some_Thread is begin   loop     --# assert (Var1 &lt; Var2 and COND2);   end loop; end Some_Thread;</pre>
<pre>thread implementation Some_Thread.imp annex BLESS {**   invariant &lt;&lt;(Some_Var &lt; Other_Var)&gt;&gt; **}; end Some_Thread.imp;</pre>	<pre>task body Some_Thread is begin   loop     --# assert (Some_Var &lt; Other_Var);   end loop; end Some_Thread;</pre>
Continued on next page	

Table 4.10 – continued from previous page

AADL/BLESS	SPARK Ada
<pre> thread implementation Some_Thread.imp annex BLESS {**   assert     &lt;&lt;State1 : :COND1() or COND2()&gt;&gt;     &lt;&lt;Var : :=       (State1()) -&gt; 0,       (State2()) -&gt; -1,       (State3()) -&gt; 9     &gt;&gt; **}; end Some_Thread.imp; </pre>	<pre> task body Some_Thread is begin   loop     --# assert (COND1 or COND2)     --#         -&gt; State1();     --# assert (Var = 0) -&gt; State1 and     --#         (Var = -1) -&gt; State2 and     --#         (Var = 9) -&gt; State3;   end loop; end Some_Thread; </pre>
<pre> subprogram Some_Subprogram features   param : out parameter Base_Types::Integer; annex subBless {**   pre &lt;&lt;(param &gt; 0)&gt;&gt;   post &lt;&lt;(param = 0)&gt;&gt; **}; end Some_Subprogram; </pre>	<pre> procedure Some_Subprogram(Param : in out Integer) ; --# pre Param &gt; 0; --# post Param = 0; </pre>

## 4.2 Port-based Communication

Communication between AADL components is realized by ports. AADL ports can be declared in subprograms, threads, processes, systems and other entities. In this Section communication between threads in single-process SPARK Ada application (4.2.1) and concept of communication between two systems (4.2.2) are presented.

### 4.2.1 Threads Communication

Example of communication between threads, in single process is depicted in the Figure 4.8. There are two threads (`some_thread` and `other_thread`) in one process. AADL model and its

translation to SPARK Ada is presented in the Table 4.11. Connection between threads has to be specified in process implementation. Based on mappings from Section 4.1, protected object is defined, but subprograms are skipped, because communication takes place only internally. The result of translation consists of two tasks and private global protected object, which enable communication between them. Additionally, both tasks has global annotation (one with `out` mode, other with `in` mode), which announce use of protected object in their bodies.

Threads can be also placed in different packages. The same example of two threads within one process, but in different packages is presented in the Table 4.12. In this case, subprograms present in mapping table, in Section 4.2 are also present in resulted translation. Moreover, body of procedure `Receive_Some_Port` is implemented as a result of defined connection between threads in the process implementation, in AADL model.

**Table 4.11:** AADL threads communication to SPARK Ada tasks communication translation

AADL/BLESS	SPARK Ada
<pre> package Some_Pkg public with Base_Types;    process Some_Proc   end Some_Proc;    process implementation Some_Proc.imp   subcomponents     some_thread: thread Some_Thread.imp;     other_thread: thread Other_Thread.imp;   connections     connection: port some_thread.Some_Port -&gt;       other_thread.Some_Port;   end Some_Proc.imp;    thread Some_Thread   features     Some_Port : out data port Base_Types::       Integer;   end Some_Thread;    thread implementation Some_Thread.imp   end Some_Thread.imp;    thread Other_Thread   features     Some_Port : in data port Base_Types::Integer     ;   end Other_Thread;    thread implementation Other_Thread.imp   end Other_Thread.imp; end Some_Pkg; </pre>	<pre> with Base_Types; --# inherit Base_Types; package Some_Pkg --# own task st : Some_Thread; --#   task ot : Other_Thread; --#   protected Some_Port : Base_Types. --#     Integer_Store (Priority =&gt; 10); is  private   task type Some_Thread   --# global out Some_Port;   is     pragma Priority (10);   end Some_Thread;    task type Other_Thread   --# global in Some_Port;   is     pragma Priority (10);   end Other_Thread; end Some_Pkg;  package body Some_Pkg is   st : Some_Thread;   ot : Other_Thread;   Some_Port : Base_Types.Integer_Store;    task body Some_Thread   is   begin     loop       -- implementation     end loop;   end Some_Thread;    task body Other_Thread   is   begin     loop       -- implementation     end loop;   end Other_Thread; end Some_Pkg; </pre>

```

package Base_Types
public
  with Data_Model;

  data Boolean
  properties
    Data_Model::Data_Representation => Boolean;
  end Boolean;
  data Integer
  properties
    Data_Model::Data_Representation => Integer;
  end Integer;
  data Natural extends Integer
  properties
    Data_Model::Integer_Range => 0 .. Max_Target_Integer;
  end Natural;
  data Integer_8 extends Integer
  properties
    Data_Model::Number_Representation => Signed;
    Source_Data_Size => 1 Bytes;
  end Integer_8;
  data Integer_16 extends Integer
  properties
    Data_Model::Number_Representation => Signed;
    Source_Data_Size => 2 Bytes;
  end Integer_16;
  data Integer_32 extends Integer
  properties
    Data_Model::Number_Representation => Signed;
    Source_Data_Size => 4 Bytes;
  end Integer_32;
  data Integer_64 extends Integer
  properties
    Data_Model::Number_Representation => Signed;
    Source_Data_Size => 8 Bytes;
  end Integer_64;
  data Unsigned_8 extends Integer
  properties
    Data_Model::Number_Representation => Unsigned;
    Source_Data_Size => 1 Bytes;
  end Unsigned_8;
  data Unsigned_16 extends Integer
  properties
    Data_Model::Number_Representation => Unsigned;
    Source_Data_Size => 2 Bytes;
  end Unsigned_16;
  data Unsigned_32 extends Integer
  properties
    Data_Model::Number_Representation => Unsigned;
    Source_Data_Size => 4 Bytes;
  end Unsigned_32;
  data Unsigned_64 extends Integer
  properties
    Data_Model::Number_Representation => Unsigned;
    Source_Data_Size => 8 Bytes;
  end Unsigned_64;
end Base_Types;

```

**Figure 4.1:** AADL `Base_Types` package

```

with Interfaces;

package Base_Types is
  type AADL_Boolean is new Standard.Boolean;
  type AADL_Integer is new Standard.Integer;
  type AADL_Natural is new Standard.Integer;
  type Integer_8 is new Interfaces.Integer_8;
  type Integer_16 is new Interfaces.Integer_16;
  type Integer_32 is new Interfaces.Integer_32;
  type Integer_64 is new Interfaces.Integer_64;
  type Unsigned_8 is new Interfaces.Unsigned_8;
  type Unsigned_16 is new Interfaces.Unsigned_16;
  type Unsigned_32 is new Interfaces.Unsigned_32;
  type Unsigned_64 is new Interfaces.Unsigned_64;
end Base_Types;

```

**Figure 4.2:** Mapping of `Base_Types` for SPARK 2014

```

package P is
  D: Integer;

  -- 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;

```

**Figure 4.3:** 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 P.M is
  Y: Integer;
private
  Bar: Integer;
end P.M;

```

**Figure 4.4:** Child packages in SPARK Ada

```

package Some_Pkg
public
with Base_Types;

feature group Some_Features
features
  Some_Out_Port: out data port Base_Types::Integer;
  Some_In_Port: in data port Base_Types::Integer;
end Some_Features;

system Some_System
features
  Some_Feature_Group : feature group Some_Features;

  In_Data_Port : in data port Base_Types::Integer;
  Out_Data_Port : out data port Base_Types::Integer;
  In_Event_Port : in event port;
  Out_Event_Port : out event port;
  In_Event_Data_Port : in event data port Base_Types::Integer;
  Out_Event_Data_Port : out event data port Base_Types::Integer;
end Some_System;

end Some_Pkg;

```

**Figure 4.5:** Sample AADL package with system

```

package Some_Pkg
--# own Some_Features_Some_Out_Port : Integer;
--#   Some_Features_Some_In_Port : Integer;
--#   In_Data_Port : Integer;
--#   Out_Data_Port : Integer;
--#   In_Event_Data_Port : Integer;
--#   Out_Event_Data_Port : Integer;
--# initializes Some_Features_Some_Out_Port,
--#             Some_Features_Some_In_Port,
--#             In_Data_Port,
--#             Out_Data_Port,
--#             In_Event_Data_Port,
--#             Out_Event_Data_Port;
is

    function Some_Features_Get_Some_Out_Port return Integer;
    --# global in Some_Features_Some_Out_Port;

    procedure Some_Features_Receive_Some_In_Port;
    --# global out Some_Features_Some_In_Port;

    procedure Receive_In_Data_Port;
    --# global out In_Data_Port;

    function Get_Out_Data_Port return Integer;
    --# global in Out_Data_Port;

    procedure Put_In_Event_Port;

    procedure Send_Out_Event_Port;

    procedure Put_In_Event_Data_Port(In_Event_Data_Port_In : Integer);
    --# global out In_Event_Data_Port;
    --# derives In_Event_Data_Port from In_Event_Data_Port_In;

    procedure Send_Out_Event_Data_Port;
    --# global in Out_Event_Data_Port;

end Some_Pkg;

```

**Figure 4.6:** Translation of sample AADL package from Figure 4.5 - package specification



```

package body Some_Pkg
is
    Some_Features_Some_Out_Port : Integer := 0;
    Some_Features_Some_In_Port : Integer := 0;
    In_Data_Port : Integer := 0;
    Out_Data_Port : Integer := 0;
    In_Event_Data_Port : Integer := 0;
    Out_Event_Data_Port : Integer := 0;

    function Some_Features_Get_Some_Out_Port return Integer
    is
    begin
        return Some_Features_Some_Out_Port;
    end Some_Features_Get_Some_Out_Port;

    procedure Some_Features_Receive_Some_In_Port
    is
    begin
        -- implementation
    end Some_Features_Receive_Some_In_Port;

    procedure Receive_In_Data_Port
    is
    begin
        -- implementation
    end Receive_In_Data_Port;

    function Get_Out_Data_Port return Integer
    is
    begin
        return Out_Data_Port;
    end Get_Out_Data_Port;

    procedure Put_In_Event_Port
    is
    begin
        -- implementation
    end Put_In_Event_Port;

    procedure Send_Out_Event_Port
    is
    begin
        -- implementation
    end Send_Out_Event_Port;

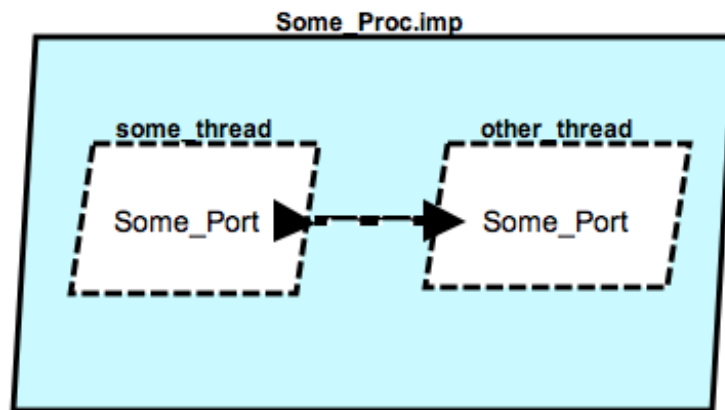
    procedure Put_In_Event_Data_Port(In_Event_Data_Port_In : Integer)
    is
    begin
        In_Event_Data_Port := In_Event_Data_Port_In;
    end Put_In_Event_Data_Port;

    procedure Send_Out_Event_Data_Port
    is
    begin
        -- implementation
    end Send_Out_Event_Data_Port;

end Some_Pkg;

```

**Figure 4.7:** Translation of sample AADL package from Figure 4.5 - package body



**Figure 4.8:** Example of port communication between threads

**Table 4.12:** AADL threads communication to SPARK Ada tasks communication translation (multiple packages)

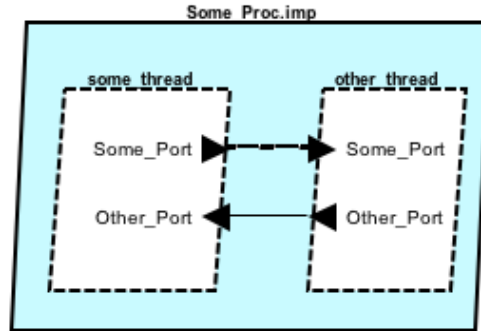
AADL/BLESS	SPARK Ada
<pre> package Pkg1 public with Base_Types, Pkg2;    process Some_Proc   end Some_Proc;    process implementation     Some_Proc.imp   subcomponents     some_thread: thread       Some_Thread.imp;     other_thread: thread Pkg2::       Other_Thread.imp;   connections     connection: port some_thread.       Some_Port -&gt; other_thread.       Some_Port;   end Some_Proc.imp;    thread Some_Thread   features     Some_Port : out data port       Base_Types::Integer;   end Some_Thread;    thread implementation     Some_Thread.imp   end Some_Thread.imp; </pre>	<pre> with Base_Types; --# inherit Base_Types; package Pkg1 --# own task st : Some_Thread; --#   protected Some_Port : Base_Types.Integer_Store (Priority =&gt; --#     10); is   procedure Get_Some_Port(Some_Port_Out : out Integer);   --# global in Some_Port;   --# derives Some_Port_Out from Some_Port;  private   task type Some_Thread   --# global out Some_Port;   is     pragma Priority (10);   end Some_Thread; end Pkg1;  package body Pkg1 is   st : Some_Thread;   Some_Port : Base_Types.Integer_Store;    procedure Get_Some_Port(Some_Port_Out : out Integer)   is   begin     Some_Port_Out := Some_Port.Get;   end Get_Some_Port;    task body Some_Thread   is   begin     loop       -- implementation     end loop;   end Some_Thread;  end Pkg1; </pre>
Continued on next page	

Table 4.12 – continued from previous page

AADL/BLESS	SPARK Ada
<pre> package Pkg2 public with Base_Types;    thread Other_Thread   features     Some_Port : in data port       Base_Types::Integer;   end Other_Thread;    thread implementation     Other_Thread.imp   end Other_Thread.imp; end Pkg2; </pre>	<pre> with Base_Types; with Pkg1; --# inherit Base_Types, --#       Pkg1; package Pkg2 --# own task ot : Other_Thread; --#   protected Some_Port : Base_Types.Integer_Store (Priority =&gt; --#       10); is   procedure Receive_Some_Port;   --# global out Some_Port;   --#       in Pkg1.Some_Port;  private   task type Other_Thread   --# global in Some_Port;   is     pragma Priority (10);     end Other_Thread; end Pkg2;  package body Pkg2 is   ot : Other_Thread;   Some_Port : Base_Types.Integer_Store;    procedure Receive_Some_Port   is     Temp : Integer;   begin     Pkg1.Get_Some_Port(Temp);     Some_Port.Put(Temp);   end Receive_Some_Port;    task body Other_Thread   is     begin       loop         -- implementation       end loop;     end Other_Thread; end Pkg2; </pre>

In the given example, communication is one way: from `Pkg1` package to `Pkg2` package. Thus, `Pkg1` package does not need to know that `Pkg2` package exists. In other words: it does not need to "with" it. However, if two way communication is needed (between `Pkg1` to `Pkg2`), then `Pkg1` package has to "with" `Pkg2` package. It is not a case in first example, where communication between threads take place in the same package. Modified model of second

example, with communication from `Pkg2` to `Pkg1`, is depicted in the Figure 4.9 and presented in the Figure 4.10.



**Figure 4.9:** Example of two way port communication between threads in different packages

This model, translated to SPARK Ada is presented in the Figure 4.11 and Figure 4.12. It will not compile. GNAT compiler returns `circular unit dependency` error. Additionally verification with SPARK Examiner returns error: `Semantic Error 135 - The package Pkg2TwoWay is undeclared or not visible, or there is a circularity in the list of inherited packages.` Now, the problem is that two-way communication is allowed in AADL, but not in SPARK, nor even in Ada. This require further investigation, which is omitted in this thesis.

## 4.2.2 Systems Communication

This Section is a concept, how communication between different systems can look like. AADL system consists of process(es) and process consists of threads. Ports would be exposed by package if they are specified in system entity. Communication between two systems cab be described by another system. Figure 4.13 presents communication between two systems: panel and pump. AADL model of this system comprises 3 packages: `Main`, `Panel` and `Pump`. They are presented in the figures 4.14, 4.15 and 4.16. `Panel` package has one thread `Panel_Thread` with two out ports: `event port` and `event data port`. Both ports are exposed by process `panel_process` and then by system `panel`. `Pump` package has similar structure, but two in ports. Both are also

```

package Pkg1TwoWay
public
with Base_Types, Pkg2TwoWay;

process Some_Proc
end Some_Proc;

process implementation Some_Proc.imp
subcomponents
  some_thread: thread Some_Thread.imp;
  other_thread: thread Pkg2TwoWay::Other_Thread.imp;
connections
  connection: port some_thread.Some_Port -> other_thread.Some_Port;
  connection2: port some_thread.Other_Port -> other_thread.Other_Port;
end Some_Proc.imp;

thread Some_Thread
features
  Some_Port : out data port Base_Types::Integer;
  Other_Port : in data port Base_Types::Integer;
end Some_Thread;

thread implementation Some_Thread.imp
end Some_Thread.imp;
end Pkg1TwoWay;

package Pkg2TwoWay
public
with Base_Types;
thread Other_Thread
features
  Some_Port : in data port Base_Types::Integer;
  Other_Port : out data port Base_Types::Integer;
end Other_Thread;

thread implementation Other_Thread.imp
end Other_Thread.imp;
end Pkg2TwoWay;

```

**Figure 4.10:** AADL model of two way port communication threads in different packages

exposed by process (`pump_process`) and system (`pump`). Connection between these two packages are defined in `Main` package.

Based on mappings from Section 4.1, conforming SPARK Ada code is presented in the figures 4.17 and 4.17. There are two packages: `Panel` and `Pump`. `Main` package is omitted. Both contain procedures representing ports interfaces, according to ports mapping from Section 4.1.2. Additionally, both consists of empty thread declarations and bodies, which conforms to translations from Section 4.1.3. However, in this case, both packages will work in different systems, thus different processes. To enable communication between different

systems, deployment methodology and the middle-ware layer has to be created. It will allow not only for system to system communication, but also for communication with devices. It is omitted in this thesis.

## 4.3 Towards an Automatic Translator

The ultimate goal is to create translator, which performs translations described in 4.1 and 4.2 automatically. Automatic translator should enable translation of entire model and parts of the model. Initially, translator should support only subset of AADL entities: the system, process, thread, subprogram and port communication. The following functions should be supported:

- data types translation (as described in Section 4.1.1)
- threads to tasks translation (as described in 4.1.3)
- single ports translation (based on Section 4.1.2)
- subprogram to procedure/function translation (based on Section 4.1.4)
- single package translation with system, which contains ports and feature groups (as described in Section 4.1.6)
- property set mapping to SPARK Ada package (like in Section 4.1.7)

Second step, would be to introduce BLESS support. Which means, add supported BLESS constructs described in Section 4.1.8:

- assertions for threads
- pre- and postconditions for subprograms

Recommended way to create translator is to parse AADL models, create Abstract Syntax Tree (AST) and emit code using Visitor pattern. Parser and AST can be generated using ANTLR<sup>4</sup> (Another Tool for Language Recognition) and its grammar development environment ANTLRWorks.<sup>5</sup> ANTLR 4 (with ANTLRWorks 2) enable automatic AST creation and handle left recursion, which makes parser development much easier and faster. Another tool, Xtext<sup>6</sup> can be also used (instead of ANTLR) for parser and AST generator. For emitting code, StringTemplate<sup>7</sup> (template engine for generating code) can be used.

Development should be performed incrementally. From adding translation for the simplest constructs, like data types or single ports, to port communication and BLESS. First step, would be AADL grammar development. It is recommended to initially, specify only part of required AADL subset and then extend it incrementally. In order to do that, AADL Syntax Card<sup>8</sup> might be helpful. During translator development unit testing and Test Driven Development is recommended. Translation schemes can be used as input and expected output of particular test cases. It will help to ensure correctness of translator while working on new features support.

Additionally, automatic translator should work in two modes:

- Ravenscar: as described above, with protected objects and multiple tasks
- Sequential: single-threaded application, without notion of tasks and protected objects

---

<sup>4</sup><http://wwwantlr.org/>

<sup>5</sup><http://tunnelvisionlabs.com/products/demo/antlrworks>

<sup>6</sup><http://www.eclipse.org/Xtext/index.html>

<sup>7</sup><http://www.stringtemplate.org/>

<sup>8</sup>[https://wiki.sei.cmu.edu/aadl/images/d/d2/AADL\\_V2.1\\_Syntax\\_Card.pdf](https://wiki.sei.cmu.edu/aadl/images/d/d2/AADL_V2.1_Syntax_Card.pdf)



```

with Base_Types;
with Pkg2TwoWay;
--# inherit Base_Types,
--#       Pkg2TwoWay;
package Pkg1TwoWay
--# own task st : Some_Thread;
--#   protected Some_Port : Base_Types.Integer_Store (Priority => 10);
--#   protected Other_Port : Base_Types.Integer_Store (Priority => 10);
is
  procedure Get_Some_Port(Some_Port_Out : out Integer);
  --# global in Some_Port;
  --# derives Some_Port_Out from Some_Port;

  procedure Receive_Other_Port;
  --# global out Other_Port;
  --#       in Pkg2TwoWay.Other_Port;

private
  task type Some_Thread
  --# global out Some_Port;
  is
    pragma Priority (10);
  end Some_Thread;
end Pkg1TwoWay;

package body Pkg1TwoWay
is
  st : Some_Thread;
  Some_Port : Base_Types.Integer_Store;
  Other_Port : Base_Types.Integer_Store;

  procedure Get_Some_Port(Some_Port_Out : out Integer)
  is
  begin
    Some_Port_Out := Some_Port.Get;
  end Get_Some_Port;

  procedure Receive_Other_Port
  is
    Temp : Integer;
  begin
    Pkg2TwoWay.Get_Other_Port(Temp);
    Other_Port.Put(Temp);
  end Receive_Other_Port;

  task body Some_Thread
  is
  begin
    loop
      -- implementation
      null;
    end loop;
  end Some_Thread;
end Pkg1TwoWay;

```

**Figure 4.11:** Two way port communication translated to SPARK Ada: package `Pkg1TwoWay`

```

with Base_Types;
with Pkg1TwoWay;
--# inherit Base_Types,
--#       Pkg1TwoWay;
package Pkg2TwoWay
--# own task ot : Other_Thread;
--#   protected Some_Port : Base_Types.Integer_Store (Priority => 10);
--#   protected Other_Port : Base_Types.Integer_Store (Priority => 10);
is
  procedure Receive_Some_Port;
  --# global out Some_Port;
  --#       in Pkg1TwoWay.Some_Port;

  procedure Get_Other_Port(Other_Port_Out : out Integer);
  --# global in Other_Port;
  --# derives Other_Port_Out from Other_Port;

private
  task type Other_Thread
  --# global in Some_Port;
  is
    pragma Priority (10);
  end Other_Thread;
end Pkg2TwoWay;

package body Pkg2TwoWay
is
  ot : Other_Thread;
  Some_Port : Base_Types.Integer_Store;
  Other_Port : Base_Types.Integer_Store;

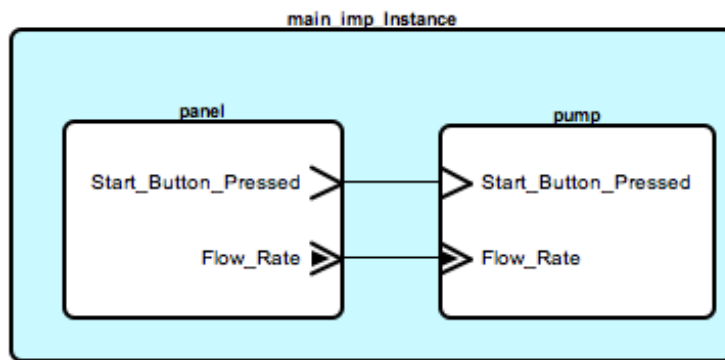
  procedure Receive_Some_Port
  is
    Temp : Integer;
  begin
    Pkg1TwoWay.Get_Some_Port(Temp);
    Some_Port.Put(Temp);
  end Receive_Some_Port;

  procedure Get_Other_Port(Other_Port_Out : out Integer)
  is
  begin
    Other_Port_Out := Other_Port.Get;
  end Get_Other_Port;

  task body Other_Thread
  is
  begin
    loop
      -- implementation
      null;
    end loop;
  end Other_Thread;
end Pkg2TwoWay;

```

**Figure 4.12:** Two way port communication translated to SPARK Ada: package `Pkg2TwoWay`



**Figure 4.13:** Example of port communication between systems

```

package Panel
public
with Base_Types;

    thread Panel_Thread
    features
        Start_Button_Pressed: out event port;
        Flow_Rate: out event data port Base_Types::Integer;
    end Panel_Thread;

    thread implementation Panel_Thread.imp
    end Panel_Thread.imp;

    process panel_process
    features
        Start_Button_Pressed: out event port;
        Flow_Rate: out event data port Base_Types::Integer;
    end panel_process;

    process implementation panel_process.imp
    subcomponents
        panel_thread: thread Panel_Thread.imp;
    connections
        sbp: port panel_thread.Start_Button_Pressed->Start_Button_Pressed;
        fr: port panel_thread.Flow_Rate->Flow_Rate;
    end panel_process.imp;

    system panel
    features
        Start_Button_Pressed: out event port;
        Flow_Rate: out event data port Base_Types::Integer;
    end panel;

    system implementation panel.imp
    subcomponents
        panel_process: process panel_process.imp;
    connections
        sbp: port panel_process.Start_Button_Pressed->Start_Button_Pressed;
        fr: port panel_process.Flow_Rate->Flow_Rate;
    end panel.imp;

end Panel;

```

**Figure 4.14:** AADL model of port communication between systems: package `Panel`

```

package Pump
public
with Base_Types;

  thread Rate_Controller
    features
      Start_Button_Pressed: in event port;
      Flow_Rate: in event data port Base_Types::Integer;
    end Rate_Controller;

  thread implementation Rate_Controller.imp
end Rate_Controller.imp;

  process pump_process
    features
      Start_Button_Pressed : in event port;
      Flow_Rate: in event data port Base_Types::Integer;
    end pump_process;

  process implementation pump_process.imp
    subcomponents
      Rate_Controller: thread Rate_Controller.imp;
    connections
      sbp: port Start_Button_Pressed->Rate_Controller.Start_Button_Pressed;
      fr: port Flow_Rate->Rate_Controller.Flow_Rate;
    end pump_process.imp;

  system pump
    features
      Start_Button_Pressed : in event port;
      Flow_Rate: in event data port Base_Types::Integer;
    end pump;

  system implementation pump.imp
    subcomponents
      pump_process : process pump_process.imp;
    connections
      sbp: port Start_Button_Pressed->pump_process.Start_Button_Pressed;
      fr: port Flow_Rate->pump_process.Flow_Rate;
    end pump.imp;
end Pump;

```

**Figure 4.15:** AADL model of port communication between systems: package Pump

```

package Main
public
with Pump,
  Panel;

  system main
  end main;

  system implementation main.imp
  subcomponents
    panel: system Panel::panel.imp;
    pump: system Pump::pump.imp;
  connections
    sbp2sbp: port panel.Start_Button_Pressed->pump.Start_Button_Pressed;
    fr2fr: port panel.Flow_Rate->pump.Flow_Rate;
  end main.imp;
end Main;

```

**Figure 4.16:** AADL model of port communication between systems: package `Main`

```

with Pump;
with Base_Types;
--# inherit Pump,
--#      Base_Types;
package Panel
--# own task pt : Panel_Thread;
--#      protected Flow_Rate : Base_Types.Integer_Store (Priority => 10);
is
    procedure Send_Start_Button_Pressed;

    procedure Send_Flow_Rate;
    --# global in Flow_Rate;
    --#      out Pump.Flow_Rate;

private
    task type Panel_Thread
    --# global in out Flow_Rate;
    is
        pragma Priority (10);
    end Panel_Thread;

end Panel;

package body Panel
is
    pt : Panel_Thread;
    Flow_Rate : Base_Types.Integer_Store;

    procedure Send_Start_Button_Pressed
    is
    begin
        Pump.Put_Start_Button_Pressed;
    end Send_Start_Button_Pressed;

    procedure Send_Flow_Rate
    is
        Flow_Rate_Temp : Integer;
    begin
        Flow_Rate_Temp := Flow_Rate.Get;
        Pump.Put_Flow_Rate(Flow_Rate_Temp);
    end Send_Flow_Rate;

    task body Panel_Thread
    is
    begin
        loop
            -- implementation
        end loop;
    end Panel_Thread;

end Panel;

```

**Figure 4.17:** Port communication translated to SPARK Ada: package `Panel`

```

with Base_Types;
--# inherit Base_Types;
package Pump
--# own task rc : Rate_Controller;
--#   protected Flow_Rate : Base_Types.Integer_Store (Priority => 10);
is
    procedure Put_Start_Button_Pressed;

    procedure Put_Flow_Rate(Flow_Rate_In : Integer);
    --# global out Flow_Rate;
    --# derives Flow_Rate from Flow_Rate_In;

private
    task type Rate_Controller
    --# global in out Flow_Rate;
    is
        pragma Priority (10);
    end Rate_Controller;
end Pump;

package body Pump
is
    rc : Rate_Controller;
    Flow_Rate : Base_Types.Integer_Store;

    procedure Put_Start_Button_Pressed
    is
    begin
        -- TODO: implement event handler
    end Put_Start_Button_Pressed;

    procedure Put_Flow_Rate(Flow_Rate_In : Integer)
    is
    begin
        Flow_Rate.Put(Flow_Rate_In);
    end Put_Flow_Rate;

    task body Rate_Controller
    is
    begin
        loop
            -- implementation
        end loop;
    end Rate_Controller;
end Pump;

```

**Figure 4.18:** Port communication translated to SPARK Ada: package `Pump`



# Chapter 5

## PCA Pump Prototype Implementation and Code Generation

This chapter describes running SPARK Ada programs on BeagleBoard-xM platform (3.3), implementation details of PCA pump prototype (5.2)) and code generation from simplified AADL/BLESS models of PCA pump (5.3). All programs presented in this section works the same on Intel processor (PC or MacBook) and on BeagleBoard-xM (ARM device).

### 5.1 Running SPARK Ada Programs on BeagleBoard-xM

To run SPARK Ada program on BeagleBoard-xM, it has to be cross-compiled. As an IDE for SPARK Ada development, GNAT Programming Studio (GPS) is used (see Section 2.5.2). To create "Hello, World!" application, new Ada project has been created (choosing Project/New... from the menu). Then main.adb file, with procedure Main printing "Hello, World!" in standard output, was added. The code is presented in the Figure 5.1. It is valid Ada 2005 and Ada 2012 code.

The main file has to be always specified in project file (.gpr) in order to compile and

```

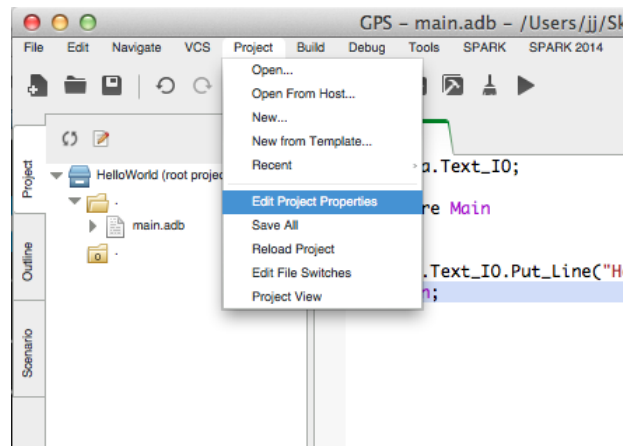
with Ada.Text_IO;
use Ada.Text_IO;

procedure Main
is
begin
    Put_Line("Hello, World!");
end Main;

```

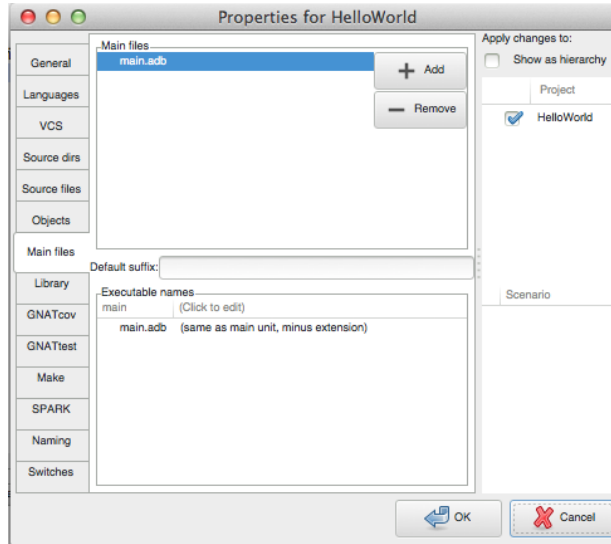
**Figure 5.1:** "Hello World" in Ada

link application, which can be runnable. It can be done in Project/Edit Project Properties (Figure 5.2), tab: Main files (Figure 5.3) or directly in project file (.gpr).



**Figure 5.2:** Edit Project Properties

To enable cross-compilation, for current version of cross-compiler, environmental variable `\$ENV_PREFIX` has to be set to directory, which contains `/lib` and `/usr` directories. Latter should also contains `/usr/lib` and `/usr/include` subdirectories. After mentioned directories has been copied into `/home/super/angstrom-arm` directory, `\$ENV_PREFIX` has been exported with following command: `export ENV_PREFIX=/home/super/angstrom-arm`. Entire project can be compiled and linked with following command: `arm-linux-gnueabi-gnatmake -d -Phelloworld.gpr` (where `helloworld.gpr` is GNAT Programming Studio project file). Additional flags can be specified in command line or directly in project file (manually or through GNAT Programming Studio Interface).



**Figure 5.3:** Project Main files

More complex example, which takes advantage of SPARK contracts is presented in Section 5.1.1.

### 5.1.1 Odometer

Odometer is a simple SPARK Ada program, which implements basic functions of standard Odometer. Figure 5.4 shows Odometer in SPARK 2005.

There are 4 subprograms (2 procedures and 2 functions), which are globally available (through other packages and program units):

- `Zero_Trip` procedure - reset Odometer to 0
- `Read_Trip` function - returns current distance
- `Read_Total` function - returns total distance traveled
- `Inc` procedure - increment total and current distance by 1

```

package Odometer
--# own
--# Trip,          -- number of meters so far on this trip (can be reset to 0).
--# Total          -- total meters traveled of vehicle since the last factory-reset.
--#   : Natural; -- has range 0 .. Integer'Last.
--# initializes Trip,
--#               Total;
is
  procedure Zero_Trip; -- sets Trip to 0 and clears all saved Trip marks.
    --# global out Trip;
    --# derives Trip from ;
    --# post Trip = 0;

    function Read_Trip return Natural; -- returns value of Trip.
      --# global in Trip;
      --# return Trip;

    function Read_Total return Natural; -- returns value of Total
      --# global in Total;
      --# return Total;

    procedure Inc; -- increments each of Trip and Total by 1.
      --# global in out Trip, Total;
      --# derives Trip from Trip & Total from Total;
      --# pre Trip < Integer'Last and Total < Integer'Last;
      --# post Trip = Trip~ + 1 and Total = Total~ + 1;
end Odometer;

package body Odometer is
  Trip : Natural := 0;
  Total : Natural := 0;

  procedure Zero_Trip is
  begin
    Trip := 0;
  end Zero_Trip;

  function Read_Trip return Natural is
  begin
    return Trip;
  end Read_Trip;

  function Read_Total return Natural is
  begin
    return Total;
  end Read_Total;

  procedure Inc is
  begin
    Trip := Trip + 1;
    Total := Total + 1;
  end Inc;
end Odometer;

```

Figure 5.4: SPARK 2005 code: Odometer

Given program contains code contracts. Tough it does not matter in compilation phase, it shows that SPARK verification tools can be used for given example.

Annotation `global` means that subprogram uses some global variable. Postfix `in`, `out` or `in out` means that particular variable is read, write or read and write respectively. Annotation `derives` says that some variable value depends on other variables. E.g. in procedure `Inc` variable `trip` is dependent on its current value (before procedure call). Annotations `pre` and `post` define pre- and postconditions of procedure. We can see, that in `Zero_Trip` procedure postcondition requires that variable `trip` is equal to 0. In procedure `Inc`, postconditions requires that variables `trip` and `total` are incremented by 1 ("`~`" is the value of variable before procedure call). Annotation `own` expose private variables for use in public methods specification. Annotation `initializes` ensures that given variables are initializes.

In order to test `odometer` package in runtime, the `Main` procedure has been created. It is presented in the Figure 5.5.

```
with Ada.Text_IO;
with Odometer;

procedure Main
is
begin
  Ada.Text_IO.Put_Line("Trip: " & Natural'Image(Odometer.Read_Trip));
  Ada.Text_IO.Put_Line("Total: " & Natural'Image(Odometer.Read_Total));

  Odometer.Inc;

  Ada.Text_IO.Put_Line("Trip: " & Natural'Image(Odometer.Read_Trip));
  Ada.Text_IO.Put_Line("Total: " & Natural'Image(Odometer.Read_Total));

  Odometer.Zero_Trip;

  Ada.Text_IO.Put_Line("Trip: " & Natural'Image(Odometer.Read_Trip));
  Ada.Text_IO.Put_Line("Total: " & Natural'Image(Odometer.Read_Total));

  Odometer.Inc;

  Ada.Text_IO.Put_Line("Trip: " & Natural'Image(Odometer.Read_Trip));
  Ada.Text_IO.Put_Line("Total: " & Natural'Image(Odometer.Read_Total));
end Main;
```

Figure 5.5: Main procedure for `odometer` package

Odometer in SPARK 2005 works fine on BeagleBoard-xM. In order to test SPARK 2014 program, SPARK 2005 annotations has been converted into Ada 2012 contracts. Figure 5.6 presents Odometer in SPARK 2014.

Odometer example was created to check possible limitations and issues related to different platform (ARM-based). No limitations were found.

### 5.1.2 Multitasking Applications

In Ada World, concurrency is referred as tasking and the task is the same construct as the thread in other programming languages. In Section 5.1.1, single-tasking application was tested. This section presents simple Ada multitasking application and multitasking version of Odometer in SPARK 2005 from Section 5.1.1. Both applications compiles correctly and works as expected on BeagleBoard-xM platform.

#### Ada Multitasking Application

Figure 5.7 presents a simple multitasking application printing numbers in different time intervals, in Ada 2005. It is also valid code for Ada 2012. There are 3 tasks:

- Main task
- S (type: `Seconds`) - simple counter printing numbers from 1 to 10 in every second
- T (type: `Tenth_Seconds`) - simple counter printing numbers from 0.1 to 10 in every 0.1 second

The program works as expected on BeagleBoard-xM. This is not valid SPARK program though. As mentioned in Section 2.5.3, tasks can be declared only in packages. Not in subprograms or in other tasks [Bar13].

```

package Odometer
with Abstract_State => (Trip_State, Total_State)
is
  function Trip_State return Integer with Convention => Ghost, Global => (Input => Trip_State);
  function Total_State return Integer with Convention => Ghost, Global => (Input => Total_State);
  procedure Zero_Trip with Global => (Output => (Trip_State)), Depends => (Trip_State => null), Post =>
    Trip_State = 0;
  function Read_Trip return Natural with Global => (Input => Trip_State),
    Post => Read_Trip'Result = Trip_State;
  function Read_Total return Natural with Global => (Input => Total_State),
    Post => Read_Total'Result = Total_State;
  procedure Inc with Global => (In_Out => (Trip_State, Total_State)),
    Depends => (Trip_State => Trip_State, Total_State => Total_State),
    Pre => Trip_State < Integer'Last and Total_State < Integer'Last,
    Post => Trip_State = Trip_State'Old + 1 and Total_State = Total_State'Old + 1;
end Odometer;

package body Odometer
with Refined_State => (Trip_State => (Trip), Total_State => (Total))
is
  Trip : Natural;
  Total : Natural;

  function Trip_State return Integer
    with Refined_Global => (Input => Trip) is begin
    return Trip;
  end Trip_State;

  function Total_State return Integer
    with Refined_Global => (Input => Total) is begin
    return Total;
  end Total_State;

  procedure Zero_Trip
    with Refined_Global => (Output => Trip), Refined_Depends => (Trip => null) is begin
    Trip := 0;
  end Zero_Trip;

  function Read_Trip return Natural
    with Refined_Global => (Input => Trip) is begin
    return Trip;
  end Read_Trip;

  function Read_Total return Natural
    with Refined_Global => (Input => Total) is begin
    return Total;
  end Read_Total;

  procedure Inc
    with Refined_Global => (In_Out => (Trip, Total)), Refined_Depends => (Trip => Trip, Total => Total)
  is begin
    Trip := Trip + 1;
    Total := Total + 1;
  end Inc;
end Odometer;

```

Figure 5.6: SPARK 2014 code: Odometer

```

with Ada.Text_IO;
use Ada.Text_IO;
with Ada.Float_Text_IO;

procedure Main is
  task type Seconds is
  end Seconds;

  task type Tenth_Seconds is
  end Tenth_Seconds;

  S : Seconds;
  T : Tenth_Seconds;

  task body Seconds is
  begin
    for I in 1..10 loop
      delay Standard.Duration(1);
      Put_Line(Integer'Image(I));
    end loop;
  end Seconds;

  task body Tenth_Seconds is
  begin
    for I in 1..100 loop
      delay 0.1;
      Ada.Float_Text_IO.Put(Float(I)/Float(10), AFT=>2, EXP=>0);
      Put_Line("");
    end loop;
  end Tenth_Seconds;
begin
  Put_Line("Started");
end Main;

```

**Figure 5.7:** Simple multitasking application in Ada

## SPARK Ada multitasking application

As mentioned in Section 2.5.3, in SPARK 2005 multitasking is possible with Ravenscar Profile. Default profile - sequential - does not enable tasking. In other words, SPARK tools cannot analyze and reason about programs if Ravenscar profile flag is not provided. In SPARK 2014 - for now tasking is not possible. It's part of SPARK 2014 road map to include support for tasking in the future. Thus, only SPARK 2005 application was tested.

Tested, multitasking application is extended version of Odometer (presented in the Figure 5.4). It has additional variable `speed`, procedure `Set_Speed` and new task: `Drive`. Thus, in total it has two tasks:



- Main
- Drive

The `Drive` task increase `Total` and `Trip` variables by `speed` (m/s) in every second. Extended Odometer is presented in the figures 5.8 and 5.9.

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 we get semantic error: `Trip is a protected own variable`. To preserve pre- and postconditions from original Odometer, atomic types (`Distance` and `Meters_Per_Second`) has been used. The capability to specify pre- and postconditions has been preserved, but now application is not thread safe.

### 5.1.3 Controlling PCA Pump Actuator

PCA pump prototype created as part of this thesis interacts with external device (physical pump) through General-purpose input/output (GPIO) pin. To control the pump, Pulse width modulation (described in 3.3) is used. BeagleBoard-xM has 28 GPIO pins. Three of them are PWM enable (pin 4 - mapped as `GPIO_144`, pin 6 - `GPIO_146` and pin 10 - `GPIO_145`). All of these pins allow to control external device by specifying frequency and duty cycle. However it requires PWM driver.<sup>1</sup> PWM can be also simulated manually. To run the pump, pin has to be turned on and off with specified frequency. In order to do that, `sleep` function can be used.

---

<sup>1</sup><http://beagleboard.org/project/PWM+driver+for+Beagle+Board/>

```

--# inherit Ada.Real_Time;
package Odometer
--# own Trip : Distance;
--#   Total : Distance;
--#   Speed : Meters_Per_Second;
--#   task d : Drive;
--# initializes Trip,
--#       Total,
--#       Speed;
is
  type Distance is range Natural'First .. Natural'Last;
  pragma Atomic (Distance);

  type Meters_Per_Second is range Natural'First .. Natural'Last;
  pragma Atomic(Meters_Per_Second);

  procedure Zero_Trip; -- sets Trip to 0 and clears all saved Trip marks.
  --# global out Trip;
  --# derives Trip from ;
  --# post Trip = 0;

  function Read_Trip return Distance; -- returns value of Trip.
  --# global in Trip;
  --# return Trip;

  function Read_Total return Distance; -- returns value of Total
  --# global in Total;
  --# return Total;

  procedure Inc; -- increments each of Trip and Total by 1.
  --# global in out Trip, Total;
  --# derives Trip from Trip & Total from Total;
  --# pre Trip < Distance'Last and Total < Distance'Last;
  --# post Trip = Trip~ + 1 and Total = Total~ + 1;

  procedure Set_Speed(New_Speed : Meters_Per_Second);
  --# global out Speed;
  --# derives Speed from New_Speed;
  --# post Speed = New_Speed;
private
  task type Drive
  --# global in   Speed;
  --#       in out Trip;
  --#       in out Total;
  --#       in   Ada.Real_Time.ClockTime;
  is
    pragma Priority(10);
  end Drive;
end Odometer;

```

**Figure 5.8:** Multitasking Odometer specification

```

with Ada.Real_Time;
use type Ada.Real_Time.Time;
package body Odometer is
    Trip : Distance := 0;
    Total : Distance := 0;
    Speed : Meters_Per_Second := 0;
    d : Drive;

    procedure Zero_Trip is
    begin
        Trip := 0;
    end Zero_Trip;

    function Read_Trip return Distance is
    begin
        return Trip;
    end Read_Trip;

    function Read_Total return Distance is
    begin
        return Total;
    end Read_Total;

    procedure Inc is
    begin
        Trip := Trip + 1;
        Total := Total + 1;
    end Inc;

    procedure Set_Speed(New_Speed : Meters_Per_Second)
    is
    begin
        Speed := New_Speed;
    end Set_Speed;

    task body Drive
    is
        Release_Time : Ada.Real_Time.Time;
        Period : constant Integer := 1000; -- update in every second
    begin
        loop
            Release_Time := Ada.Real_Time.Clock + Ada.Real_Time.Milliseconds(Period);
            delay until Release_Time;
            -- each time round, increase Trip and Total
            for I in Meters_Per_Second range 0 .. Speed loop
                Inc;
            end loop;
        end loop;
    end Drive;
end Odometer;

```

**Figure 5.9:** Multitasking Odometer body

GPIO ports interact with the BeagleBoard platform through memory maps. This means that turning particular pin on or off is achieved by writing values into a memory segment associated with the pin. Memory segment is further mapped into file system. Memory maps are synchronized via continuous refresh loops.

Pin, used for controlling PCA pump, is the pin 14 (mapped as `GPIO_162`). It is mapped into directory `/sys/class/gpio/gpio162/`. To turn pin on, file `/sys/class/gpio/gpio162/value` has to contain '1'. To turn it off - '0'. Pump is also connected to ground (GND). In that purpose pin 28 is used. Figure 5.10 shows simple bash script, which turns pin on and off every second. Before pin can be used, it has to be opened by writing pin mapping number (in this case: 162 for pin 14) into `/sys/class/gpio/export` file. When communication is over, connection should be closed with writing the same value to file `/sys/class/gpio/unexport`. Setting 'high' (1) for 1 second and 'low' (0) also for 1 second gives 50% duty cycle.

```
#!/bin/sh

if [ $# = 0 ]
then
    GPIO=162
else
    GPIO=$1
fi

cleanup() {
    echo $GPIO > /sys/class/gpio/unexport
    exit
}

trap cleanup SIGINT

echo $GPIO > /sys/class/gpio/export
echo "out" > /sys/class/gpio/gpio$GPIO/direction

while [ "1" = "1" ]; do
    echo "1" > /sys/class/gpio/gpio$GPIO/value
    sleep 1
    echo "0" > /sys/class/gpio/gpio$GPIO/value
    sleep 1
done

cleanup
```

**Figure 5.10:** Turning pin on and off in bash

Initial tests of interaction with pump actuator has been made in bash and Java, because it does not require cross-compilation. Bash script runs natively on Angstrom Linux. Java application - on JVM distribution for Angstrom.

BeagleBoard-xM with Linux Angstrom allows to install software packages using package manager `opkg`.<sup>2</sup> Packages feeds can be found on <http://feeds.angstrom-distribution.org/feeds> and set in `.conf` files in `/etc/opkg` directory. In this thesis version 2012.01 of Angstrom (with Linux 3.0.14+) has been used and the following feeds:

- `base-feed.conf`: `src/gz base http://feeds.angstrom-distribution.org/feeds/v2012.05/ipk/eglibc/armv7a/base`
- `beagleboard-feed.conf`: `src/gz beagleboard http://feeds.angstrom-distribution.org/feeds/v2012.05/ipk/eglibc/armv7a/beagleboard`
- `debug-feed.conf`: `src/gz debug http://feeds.angstrom-distribution.org/feeds/v2012.05/ipk/eglibc/armv7a/debug`
- `gststreamer-feed.conf`: `src/gz gststreamer http://feeds.angstrom-distribution.org/feeds/v2012.05/ipk/eglibc/armv7a/gststreamer`
- `noarch-feed.conf`: `src/gz no-arch http://feeds.angstrom-distribution.org/feeds/v2012.05/ipk/eglibc/armv7a/all`
- `perl-feed.conf`: `src/gz perl http://feeds.angstrom-distribution.org/feeds/v2012.05/ipk/eglibc/armv7a/perl`
- `python-feed.conf`: `src/gz python http://feeds.angstrom-distribution.org/feeds/v2012.05/ipk/eglibc/armv7a/python`

---

<sup>2</sup><http://wiki.openwrt.org/doc/techref/opkg>

Once, feeds are set, it is recommended to update list of available packages with command: `opkg update`. To update all installed packages, following command has to be used: `opkg upgrade`. To install Java runtime-environment (JVM), the following command can be used: `opkg install openjdk-6-java`. Java Development Kit, which contains Java compiler and allows to compile Java programs on BeagleBoard, can be installed with: `opkg install openjdk-6-jdk`.

Similar program to bash script presented in the Figure 5.10, but working for 20 seconds and terminating, written in Java is presented in the Figure 5.11.

```
import java.io.*;

public class PcaMain {
    public static void main(String[] args) throws IOException, InterruptedException {
        final String GPIO = "162";
        final String BASE_DIR = "/sys/class/gpio";
        WriteToFile(BASE_DIR+"/export", GPIO);
        WriteToFile(BASE_DIR+"/gpio"+GPIO+"/direction", "out");
        for(int i=0; i<10; ++i) {
            WriteToFile(BASE_DIR+"/gpio"+GPIO+"/value", "1");
            Thread.sleep(1000);
            WriteToFile(BASE_DIR+"/gpio"+GPIO+"/value", "0");
            Thread.sleep(1000);
        }
        WriteToFile(BASE_DIR+"/unexport", GPIO);
    }

    public static void WriteToFile(String filename, String content) throws IOException {
        File file = new File(filename);
        if (!file.exists()) {
            file.createNewFile();
        }
        PrintWriter writer = new PrintWriter(filename, "UTF-8");
        writer.println(content);
        writer.close();
    }
}
```

**Figure 5.11:** Turning pin on and off in Java

Extended program from Figure 5.11, with procedures to start and stop the pump, written in Ada, is presented in the figures 5.12 and 5.13.

```

with Ada.Real_Time; use type Ada.Real_Time.Time;
package Pca_Pump is
  procedure Start_Pump;
  procedure Stop_Pump;
  procedure Run_Pump(N: in Integer);
  procedure Write_Signal(Signal: in Integer);
end Pca_Pump;

```

**Figure 5.12:** Simple pump in Ada: package specification

## 5.2 Implementation Based on Requirements Document and AADL Models

In order to confirm that implementation of PCA Pump, specified in Requirements Document, is feasible on BeagleBoard-xM, simple PCA pump prototype has been created. Implemented prototype is multitasking application (using Ravenscar profile) running on BeagleBoard-xM. The base for implementation was `Pca_Operation` package. Only two AADL threads are implemented: `Rate_Controller` and `Max_Drug_Per_Hour_Watcher`. Thus, pump has three tasks in total:

- main task - interface for controlling and monitoring the pump
- `Rate_Controller` - control the speed of infusion rate
- `Max_Drug_Per_Hour_Watcher` - control over infusion

The first step was to translate types required by operation module. Strings and float types were skipped to keep verification simple (using only integer types and its subtypes). Besides that, all types from following packages are translated:

- `Base_Types`
- `Bless_Types`
- `Ice_Types`

- `Pca_Types`

The Open PCA pump, according to requirements document [LH14], has 5 operational modes:

- Stopped:  $F = 0ml/hr$
- Keep Vein Open (KVO):  $F = 0.1ml/hr$
- Basal infusion:  $F = F_{Basal}$
- Patient bolus:  $F = F_{Basal} + F_{Bolus}$
- Clinician bolus:  $F = F_{Basal} + F_{SquareBolus}$  (square bolus is calculated value: VTBI divided by the duration chosen by the clinician)

Requirements document does not specify implementation details. One of implementation decisions, which had to be made, was to decide how basal infusion will work. One solution was to run actuator continuously on speed calculated based on current flow rate. Another solution was to dose drug in 0.1 ml increments. This is how CADD-Prizm Ambulatory Infusion Pump [Med10] works and this implementation was chosen. It allows for easier bolus monitoring and calculations. Pump engine controller is separated module. It is written in Ada, so it will not be verified with SPARK tools. Using increments, instead of continues speed allows to issue request of 0.1 ml dose to engine module, and it is its responsibility to deliver requested amount of dose. Performing calculations based on speed changes would be much more complicated. For monitoring, amount of drug dosed in last hour (to guard against over infusion), array with size = (60 \* 60) has been created. Its elements represents all seconds of last hour. Last element is incremented once request to the engine is issued. This is done in `Rate_Controller` task. `Max_Drug_Per_Hour_Watcher` checks dosed amount by summing all elements. It also shifts array in every second, so doses older than 1 hour are not take into account anymore.



To avoid using floating point types, internal calculations are in micro liters: 1 micro liter ( $\mu\text{l}$ ) = 0.001 ml, thus 1 ml = 1000 $\mu\text{l}$ .

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 or being separated entities on which SPARK tools are not run. `Pca_Engine` package is separated entity, which control the pump actuator. It use Ada features not present in SPARK, thus it is not verified by SPARK tools.

Implemented PCA pump prototype is console Ada application with textual interface, which has following functionalities:

- Entering prescription, which comprises of following parameters:
  - Basal flow rate
  - Volume to be infused (VTBI) during patient or clinician bolus
  - Maximum dose of drug allowed per hour
  - Minimum time between patient's boluses
- Starting the pump
- Stopping the pump
- Monitoring drug dosed in last hour: when maximum allowed dose is exceeded, it switches pump state to KVO rate
- Performing patient bolus:
  - if bolus request too soon (faster than minimum time between bolus) then it is ignored

- if bolus is requested during clinician bolus, then clinician bolus is paused and patient bolus starts; once patient bolus is done, pump switches back to clinician bolus
- Performing clinician bolus (time has to be specified):
  - bolus requested during previously requested (not finished) clinician bolus is ignored
  - bolus requested during patient bolus is performed right after patient bolus is done

The code of implemented PCA Pump Prototype, along with mapped types, is attached in Appendix [B](#).

### 5.3 Code Translation from AADL/BLESS Models

The original AADL/BLESS models were simplified and truncated to demonstrate sample translation. Finally only `PCA_Operation` module with 3 threads (`Max_Drug_Per_Hour_Watcher`, `Rate_Controller`, `Patient_Bolus_Checker`), types definitions (`Base_Types`, `PCA_Types`, `ICE_Types`, `Bless_Types`) and property set `PCA_Properties` were used as the source for code translation. Simplified AADL/BLESS models can be found in Appendix [E](#). The translation was performed based on translation schemes from chapter [4](#). Appendix [F](#) contains translated PCA pump code.

Raw, translated code cannot be verified with SPARK tools, because it contains not implemented parts. E.g. translated from BLESS assertions, which are defined but not implemented in models. Once, these missing parts will be implemented, code can be verified.

```

with Ada.Strings.Unbounded; use type Ada.Strings.Unbounded;
with Ada.Text_IO.Unbounded_IO; use type Ada.Text_IO;
package body Pca_Pump is
  procedure Start_Pump is
    F      : Ada.Text_IO.File_Type; Data : Unbounded_String := To_Unbounded_String("pumping");
    File_Export : Ada.Text_IO.File_Type;
    File_Direction : Ada.Text_IO.File_Type;
  begin
    Create(File_Export, Ada.Text_IO.Out_File, "/sys/class/gpio/export");
    Put_Line(File_Export, "162");
    Close(File_Export);
    Create(File_Direction, Ada.Text_IO.Out_File, "/sys/class/gpio/gpio162/direction");
    Put_Line(File_Direction, "out");
    Close(File_Direction);
    Create(F, Ada.Text_IO.Out_File, "/home/root/pump_status.txt");
    Unbounded_IO.Put_Line(F, Data); Put_Line("Pumping...");
    Close(F);
  end Start_Pump;

  procedure Stop_Pump is
    F      : Ada.Text_IO.File_Type; Data : Unbounded_String := To_Unbounded_String("IDLE");
    File_Unexport : Ada.Text_IO.File_Type;
  begin
    Create(File_Unexport, Ada.Text_IO.Out_File, "/sys/class/gpio/unexport");
    Put_Line(File_Unexport, "162");
    Close(File_Unexport);
    Create(F, Ada.Text_IO.Out_File, "/home/root/pump_status.txt");
    Unbounded_IO.Put_Line(F, Data); Put_Line("Stopped");
    Close(F);
  end Stop_Pump;

  procedure Run_Pump(N: in Integer) is
    Interval: constant Ada.Real_Time.Time_Span := Ada.Real_Time.Milliseconds(100);
    Next_Time: Ada.Real_Time.Time;
  begin
    Next_Time := Ada.Real_Time.Clock;
    Start_Pump;
    for I in Integer range 1 .. N*1000 loop
      Next_Time := Next_Time + Interval; Write_Signal(1); delay until Next_Time;
      Next_Time := Next_Time + Interval; Write_Signal(0); delay until Next_Time;
    end loop;
    Stop_Pump;
  end Run_Pump;

  procedure Write_Signal(Signal : in Integer) is
    Filename : String := "/sys/class/gpio/gpio162/value";
    File : Ada.Text_IO.File_Type; Data : Unbounded_String;
  begin
    Ada.Text_IO.Open (File => File, Mode => Ada.Text_IO.Out_File, Name => Filename);
    if Signal = 1 then Data := To_Unbounded_String("1");
    else Data := To_Unbounded_String("0");
    end if;
    Unbounded_IO.Put_Line(File, Data);
    Ada.Text_IO.Close(File);
  end Write_Signal;
end Pca_Pump;

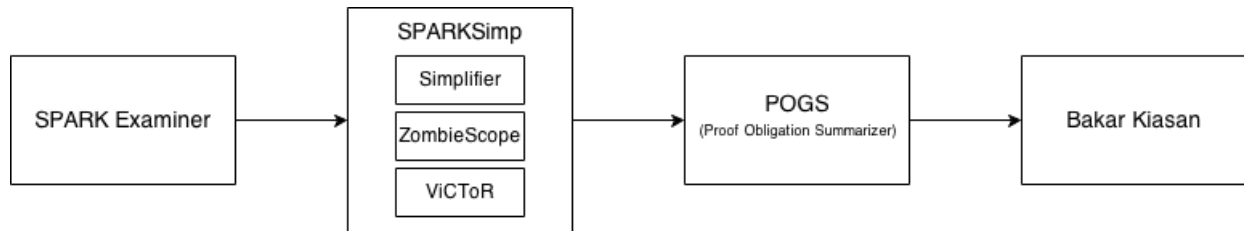
```

Figure 5.13: Simple pump in Ada: package body

# Chapter 6

## Verification

The strategy for Software Verification using SPARK tools is as follows. First, Examiner generates and discharge some Verification Conditions (VCs) and Dead Path Conjectures (DPCs). Next, SPARKSimp runs Simplifier to simplify and discharge some (or all) VCs, which were not discharged by Examiner. SPARKSimp runs also ZombieScope to analyze DPCs and ViCToR to discharge VCs (not discharged by Examiner nor Simplifier) with SMT Solver. To get summary of results, POGS report is generated. In case, when not all Verification Conditions are discharged, analysis continues with Bakar Kiasan. After fixes made with Kiasan help, Examiner and SPARKSimp tools are run again to confirm correctness. This approach is presented in the Figure 6.1. Detailed overview of SPARK verification tools can be found in chapter 12 of SPARK book [Bar13].



**Figure 6.1:** SPARK verification strategy

## 6.1 Verification of Implemented Prototype

During PCA pump prototype implementation, syntax was regularly checked with SPARK Examiner. Complete, manually implemented prototype, which can be found in Appendix B, was verified with strategy given at the beginning of this chapter (excluding Bakar Kiasan, which does not handle Ravenscar programs). Thus SPARK Examiner, SPARKSimp (Simplifier, ZombieScope and ViCToR) and POGS were used. Package `pca_Engine` was excluded from verification, using `--# hide` annotation, because it contains Ada code, which is non-valid SPARK. The result of this analysis, in the form of POGS report summary, is presented in the Figure 6.2. Full report can be found in Appendix C.

POGS report shows that 30% (90) of VCs were discharged by Examiner and 61% (183) by Simplifier. There are 29 undischarged VCs. In addition to VCs, DPCs were generated and 32 dead paths were found. Some undischarged VCs and dead paths come from procedures responsible for maximum dose monitoring. As mentioned in chapter 2.6.9, Bakar Kiasan does not support Ravenscar profile. Thus, to be able to analyze monitoring dosed amount of drug, separate, sequential module was created. Verification process of this module is described in Section 6.2.

## 6.2 Monitoring Dosed Amount

This section is case study of verification of module responsible for tracking dosed amount of drug. The module was created with sequential profile, based on implemented PCA prototype presented in Appendix B. Isolated module is presented in the Figure 6.3.

Verification strategy is the same like described at the beginning of the chapter and depicted in the Figure 6.1. First, program is verified with Examiner, SPARKSimp (Simplifier, ZombieScope and Victor). Verification report is generated by POGS. In case of any issues, verification is continued with Bakar Kiasan, which gives more user friendly experience that

Summary:				
Proof strategies used by subprograms				
-----				
Total subprograms with at least one VC proved by examiner:	15			
Total subprograms with at least one VC proved by simplifier:	20			
Total subprograms with at least one VC proved by contradiction:	0			
Total subprograms with at least one VC proved with user proof rule:	0			
Total subprograms with at least one VC proved by Victor:	0			
Total subprograms with at least one VC proved by Riposte:	0			
Total subprograms with at least one VC proved using checker:	0			
Total subprograms with at least one VC discharged by review:	0			
Maximum extent of strategies used for fully proved subprograms:				
-----				
Total subprograms with proof completed by examiner:	0			
Total subprograms with proof completed by simplifier:	14			
Total subprograms with proof completed with user defined rules:	0			
Total subprograms with proof completed by Victor:	0			
Total subprograms with proof completed by Riposte:	0			
Total subprograms with proof completed by checker:	0			
Total subprograms with VCs discharged by review:	0			
Overall subprogram summary:				
-----				
Total subprograms fully proved:	14			
Total subprograms with at least one undischarged VC:	8	<<<		
Total subprograms with at least one false VC:	0			
-----				
Total subprograms for which VCs have been generated:	22			
ZombieScope Summary:				
-----				
Total subprograms for which DPCs have been generated:	22			
Total number subprograms with dead paths found:	3			
Total number of dead paths found:	32			
VC summary:				
-----				
Note: (User) denotes where the Simplifier has proved VCs using one or more user-defined proof rules.				
Total VCs by type:				
-----				
	Total	Examiner	Simplifier	Undisc.
Assert/Post	93	80	12	1
Precondition	12	0	12	0
Check stmt.	0	0	0	0
Runtime check	187	0	159	28
Refinem. VCs	10	10	0	0
Inherit. VCs	0	0	0	0
=====				
Totals:	302	90	183	29 <<<
%Totals:		30%	61%	10%
===== End of Semantic Analysis Summary =====				

**Figure 6.2:** Summary of POGS report for PCA Pump prototype

```

package Pca_Pump
--# own Dosed;
--#   Dose_Volume;
--# initializes Dosed,
--#   Dose_Volume;
is
  subtype Integer_Array_Index is Integer range 1 .. 60*60;
  type Integer_Array is array (Integer_Array_Index) of Integer;

  procedure Increase_Dosed;
  --# global in out Dosed;
  --#   in Dose_Volume;
  --# derives Dosed from Dosed, Dose_Volume;

  function Read_Dosed return Integer;
  --# global in Dosed;

  procedure Move_Dosed;
  --# global in out Dosed;
  --# derives Dosed from Dosed;

end Pca_Pump;

package body Pca_Pump
is
  Dosed : Integer_Array := Integer_Array'(others => 0);
  Dose_Volume : Integer := 1;

  procedure Increase_Dosed
  is
  begin
    Dosed(Integer_Array_Index'Last) := Dosed(Integer_Array_Index'Last) + Dose_Volume;
  end Increase_Dosed;

  function Read_Dosed return Integer
  is
    Result : Integer := 0;
  begin
    for I in Integer_Array_Index loop
      --# assert I > 1 -> Dosed(I-1) = Dosed(I);
      Result := Result + Dosed(I);
    end loop;
    return Result;
  end Read_Dosed;

  procedure Move_Dosed
  is
  begin
    for I in Integer_Array_Index range 1 .. Integer_Array_Index'Last-1 loop
      --# assert I > 1 -> Dosed(I-1) = Dosed(I);
      Dosed(I) := Dosed(I+1);
    end loop;
    Dosed(Integer_Array_Index'Last) := 0;
  end Move_Dosed;

end Pca_Pump;

```

**Figure 6.3:** Dose monitor module specification

POGS report and generated VC files.

First verification report generated by POGS is presented in the Figure 6.4. It indicates presence of three undischarged (not proved) VCs.

Next, according to verification strategy, Bakar Kiasan was run. Kiasan report is presented in the Figure 6.5.

First issue we can notice is problem with data types' ranges. To solve it (in SPARK 2005) configuration file `Standard.ads` (presented in the Figure 6.6) was created. Kiasan verification report created after that is presented in the Figure 6.7. Number of errors is reduced, but there is still problem with range violation.

From functional perspective, negative values are not needed in this case, thus new type `Drug_Volume` type was created. `Integer_Array` type was renamed to `Doses_Array` and its type was changed to `Drug_Volume`. Result of Kiasan analysis after this change is presented in the Figure 6.8.

After this change, only upper overflow in `Increase_Dosed` procedure error was left. Fix, for this is introduction of precondition for `Increase_Dosed`: `--# pre Read_Dosed(Dosed) <= Drug_Volume'Last - Dose_Volume;`. It caused semantic error (detected by Examiner): `The identifier Read_Dosed is either undeclared or not visible at this point.` The reason of that is definition of `Increase_Dosed` procedure before `Read_Dosed` procedure. To fix, this `Read_Dosed` procedure was moved before `Increase_Dosed`. However, after that Examiner returned different error: `Binary operator is not declared for types Drug_Volume and Dose_Volume__type.` To make operator visible, `Dose_Volume` type has to be declared in `--# own` annotation: `--# Dose_Volume : Drug_Volume;`. After these fixes Kiasan analysis has been run again. Result is depicted in the Figure 6.9.

There were no error cases in `Move_Dosed` and `Increase_Dosed` procedures. Error case in `Read_Dosed` is shown in the Figure 6.9. It is `ConstraintError: the value being assigned to Result is too small.` This error is not very informative. After investigation and talk with Kiasan Developer, it was determined that there is a bug in Kiasan v1 (for SPARK 2005). More precisely: in checking



Summary:				
Proof strategies used by subprograms				
-----				
Total subprograms with at least one VC proved by examiner:	2			
Total subprograms with at least one VC proved by simplifier:	2			
Total subprograms with at least one VC proved by contradiction:	0			
Total subprograms with at least one VC proved with user proof rule:	0			
Total subprograms with at least one VC proved by Victor:	0			
Total subprograms with at least one VC proved by Riposte:	0			
Total subprograms with at least one VC proved using checker:	0			
Total subprograms with at least one VC discharged by review:	0			
Maximum extent of strategies used for fully proved subprograms:				
-----				
Total subprograms with proof completed by examiner:	0			
Total subprograms with proof completed by simplifier:	1			
Total subprograms with proof completed with user defined rules:	0			
Total subprograms with proof completed by Victor:	0			
Total subprograms with proof completed by Riposte:	0			
Total subprograms with proof completed by checker:	0			
Total subprograms with VCs discharged by review:	0			
Overall subprogram summary:				
-----				
Total subprograms fully proved:	1			
Total subprograms with at least one undischarged VC:	2	<<<		
Total subprograms with at least one false VC:	0			
-----				
Total subprograms for which VCs have been generated:	3			
ZombieScope Summary:				
-----				
Total subprograms for which DPCs have been generated:	3			
Total number subprograms with dead paths found:	1			
Total number of dead paths found:	1			
VC summary:				
-----				
Note: (User) denotes where the Simplifier has proved VCs using one or more user-defined proof rules.				
Total VCs by type:				
-----				
	Total	Examiner	Simplifier	Undisc.
Assert/Post	8	3	4	1
Precondition	0	0	0	0
Check stmt.	0	0	0	0
Runtime check	7	0	5	2
Refinem. VCs	0	0	0	0
Inherit. VCs	0	0	0	0
=====				
Totals:	15	3	9	3 <<<
%Totals:		20%	60%	20%
===== End of Semantic Analysis Summary =====				

Figure 6.4: POGS report

Kiasan					
Package/Unit	T#	E#	Instruction Coverage	Branch Coverage	Time
▼ Pca_Pump	1	45	90%	50%	2.427s
Move_Dosed	0	4	88%	50%	0.236s
Read_Dosed	0	39	89%	50%	1.826s
Increase_Dosed	1	2	100%	0%	0.365s
Read_Dosed Cases: Read_Dosed:0 Range violation (LOWER) at Pca_Pump.Read_Dosed: [14, 15]					
▼ pre-state			▼ post-state:0		
▼ Globals			▼ Globals		
▼ Pca_Pump			▼ Pca_Pump		
Integer_Array_Index'First = 1			Integer_Array_Index'First = 1		
Integer_Array_Index'Last = 3600			Integer_Array_Index'Last = 3600		
▼ Dosed = Pca_Pump.Integer_Array			▼ Dosed = Pca_Pump.Integer_Array		
size = 3600			size = 3600		
▼ Standard			▼ Standard		
Boolean'First = 0			Boolean'First = 0		
Boolean'Last = 1			Boolean'Last = 1		
Integer'First = 1			Integer'First = 1		
Integer'Last = 1			Integer'Last = 1		
Long_Integer'First = 0			Long_Integer'First = 0		
Long_Integer'Last = 0			Long_Integer'Last = 0		
Natural'First = 0			Natural'First = 0		
Natural'Last = 0			Natural'Last = 0		
Positive'First = 1			Positive'First = 1		
Positive'Last = 1			Positive'Last = 1		
▼ Call Stack Frames			▼ Call Stack Frames		
-1:Read_Dosed			14:Read_Dosed		

**Figure 6.5:** Bakar Kiasan verification report

overflows. For the purpose of verification `Drug_Volume` type range was changed to  $0 - (2^{15} - 1)$ . It will give range up to around 1000000. Which is sufficient even if calculations are made in micro liters (as it is in case of PCA pump prototype implementation). 1000000 micro liters is 1000 ml, which is 1 liter. This is extreme amount of drug in case of PCA pump, according to Requirements Document [LH14]. The bug with type ranges is fixed in Kiasan v2 (for SPARK 2014).

Another problem was the size of `Dosed` array (3600 elements). Kiasan allows to set array

```

package Standard is
    type Integer is range -2**31 .. 2**31-1;
end Standard;

```

**Figure 6.6:** Configuration file for Bakar Kiasan

bound and loop bound. Both had to be increased (from default 10). Another thing was computational complexity. For 3600 elements, state space grows exponentially and it takes a lot of time to analyze it. Thus, for verification purposes, array size was changed to 60 elements. Along with change to array bounds and loop bounds, also to 60.

After rerun Kiasan, there is valid test case for `Read_Dose`, but there are also 59 Exception cases: **Range violation (UPPER)**, which means possible overflow. One way of fix it, was to add `--# assume` annotation to loop in function body, but Kiasan v1 does not support it. Another way was to add precondition, which assure, that sum of elements is lower than `Drug_Volume'` `Last`. SPARK does not provide simple library for summing array (like Contracts language for Java provide). Thus, this function had to be implemented. Its implementation is the same like `Read_Dosed`. It sum all elements of array. `sum` function specification and body is presented in the Figure 6.10.

After rerunning Kiasan, only valid test case were found, which is depicted in the Figure 6.11.

The last thing which was improved by code contracts is checking if `Move_Dosed` procedure works as expected. In that purpose three postconditions were added (Figure 6.12). First checks if the last element is equal to 0. Second and third checks two possible scenarios:

- before running procedure, the first element is equal to 0: amount of dosed drug in last hour will not change after Dosed procedure execution
- the first element is greater than 0: after Dosed procedure execution, the amount of

Kiasan					
Package/Unit	T#	E#	Instruction Coverage	Branch Coverage	Time
▼ Pca_Pump	1	3	81%	37%	0.295s
Move_Dosed	0	0	88%	50%	0.035s
Read_Dosed	0	1	70%	25%	0.112s
Increase_Dosed	1	2	100%	0%	0.148s
Increase_Dosed Cases: Increase_Dosed:0 Arithmetic overflow violation (LOWER) at Pca_Pump.Increase_Dosed: [9, 90]					
▼ pre-state			▼ post-state:0		
▼ Globals			▼ Globals		
▼ Pca_Pump			▼ Pca_Pump		
Dose_Volume = -1			Dose_Volume = -1		
Integer_Array_Index'First = 1			Integer_Array_Index'First = 1		
Integer_Array_Index'Last = 3600			Integer_Array_Index'Last = 3600		
▼ Dosed = Pca_Pump.Integer_Array			▼ Dosed = Pca_Pump.Integer_Array		
3600 = -2147483648			3600 = -2147483648		
size = 3600			size = 3600		
▼ Standard			▼ Standard		
Boolean'First = 0			Boolean'First = 0		
Boolean'Last = 1			Boolean'Last = 1		
Integer'First = -2147483648			Integer'First = -2147483648		
Integer'Last = 2147483647			Integer'Last = 2147483647		
Long_Integer'First = 0			Long_Integer'First = 0		
Long_Integer'Last = 0			Long_Integer'Last = 0		
Natural'First = 0			Natural'First = 0		
Natural'Last = 2147483647			Natural'Last = 2147483647		
Positive'First = 1			Positive'First = 1		
Positive'Last = 2147483647			Positive'Last = 2147483647		
▼ Call Stack Frames			▼ Call Stack Frames		
-1:Increase_Dosed			9:Increase_Dosed		

**Figure 6.7:** Bakar Kiasan verification report, second run

drug dosed in last hour will decrease, because first element value will no longer be in last hour range

After adding these postconditions Kiasan generates 2 test cases to check both mentioned scenarios. There is no error cases, which means that procedure works as expected.

Better way to validate such requirements is Unit testing. In Section 6.4, there is overview of unit tests created to test behavior described above.

To validate changes made, while working with Kiasan, SPARK Examiner and SPARK-Simp were rerun again. POGS report is presented in the Figure 6.13.

There are 4 undischarged VCs, but total number of generated VCs is 19. In previous

Kiasan					
Package/Unit	T#	E#	Instruction Coverage	Branch Coverage	Time
▼ Pca_Pump	1	2	81%	37%	0.307s
Move_Dosed	0	0	88%	50%	0.043s
Read_Dosed	0	1	70%	25%	0.12s
Increase_Dosed	1	1	100%	0%	0.144s
Increase_Dosed Cases: Increase_Dosed:0 Arithmetic overflow violation (UPPER) at Pca_Pump.Increase_Dosed: [9, 86]					
pre-state			post-state:0		
▼ Globals			▼ Globals		
▼ Pca_Pump			▼ Pca_Pump		
Dose_Volume = 1			Dose_Volume = 1		
Doses_Array_Index'First = 1			Doses_Array_Index'First = 1		
Doses_Array_Index'Last = 3600			Doses_Array_Index'Last = 3600		
Drug_Volume'First = 0			Drug_Volume'First = 0		
Drug_Volume'Last = 2147483647			Drug_Volume'Last = 2147483647		
▼ Dosed = Pca_Pump.Doses_Array			▼ Dosed = Pca_Pump.Doses_Array		
3600 = 2147483647			3600 = 2147483647		
size = 3600			size = 3600		
▼ Standard			▼ Standard		
Boolean'First = 0			Boolean'First = 0		
Boolean'Last = 1			Boolean'Last = 1		
Integer'First = -2147483648			Integer'First = -2147483648		
Integer'Last = 2147483647			Integer'Last = 2147483647		
Long_Integer'First = 0			Long_Integer'First = 0		
Long_Integer'Last = 0			Long_Integer'Last = 0		
Natural'First = 0			Natural'First = 0		
Natural'Last = 2147483647			Natural'Last = 2147483647		
Positive'First = 1			Positive'First = 1		
Positive'Last = 2147483647			Positive'Last = 2147483647		
▼ Call Stack Frames			▼ Call Stack Frames		
-1:Increase_Dosed			9:Increase_Dosed		

**Figure 6.8:** Bakar Kiasan verification report, third run

run there were only 15. Thus there is 4 new VCs and 2 of them are undischarged. The reason is introduction of `sum` function. Actually, all subprograms use it. To confirm this, look at all undischarged VCs. Which is: 1st VC in `increase_dosed.siv` file (Figure 6.14), 9th VC in `move_dosed.siv` file (Figure 6.15), 3rd VC in `read_dosed.vcg` file (Figure 6.16) and 3rd VC in `sum.vcg` file (Figure 6.17). They conform to subprograms: `Increase_Dosed`, `Move_Dosed`, `Read_Dosed` and `sum` respectively.

In `Move_Dosed` procedure, tools cannot prove implications in post conditions. Fortunately, it is already proved by Bakar Kiasan. The problem in `Increase_Dosed`, `Read_Dosed` and `sum` is the same. Tools cannot verify, that adding `Result` and some element of `Dosed` array will not cause overflow. Bakar Kiasan can prove correctness of `Increase_Dosed` and `Read_Dosed`. However only,

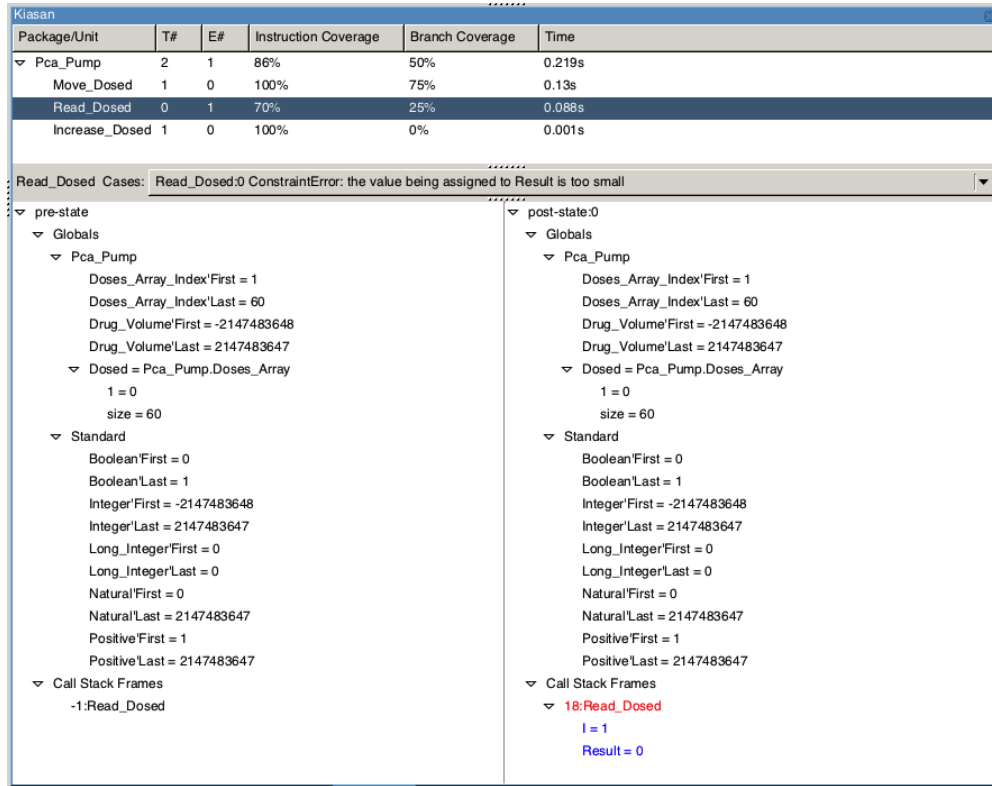


Figure 6.9: Bakar Kiasan verification report, forth run

with assumption that `sum` is correct. `sum` cannot be proved by Bakar Kiasan. Four exception cases indicating possible overflow are generated. Thus, the only way to prove correctness of this module is to assume, that proof function `sum` is correct.

In procedure `Move_Dosed`, there is one dead path found. POGS report gives only information where dead path exists, but not in which circumstances. The information about conditions, in which dead path occurs is stored in `.apc` file. The file path to concrete file is given in the POGS report just before summary table for procedure `Move_Dosed`. In this case it is `move_dosed.dpc` file. Figure 6.13 presents truncated POGS report, but as an example, full POGS report of implemented PCA prototype can be found in Appendix C (e.g. see line 50, which contains DPC analysis for `start_Pumping` procedure).

Relevant fragment, which applies to found dead path is presented in the Figure 6.18.

```

function Sum(Arr : Doses_Array) return Drug_Volume;

function Sum(Arr : Doses_Array) return Drug_Volume
is
    Result : Drug_Volume := 0;
begin
    for I in Doses_Array_Index loop
        --# assert true;
        Result := Result + Arr(I);
    end loop;
    return Result;
end Sum;

```

**Figure 6.10:** Sum function for summing all elements of array

Kiasan					
Package/Unit	T#	E#	Instruction Coverage	Branch Coverage	Time
▼ Pca_Pump	1	0	100%	75%	0.314s
Read_Dosed	1	0	100%	75%	0.314s
Read_Dosed Cases: Read_Dosed:0					
pre-state			post-state:0		
▼ Globals			▼ Globals		
▼ Pca_Pump			▼ Pca_Pump		
Doses_Array_Index'First = 1			Doses_Array_Index'First = 1		
Doses_Array_Index'Last = 60			Doses_Array_Index'Last = 60		
Drug_Volume'First = 0			Drug_Volume'First = 0		
Drug_Volume'Last = 32767			Drug_Volume'Last = 32767		
▼ Dosed = Pca_Pump.Doses_Array			▼ Dosed = Pca_Pump.Doses_Array		
1 = 0			1 = 0		
2 = 0			2 = 0		
3 = 0			3 = 0		
4 = 0			4 = 0		
5 = 0			5 = 0		
6 = 0			6 = 0		
7 = 0			7 = 0		
8 = 0			8 = 0		
9 = 0			9 = 0		
10 = 0			10 = 0		
11 = 0			11 = 0		
12 = 0			12 = 0		

**Figure 6.11:** Bakar Kiasan verification report, fifth run

It is a list of hypothesis, in which hypothesis 10 (H10) states that number of elements in `Doses_Array` is 1 or less. In this case (or more precisely: in this path), `for loop` will not be visited. `Doses_Array` has always 60 elements, thus this path is impossible (dead). It does not mean something bad, because dead path indicate possible issues. In this case it is not issue. It is expected behavior.

Complete code of module for dose monitoring, after changes described above, is presented

```

--# post Dosed(Doses_Array_Index'Last) = 0
--#      and (Dosed^(Doses_Array_Index'First)=0 -> Read_Dosed(Dosed~) = Read_Dosed(Dosed))
--#      and (Dosed^(Doses_Array_Index'First)>0 -> Read_Dosed(Dosed~) > Read_Dosed(Dosed));

```

**Figure 6.12:** Postconditions added to `Move_Dosed` procedure

in the figures 6.19 and 6.20.

Unfortunately, introduced changes (pre- and postconditions) cannot be applied to PCA pump prototype implementation, because - as mentioned in chapter 2.6 - protected objects cannot be used in proof annotations (pre- and postconditions). However, code fixes made in this section can be applied. This shows, how code implemented based on translation from AADL/BLESS can be verified using SPARK tools.

## 6.3 Verification of Generated Code

Code translated from AADL models is presented in Appendix F. Verification with Examiner of package `Pca_Operation` specification returns syntax error: `Neither KNOWN_DISCRIMINANT_PART nor TASK_TYPE_ANNOTATION can start with reserved word "IS"`. It means, that discriminants or task annotation are expected here. In order to pass Examiner syntax check at least one annotation has to be declared. For demonstration purposes, `Ada.Real_Time.ClockTime` is used. Complete task declaration is presented in the Figure 6.21.

Once annotation is added, `Pca_Operation` package specification passes Examiner syntax check. Verification of package body returns errors, which are caused by not implemented assertions (translated from BLESS). When all assertions are removed, only flow errors (presented in the Figure 6.22) are found by Examiner.

This is nice indication what has to be implemented in particular parts of the program. It is recommended to not use VC and DPC generation until there are some syntax errors. When all errors are fixed, program can be initially verified as described in previous sections.



VCs for procedure_increase_dosed :						
#	From	To	Proved By	Dead Path	Status	
1	start	rtc check @ 20	Undischarged	Unchecked	UU	
2	start	assert @ finish	Examiner	Live	EL	
VCs for procedure_move_dosed :						
#	From	To	Proved By	Dead Path	Status	
1	start	rtc check @ 37	Inference	Unchecked	IU	
2	start	rtc check @ 37	Inference	Unchecked	IU	
3	start	assert @ 38	Inference	Live	IL	
4	38	assert @ 38	Inference	Live	IL	
5	38	rtc check @ 39	Inference	Unchecked	IU	
6	start	rtc check @ 41	Inference	Unchecked	IU	
7	38	rtc check @ 41	Inference	Unchecked	IU	
8	start	assert @ finish	Inference	Dead	ID	
9	38	assert @ finish	Undischarged	Live	UL	
VCs for function_read_dosed :						
#	From	To	Proved By	Dead Path	Status	
1	start	assert @ 28	Inference	Live	IL	
2	28	assert @ 28	Inference	Live	IL	
3	28	rtc check @ 29	Undischarged	Unchecked	UU	
4	28	assert @ finish	Inference	Live	IL	
VCs for function_sum :						
#	From	To	Proved By	Dead Path	Status	
1	start	assert @ 11	Inference	Live	IL	
2	11	assert @ 11	Inference	Live	IL	
3	11	rtc check @ 12	Undischarged	Unchecked	UU	
4	11	assert @ finish	Inference	Live	IL	
Summary:						
Total VCs by type:						
	Total	Examiner	Simplifier	Undisc.		
Assert/Post	11	1	9	1		
Precondition	0	0	0	0		
Check stmt.	0	0	0	0		
Runtime check	8	0	5	3		
Refinem. VCs	0	0	0	0		
Inherit. VCs	0	0	0	0		
Totals:	19	1	14	4 <<<		
%Totals:		5%	74%	21%		

Figure 6.13: Third POGS report

```

procedure_increase_dosed_1.
H1:   read_dosed(dosed) <= 32767 - dose_volume .
H2:   for_all(i___1 : integer, 1 <= i___1 and i___1 <= 60 -> 0 <= element(
      dosed, [i___1]) and element(dosed, [i___1]) <= 32767) .
H3:   dose_volume >= 0 .
H4:   dose_volume <= 32767 .
H5:   integer__size >= 0 .
H6:   drug_volume__size >= 0 .
H7:   drug_volume__base__first <= drug_volume__base__last .
H8:   doses_array_index__size >= 0 .
H9:   drug_volume__base__first <= 0 .
H10:  drug_volume__base__last >= 32767 .
->
C1:   element(dosed, [60]) + dose_volume <= 32767 .

```

**Figure 6.14:** Undischarged Verification Condition from `increase_dosed.siv` file

```

procedure_move_dosed_9.
H1:   element(dosed, [58]) = element(dosed, [59]) .
H2:   for_all(i___1 : integer, 1 <= i___1 and i___1 <= 60 -> 0 <= element(
      dosed, [i___1]) and element(dosed, [i___1]) <= 32767) .
H3:   element(dosed, [60]) >= 0 .
H4:   element(dosed, [60]) <= 32767 .
H5:   integer__size >= 0 .
H6:   drug_volume__size >= 0 .
H7:   drug_volume__base__first <= drug_volume__base__last .
H8:   doses_array_index__size >= 0 .
H9:   drug_volume__base__first <= 0 .
H10:  drug_volume__base__last >= 32767 .
->
C1:   element(dosed~, [1]) = 0 -> read_dosed(dosed~) = read_dosed(update(
      update(dosed, [59], element(dosed, [60])), [60], 0)) .
C2:   element(dosed~, [1]) > 0 -> read_dosed(dosed~) > read_dosed(update(
      update(dosed, [59], element(dosed, [60])), [60], 0)) .

```

**Figure 6.15:** Undischarged Verification Condition from `move_dosed.siv` file

```

function_read_dosed_3.
H1:   loop__1__i > 1 -> result >= element(dosed, [loop__1__i - 1]) .
H2:   for_all(i__1 : integer, 1 <= i__1 and i__1 <= 60 -> 0 <= element(
      dosed, [i__1]) and element(dosed, [i__1]) <= 32767) .
H3:   sum(dosed) <= 32767 .
H4:   loop__1__i >= 1 .
H5:   loop__1__i <= 60 .
H6:   result >= 0 .
H7:   result <= 32767 .
H8:   integer__size >= 0 .
H9:   drug_volume__size >= 0 .
H10:  drug_volume__base__first <= drug_volume__base__last .
H11:  doses_array_index__size >= 0 .
H12:  drug_volume__base__first <= 0 .
H13:  drug_volume__base__last >= 32767 .
->
C1:   result + element(dosed, [loop__1__i]) <= 32767 .

```

**Figure 6.16:** Undischarged Verification Condition from `read_dosed.siv` file

```

function_sum_3.
H1:   for_all(i__1 : integer, 1 <= i__1 and i__1 <= 60 -> 0 <= element(arr,
      [i__1]) and element(arr, [i__1]) <= 32767) .
H2:   loop__1__i >= 1 .
H3:   loop__1__i <= 60 .
H4:   result >= 0 .
H5:   result <= 32767 .
H6:   integer__size >= 0 .
H7:   drug_volume__size >= 0 .
H8:   drug_volume__base__first <= drug_volume__base__last .
H9:   doses_array_index__size >= 0 .
H10:  drug_volume__base__first <= 0 .
H11:  drug_volume__base__last >= 32767 .
->
C1:   result + element(arr, [loop__1__i]) <= 32767 .

```

**Figure 6.17:** Undischarged Verification Condition from `sum.siv` file

```

procedure_move_dosed_8.
H1:   for_all(i__1: integer, ((i__1 >= doses_array_index__first) and (
      i__1 <= doses_array_index__last)) -> ((element(
      dosed, [i__1]) >= drug_volume__first) and (element(
      dosed, [i__1]) <= drug_volume__last))) .
H2:   doses_array_index__last - 1 >= integer__first .
H3:   doses_array_index__last - 1 <= integer__last .
H4:   doses_array_index__last - 1 >= integer__base__first .
H5:   doses_array_index__last - 1 <= integer__base__last .
H6:   doses_array_index__first >= integer__first .
H7:   doses_array_index__first <= integer__last .
H8:   (doses_array_index__first <= doses_array_index__last - 1) -> ((
      doses_array_index__last - 1 >= doses_array_index__first) and (
      doses_array_index__last - 1 <= doses_array_index__last)) .
H9:   (doses_array_index__first <= doses_array_index__last - 1) -> ((
      doses_array_index__first >= doses_array_index__first) and (
      doses_array_index__first <= doses_array_index__last)) .
H10:  not (doses_array_index__first <= doses_array_index__last - 1) .
H11:  0 >= drug_volume__first .
H12:  0 <= drug_volume__last .
H13:  doses_array_index__last >= doses_array_index__first .
H14:  doses_array_index__last <= doses_array_index__last .
      ->
C1:   false .

```

**Figure 6.18:** Dead path in `Move_Dosed` procedure

## 6.4 AUnit Tests

Better way to prove expected behavior of `Move_Dosed` in Dose monitoring module, presented in Section 6.2, is to create AUnit tests. To check both behaviors of `Move_Dosed` procedure, two tests have been created:

- `Test_Move_Dosed_First_Element_Zero` - first element is 0, then after execution of the procedure dosed amount of drug should be not changed
- `Test_Move_Dosed_First_Element_Not_Zero` - first element is greater than 0, then after execution of the procedure dosed amount of drug should be smaller than before

Both test cases are presented in the Figure 6.23. All AUnit tests can be found in Appendix G.

```

package Pca_Pump
--# own Dosed : Doses_Array;
--#     Dose_Volume : Drug_Volume;
--# initializes Dosed,
--#     Dose_Volume;
is
    type Drug_Volume is range 0 .. 2**15-1;

    subtype Doses_Array_Index is Positive range 1 .. 60;
    type Doses_Array is array (Doses_Array_Index) of Drug_Volume;

    function Sum(Arr : Doses_Array) return Drug_Volume;

    function Read_Dosed return Drug_Volume;
    --# global in Dosed;
    --# pre Sum(Dosed) <= Drug_Volume'Last;

    procedure Increase_Dosed;
    --# global in out Dosed;
    --#     in Dose_Volume;
    --# derives Dosed from Dosed, Dose_Volume;
    --# pre Read_Dosed(Dosed) <= Drug_Volume'Last - Dose_Volume;

    procedure Move_Dosed;
    --# global in out Dosed;
    --# derives Dosed from Dosed;
    --# post Dosed(Doses_Array_Index'Last) = 0
    --#     and (Dosed~(Doses_Array_Index'First)=0 -> Read_Dosed(Dosed~) = Read_Dosed(Dosed))
    --#     and (Dosed~(Doses_Array_Index'First)>0 -> Read_Dosed(Dosed~) > Read_Dosed(Dosed));

end Pca_Pump;

```

**Figure 6.19:** Dose monitoring module after changes: package specification

```

package body Pca_Pump
is
  Dosed : Doses_Array := Doses_Array'(others => 0);
  Dose_Volume : Drug_Volume := 1;

  function Sum(Arr : Doses_Array) return Drug_Volume
  is
    Result : Drug_Volume := 0;
  begin
    for I in Doses_Array_Index loop
      --# assert true;
      Result := Result + Arr(I);
    end loop;
    return Result;
  end Sum;

  procedure Increase_Dosed
  is
  begin
    Dosed(Doses_Array_Index'Last) := Dosed(Doses_Array_Index'Last) + Dose_Volume;
  end Increase_Dosed;

  function Read_Dosed return Drug_Volume
  is
    Result : Drug_Volume := 0;
  begin
    for I in Doses_Array_Index loop
      --# assert I > 1 -> Result >= Dosed(I-1);
      Result := Result + Dosed(I);
    end loop;
    return Result;
  end Read_Dosed;

  procedure Move_Dosed
  is
  begin
    for I in Doses_Array_Index range Doses_Array_Index'First .. Doses_Array_Index'Last-1 loop
      --# assert I > 1 -> Dosed(I-1) = Dosed(I);
      Dosed(I) := Dosed(I+1);
    end loop;
    Dosed(Doses_Array_Index'Last) := 0;
  end Move_Dosed;

end Pca_Pump;

```

**Figure 6.20:** Dose monitoring module after changes: package body

```

task type Patient_Bolus_Checker
--# global in Ada.Real_Time.ClockTime;
--# derives null from Ada.Real_Time.ClockTime;
is
  pragma Priority(10);
end Patient_Bolus_Checker;

```

**Figure 6.21:** Undischarged Verification Condition from `sum.siv` file

pca_operation.adb:82:9: Flow Error	30	- The variable Infusion_Flow_Rate is imported but neither referenced nor exported.
pca_operation.adb:92:9: Flow Error	30	- The variable Bolus_Duration is imported but neither referenced nor exported.
pca_operation.adb:92:9: Flow Error	32	- The variable Infusion_Flow_Rate is neither imported nor defined.
pca_operation.adb:92:9: Flow Error	31	- The variable Infusion_Flow_Rate is exported but not (internally) defined.
pca_operation.adb:92:9: Flow Error	32	- The variable System_Status is neither imported nor defined.
pca_operation.adb:92:9: Flow Error	31	- The variable System_Status is exported but not (internally) defined.
pca_operation.adb:92:9: Flow Error	30	- The variable Rx is imported but neither referenced nor exported.
pca_operation.adb:92:9: Warning	400	- Variable Ia is declared but not used.
pca_operation.adb:101:9: Flow Error	35	- Importation of the initial value of variable Ada.Real_Time.ClockTime is ineffective.

**Figure 6.22:** Flow errors returned by Examiner for Pca\_Operation package body

## 6.5 GNATprove

The sequential module for monitoring dosed amount verification presented in Section 6.2 has been converted to SPARK 2014. For conversion, "SPARK 2005 to 2014" translator (created by AdaCore) has been used. Translated code is presented in the figures 6.24 and 6.25.

In SPARK 2014, the `standard.ads` file with type ranges is not necessary, because it is handled by language. SPARK 2014 introduces notion of ghost functions. They are used to declare functions that are needed only in annotations. Proof function `sum` is defined as ghost function. In order to use private, global variables in package specification, abstract refinement and ghost functions (`Dosed_State` and `Dose_Volume_State`) have been used. The **Pragma** `Unevaluated_Use_Of_Old` is used in order to avoid error: prefix of attribute `"Old"` that is potentially unevaluated must denote an entity.

Above code has been verified with GNATprove tool. Data and information flow analysis did not return any warnings nor errors. Proof analysis was performed with the following parameters:

- Proof strategy: One proof per path
- Prover timeout: 60

```

procedure Test_Move_Dosed_First_Element_Zero (GnatTest_T : in out Test) is
  pragma Unreferenced (GnatTest_T);
  Pre_Sum : Pca_Pump.Drug_Volume := 0;
  Post_Sum : Pca_Pump.Drug_Volume := 0;
begin
  -- Arrange
  Pre_Sum := Pca_Pump.Read_Dosed;

  -- Act
  Pca_Pump.Move_Dosed;
  Post_Sum := Pca_Pump.Read_Dosed;

  -- Assert
  AUnit.Assertions.Assert
    (Post_Sum = Pre_Sum,
     "Total dose changed: " & Pca_Pump.Drug_Volume'Image(Pre_Sum) & " /= " & Pca_Pump.Drug_Volume'Image(
       Post_Sum));
end Test_Move_Dosed_First_Element_Zero;

procedure Test_Move_Dosed_First_Element_Not_Zero (GnatTest_T : in out Test) is
  pragma Unreferenced (GnatTest_T);
  Pre_Sum : Pca_Pump.Drug_Volume := 0;
  Post_Sum : Pca_Pump.Drug_Volume := 0;
begin
  -- Arrange
  Pca_Pump.Increase_Dosed;
  for I in Pca_Pump.Doses_Array_Index range 1 .. Pca_Pump.Doses_Array_Index'Last-1 loop
    Pca_Pump.Move_Dosed;
  end loop;
  Pre_Sum := Pca_Pump.Read_Dosed;

  -- Act
  Pca_Pump.Move_Dosed;
  Post_Sum := Pca_Pump.Read_Dosed;

  -- Assert
  AUnit.Assertions.Assert
    (Post_Sum < Pre_Sum,
     "Total dose changed: " & Pca_Pump.Drug_Volume'Image(Pre_Sum) & " should be greater than " & Pca_Pump.
       Drug_Volume'Image(Post_Sum));
end Test_Move_Dosed_First_Element_Not_Zero;

```

Figure 6.23: AUnit tests for `Move_Dosed` procedure



```

package Pca_Pump
with SPARK_Mode,
  Abstract_State => (Dosed_State, Dose_Volume_State),
  Initializes   => (Dosed_State, Dose_Volume_State)
is
  type Drug_Volume is range 0 .. 2**15-1;

  subtype Doses_Array_Index is Integer range 1 .. 60;
  type Doses_Array is array (Doses_Array_Index) of Drug_Volume;

  function Dosed_State return Doses_Array
    with Convention => Ghost,
    Global => (Input => Dosed_State);

  function Dose_Volume_State return Drug_Volume
    with Convention => Ghost,
    Global => (Input => Dose_Volume_State);

  function Sum(Arr : Doses_Array) return Drug_Volume
    with Convention => Ghost;

  function Read_Dosed return Drug_Volume
    with Global => (Input => (Dosed_State)),
    Pre      => Sum(Dosed_State) <= Drug_Volume'Last;

  procedure Increase_Dosed
    with Global => (Input => Dose_Volume_State, In_Out => Dosed_State),
    Depends => (Dosed_State => (Dosed_State, Dose_Volume_State)),
    Pre      => Read_Dosed <= Drug_Volume'Last - Dose_Volume_State;

  pragma Unevaluated_Use_Of_Old (Allow);

  procedure Move_Dosed
    with Global => (In_Out => Dosed_State),
    Depends => (Dosed_State => Dosed_State),
    Post => (Dosed_State (Doses_Array_Index'Last) = 0),
    Contract_Cases => (Dosed_State(Doses_Array_Index'First) = 0 => Read_Dosed'Old = Read_Dosed,
                      Dosed_State(Doses_Array_Index'First) > 0 => Read_Dosed'Old > Read_Dosed);

end Pca_Pump;

```

**Figure 6.24:** Sequential module for dose monitoring in SPARK 2014: package specification

```

package body Pca_Pump
with SPARK_Mode, Refined_State => (Dosed_State => Dosed, Dose_Volume_State => Dose_Volume)
is
  Dosed : Doses_Array := Doses_Array'(others => 0);
  Dose_Volume : Drug_Volume := 1;

  function Dosed_State return Doses_Array
  with Refined_Global => (Input => Dosed)
  is begin
    return Dosed;
  end Dosed_State;
  function Dose_Volume_State return Drug_Volume
  with Refined_Global => (Input => Dose_Volume)
  is begin
    return Dose_Volume;
  end Dose_Volume_State;

  function Sum(Arr : Doses_Array) return Drug_Volume
  is
    Result : Drug_Volume := 0;
  begin
    for I in Doses_Array_Index loop
      pragma Loop_Invariant (true);
      Result := Result + Arr(I);
    end loop;
    return Result;
  end Sum;

  procedure Increase_Dosed
  with Refined_Global => (Input => Dose_Volume, In_Out => Dosed),
  Refined_Depends => (Dosed => (Dosed, Dose_Volume))
  is begin
    Dosed(Doses_Array_Index'Last) := Dosed(Doses_Array_Index'Last) + Dose_Volume;
  end Increase_Dosed;

  function Read_Dosed return Drug_Volume
  with Refined_Global => (Input => (Dosed))
  is
    Result : Drug_Volume := 0;
  begin
    for I in Doses_Array_Index loop
      pragma Loop_Invariant (if I > 1 then Result >= Dosed (I-1));
      Result := Result + Dosed(I);
    end loop;
    return Result;
  end Read_Dosed;

  procedure Move_Dosed
  with Refined_Global => (In_Out => (Dosed)),
  Refined_Depends => (Dosed => Dosed)
  is begin
    for I in Doses_Array_Index range 1 .. Doses_Array_Index'Last-1 loop
      pragma Loop_Invariant (if I > 1 then Dosed (I-1) = Dosed (I));
      Dosed(I) := Dosed(I+1);
    end loop;
    Dosed(Doses_Array_Index'Last) := 0;
  end Move_Dosed;
end Pca_Pump;

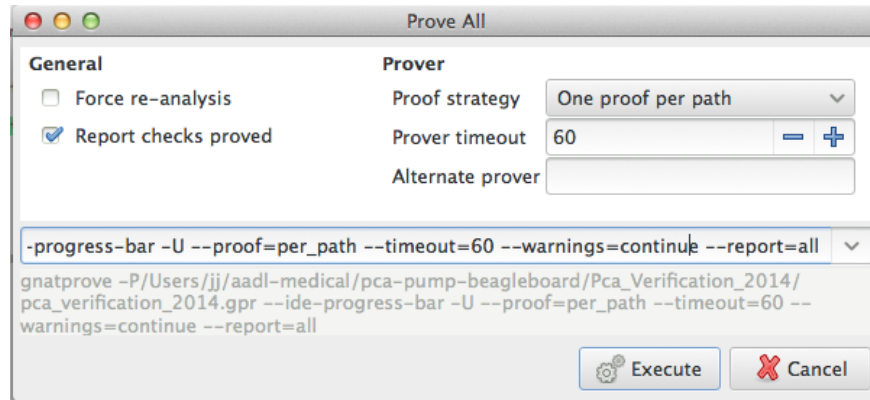
```

**Figure 6.25:** Sequential module for dose monitoring in SPARK 2014: package body

- Do not treat warnings as errors: `--warnings=continue` flag
- Report checks proved

All above parameters gives following command: `gnatprove -P\%PP --ide-progress-bar -U --proof=per_path --timeout=60 --warnings=continue --report=all` (where `\%PP` is path of verified project file `.gpr`).

Proof analysis can be run from GPS (menu: SPARK 2014 / Prove All). There is GUI for options customization (see Figure 6.26).



**Figure 6.26:** GNATprove settings

Summary of proof analysis is presented in the Figure 6.27. Proof analysis returned three warnings: `overflow check might fail` and one warning: `contract case might fail`. It indicates the same problem like in verification with SPARK 2005 tools: overflow hazard. Additionally, there is a warning (`postcondition might fail`) caused by tools limitations. If state refinement is not used (i.e. refined variables are defined in package specification), this warning does not occur. The same program without abstract state is presented in the figures 6.28 and 6.29. Its verification summary is shown in the Figure 6.30.

```

analyzing Pca_Pump, 1 checks
analyzing Pca_Pump.Dosed_State, 0 checks
analyzing Pca_Pump.Dose_Volume_State, 0 checks
analyzing Pca_Pump.Sum, 3 checks
analyzing Pca_Pump.Read_Dosed, 4 checks
analyzing Pca_Pump.Increase_Dosed, 3 checks
analyzing Pca_Pump.Move_Dosed, 12 checks
pca_pump.adb:5:39: info: length check proved
pca_pump.adb:27:10: info: loop invariant initialization proved
pca_pump.adb:27:10: info: loop invariant preservation proved
pca_pump.adb:28:27: warning: overflow check might fail
pca_pump.adb:38:70: warning: overflow check might fail
pca_pump.adb:47:10: info: loop invariant initialization proved
pca_pump.adb:47:10: info: loop invariant preservation proved
pca_pump.adb:47:65: info: index check proved
pca_pump.adb:48:27: warning: overflow check might fail
pca_pump.adb:59:10: info: loop invariant initialization proved
pca_pump.adb:59:10: info: loop invariant preservation proved
pca_pump.adb:59:55: info: index check proved
pca_pump.ads:29:17: info: precondition proved
pca_pump.ads:29:48: info: overflow check proved
pca_pump.ads:36:14: warning: postcondition might fail, requires Dosed_State (Doses_Array_Index'Last) = 0
pca_pump.ads:37:6: info: disjoint contract cases proved
pca_pump.ads:37:6: info: complete contract cases proved
pca_pump.ads:37:66: warning: contract case might fail
pca_pump.ads:37:69: info: precondition proved
pca_pump.ads:37:86: info: precondition proved
pca_pump.ads:38:66: warning: contract case might fail
pca_pump.ads:38:69: info: precondition proved
pca_pump.ads:38:86: info: precondition proved

```

**Figure 6.27:** GNATprove verification summary of module for dose monitoring in SPARK 2014

```

package Pca_Pump_No_Refinement
with SPARK_Mode
is
  type Drug_Volume is range 0 .. 2**15-1;

  subtype Doses_Array_Index is Integer range 1 .. 60;
  type Doses_Array is array (Doses_Array_Index) of Drug_Volume;

  Dosed : Doses_Array := Doses_Array'(others => 0);
  Dose_Volume : Drug_Volume := 1;

  function Sum(Arr : Doses_Array) return Drug_Volume
  with Convention => Ghost;

  function Read_Dosed return Drug_Volume
  with Global => (Input => (Dosed)),
  Pre      => Sum(Dosed) <= Drug_Volume'Last;

  procedure Increase_Dosed
  with Global => (Input => Dose_Volume, In_Out => Dosed),
  Depends => (Dosed => (Dosed, Dose_Volume)),
  Pre      => Read_Dosed <= Drug_Volume'Last - Dose_Volume;

  pragma Unevaluated_Use_Of_Old (Allow);

  procedure Move_Dosed
  with Global => (In_Out => Dosed),
  Depends => (Dosed => Dosed),
  Post => (Dosed(Doses_Array_Index'Last) = 0),
  Contract_Cases => (Dosed(Doses_Array_Index'First) = 0 => Read_Dosed'Old = Read_Dosed,
                    Dosed(Doses_Array_Index'First) > 0 => Read_Dosed'Old > Read_Dosed);
end Pca_Pump_No_Refinement;

```

**Figure 6.28:** Sequential module for dose monitoring in SPARK 2014 without variable refinement: package specification

```

package body Pca_Pump_No_Refinement
with SPARK_Mode
is
  function Sum(Arr : Doses_Array) return Drug_Volume
  is
    Result : Drug_Volume := 0;
  begin
    for I in Doses_Array_Index loop
      pragma Loop_Invariant (true);
      Result := Result + Arr(I);
    end loop;
    return Result;
  end Sum;

  procedure Increase_Dosed
  is
  begin
    Dosed(Doses_Array_Index'Last) := Dosed(Doses_Array_Index'Last) + Dose_Volume;
  end Increase_Dosed;

  function Read_Dosed return Drug_Volume
  is
    Result : Drug_Volume := 0;
  begin
    for I in Doses_Array_Index loop
      pragma Loop_Invariant (if I > 1 then Result >= Dosed (I-1));
      Result := Result + Dosed(I);
    end loop;
    return Result;
  end Read_Dosed;

  procedure Move_Dosed
  is
  begin
    for I in Doses_Array_Index range 1 .. Doses_Array_Index'Last-1 loop
      pragma Loop_Invariant (if I > 1 then Dosed (I-1) = Dosed (I));
      Dosed(I) := Dosed(I+1);
    end loop;
    Dosed(Doses_Array_Index'Last) := 0;
  end Move_Dosed;
end Pca_Pump_No_Refinement;

```

**Figure 6.29:** Sequential module for dose monitoring in SPARK 2014 without variable refinement: package body

```

analyzing Pca_Pump_No_Refinement, 1 checks
analyzing Pca_Pump_No_Refinement.Sum, 3 checks
analyzing Pca_Pump_No_Refinement.Read_Dosed, 4 checks
analyzing Pca_Pump_No_Refinement.Increase_Dosed, 3 checks
analyzing Pca_Pump_No_Refinement.Move_Dosed, 12 checks
pca_pump_no_refinement.adb:9:10: info: loop invariant initialization proved
pca_pump_no_refinement.adb:9:10: info: loop invariant preservation proved
pca_pump_no_refinement.adb:10:27: warning: overflow check might fail
pca_pump_no_refinement.adb:18:70: warning: overflow check might fail
pca_pump_no_refinement.adb:26:10: info: loop invariant initialization proved
pca_pump_no_refinement.adb:26:10: info: loop invariant preservation proved
pca_pump_no_refinement.adb:26:65: info: index check proved
pca_pump_no_refinement.adb:27:27: warning: overflow check might fail
pca_pump_no_refinement.adb:36:10: info: loop invariant initialization proved
pca_pump_no_refinement.adb:36:10: info: loop invariant preservation proved
pca_pump_no_refinement.adb:36:55: info: index check proved
pca_pump_no_refinement.ads:9:39: info: length check proved
pca_pump_no_refinement.ads:22:17: info: precondition proved
pca_pump_no_refinement.ads:22:48: info: overflow check proved
pca_pump_no_refinement.ads:29:14: info: postcondition proved
pca_pump_no_refinement.ads:30:6: info: disjoint contract cases proved
pca_pump_no_refinement.ads:30:6: info: complete contract cases proved
pca_pump_no_refinement.ads:30:60: warning: contract case might fail
pca_pump_no_refinement.ads:30:63: info: precondition proved
pca_pump_no_refinement.ads:30:80: info: precondition proved
pca_pump_no_refinement.ads:31:60: warning: contract case might fail
pca_pump_no_refinement.ads:31:63: info: precondition proved
pca_pump_no_refinement.ads:31:80: info: precondition proved

```

**Figure 6.30:** GNATprove verification summary of module for dose monitoring in SPARK 2014 without variable refinement

# Chapter 7

## Summary

In this thesis PCA Pump prototype, in SPARK 2005 with Ravenscar profile, has been created. It runs on BeagleBoard-xM platform and control physical device. Furthermore, AADL/BLESS to SPARK Ada translation is proposed. Based on that sample translation from simplified AADL models of PCA pump has been performed. At the end, example verification of created prototype, isolated module for dose monitoring and translated code has been shown.

All work done in this thesis targets SPARK 2005. SPARK 2014 and its tools (such as GNATprove) were not ready at the time, when this thesis was written. However, an example verification (of dose monitoring module, which has been translated to SPARK 2014) was presented.

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 is required to isolate some functionalities or implement them in different way. Another issue was lack of resources and SPARK code samples. Especially industry code examples, which are keep secretly as intellectual property by companies. Available resources are usually small examples used in research or reference manuals, which were created couple years age. Although



still valid, not updated for years.

Furthermore, BLESS and SPARK are still under development. Thus, it was very hard to take advantage of all desirable capabilities (most of features are not yet implemented). An example may be lack of support for pre- and post conditions in RavenSPARK.

In addition to that, community working with above technologies is very small. On StackOverflow<sup>1</sup> there is 728 question related to Ada<sup>2</sup> and only 3 to SPARK.<sup>3</sup> In the same time, C# has 673,721 questions<sup>4</sup> and Java - 682,308.<sup>5</sup>

Proposed mapping from AADL to SPARK Ada is not consulted with industry engineers. Thus, it would be first thing to do, in order to continue this research. Lot of work can be done in this topic. It is described in chapter 8.

---

<sup>1</sup><http://stackoverflow.com>

<sup>2</sup><http://stackoverflow.com/questions/tagged/ada>

<sup>3</sup><http://stackoverflow.com/questions/tagged/spark-ada>

<sup>4</sup><http://stackoverflow.com/questions/tagged/c%23>

<sup>5</sup><http://stackoverflow.com/questions/tagged/java>

# Chapter 8

## Future Work

The following are possible extensions for work done in this thesis:

- The most important thing, which would be extremely helpful to proceed with work done in this thesis, would be to review it by some industry expert and experienced engineer.
- Creation of automatic translator described in Section 4.3 would be good validation of created translation schemes. It may reveal some issues not present for manual translation.
- Currently AADL thread properties are not take into account in thread to task mapping, in Section 4.1.3. Properties like priority or period would be very useful in SPARK Ada programs. For now, former is hard-coded as 10 and latter simply skipped, which requires developer to handle it. However, such property modeled and analyzed in AADL models, should be translated automatically to maintain synchronization between model and the code. AADL properties are described in [FG13], in the Appendix A.
- Data types translation presented in Section 4.1.1, in additions to straightforward type

mapping, comprises of protected types. However, all protected types has the same set of subprograms (`Put` and `Get`). It is worth to consider introduction of generics, which will allow to specify generic protected type and then reuse it for all types.

- In feature groups translation (Section 4.1.5), idea of child or nested packages is abandoned. However, it would be good to reconsider it. Maybe by introduction of getter functions in parent package or some other techniques, which will allow for better separation and decomposition.
- AADL property set mapping in Section 4.1.7 handles only `aadlinteger` type. Thus, it requires extension for handling other, more complex constructs.
- Current translation schemes cause creation of pretty big packages, which will become bigger after adding implementation. Thus, some decomposition is desired. Following techniques can be considered:
  - partition of packages
  - take advantage of child packages
  - separation of threads to different packages (e.g. one thread per child package and all common functionalities in parent package)

simple package separation

- Mapping for BLESS are limited only to small subset. Development of translations for BLESS state machine (states and transitions) would be good addition. It will allow for behavior translation. Good point to start is `Rate_Controller` thread, which can be found in `PCA_Operation_Threads` package in original AADL models created by Brian Larson. The semantics of BLESS contain notions of time that make translation to SPARK difficult. This problem occurs in state machine models. Finding solution for that is needed. Maybe even, by changing BLESS semantics.

- For the time, when this thesis was written, SPARK 2014 did not support multitasking. However, there were plans to introduce it into SPARK 2014 like it took place in case of SPARK 2005. Once, multitasking support would be present, translations for SPARK 2014 will be possible.
- There is an issue with two way communication between SPARK packages caused by circular dependency. It is described in Section [4.2.1](#).
- Port communication presented in Section [4.2](#) captures only 1:1 connections between ports of the same type and opposite direction. In AADL there are also inter-port connections and one-to-many or many-to-one connections. [\[FG13\]](#) They should be taken into AADL subset for medical devices modeling and translation.
- Created PCA pump prototype contains only basic functionalities. Some parameters (like drug concentration) are ignored. The next step is its development, would be taken skipped parts into account. In addition to that, interaction with external modules, like sensors for monitoring drug flow, or communication with ICE through Ethernet port is desired. It requires creation of communication channel between BeagleBoard (SPARK Ada application) and these systems.

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# Appendix A

## 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)
- **FDA** - Food and Drug Administration
- **GPS** - GNAT Programming Studio
- **GCC** - GNU Compiler Collection
- **GUI** - Graphical user interface
- **VC** - Verification Condition
- **DPC** - Dead Path Conjecture
- **POGS** - Proof Obligation Summarizer

- **VTBI** - Volume to be infused
- **KVO** - Keep Vein Open
- **SAnToS Laboratory** - Laboratory for Specification, Analysis, and Transformation of Software

# Appendix B

## PCA pump prototype - simple, implemented, working pump

This appendix contains implemented, simple version of PCA Pump, created based on [3.1](#) and AADL models created by Brian Larson. Data types used by this pump are the same like translated from AADL models presented in [appendix F](#).

```
1 with Base_Types;
2 with Pca_Types;
3 with Ice_Types;
4 --# inherit Ada.Real_Time,
5 --#         Ada.Synchronous_Task_Control,
6 --#         Base_Types,
7 --#         Pca_Types,
8 --#         Ice_Types,
9 --#         Pca_Engine;
10 package Pca_Operation
11 --# own protected Operate (suspendable);
12 --#   protected Fluid_Pulses : Integer_Array_Store(Priority => 10);
13 --#   protected Prescription : Pca_Types.Prescription_Store(Priority => 10);
14 --#   protected State : Pca_Types.Status_Type_Store(Priority => 10);
15 --#   protected Clinician_Bolus_Paused : Base_Types.Boolean_Store(Priority => 10);
16 --#   protected Clinician_Bolus_Duration : Ice_Types.Minute_Store(Priority => 10);
17 --#   task rc : Rate_Controller;
18 --#   task mdphw : Max_Drug_Per_Hour_Watcher;
19 --#   Last_Patient_Bolus;
20 --# initializes Last_Patient_Bolus;
21 is
22
23   subtype Integer_Array_Index is Integer range 1 .. 60*60;
24   type Integer_Array is array (Integer_Array_Index) of Integer;
25
26   protected type Integer_Array_Store
27   is
```

```

28     pragma Priority (10);
29
30     function Get(Ind : in Integer) return Integer;
31     --# global in Integer_Array_Store;
32
33     procedure Put(Ind : in Integer; Val : in Integer);
34     --# global in out Integer_Array_Store;
35     --# derives Integer_Array_Store from Integer_Array_Store, Ind, Val;
36
37     procedure Inc(Ind : in Integer);
38     --# global in out Integer_Array_Store;
39     --# derives Integer_Array_Store from Integer_Array_Store, Ind;
40
41     function Sum return Integer;
42     --# global in Integer_Array_Store;
43
44     procedure Pulse;
45     --# global in out Integer_Array_Store;
46     --# derives Integer_Array_Store from Integer_Array_Store;
47 private
48     TheStoredData : Integer_Array := Integer_Array'(others => 0);
49 end Integer_Array_Store;
50
51 function Get_Volume_Infused return Integer; -- microliters
52 --# global in Fluid_Pulses;
53
54 function Get_State return Pca_Types.Status_Type;
55 --# global in State;
56
57 procedure Panel_Set_Basal_Flow_Rate(Flow_Rate : Pca_Types.Flow_Rate);
58 --# global in out Prescription;
59
60 function Panel_Get_Basal_Flow_Rate return Pca_Types.Flow_Rate;
61 --# global in Prescription;
62
63 procedure Panel_Set_Vtbi(Vtbi : Pca_Types.Drug_Volume);
64 --# global in out Prescription;
65
66 function Panel_Get_Vtbi return Pca_Types.Drug_Volume;
67 --# global in Prescription;
68
69 procedure Panel_Set_Max_Drug_Per_Hour(Max_Drug_Per_Hour : Pca_Types.Drug_Volume);
70 --# global in out Prescription;
71
72 function Panel_Get_Max_Drug_Per_Hour return Pca_Types.Drug_Volume;
73 --# global in Prescription;
74
75 procedure Panel_Set_Minimum_Time_Between_Bolus(Minimum_Time_Between_Bolus : Ice_Types.Minute);
76 --# global in out Prescription;
77
78 function Panel_Get_Minimum_Time_Between_Bolus return Ice_Types.Minute;
79 --# global in Prescription;
80
81 procedure StartPump;
82 --# global out Operate;
83 --# out State;
84 --# derives Operate from &
85 --# State from ;
86
87 procedure StopPump;
88 --# global out Operate;
89 --# out State;
90 --# derives Operate from &
91 --# State from ;
92

```

```

93  procedure PatientBolus;
94  --# global in out State;
95  --#      in out Last_Patient_Bolus;
96  --#      in out Clinician_Bolus_Paused;
97  --#      in      Prescription;
98  --#      in      Ada.Real_Time.ClockTime;
99  --# derives State from State, Last_Patient_Bolus, Prescription, Ada.Real_Time.ClockTime &
100 --#      Last_Patient_Bolus from Last_Patient_Bolus, Prescription, Ada.Real_Time.ClockTime &
101 --#      Clinician_Bolus_Paused from Clinician_Bolus_Paused, State, Last_Patient_Bolus, Prescription,
      Ada.Real_Time.ClockTime;
102
103  procedure ClinicianBolus(Cb_Duration : in      Ice_Types.Minute);
104  --# global in out State;
105  --#      in out Clinician_Bolus_Duration;
106  --#      in out Clinician_Bolus_Paused;
107  --# pre Cb_Duration <= 6 * 60; -- from Requirements 4.3.5
108
109
110 private
111  task type Rate_Controller
112  --# global out Operate;
113  --#      in out Fluid_Pulses;
114  --#      in out Clinician_Bolus_Paused;
115  --#      in      Prescription;
116  --#      in out State;
117  --#      in      Ada.Real_Time.ClockTime;
118  --#      in      Clinician_Bolus_Duration;
119  --# derives Operate      from &
120  --#      Fluid_Pulses from Fluid_Pulses, State, Clinician_Bolus_Paused, Ada.Real_Time.ClockTime,
      Prescription, Clinician_Bolus_Duration &
121  --#      Clinician_Bolus_Paused from State, Clinician_Bolus_Paused, Ada.Real_Time.ClockTime,
      Prescription, Clinician_Bolus_Duration &
122  --#      State      from State, Prescription, Ada.Real_Time.ClockTime, Clinician_Bolus_Duration,
      Clinician_Bolus_Paused;
123  --# declare suspends => Operate;
124  is
125      pragma Priority (9);
126  end Rate_Controller;
127
128  task type Max_Drug_Per_Hour_Watcher
129  --# global in out Fluid_Pulses;
130  --#      in      Prescription;
131  --#      in out State;
132  --#      in      Ada.Real_Time.ClockTime;
133  --# derives Fluid_Pulses from Fluid_Pulses &
134  --#      State      from Prescription, Fluid_Pulses, State &
135  --#      null      from Ada.Real_Time.ClockTime;
136  is
137      pragma Priority (9);
138  end Max_Drug_Per_Hour_Watcher;
139
140 end Pca_Operation;
141
142 with Ada.Synchronous_Task_Control,
143      Ada.Real_Time,
144      Base_Types,
145      Pca_Types,
146      Pca_Engine;
147 use type Ada.Real_Time.Time;
148 use type Pca_Types.Status_Type;
149
150 package body Pca_Operation
151 is
152     Operate : Ada.Synchronous_Task_Control.Suspension_Object;
153     rc : Rate_Controller;

```

```

154 mdphw : Max_Drug_Per_Hour_Watcher;
155
156 Fluid_Pulses : Integer_Array_Store;
157
158 State : Pca_Types.Status_Type_Store;
159
160 Prescription : Pca_Types.Prescription_Store;
161
162 Fluid_Pulse_Volume : constant Natural := 100; -- in microliters
163
164 Kvo_Rate : constant Pca_Types.Flow_Rate := 1; -- in mililiters
165
166 Bolus_Flow_Rate : constant Pca_Types.Flow_Rate := 100; -- in mililiters
167
168 Last_Patient_Bolus : Ada.Real_Time.Time := Ada.Real_Time.Time_First;
169
170 Clinician_Bolus_Duration : Ice_Types.Minute_Store;
171
172 Clinician_Bolus_Paused : Base_Types.Boolean_Store;
173
174 protected body Integer_Array_Store
175 is
176     function Get(Ind : in Integer) return Integer
177     --# global in TheStoredData;
178     is
179     begin
180         return TheStoredData(Ind);
181     end Get;
182
183
184     procedure Put(Ind : in Integer; Val : in Integer)
185     --# global in out TheStoredData;
186     --# derives TheStoredData from TheStoredData, Ind, Val;
187     is
188     begin
189         TheStoredData(Ind) := Val;
190     end Put;
191
192     procedure Inc(Ind : in Integer)
193     --# global in out TheStoredData;
194     --# derives TheStoredData from TheStoredData, Ind;
195     is
196     begin
197         TheStoredData(Ind) := TheStoredData(Ind) + Fluid_Pulse_Volume;
198     end Inc;
199
200     function Sum return Integer
201     --# global in TheStoredData;
202     is
203         Result : Integer := 0;
204     begin
205         for I in Integer_Array_Index loop
206             --# assert I > 1 -> Result >= TheStoredData(I-1);
207             Result := Result + TheStoredData(I);
208         end loop;
209         return Result;
210     end Sum;
211
212     procedure Pulse
213     --# global in out TheStoredData;
214     --# derives TheStoredData from TheStoredData;
215     is
216     begin
217         for I in Integer_Array_Index range 1 .. Integer_Array_Index'Last-1 loop
218             --# assert I > 1 -> TheStoredData(I-1) = TheStoredData(I);

```

```

219         TheStoredData(I) := TheStoredData(I+1);
220     end loop;
221     TheStoredData(Integer_Array_Index'Last) := 0;
222 end Pulse;
223
224 end Integer_Array_Store;
225
226 function Get_Time_Between_Activations(Flow_Rate : in Pca_Types.Flow_Rate) return Natural
227 is
228     Result : Natural;
229     Flow_Rate_In_Microliters : Natural;
230     Activations_Per_Hour : Natural;
231 begin
232     Flow_Rate_In_Microliters := Natural(Flow_Rate) * 1000; -- convert mL to uL
233     Activations_Per_Hour := Flow_Rate_In_Microliters / Fluid_Pulse_Volume;
234
235     -- milliseconds between activations
236     Result := ((60 * 60) * 1000) / Activations_Per_Hour;
237     return Result;
238 end Get_Time_Between_Activations;
239
240
241 function Get_Volume_Infused return Integer
242 is
243 begin
244     return Fluid_Pulses.Sum;
245 end Get_Volume_Infused;
246
247 function Get_State return Pca_Types.Status_Type
248 is
249     Current_State : Pca_Types.Status_Type;
250 begin
251     Current_State := State.Get;
252     return Current_State;
253 end Get_State;
254
255 procedure Panel_Set_Basal_Flow_Rate(Flow_Rate : Pca_Types.Flow_Rate)
256 is
257 begin
258     Prescription.Set_Basal_Flow_Rate(Flow_Rate);
259 end Panel_Set_Basal_Flow_Rate;
260
261 function Panel_Get_Basal_Flow_Rate return Pca_Types.Flow_Rate
262 is
263 begin
264     return Prescription.Get_Basal_Flow_Rate;
265 end Panel_Get_Basal_Flow_Rate;
266
267 procedure Panel_Set_Vtbi(Vtbi : Pca_Types.Drug_Volume)
268 is
269 begin
270     Prescription.Set_Vtbi(Vtbi);
271 end Panel_Set_Vtbi;
272
273 function Panel_Get_Vtbi return Pca_Types.Drug_Volume
274 is
275 begin
276     return Prescription.Get_Vtbi;
277 end Panel_Get_Vtbi;
278
279 procedure Panel_Set_Max_Drug_Per_Hour(Max_Drug_Per_Hour : Pca_Types.Drug_Volume)
280 is
281 begin
282     Prescription.Set_Max_Drug_Per_Hour(Max_Drug_Per_Hour);
283 end Panel_Set_Max_Drug_Per_Hour;

```



```

284
285 function Panel_Get_Max_Drug_Per_Hour return Pca_Types.Drug_Volume
286 is
287 begin
288     return Prescription.Get_Max_Drug_Per_Hour;
289 end Panel_Get_Max_Drug_Per_Hour;
290
291 procedure Panel_Set_Minimum_Time_Between_Bolus(Minimum_Time_Between_Bolus : Ice_Types.Minute)
292 is
293 begin
294     Prescription.Set_Minimum_Time_Between_Bolus(Minimum_Time_Between_Bolus);
295 end Panel_Set_Minimum_Time_Between_Bolus;
296
297 function Panel_Get_Minimum_Time_Between_Bolus return Ice_Types.Minute
298 is
299 begin
300     return Prescription.Get_Minimum_Time_Between_Bolus;
301 end Panel_Get_Minimum_Time_Between_Bolus;
302
303 procedure StartPump
304 is
305 begin
306     Ada.Synchronous_Task_Control.Set_True (Operate);
307     State.Put(Pca_Types.Basal);
308 end StartPump;
309
310 procedure StopPump
311 is
312 begin
313     Ada.Synchronous_Task_Control.Set_False (Operate);
314     State.put(Pca_Types.Stopped);
315 end StopPump;
316
317 procedure PatientBolus
318 is
319     Minimum_Time_Between_Bolus : Ice_Types.Minute;
320     Time_Now : Ada.Real_Time.Time;
321     Current_State : Pca_Types.Status_Type;
322 begin
323     Minimum_Time_Between_Bolus := Prescription.Get_Minimum_Time_Between_Bolus;
324     Time_Now := Ada.Real_Time.Clock;
325     if Last_Patient_Bolus + Ada.Real_Time.Milliseconds(Natural(Minimum_Time_Between_Bolus)*(60*1000)) <=
Time_Now then
326         Last_Patient_Bolus := Time_Now;
327         Current_State := State.Get;
328         if Current_State = Pca_Types.Square_Bolus then
329             Clinician_Bolus_Paused.Put(True);
330         end if;
331         State.Put(Pca_Types.Bolus);
332     end if;
333 end PatientBolus;
334
335 procedure ClinicianBolus(Cb_Duration : in Ice_Types.Minute)
336 is
337     Current_State : Pca_Types.Status_Type;
338 begin
339     Current_State := State.Get;
340     if Current_State = Pca_Types.Basal then
341         Clinician_Bolus_Duration.Put(Cb_Duration);
342         State.Put(Pca_Types.Square_Bolus);
343     elsif Current_State = Pca_Types.Bolus then
344         Clinician_Bolus_Duration.Put(Cb_Duration);
345         Clinician_Bolus_Paused.Put(True);
346     end if;
347 end ClinicianBolus;

```

```

348
349
350 task body Rate_Controller
351 is
352     --Release_Time : Ada.Real_Time.Time;
353     Now : Ada.Real_Time.Time;
354     Period : Natural;
355     Last_Basal_Pulse : Ada.Real_Time.Time := Ada.Real_Time.Time_First; -- Ada.Real_Time.Clock - Ada.
Real_Time.Milliseconds(1000 * 60 * 60);
356     Last_Kvo_Pulse : Ada.Real_Time.Time := Ada.Real_Time.Time_First; -- Ada.Real_Time.Clock - Ada.
Real_Time.Milliseconds(1000 * 60 * 60);
357     Last_Patient_Bolus_Pulse : Ada.Real_Time.Time := Ada.Real_Time.Time_First; -- Ada.Real_Time.Clock -
Ada.Real_Time.Milliseconds(1000 * 60 * 60);
358     Last_Clinician_Bolus_Pulse : Ada.Real_Time.Time := Ada.Real_Time.Time_First; -- Ada.Real_Time.Clock -
Ada.Real_Time.Milliseconds(1000 * 60 * 60);
359     Patient_Bolus_Volume_Left : Natural := 0;
360     Clinician_Bolus_Vtbi : Pca_Types.Drug_Volume;
361     Clinician_Bolus_Volume_Left : Natural := 0;
362     Current_State : Pca_Types.Status_Type;
363     Flow_Rate : Pca_Types.Flow_Rate;
364     Drug_Volume : Pca_Types.Drug_Volume;
365     Clinician_Bolus_Paused_Temp : Boolean;
366     Clinician_Bolus_Duration_Temp : Ice_Types.Minute;
367 begin
368     loop
369         Ada.Synchronous_Task_Control.Suspend_Until_True (Operate); -- wait until user allows Pump to
operate
370         Ada.Synchronous_Task_Control.Set_True (Operate); -- Keep the task running, the previous call will
have set Operate to False.
371
372         Now := Ada.Real_Time.Clock;
373         Current_State := State.Get;
374
375         --# assert true;
376
377         case Current_State is
378         when Pca_Types.Stopped =>
379             null;
380         when Pca_Types.KVO =>
381             Period := Get_Time_Between_Activations(Kvo_Rate);
382             if Last_Kvo_Pulse + Ada.Real_Time.Milliseconds(Period) <= Now then
383                 Last_Kvo_Pulse := Now;
384                 Fluid_Pulses.Inc(Integer_Array_Index'Last); -- each time round, update the volume infused
385                 Pca_Engine.Run_Pumping(100); -- and pump 0.1 ml
386             end if;
387         when Pca_Types.Basal =>
388             Flow_Rate := Prescription.Get_Basal_Flow_Rate;
389             Period := Get_Time_Between_Activations(Flow_Rate);
390             if Last_Basal_Pulse + Ada.Real_Time.Milliseconds(Period) <= Now then
391                 Last_Basal_Pulse := Now;
392                 Fluid_Pulses.Inc(Integer_Array_Index'Last); -- each time round, update the volume infused
393                 Pca_Engine.Run_Pumping(100); -- and pump 0.1 ml
394             end if;
395         when Pca_Types.Bolus =>
396             -- basal
397             Flow_Rate := Prescription.Get_Basal_Flow_Rate;
398             Period := Get_Time_Between_Activations(Flow_Rate);
399             if Last_Basal_Pulse + Ada.Real_Time.Milliseconds(Period) <= Now then
400                 Last_Basal_Pulse := Now;
401                 Fluid_Pulses.Inc(Integer_Array_Index'Last); -- each time round, update the volume infused
402                 Pca_Engine.Run_Pumping(100); -- and pump 0.1 ml
403             end if;
404
405             -- patient
406             Period := Get_Time_Between_Activations(Bolus_Flow_Rate);

```

```

407         if Last_Patient_Bolus_Pulse + Ada.Real_Time.Milliseconds(Period) <= Now then
408             Last_Patient_Bolus_Pulse := Now;
409
410             if Patient_Bolus_Volume_Left = 0 then
411                 Drug_Volume := Prescription.Get_Vtbi;
412                 Patient_Bolus_Volume_Left := Natural(Drug_Volume);
413                 Patient_Bolus_Volume_Left := Patient_Bolus_Volume_Left * 1000; -- convert to
microliters
414             end if;
415
416             Fluid_Pulses.Inc(Integer_Array_Index'Last); -- each time round, update the volume infused
417             Pca_Engine.Run_Pumping(100); -- and pump 0.1 ml
418
419             Patient_Bolus_Volume_Left := Patient_Bolus_Volume_Left - 100;
420             if Patient_Bolus_Volume_Left = 0 then
421                 Clinician_Bolus_Paused_Temp := Clinician_Bolus_Paused.Get;
422                 if Clinician_Bolus_Paused_Temp then
423                     State.Put(Pca_Types.Square_Bolus);
424                     Clinician_Bolus_Paused.Put(False);
425                 else
426                     State.Put(Pca_Types.Basal);
427                 end if;
428             end if;
429         end if;
430         when Pca_Types.Square_Bolus =>
431             -- basal
432             Flow_Rate := Prescription.Get_Basal_Flow_Rate;
433             Period := Get_Time_Between_Activations(Flow_Rate);
434             if Last_Basal_Pulse + Ada.Real_Time.Milliseconds(Period) <= Now then
435                 Last_Basal_Pulse := Now;
436                 Fluid_Pulses.Inc(Integer_Array_Index'Last); -- each time round, update the volume infused
437                 Pca_Engine.Run_Pumping(100); -- and pump 0.1 ml
438             end if;
439
440             -- clinician
441             Clinician_Bolus_Duration_Temp := Clinician_Bolus_Duration.Get;
442             Clinicaian_Bolus_Vtbi := Prescription.Get_Vtbi;
443             Period := Get_Time_Between_Activations(Pca_Types.Flow_Rate(Natural(Clinicaian_Bolus_Vtbi) *
(60/Natural(Clinician_Bolus_Duration_Temp))));
444             if Last_Clinician_Bolus_Pulse + Ada.Real_Time.Milliseconds(Period) <= Now then
445                 Last_Clinician_Bolus_Pulse := Now;
446
447                 if Clinician_Bolus_Volume_Left = 0 then
448                     Clinicaian_Bolus_Vtbi := Prescription.Get_Vtbi;
449                     Clinician_Bolus_Volume_Left := Natural(Clinicaian_Bolus_Vtbi) * 1000; -- in
microliters
450                 end if;
451
452                 Fluid_Pulses.Inc(Integer_Array_Index'Last); -- each time round, update the volume infused
453                 Pca_Engine.Run_Pumping(100); -- and pump 0.1 ml
454
455                 Clinician_Bolus_Volume_Left := Clinician_Bolus_Volume_Left - 100;
456                 if Clinician_Bolus_Volume_Left = 0 then
457                     State.Put(Pca_Types.Basal);
458                 end if;
459             end if;
460         end case;
461     end loop;
462 end Rate_Controller;
463
464 task body Max_Drug_Per_Hour_Watcher is
465     Release_Time : Ada.Real_Time.Time;
466     Period : constant Integer := 1000; -- update in every second
467     Volume_Infused : Integer;
468     Max_Drug_Per_Hour : Pca_Types.Drug_Volume;

```

```

469     begin
470         loop
471             --# assert true;
472
473             Release_Time := Ada.Real_Time.Clock; -- must be simple assignment
474             Release_Time := Release_Time + Ada.Real_Time.Milliseconds(Period);
475             delay until Release_Time;
476             Fluid_Pulses.Pulse; -- each time round, update the volume infused moving window
477             Max_Drug_Per_Hour := Prescription.Get_Max_Drug_Per_Hour;
478             Volume_Infused := Get_Volume_Infused;
479             if Volume_Infused > (Integer(Max_Drug_Per_Hour)*1000) then -- convert to microliters
480                 State.Put(Pca_Types.KV0);
481             end if;
482         end loop;
483     end Max_Drug_Per_Hour_Watcher;
484 end Pca_Operation;

```

### Listing B.1: Pca\_Operation package

```

1  with Ada.Real_Time;
2  use type Ada.Real_Time.Time;
3  --# inherit Ada.Real_Time;
4  package Pca_Engine
5  is
6      procedure Start_Pumping;
7
8      procedure Stop_Pumping;
9
10     procedure Run_Pumping(Microliters : in Natural);
11     --# global in Ada.Real_Time.ClockTime;
12     --# derives null from Microliters, Ada.Real_Time.ClockTime;
13     --# pre Microliters > 0;
14
15 end Pca_Engine;
16
17 with Ada.Strings.Unbounded;
18 use Ada.Strings.Unbounded;
19 with Ada.Text_IO.Unbounded_IO;
20 use Ada.Text_IO;
21
22 package body Pca_Engine
23 --# hide Pca_Engine
24 is
25     GPIO_Path : constant String := "/sys/class/gpio/";
26     Status_File_Path : constant String := "/home/root/pump_status.txt";
27
28     GPIO_Export_File_Path : constant String := GPIO_Path & "export";
29     GPIO_Unexport_File_Path : constant String := GPIO_Path & "unexport";
30     GPIO162_Direction_File_Path : constant String := GPIO_Path & "gpio162/direction";
31     GPIO162_Value_File_Path : constant String := GPIO_Path & "gpio162/value";
32
33     procedure Start_Pumping
34     is
35         F : Ada.Text_IO.File_Type;
36         Data : Unbounded_String := To_Unbounded_String("pumping");
37         File_Export : Ada.Text_IO.File_Type;
38         File_Direction : Ada.Text_IO.File_Type;
39     begin
40         Create(File_Export, Ada.Text_IO.Out_File, GPIO_Export_File_Path);
41         Put_Line(File_Export, "162");
42         Close(File_Export);
43
44         Create(File_Direction, Ada.Text_IO.Out_File, GPIO162_Direction_File_Path);

```

```

45     Put_Line(File_Direction, "out");
46     Close(File_Direction);
47
48     Create(F, Ada.Text_IO.Out_File, Status_File_Path);
49     Unbounded_IO.Put_Line(F, Data);
50     Put_Line("Pumping...");
51     Close(F);
52 end Start_Pumping;
53
54
55 procedure Stop_Pumping is
56     F : Ada.Text_IO.File_Type;
57     Data : Unbounded_String := To_Unbounded_String("IDLE");
58     File_Unexport : Ada.Text_IO.File_Type;
59 begin
60     Create(File_Unexport, Ada.Text_IO.Out_File, GPIO_Unexport_File_Path);
61     Put_Line(File_Unexport, "162");
62     Close(File_Unexport);
63
64     Create(F, Ada.Text_IO.Out_File, Status_File_Path);
65     Unbounded_IO.Put_Line(F, Data);
66     Put_Line("Idle...");
67     Close(F);
68 end Stop_Pumping;
69
70 procedure Write_Signal(Signal : in Integer) is
71     File : Ada.Text_IO.File_Type;
72     Data : Unbounded_String;
73 begin
74     Ada.Text_IO.Open (File => File,
75                      Mode => Ada.Text_IO.Out_File,
76                      Name => GPIO162_Value_File_Path);
77     if Signal = 1 then
78         Data := To_Unbounded_String("1");
79     else
80         Data := To_Unbounded_String("0");
81     end if;
82     Unbounded_IO.Put_Line(File, Data);
83     Ada.Text_IO.Close(File);
84 end Write_Signal;
85
86 procedure Run_Pumping(Microliters : in Natural)
87 is
88     Interval_High: constant Ada.Real_Time.Time_Span := Ada.Real_Time.Microseconds(9000);
89     Interval_Low: constant Ada.Real_Time.Time_Span := Ada.Real_Time.Microseconds(1000);
90     Next_Time: Ada.Real_Time.Time;
91 begin
92     Next_Time := Ada.Real_Time.Clock;
93     Start_Pumping;
94     for I in Integer range 1 .. (15*Microliters) loop
95         Next_Time := Next_Time + Interval_High;
96         Write_Signal(1);
97         delay until Next_Time;
98         Next_Time := Next_Time + Interval_Low;
99         Write_Signal(0);
100        delay until Next_Time;
101    end loop;
102    Stop_Pumping;
103 end Run_Pumping;
104
105 end Pca_Engine;

```

Listing B.2: Pca\_Engine package

```

1 with Pca_Operation;
2 with Pca_Types;
3 with Ice_Types;
4 with Ada.Text_IO;
5 with Ada.Float_Text_IO;
6 --# inherit Pca_Operation,
7 --#         Ada.Real_Time,
8 --#         Pca_Types,
9 --#         Ice_Types;
10 --# main_program;
11 procedure Main
12 is
13     pragma Priority (10);
14     Input : String(1..10) := (others => ' ');
15     Input_Last : Integer;
16     Option : Integer;
17     use Ada.Text_IO;
18 begin
19
20     Put_Line("Menu: ");
21     Put_Line("0 - Enter prescription");
22     Put_Line("1 - Start PCA Pump");
23     Put_Line("2 - Stop PCA Pump");
24     Put_Line("3 - Display Volume Infused");
25     Put_Line("4 - Display Prescription");
26     Put_Line("5 - Set Basal Flow Rate");
27     Put_Line("6 - Patient bolus");
28     Put_Line("7 - Clinician bolus");
29     Put_Line("8 - Display Current State");
30     loop
31         Input := (others => ' ');
32         Get_Line(Input, Input_Last);
33         Option := Integer'Value(Input);
34         case Option is
35             when 0 =>
36                 Put_Line("Enter Basal Flow Rate (ml/hr): ");
37                 Input := (others => ' ');
38                 Get_Line(Input, Input_Last);
39                 Pca_Operation.Panel_Set_Basal_Flow_Rate(Pca_Types.Flow_Rate(Integer'Value(Input)));
40                 Put_Line("Enter Volume to be infused during patient bolus (ml): ");
41                 Input := (others => ' ');
42                 Get_Line(Input, Input_Last);
43                 Pca_Operation.Panel_Set_Vtbi(Pca_Types.Drug_Volume(Integer'Value(Input)));
44                 Put_Line("Enter Max Drug Per Hour (ml): ");
45                 Input := (others => ' ');
46                 Get_Line(Input, Input_Last);
47                 Pca_Operation.Panel_Set_Max_Drug_Per_Hour(Pca_Types.Drug_Volume(Integer'Value(Input)));
48                 Put_Line("Enter Minimum Time Between Boluses (min.): ");
49                 Input := (others => ' ');
50                 Get_Line(Input, Input_Last);
51                 Pca_Operation.Panel_Set_Minimum_Time_Between_Bolus(Ice_Types.Minute(Integer'Value(Input)));
52             when 1 =>
53                 Pca_Operation.StartPump;
54                 Put_Line("Pump Started");
55             when 2 =>
56                 Pca_Operation.StopPump;
57                 Put_Line("Pump Stopped");
58             when 3 =>
59                 Put_Line("Volume Infused (ml):");
60                 Ada.Float_Text_IO.Put(Float(Pca_Operation.Get_Volume_Infused) / Float(1000), AFT=>2, EXP=>0);
61                 Put_Line("");
62             when 4 =>
63                 Put_Line("Current Basal Flow Rate (ml/hr): " & Integer'Image(Integer(Pca_Operation.
Panel_Get_Basal_Flow_Rate)));

```

```

64         Put_Line("Current Volume to be Infused (ml): " & Integer'Image(Integer(Pca_Operation.
Panel_Get_Vtbi)));
65         Put_Line("Current Max Drug Per Hour (ml): " & Integer'Image(Integer(Pca_Operation.
Panel_Get_Max_Drug_Per_Hour)));
66         Put_Line("Current minimum time between bolus (min): " & Integer'Image(Integer(Pca_Operation.
Panel_Get_Minimum_Time_Between_Bolus)));
67         when 5 =>
68             Put_Line("Enter Basal Flow Rate (ml/hr): ");
69             Input := (others => ' ');
70             Get_Line(Input, Input_Last);
71             Pca_Operation.Panel_Set_Basal_Flow_Rate(Pca_Types.Flow_Rate(Integer'Value(Input)));
72         when 6 =>
73             Pca_Operation.PatientBolus;
74         when 7 =>
75             Put_Line("Enter Duration (min): ");
76             Input := (others => ' ');
77             Get_Line(Input, Input_Last);
78             Pca_Operation.ClinicianBolus(Ice_Types.Minute'Value(Input));
79         when 8 =>
80             case Pca_Operation.Get_State is
81                 when Pca_Types.Stopped =>
82                     Put_Line("Stopped");
83                 when Pca_Types.Bolus =>
84                     Put_Line("Bolus");
85                 when Pca_Types.Basal =>
86                     Put_Line("Basal");
87                 when Pca_Types.KVO =>
88                     Put_Line("KVO");
89                 when Pca_Types.Square_Bolus =>
90                     Put_Line("Square Bolus");
91             end case;
92         when others => exit;
93     end case;
94 end loop;
95 Put_Line("Program end");
96 end Main;

```

Listing B.3: Main procedure

# Appendix C

## PCA pump prototype verification - POGS report

```
1 -----
2                               Semantic Analysis Summary
3                               POGS GPL 2012
4                               Copyright (C) 2012 Altran Praxis Limited, Bath, U.K.
5 -----
6
7 Summary of:
8
9 Verification Condition files (.vcg)
10 Simplified Verification Condition files (.siv)
11 Victor result files (.vct)
12 Riposte result files (.rsm)
13 Proof Logs (.plg)
14 Dead Path Conjecture files (.dpc)
15 Summary Dead Path files (.sdp)
16
17 "status" column keys:
18   1st character:
19     '-' - No VC
20     'S' - No SIV
21     'U' - Undischarged
22     'E' - Proved by Examiner
23     'I' - Proved by Simplifier by Inference
24     'X' - Proved by Simplifier by Contradiction
25     'P' - Proved by Simplifier using User Defined Proof Rules
26     'V' - Proved by Victor
27     'O' - Proved by Riposte
28     'C' - Proved by Checker
29     'R' - Proved by Review
30     'F' - VC is False
31   2nd character:
32     '-' - No DPC
33     'S' - No SDP
34     'U' - Unchecked
```



```

35      'D' - Dead path
36      'L' - Live path
37
38 in the directory:
39 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar
40
41 Summary produced: 25-JUL-2014 14:16:50.13
42
43 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/clinicianbolus.vcg
44 procedure Pca_Operation.ClinicianBolus
45
46 VCs generated 25-JUL-2014 14:16:24
47
48 VCs simplified 25-JUL-2014 14:16:28
49
50 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/clinicianbolus.dpc
51 DPCs generated 25-JUL-2014 14:16:24
52
53 DPC ZombieScoped 25-JUL-2014 14:16:2
54
55 VCs for procedure_clinicianbolus :
56 -----
57 | # | From | To | Proved By | Dead Path | Status |
58 |-----|
59 | 1 | start | rtc check @ 198 | Inference | Unchecked | IU |
60 | 2 | start | rtc check @ 200 | Inference | Unchecked | IU |
61 | 3 | start | rtc check @ 201 | Inference | Unchecked | IU |
62 | 4 | start | rtc check @ 203 | Inference | Unchecked | IU |
63 | 5 | start | assert @ finish | Examiner | Live | EL |
64 | 6 | start | assert @ finish | Examiner | Live | EL |
65 | 7 | start | assert @ finish | Examiner | Live | EL |
66 |-----|
67
68
69 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/get_state.vcg
70 function Pca_Operation.Get_State
71
72 VCs generated 25-JUL-2014 14:16:24
73
74 VCs simplified 25-JUL-2014 14:16:28
75
76 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/get_state.dpc
77 DPCs generated 25-JUL-2014 14:16:24
78
79 DPC ZombieScoped 25-JUL-2014 14:16:2
80
81 VCs for function_get_state :
82 -----
83 | # | From | To | Proved By | Dead Path | Status |
84 |-----|
85 | 1 | start | rtc check @ 110 | Inference | Unchecked | IU |
86 | 2 | start | assert @ finish | Inference | Live | IL |
87 |-----|
88
89
90 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/get_time_between_activations.vcg
91 function Pca_Operation.Get_Time_Between_Activations
92
93 VCs generated 25-JUL-2014 14:16:24
94
95 VCs simplified 25-JUL-2014 14:16:28
96
97 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/get_time_between_activations.dpc
98 DPCs generated 25-JUL-2014 14:16:24
99

```

```

100 DPC ZombieScoped 25-JUL-2014 14:16:2
101
102 VCs for function_get_time_between_activations :
103 -----
104 | # | From | To | Proved By | Dead Path | Status |
105 |-----|
106 | 1 | start | rtc check @ 91 | Undischarged | Unchecked | UU |
107 | 2 | start | rtc check @ 92 | Inference | Unchecked | IU |
108 | 3 | start | rtc check @ 95 | Undischarged | Unchecked | UU |
109 | 4 | start | assert @ finish | Inference | Live | IL |
110 -----
111
112
113 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/get_volume_infused.vcg
114 function Pca_Operation.Get_Volume_Infused
115
116 VCs generated 25-JUL-2014 14:16:24
117
118 VCs simplified 25-JUL-2014 14:16:29
119
120 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/get_volume_infused.dpc
121 DPCs generated 25-JUL-2014 14:16:24
122
123 DPC ZombieScoped 25-JUL-2014 14:16:2
124
125 VCs for function_get_volume_infused :
126 -----
127 | # | From | To | Proved By | Dead Path | Status |
128 |-----|
129 | 1 | start | assert @ finish | Inference | Live | IL |
130 -----
131
132
133 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/get.vcg
134 function Pca_Operation.Integer_Array_Store.Get
135
136 VCs generated 25-JUL-2014 14:16:24
137
138 VCs simplified 25-JUL-2014 14:16:29
139
140 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/get.dpc
141 DPCs generated 25-JUL-2014 14:16:24
142
143 DPC ZombieScoped 25-JUL-2014 14:16:2
144
145 VCs for function_get :
146 -----
147 | # | From | To | Proved By | Dead Path | Status |
148 |-----|
149 | 1 | start | rtc check @ 39 | Undischarged | Unchecked | UU |
150 | 2 | start | assert @ finish | Inference | Live | IL |
151 | 3 | | refinement | Examiner | No DPC | E- |
152 | 4 | | refinement | Examiner | No DPC | E- |
153 -----
154
155
156 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/inc.vcg
157 procedure Pca_Operation.Integer_Array_Store.Inc
158
159 VCs generated 25-JUL-2014 14:16:24
160
161 VCs simplified 25-JUL-2014 14:16:29
162
163 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/inc.dpc
164 DPCs generated 25-JUL-2014 14:16:24

```

```

165
166 DPC ZombieScoped 25-JUL-2014 14:16:2
167
168 VCs for procedure_inc :
169 -----
170 | # | From | To | Proved By | Dead Path | Status |
171 |-----|
172 | 1 | start | rtc check @ 56 | Undischarged | Unchecked | UU |
173 | 2 | start | assert @ finish | Examiner | Live | EL |
174 | 3 | | refinement | Examiner | No DPC | E- |
175 | 4 | | refinement | Examiner | No DPC | E- |
176 -----
177
178
179 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/pulse.vcg
180 procedure Pca_Operation.Integer_Array_Store.Pulse
181
182 VCs generated 25-JUL-2014 14:16:24
183
184 VCs simplified 25-JUL-2014 14:16:29
185
186 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/pulse.dpc
187 DPCs generated 25-JUL-2014 14:16:24
188
189 DPC ZombieScoped 25-JUL-2014 14:16:2
190
191 VCs for procedure_pulse :
192 -----
193 | # | From | To | Proved By | Dead Path | Status |
194 |-----|
195 | 1 | start | rtc check @ 76 | Inference | Unchecked | IU |
196 | 2 | start | rtc check @ 76 | Inference | Unchecked | IU |
197 | 3 | start | assert @ 77 | Inference | Live | IL |
198 | 4 | 77 | assert @ 77 | Inference | Live | IL |
199 | 5 | 77 | rtc check @ 78 | Inference | Unchecked | IU |
200 | 6 | start | rtc check @ 80 | Inference | Unchecked | IU |
201 | 7 | 77 | rtc check @ 80 | Inference | Unchecked | IU |
202 | 8 | start | assert @ finish | Examiner | Dead | ED |
203 | 9 | 77 | assert @ finish | Examiner | Live | EL |
204 | 10 | | refinement | Examiner | No DPC | E- |
205 | 11 | | refinement | Examiner | No DPC | E- |
206 -----
207
208
209 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/put.vcg
210 procedure Pca_Operation.Integer_Array_Store.Put
211
212 VCs generated 25-JUL-2014 14:16:24
213
214 VCs simplified 25-JUL-2014 14:16:29
215
216 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/put.dpc
217 DPCs generated 25-JUL-2014 14:16:24
218
219 DPC ZombieScoped 25-JUL-2014 14:16:2
220
221 VCs for procedure_put :
222 -----
223 | # | From | To | Proved By | Dead Path | Status |
224 |-----|
225 | 1 | start | rtc check @ 48 | Undischarged | Unchecked | UU |
226 | 2 | start | assert @ finish | Examiner | Live | EL |
227 | 3 | | refinement | Examiner | No DPC | E- |
228 | 4 | | refinement | Examiner | No DPC | E- |
229 -----

```

```

230
231
232 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/sum.vcg
233 function Pca_Operation.Integer_Array_Store.Sum
234
235 VCs generated 25-JUL-2014 14:16:24
236
237 VCs simplified 25-JUL-2014 14:16:30
238
239 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/sum.dpc
240 DPCs generated 25-JUL-2014 14:16:24
241
242 DPC ZombieScoped 25-JUL-2014 14:16:3
243
244 VCs for function_sum :
245 -----
246 | # | From | To | Proved By | Dead Path | Status |
247 |-----|
248 | 1 | start | assert @ 65 | Inference | Live | IL |
249 | 2 | 65 | assert @ 65 | Undischarged | Live | UL |
250 | 3 | 65 | rtc check @ 66 | Undischarged | Unchecked | UU |
251 | 4 | 65 | assert @ finish | Inference | Live | IL |
252 | 5 | | refinement | Examiner | No DPC | E- |
253 | 6 | | refinement | Examiner | No DPC | E- |
254 -----
255
256
257 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/max_drug_per_hour_watcher.vcg
258 task_type Pca_Operation.Max_Drug_Per_Hour_Watcher
259
260 VCs generated 25-JUL-2014 14:16:25
261
262 VCs simplified 25-JUL-2014 14:16:30
263
264 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/max_drug_per_hour_watcher.dpc
265 DPCs generated 25-JUL-2014 14:16:25
266
267 DPC ZombieScoped 25-JUL-2014 14:16:3
268
269 VCs for task_type_max_drug_per_hour_watcher :
270 -----
271 | # | From | To | Proved By | Dead Path | Status |
272 |-----|
273 | 1 | start | assert @ 330 | Examiner | Live | EL |
274 | 2 | 330 | assert @ 330 | Examiner | Live | EL |
275 | 3 | 330 | assert @ 330 | Examiner | Live | EL |
276 | 4 | 330 | rtc check @ 332 | Inference | Unchecked | IU |
277 | 5 | 330 | rtc check @ 333 | Inference | Unchecked | IU |
278 | 6 | 330 | rtc check @ 333 | Undischarged | Unchecked | UU |
279 | 7 | 330 | rtc check @ 336 | Inference | Unchecked | IU |
280 | 8 | 330 | rtc check @ 337 | Inference | Unchecked | IU |
281 | 9 | 330 | rtc check @ 338 | Inference | Unchecked | IU |
282 | 10 | 330 | rtc check @ 339 | Inference | Unchecked | IU |
283 | 11 | 330 | assert @ finish | Examiner | Dead | ED |
284 | 12 | 330 | assert @ finish | Examiner | Dead | ED |
285 -----
286
287
288 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_get_basal_flow_rate.vcg
289 function Pca_Operation.Panel_Get_Basal_Flow_Rate
290
291 VCs generated 25-JUL-2014 14:16:24
292
293 VCs simplified 25-JUL-2014 14:16:30
294

```

```

295 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_get_basal_flow_rate.dpc
296 DPCs generated 25-JUL-2014 14:16:24
297
298 DPC ZombieScoped 25-JUL-2014 14:16:3
299
300 VCs for function_panel_get_basal_flow_rate :
301 -----
302 | # | From | To | Proved By | Dead Path | Status |
303 |-----|
304 | 1 | start | assert @ finish | Inference | Live | IL |
305 -----
306
307
308 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_get_max_drug_per_hour.vcg
309 function Pca_Operation.Panel_Get_Max_Drug_Per_Hour
310
311 VCs generated 25-JUL-2014 14:16:24
312
313 VCs simplified 25-JUL-2014 14:16:30
314
315 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_get_max_drug_per_hour.dpc
316 DPCs generated 25-JUL-2014 14:16:24
317
318 DPC ZombieScoped 25-JUL-2014 14:16:3
319
320 VCs for function_panel_get_max_drug_per_hour :
321 -----
322 | # | From | To | Proved By | Dead Path | Status |
323 |-----|
324 | 1 | start | assert @ finish | Inference | Live | IL |
325 -----
326
327
328 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/
panel_get_minimum_time_between_bolus.vcg
329 function Pca_Operation.Panel_Get_Minimum_Time_Between_Bolus
330
331 VCs generated 25-JUL-2014 14:16:24
332
333 VCs simplified 25-JUL-2014 14:16:31
334
335 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/
panel_get_minimum_time_between_bolus.dpc
336 DPCs generated 25-JUL-2014 14:16:24
337
338 DPC ZombieScoped 25-JUL-2014 14:16:3
339
340 VCs for function_panel_get_minimum_time_between_bolus :
341 -----
342 | # | From | To | Proved By | Dead Path | Status |
343 |-----|
344 | 1 | start | assert @ finish | Inference | Live | IL |
345 -----
346
347
348 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_get_vtbi.vcg
349 function Pca_Operation.Panel_Get_Vtbi
350
351 VCs generated 25-JUL-2014 14:16:24
352
353 VCs simplified 25-JUL-2014 14:16:31
354
355 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_get_vtbi.dpc
356 DPCs generated 25-JUL-2014 14:16:24
357

```

```

358 DPC ZombieScoped 25-JUL-2014 14:16:3
359
360 VCs for function_panel_get_vtbi :
361 -----
362 | # | From | To | Proved By | Dead Path | Status |
363 |-----|
364 | 1 | start | assert @ finish | Inference | Live | IL |
365 |-----|
366
367
368 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_set_basal_flow_rate.vcg
369 procedure Pca_Operation.Panel_Set_Basal_Flow_Rate
370
371 VCs generated 25-JUL-2014 14:16:24
372
373 VCs simplified 25-JUL-2014 14:16:31
374
375 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_set_basal_flow_rate.dpc
376 DPCs generated 25-JUL-2014 14:16:24
377
378 DPC ZombieScoped 25-JUL-2014 14:16:3
379
380 VCs for procedure_panel_set_basal_flow_rate :
381 -----
382 | # | From | To | Proved By | Dead Path | Status |
383 |-----|
384 | 1 | start | rtc check @ 117 | Inference | Unchecked | IU |
385 | 2 | start | assert @ finish | Examiner | Live | EL |
386 |-----|
387
388
389 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_set_max_drug_per_hour.vcg
390 procedure Pca_Operation.Panel_Set_Max_Drug_Per_Hour
391
392 VCs generated 25-JUL-2014 14:16:24
393
394 VCs simplified 25-JUL-2014 14:16:31
395
396 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_set_max_drug_per_hour.dpc
397 DPCs generated 25-JUL-2014 14:16:24
398
399 DPC ZombieScoped 25-JUL-2014 14:16:3
400
401 VCs for procedure_panel_set_max_drug_per_hour :
402 -----
403 | # | From | To | Proved By | Dead Path | Status |
404 |-----|
405 | 1 | start | rtc check @ 141 | Inference | Unchecked | IU |
406 | 2 | start | assert @ finish | Examiner | Live | EL |
407 |-----|
408
409
410 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/
panel_set_minimum_time_between_bolus.vcg
411 procedure Pca_Operation.Panel_Set_Minimum_Time_Between_Bolus
412
413 VCs generated 25-JUL-2014 14:16:24
414
415 VCs simplified 25-JUL-2014 14:16:31
416
417 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/
panel_set_minimum_time_between_bolus.dpc
418 DPCs generated 25-JUL-2014 14:16:24
419
420 DPC ZombieScoped 25-JUL-2014 14:16:3

```

```

421
422 VCs for procedure_panel_set_minimum_time_between_bolus :
423 -----
424 | # | From | To | Proved By | Dead Path | Status |
425 |-----|
426 | 1 | start | rtc check @ 153 | Inference | Unchecked | IU |
427 | 2 | start | assert @ finish | Examiner | Live | EL |
428 |-----|
429
430
431 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_set_vtbi.vcg
432 procedure Pca_Operation.Panel_Set_Vtbi
433
434 VCs generated 25-JUL-2014 14:16:24
435
436 VCs simplified 25-JUL-2014 14:16:31
437
438 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/panel_set_vtbi.dpc
439 DPCs generated 25-JUL-2014 14:16:24
440
441 DPC ZombieScoped 25-JUL-2014 14:16:3
442
443 VCs for procedure_panel_set_vtbi :
444 -----
445 | # | From | To | Proved By | Dead Path | Status |
446 |-----|
447 | 1 | start | rtc check @ 129 | Inference | Unchecked | IU |
448 | 2 | start | assert @ finish | Examiner | Live | EL |
449 |-----|
450
451
452 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/patientbolus.vcg
453 procedure Pca_Operation.PatientBolus
454
455 VCs generated 25-JUL-2014 14:16:24
456
457 VCs simplified 25-JUL-2014 14:16:32
458
459 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/patientbolus.dpc
460 DPCs generated 25-JUL-2014 14:16:24
461
462 DPC ZombieScoped 25-JUL-2014 14:16:3
463
464 VCs for procedure_patientbolus :
465 -----
466 | # | From | To | Proved By | Dead Path | Status |
467 |-----|
468 | 1 | start | rtc check @ 182 | Inference | Unchecked | IU |
469 | 2 | start | rtc check @ 183 | Inference | Unchecked | IU |
470 | 3 | start | rtc check @ 184 | Inference | Unchecked | IU |
471 | 4 | start | rtc check @ 184 | Undischarged | Unchecked | UU |
472 | 5 | start | rtc check @ 185 | Inference | Unchecked | IU |
473 | 6 | start | rtc check @ 186 | Inference | Unchecked | IU |
474 | 7 | start | rtc check @ 190 | Inference | Unchecked | IU |
475 | 8 | start | rtc check @ 190 | Inference | Unchecked | IU |
476 | 9 | start | assert @ finish | Examiner | Live | EL |
477 | 10 | start | assert @ finish | Examiner | Live | EL |
478 | 11 | start | assert @ finish | Examiner | Live | EL |
479 |-----|
480
481
482 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/rate_controller.vcg
483 task_type Pca_Operation.Rate_Controller
484
485 VCs generated 25-JUL-2014 14:16:24

```

```

486
487 VCs simplified 25-JUL-2014 14:16:39
488
489 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/rate_controller.dpc
490 DPCs generated 25-JUL-2014 14:16:24
491
492 DPC ZombieScoped 25-JUL-2014 14:16:3
493
494 VCs for task_type_rate_controller :
495 -----
496 | # | From | To | Proved By | Dead Path | Status |
497 |-----|
498 | 1 | start | rtc check @ 231 | Inference | Unchecked | IU |
499 | 2 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
500 | 3 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
501 | 4 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
502 | 5 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
503 | 6 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
504 | 7 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
505 | 8 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
506 | 9 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
507 | 10 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
508 | 11 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
509 | 12 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
510 | 13 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
511 | 14 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
512 | 15 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
513 | 16 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
514 | 17 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
515 | 18 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
516 | 19 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
517 | 20 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
518 | 21 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
519 | 22 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
520 | 23 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
521 | 24 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
522 | 25 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
523 | 26 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
524 | 27 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
525 | 28 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
526 | 29 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
527 | 30 | 234 | rtc check @ 231 | Inference | Unchecked | IU |
528 | 31 | start | rtc check @ 232 | Inference | Unchecked | IU |
529 | 32 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
530 | 33 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
531 | 34 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
532 | 35 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
533 | 36 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
534 | 37 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
535 | 38 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
536 | 39 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
537 | 40 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
538 | 41 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
539 | 42 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
540 | 43 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
541 | 44 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
542 | 45 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
543 | 46 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
544 | 47 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
545 | 48 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
546 | 49 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
547 | 50 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
548 | 51 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
549 | 52 | 234 | rtc check @ 232 | Inference | Unchecked | IU |
550 | 53 | 234 | rtc check @ 232 | Inference | Unchecked | IU |

```



551	54	234	rtc check @ 232	Inference	Unchecked	IU
552	55	234	rtc check @ 232	Inference	Unchecked	IU
553	56	234	rtc check @ 232	Inference	Unchecked	IU
554	57	234	rtc check @ 232	Inference	Unchecked	IU
555	58	234	rtc check @ 232	Inference	Unchecked	IU
556	59	234	rtc check @ 232	Inference	Unchecked	IU
557	60	234	rtc check @ 232	Inference	Unchecked	IU
558	61	start	assert @ 234	Examiner	Live	EL
559	62	234	assert @ 234	Examiner	Live	EL
560	63	234	assert @ 234	Examiner	Live	EL
561	64	234	assert @ 234	Examiner	Live	EL
562	65	234	assert @ 234	Examiner	Live	EL
563	66	234	assert @ 234	Examiner	Live	EL
564	67	234	assert @ 234	Examiner	Live	EL
565	68	234	assert @ 234	Examiner	Live	EL
566	69	234	assert @ 234	Examiner	Live	EL
567	70	234	assert @ 234	Examiner	Live	EL
568	71	234	assert @ 234	Examiner	Live	EL
569	72	234	assert @ 234	Examiner	Live	EL
570	73	234	assert @ 234	Examiner	Live	EL
571	74	234	assert @ 234	Examiner	Live	EL
572	75	234	assert @ 234	Examiner	Live	EL
573	76	234	assert @ 234	Examiner	Live	EL
574	77	234	assert @ 234	Examiner	Live	EL
575	78	234	assert @ 234	Examiner	Live	EL
576	79	234	assert @ 234	Examiner	Live	EL
577	80	234	assert @ 234	Examiner	Live	EL
578	81	234	assert @ 234	Examiner	Live	EL
579	82	234	assert @ 234	Examiner	Live	EL
580	83	234	assert @ 234	Examiner	Live	EL
581	84	234	assert @ 234	Examiner	Live	EL
582	85	234	assert @ 234	Examiner	Live	EL
583	86	234	assert @ 234	Examiner	Live	EL
584	87	234	assert @ 234	Examiner	Live	EL
585	88	234	assert @ 234	Examiner	Live	EL
586	89	234	assert @ 234	Examiner	Live	EL
587	90	234	assert @ 234	Examiner	Live	EL
588	91	234	rtc check @ 240	Inference	Unchecked	IU
589	92	234	rtc check @ 240	Inference	Unchecked	IU
590	93	234	rtc check @ 241	Inference	Unchecked	IU
591	94	234	rtc check @ 241	Undischarged	Unchecked	UU
592	95	234	rtc check @ 242	Inference	Unchecked	IU
593	96	234	rtc check @ 243	Inference	Unchecked	IU
594	97	234	pre check @ 244	Inference	Unchecked	IU
595	98	234	rtc check @ 247	Inference	Unchecked	IU
596	99	234	rtc check @ 248	Inference	Unchecked	IU
597	100	234	rtc check @ 248	Inference	Unchecked	IU
598	101	234	rtc check @ 249	Inference	Unchecked	IU
599	102	234	rtc check @ 249	Undischarged	Unchecked	UU
600	103	234	rtc check @ 250	Inference	Unchecked	IU
601	104	234	rtc check @ 251	Inference	Unchecked	IU
602	105	234	pre check @ 252	Inference	Unchecked	IU
603	106	234	rtc check @ 256	Inference	Unchecked	IU
604	107	234	rtc check @ 257	Inference	Unchecked	IU
605	108	234	rtc check @ 257	Inference	Unchecked	IU
606	109	234	rtc check @ 258	Inference	Unchecked	IU
607	110	234	rtc check @ 258	Undischarged	Unchecked	UU
608	111	234	rtc check @ 259	Inference	Unchecked	IU
609	112	234	rtc check @ 260	Inference	Unchecked	IU
610	113	234	pre check @ 261	Inference	Unchecked	IU
611	114	234	rtc check @ 265	Inference	Unchecked	IU
612	115	234	rtc check @ 265	Inference	Unchecked	IU
613	116	234	rtc check @ 265	Inference	Unchecked	IU
614	117	234	rtc check @ 265	Inference	Unchecked	IU
615	118	234	rtc check @ 266	Inference	Unchecked	IU



681	184	234	rtc check @ 314	Undischarged	Unchecked	UU
682	185	234	rtc check @ 314	Undischarged	Unchecked	UU
683	186	234	rtc check @ 314	Undischarged	Unchecked	UU
684	187	234	rtc check @ 314	Undischarged	Unchecked	UU
685	188	234	rtc check @ 316	Inference	Unchecked	IU
686	189	234	rtc check @ 316	Inference	Unchecked	IU
687	190	234	rtc check @ 316	Inference	Unchecked	IU
688	191	234	rtc check @ 316	Inference	Unchecked	IU
689	192	234	assert @ finish	Examiner	Dead	ED
690	193	234	assert @ finish	Examiner	Dead	ED
691	194	234	assert @ finish	Examiner	Dead	ED
692	195	234	assert @ finish	Examiner	Dead	ED
693	196	234	assert @ finish	Examiner	Dead	ED
694	197	234	assert @ finish	Examiner	Dead	ED
695	198	234	assert @ finish	Examiner	Dead	ED
696	199	234	assert @ finish	Examiner	Dead	ED
697	200	234	assert @ finish	Examiner	Dead	ED
698	201	234	assert @ finish	Examiner	Dead	ED
699	202	234	assert @ finish	Examiner	Dead	ED
700	203	234	assert @ finish	Examiner	Dead	ED
701	204	234	assert @ finish	Examiner	Dead	ED
702	205	234	assert @ finish	Examiner	Dead	ED
703	206	234	assert @ finish	Examiner	Dead	ED
704	207	234	assert @ finish	Examiner	Dead	ED
705	208	234	assert @ finish	Examiner	Dead	ED
706	209	234	assert @ finish	Examiner	Dead	ED
707	210	234	assert @ finish	Examiner	Dead	ED
708	211	234	assert @ finish	Examiner	Dead	ED
709	212	234	assert @ finish	Examiner	Dead	ED
710	213	234	assert @ finish	Examiner	Dead	ED
711	214	234	assert @ finish	Examiner	Dead	ED
712	215	234	assert @ finish	Examiner	Dead	ED
713	216	234	assert @ finish	Examiner	Dead	ED
714	217	234	assert @ finish	Examiner	Dead	ED
715	218	234	assert @ finish	Examiner	Dead	ED
716	219	234	assert @ finish	Examiner	Dead	ED
717	220	234	assert @ finish	Examiner	Dead	ED

-----

718

719

720

721 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca\_ravenscar/pca\_operation/startpump.vcg

722 procedure Pca\_Operation.StartPump

723

724 VCs generated 25-JUL-2014 14:16:24

725

726 VCs simplified 25-JUL-2014 14:16:46

727

728 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca\_ravenscar/pca\_operation/startpump.dpc

729 DPCs generated 25-JUL-2014 14:16:24

730

731 DPC ZombieScoped 25-JUL-2014 14:16:4

732

733 VCs for procedure\_startpump :

734 -----

#	From	To	Proved By	Dead Path	Status	
735	1	start	rtc check @ 166	Inference	Unchecked	IU
736	2	start	assert @ finish	Examiner	Live	EL

-----

737

738

739

740

741

742 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca\_ravenscar/pca\_operation/stoppump.vcg

743 procedure Pca\_Operation.StopPump

744

745 VCs generated 25-JUL-2014 14:16:24

```

746
747 VCs simplified 25-JUL-2014 14:16:46
748
749 File /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/stoppump.dpc
750 DPCs generated 25-JUL-2014 14:16:24
751
752 DPC ZombieScoped 25-JUL-2014 14:16:4
753
754 VCs for procedure_stoppump :
755 -----
756 | # | From | To | Proved By | Dead Path | Status |
757 |-----|
758 | 1 | start | rtc check @ 173 | Inference | Unchecked | IU |
759 | 2 | start | assert @ finish | Examiner | Live | EL |
760 -----
761
762
763 =====
764 Summary:
765
766 The following subprograms have undischarged VCs (excluding those proved false):
767
768 2 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/get_time_between_activations.
   vcg
769 1 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/get.vcg
770 1 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/inc.vcg
771 1 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/put.vcg
772 2 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/integer_array_store/sum.vcg
773 1 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/max_drug_per_hour_watcher.vcg
774 1 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/patientbolus.vcg
775 20 /Users/jj/aadl-medical/pca-pump-beagleboard/pca_ravenscar/pca_operation/rate_controller.vcg
776
777 Proof strategies used by subprograms
778 -----
779 Total subprograms with at least one VC proved by examiner: 15
780 Total subprograms with at least one VC proved by simplifier: 20
781 Total subprograms with at least one VC proved by contradiction: 0
782 Total subprograms with at least one VC proved with user proof rule: 0
783 Total subprograms with at least one VC proved by Victor: 0
784 Total subprograms with at least one VC proved by Riposte: 0
785 Total subprograms with at least one VC proved using checker: 0
786 Total subprograms with at least one VC discharged by review: 0
787
788 Maximum extent of strategies used for fully proved subprograms:
789 -----
790 Total subprograms with proof completed by examiner: 0
791 Total subprograms with proof completed by simplifier: 14
792 Total subprograms with proof completed with user defined rules: 0
793 Total subprograms with proof completed by Victor: 0
794 Total subprograms with proof completed by Riposte: 0
795 Total subprograms with proof completed by checker: 0
796 Total subprograms with VCs discharged by review: 0
797
798 Overall subprogram summary:
799 -----
800 Total subprograms fully proved: 14
801 Total subprograms with at least one undischarged VC: 8 <<<
802 Total subprograms with at least one false VC: 0
803 -----
804 Total subprograms for which VCs have been generated: 22
805
806
807 ZombieScope Summary:
808 -----
809 Total subprograms for which DPCs have been generated: 22

```

```

810 Total number subprograms with dead paths found: 3
811 Total number of dead paths found: 32
812
813
814 VC summary:
815 -----
816 Note: (User) denotes where the Simplifier has proved VCs using one or
817       more user-defined proof rules.
818
819 Total VCs by type:
820 -----
821
822      Total    Examiner Simplifier    Undisc.
823 Assert/Post      93         80         12         1
824 Precondition     12          0         12         0
825 Check stmt.       0          0          0         0
826 Runtime check    187          0        159        28
827 Refinem. VCs      10         10          0         0
828 Inherit. VCs       0          0          0         0
829 =====
829 Totals:           302         90        183        29 <<<
830 %Totals:              30%        61%        10%
831
832 ===== End of Semantic Analysis Summary =====

```

### Listing C.1: POGS report for PCA Pump prototype

# Appendix D

## Rate controller thread from PCA pump

### AADL models

This appendix presents `Rate_Controller` thread from `PCA_Operation` module, from AADL/BLESS models of PCA pump, created by Brian Larson.

```
1 thread Rate_Controller
2 features
3   Infusion_Flow_Rate: out data port PCA_Types::Flow_Rate
4     {BLESS::Assertion => "<<:=PUMP_RATE()>>";};
5   System_Status: out event data port PCA_Types::Status_Type;
6   Begin_Infusion: in event port
7     {BLESS::Assertion => "<<Rx_APPROVED()>>";};
8   Begin_Priming: in event port;
9   End_Priming: in event port;
10  Halt_Infusion: in event port;
11  Square_Bolus_Rate: in data port PCA_Types::Flow_Rate
12    {BLESS::Assertion => "<<:=SQUARE_BOLUS_RATE>>";};
13  Patient_Bolus_Rate: in data port PCA_Types::Flow_Rate
14    {BLESS::Assertion => "<<:=PATIENT_BOLUS_RATE>>";};
15  Basal_Rate: in data port PCA_Types::Flow_Rate
16    {BLESS::Assertion => "<<:=BASAL_RATE>>";};
17  VTBI: in data port PCA_Types::Drug_Volume
18    {BLESS::Assertion => "<<:=VTBI>>";};
19  HW_Detected_Failure: in event port;
20  Stop_Pump_Completely: in event port;
21  Pump_At_KVO_Rate: in event port;
22  Alarm : in event data port PCA_Types::Alarm_Type;
23  Warning : in event data port PCA_Types::Warning_Type;
24  Patient_Request_Not_Too_Soon: in event port
25    {BLESS::Assertion => "<<:=PATIENT_REQUEST_NOT_TOO_SOON(now)>>";};
26  Door_Open: in data port Base_Types::Boolean;
27  Pause_Infusion: in event port;
28  Resume_Infusion: in event port;
29  CP_Clinician_Request_Bolus: in event port;
```

```

30 CP_Bolus_Duration: in event data port ICE_Types::Minute;
31 Near_Max_Drug_Per_Hour: in event port --near maximum drug infused in any hour
32 {BLESS::Assertion => "<<PATIENT_NEAR_MAX_DRUG_PER_HOUR()>>";};
33 Over_Max_Drug_Per_Hour: in event port --over maximum drug infused in any hour
34 {BLESS::Assertion => "<<PATIENT_OVER_MAX_DRUG_PER_HOUR()>>";};
35 ICE_Stop_Pump: in event port;
36 properties
37   Thread_Properties::Dispatch_Protocol => Aperiodic;
38 end Rate_Controller;
39
40 thread implementation Rate_Controller.imp
41 annex BLESS
42 {**
43 assert
44 <<HALT : :(la=SafetyPumpStop) or (la=StopButton) or (la=EndPriming)>> --pump at 0 if stop button, or safety
    architecture says, or done priming
45 <<KVO_RATE : :(la=KVOcommand) or (la=KVOalarm) or (la=TooMuchJuice)>> --pump at KVO rate when commanded,
    some alarms, or excedded hourly limit
46 <<PB_RATE : :la=PatientButton>> --patient button pressed, and allowed
47 <<CCB_RATE : :(la=StartSquareBolus) or (la=ResumeSquareBolus)>> --clinician-commanded bolus start or
    resumption after patient bolus
48 <<PRIME_RATE : :la=StartPriming>> --priming pump
49 <<BASAL_RATE : :(la=StartButton) or (la=ResumeBasal) or (la=SquareBolusDone)>> --regular infusion
50 <<PUMP_RATE : :=
51   (HALT()) -> 0, --no flow
52   (KVO_RATE()) -> PCA_Properties::KVO_Rate, --KVO rate
53   (PB_RATE()) -> Patient_Bolus_Rate, --maximum infusion upon patient request
54   (CCB_RATE()) -> Square_Bolus_Rate, --square bolus rate=VTBI/duration, from data port
55   (PRIME_RATE()) -> PCA_Properties::Prime_Rate, --pump priming
56   (BASAL_RATE()) -> Basal_Rate --basal rate, from data port
57 >>
58 invariant <<true>>
59 variables
60   --time of last action
61   tla :BLESS_Types::Time := 0;
62   la : --last action
63   enumeration (
64     SafetyStopPump, --safety architecture found a problem
65     StopButton, --clinician pressed stop button
66     KVOcommand, --from control panel (clinician) or ICE (app) to pump Keep-vein-open rate
67     KVOalarm, --some alarms should pump at KVO rate
68     TooMuchJuice, --exceeded max drug per hour, pump at KVO until prescription and patient are re-
    authenticated
69     PatientButton, --patient requested drug
70     ResumeSquareBolus, --infusion of VTBI finished, resume clinician-commanded bolus
71     ResumeBasal, --infusion of VTBI finished, resume basal-rate
72     StartSquareBolus, --begin clinician-commanded bolus
73     SquareBolusDone, --infusion of VTBI finished
74     StartPriming, --begin pump/line priming, pressed "prime" button
75     EndPriming, --end priming, pressed "prime" button again, or time-out
76     StartButton --start pumping at basal rate
77   );
78   pb_duration :BLESS_Types::Time --patient button duration = VTBI/Patient_Bolus_Rate
79   <<PB_DURATION : :pb_duration=(VTBI/Patient_Bolus_Rate)>>;
80 states
81   PowerOn : initial state; --power-on
82   WaitForRx : complete state; --wait for valid prescription
83   CheckPBR : state --check Patient_Bolus_Rate is positive
84   <<Rx_APPROVED()>>;
85   RxApproved : complete state --prescription verified
86   <<Rx_APPROVED() and PB_DURATION()>>;
87   Priming : complete state --priming the pump, 1 ml in 6 sec
88   <<(la=StartPriming) and (Infusion_Flow_Rate@now = PCA_Properties::Prime_Rate) and PB_DURATION()>>;
89   WaitForStart : complete state --wait for clinician to press 'start' button
90   <<HALT() and (Infusion_Flow_Rate@now=0) and PB_DURATION()>>;

```

```

91 PumpBasalRate : complete state --pumping at basal rate
92   <<((la=StartButton) or (la=ResumeBasal)) and (Infusion_Flow_Rate@now=Basal_Rate@now) and PB_DURATION(>>;
93 PumpPatientButtonVTBI : complete state --pumping patient-requested bolus
94   <<((la=PatientButton) and PB_DURATION()
95     and (Infusion_Flow_Rate@now=Patient_Bolus_Rate)>>;
96 PumpCCBRate : complete state --pumping at clinician-commanded bolus rate
97   <<((la=StartSquareBolus) or (la=ResumeSquareBolus)) and (Infusion_Flow_Rate@now=Square_Bolus_Rate@now)
98     and PB_DURATION(>>;
99 PumpKVORate : complete state --pumping at keep-vein-open rate
100   <<((la=KVOcommand) or (la=KVOalarm) or (la=TooMuchJuice)) and PB_DURATION()
101     and (Infusion_Flow_Rate@now=PCA_Properties::KVO_Rate)>>;
102 PumpingSuspended : complete state --clinician pressed 'stop' button
103   <<((la=StopButton) or (la=SafetyStopPump)) and (Infusion_Flow_Rate@now=0)>>;
104 Crash : final state; --abnormal termination
105 Done : final state --normal termination
106   <<Infusion_Flow_Rate@now=0>>;
107 transitions
108   go : PowerOn-[ true ]->WaitForRx{};
109 --prescription validated
110   rxo : WaitForRx-[ on dispatch Begin_Infusion ]-> CheckPBR{};
111   pbr0 : CheckPBR-[ Patient_Bolus_Rate<=0 ]->Crash{}; --bad Patient_Bolus_Rate
112   pbr0k : CheckPBR-[ Patient_Bolus_Rate>0 ]->RxApproved
113     {<<Rx_APPROVED() and (Patient_Bolus_Rate>0)>> --likely will change from logic variable to predicate
114       Rx_APPROVED()
115       pb_duration := VTBI/Patient_Bolus_Rate --calculate patient bolus duration
116       --note division without knowing divsor is non-zero; should generate additional proof obligations for
117       assignment using division
118       <<Rx_APPROVED() and PB_DURATION(>>>;
119 --clinician press 'prime' button
120   rxpri : RxApproved-[ on dispatch Begin_Priming ]-> Priming
121     {
122       la :=StartPriming
123       <<Begin_Priming@now and Rx_APPROVED() and (la = StartPriming) and PB_DURATION(>>
124       ;
125       Infusion_Flow_Rate!(PCA_Properties::Prime_Rate) --infuse at prime rate
126       <<(la = StartPriming) and Rx_APPROVED() and PB_DURATION() and
127         (Infusion_Flow_Rate@now=PCA_Properties::Prime_Rate)>>
128     };
129 --priming done, wait for start
130   prd: Priming-[ on dispatch End_Priming or timeout (Begin_Priming) PCA_Properties::Prime_Time sec]->
131     WaitForStart
132     {
133       la:=EndPriming
134       <<HALT() and PB_DURATION(>> --and Begin_Priming timed out
135       ;
136       Infusion_Flow_Rate!(0) --stop priming flow
137       <<HALT() and (Infusion_Flow_Rate@now=0) and PB_DURATION(>>
138     };
139 --prime again
140   pri: WaitForStart-[ on dispatch Begin_Priming ]-> Priming
141     {
142       la:=StartPriming
143       <<Begin_Priming@now and PB_DURATION() and PRIME_RATE(>>
144       ;
145       Infusion_Flow_Rate!(PCA_Properties::Prime_Rate) --infuse at prime rate
146       <<PRIME_RATE() and PB_DURATION() and
147         (Infusion_Flow_Rate@now=PCA_Properties::Prime_Rate)>>
148     };
149 --clinician press 'start' button after priming
150   sap: WaitForStart-[ on dispatch Begin_Infusion ]-> PumpBasalRate --start after priming
151     {
152       la:=StartButton
153       <<(la=StartButton) and Begin_Infusion@now and PB_DURATION(>>
154     };

```



```

152     Infusion_Flow_Rate!(Basal_Rate)    --infuse at basal rate
153     <<(la=StartButton) and (Infusion_Flow_Rate@now=Basal_Rate@now) and PB_DURATION()>>
154 };
155 --Patient_Request_Bolus during basal rate infusion
156 pump_basal_rate:
157 PumpBasalRate-[ on dispatch Patient_Request_Not_Too_Soon]-> PumpPatientButtonVTBI
158 {
159     la := PatientButton
160     <<(la=PatientButton) and Patient_Request_Bolus@now and PB_DURATION()>>
161     ;
162     Infusion_Flow_Rate!(Patient_Bolus_Rate)    --infuse at patient button rate
163     <<(la=PatientButton) and PB_DURATION()
164     and (Infusion_Flow_Rate@now=Patient_Bolus_Rate)>>
165 }; --end of pump_basal_rate
166 --VTBI delivered
167 vtbi_delivered:
168 PumpPatientButtonVTBI -[ on dispatch timeout (Infusion_Flow_Rate) pb_duration ms ]-> PumpBasalRate
169 {
170     la:=ResumeBasal
171     ;
172     <<(la=ResumeBasal) and PB_DURATION()>> --and timeout of patient button duration
173     Infusion_Flow_Rate!(Basal_Rate)    --infuse at basal rate
174     <<(la=ResumeBasal) and (Infusion_Flow_Rate@now=Basal_Rate@now) and PB_DURATION()>>
175 }; --end of vtbi_delivered
176 **};
177 end Rate_Controller.imp;

```

**Listing D.1:** Rate\_Controller thread

# Appendix E

## Simplified PCA pump AADL models

This appendix contains simplified AADL/BLESS models. They were created based on AADL/BLESS models of PCA pump, created by Brian Larson.

```
1 property set BLESS_Properties is
2   with AADL_Project;
3
4   Supported_Operators : list of aadlstring applies to ( data );
5   Supported_Relations : list of aadlstring applies to ( data );
6   Radix : AADL_Project::Size_Units applies to ( data );
7 end BLESS_Properties;
```

**Listing E.1:** BLESS\_Properties property set

```
1 property set BLESS is
2   Assertion : aadlstring applies to ( all );
3   Typed : aadlstring applies to ( all );
4   Invariant : aadlstring applies to ( all );
5 end BLESS;
```

**Listing E.2:** BLESS property set

```
1 property set PCA_Properties is
2   with PCA_Types;
3
4   Drug_Library_Size : constant aadlinteger => 500;
5   Fault_Log_Size : constant aadlinteger => 150;
6   Event_Log_Size : constant aadlinteger => 1500;
7   KVO_Rate_Constant : constant aadlinteger => 1;
8   KVO_Rate : constant aadlinteger => PCA_Properties::KVO_Rate_Constant;
9   Max_Rate : constant aadlinteger => 10;
10 end PCA_Properties;
```

**Listing E.3:** PCA\_Properties property set

```

1 package BLESS_Types public
2 with Base_Types, BLESS_Properties, Data_Model, Memory_Properties, BLESS;
3
4 data Integer extends Base_Types::Integer
5   properties --operators and relation symbols defined for Integer
6     BLESS::Typed => "integer";
7     BLESS_Properties::Supported_Operators => ("+", "*", "-", "/", "mod", "rem", "**");
8     BLESS_Properties::Supported_Relations => ("=", "!=", "<", "<=", ">=", ">");
9 end Integer;
10
11 data Natural extends Base_Types::Natural
12   properties --operators and relation symbols defined for Natural
13     BLESS::Typed => "natural";
14     BLESS_Properties::Supported_Operators => ("+", "*", "-", "/", "mod", "rem", "**");
15     BLESS_Properties::Supported_Relations => ("=", "!=", "<", "<=", ">=", ">");
16 end Natural;
17
18 data Real extends Base_Types::Float
19   properties --operators and relation symbols defined for Float
20     BLESS::Typed => "real";
21     BLESS_Properties::Supported_Operators => ("+", "*", "-", "/", "**");
22     BLESS_Properties::Supported_Relations => ("=", "!=", "<", "<=", ">=", ">");
23 end Real;
24
25 data String extends Base_Types::String
26   properties --operators and relation symbols defined for String
27     BLESS::Typed => "string";
28     BLESS_Properties::Supported_Operators => ("+", "-"); --just concatenation
29     BLESS_Properties::Supported_Relations => ("=", "!=", "<", "<=", ">=", ">");
30 end String;
31
32 data Fixed_Point
33   properties --operators and relation symbols defined for fixed-point arithmetic
34     BLESS::Typed => "fixed";
35     BLESS_Properties::Supported_Operators => ("+", "*", "-", "/", "**");
36     BLESS_Properties::Supported_Relations => ("=", "!=", "<", "<=", ">=", ">");
37     Data_Model::Data_Representation => Integer;
38 end Fixed_Point;
39
40 data Time extends Base_Types::Integer_64 --in milliseconds
41   properties --operators and relation symbols defined for Time
42     --don't have a way to say that Time may be multiplied or divided by scalar
43     --but not another Time
44     BLESS::Typed => "integer";
45     BLESS_Properties::Supported_Operators => ("+", "*", "-", "/");
46     BLESS_Properties::Supported_Relations => ("=", "!=", "<", "<=", ">=", ">");
47 end Time;
48
49 end BLESS_Types;

```

Listing E.4: BLESS\_Types package

```

1 package ICE_Types
2 public
3 with Data_Model;
4 with Base_Types;
5   data Milliliter
6   properties
7     Data_Model::Data_Representation => Integer;
8     Data_Model::Base_Type => (classifier (Base_Types::Unsigned_16)); --two bytes for 0-1000 ml
9     Data_Model::Integer_Range => 0 .. 1000;
10    Data_Model::Measurement_Unit => "ml";
11  end Milliliter;
12
13  data Milliliter_Per_Hour
14  properties
15    Data_Model::Data_Representation => Integer;
16    Data_Model::Base_Type => (classifier (Base_Types::Unsigned_16)); --two bytes for 0-1000 ml/hr
17    Data_Model::Integer_Range => 0 .. 1000;
18    Data_Model::Measurement_Unit => "ml_per_hr";
19  end Milliliter_Per_Hour;
20
21  data Microliter_Per_Hour
22  properties
23    Data_Model::Data_Representation => Integer;
24    Data_Model::Base_Type => (classifier (Base_Types::Unsigned_16)); --two bytes for 0-1000 ul/hr
25    Data_Model::Integer_Range => 0 .. 1000;
26    Data_Model::Measurement_Unit => "ul_per_hr";
27  end Microliter_Per_Hour;
28
29  data Minute
30  properties
31    Data_Model::Data_Representation => Integer;
32    Data_Model::Base_Type => (classifier (Base_Types::Unsigned_16)); --two bytes for 0-1000 minutes
33    Data_Model::Integer_Range => 0 .. 1000;
34    Data_Model::Measurement_Unit => "min";
35  end Minute;
36
37  data Alarm_Signal --according to IEC 60601-1-8/FDIS AAA.201.8 ALARM SIGNAL inactivation states
38  properties
39    Data_Model::Data_Representation => Enum;
40    Data_Model::Enumerators => ("On", "Alarm_Off", "Alarm_Paused", "Audio_Off", "Audio_Paused");
41  end Alarm_Signal;
42
43  data Percent
44  properties
45    Data_Model::Data_Representation => Integer;
46    Data_Model::Base_Type => (classifier (Base_Types::Unsigned_8)); --one byte for 0-100 percent
47    Data_Model::Integer_Range => 0 .. 100;
48  end Percent;
49
50  data Minute_Count extends Base_Types::Integer
51  end Minute_Count;
52
53  data Second_Count extends Base_Types::Integer
54  end Second_Count;
55
56 end ICE_Types;

```

Listing E.5: ICE\_Types package

```

1 package PCA_Types
2 public
3   with Base_Types, Data_Model, PCA_Properties, ICE_Types, BLESS_Types, BLESS;
4
5 data Alarm_Type
6   properties
7     BLESS::Typed=>"enumeration (
8       No_Alarm,
9       Pump_Overheated,
10      Defective_Battery,
11      Low_Battery,
12      POST_Failure,
13      RAM_Failure,
14      ROM_failure,
15      CPU_Failure,
16      Thread_Monitor_Failure,
17      Air_In_Line,
18      Upstream_Occlusion,
19      Downstream_Occlusion,
20      Empty_Reservoir,
21      Basal_Overinfusion,
22      Bolus_Overinfusion,
23      Square_Bolus_Overinfusion)";
24   Data_Model::Data_Representation => Enum;
25   Data_Model::Enumerators => (
26     "No_Alarm",
27     "Pump_Overheated",
28     "Defective_Battery",
29     "Low_Battery",
30     "POST_Failure",
31     "RAM_Failure",
32     "ROM_failure",
33     "CPU_Failure",
34     "Thread_Monitor_Failure",
35     "Air_In_Line",
36     "Upstream_Occlusion",
37     "Downstream_Occlusion",
38     "Empty_Reservoir",
39     "Basal_Overinfusion",
40     "Bolus_Overinfusion",
41     "Square_Bolus_Overinfusion");
42 end Alarm_Type;
43
44 data Warning_Type
45   properties
46     BLESS::Typed=>
47       "enumeration (No_Warning,
48         Over_Max_Drug_Per_Hour,
49         Soft_Limit,
50         Low_Reservoir,
51         Priming_Failure,
52         Basal_Underinfusion,
53         Bolus_Underinfusion,
54         Square_Bolus_Underinfusion,
55         Input_Needed,
56         Long_Pause,
57         Drug_Not_In_Library,
58         Hard_Limit_Violated,
59         Voltage_OOR)";
60   Data_Model::Data_Representation => Enum;
61   Data_Model::Enumerators => (
62     "No_Warning",
63     "Over_Max_Drug_Per_Hour",
64     "Soft_Limit",
65     "Low_Reservoir",

```

```

66     "Priming_Failure",
67     "Basal_Underinfusion",
68     "Bolus_Underinfusion",
69     "Square_Bolus_Underinfusion",
70     "Input_Needed",
71     "Long_Pause",
72     "Drug_Not_In_Library",
73     "Hard_Limit_Violated",
74     "Voltage_OOR");
75 end Warning_Type;
76
77 data Status_Type
78     properties
79         BLESS::Typed=>"enumeration (Stopped,Bolus,Basal,KVO,Square_Bolus)";
80         Data_Model::Data_Representation => Enum;
81         Data_Model::Enumerators => ("Stopped","Bolus","Basal","KVO","Square_Bolus");
82 end Status_Type;
83
84 data Flow_Rate --dose rate
85     properties
86         BLESS::Typed=>"integer";
87         Data_Model::Base_Type => (classifier(Base_Types::Integer_16));
88         Data_Model::Measurement_Unit => "ml/hr";
89 end Flow_Rate;
90
91 data Drug_Volume --volume of VTBI
92     properties
93         BLESS::Typed=>"integer";
94         Data_Model::Base_Type => (classifier(Base_Types::Integer_16));
95         Data_Model::Measurement_Unit => "ml";
96 end Drug_Volume;
97
98 data Drug_Weight --string representing what drug, concentration, and volume is in the reservoir
99     properties
100         BLESS::Typed=>"integer";
101         Data_Model::Base_Type => (classifier(Base_Types::Integer_16));
102         Data_Model::Measurement_Unit => "mg";
103 end Drug_Weight;
104
105 data Drug_Concentration --string representing what drug, concentration, and volume is in the reservoir
106     properties
107         BLESS::Typed=>"integer";
108         Data_Model::Base_Type => (classifier(Base_Types::Integer));
109         Data_Model::Measurement_Unit => "mg/l";
110 end Drug_Concentration;
111
112 data Drug_Record --holds pharmacy data for a drug that may be used with the pump
113     properties
114         BLESS::Typed =>
115         "record (
116             Amount : PCA_Types::Drug_Weight;           --The weight of the drug dissolved in the diluent (mg)
117             Concentration : PCA_Types::Drug_Concentration; --Drug concentration; as prescribed
118             Vtbi_Lower_Soft : PCA_Types::Drug_Volume;    --Lower soft limit of drug volume to be infused
119             Vtbi_Lower_Hard : PCA_Types::Drug_Volume;    --Lower hard limit of drug volume to be infused
120             Vtbi_Typical : PCA_Types::Drug_Volume;       --Typical drug volume to be infused
121             Vtbi_Upper_Soft : PCA_Types::Drug_Volume;    --Upper soft limit of drug volume to be infused
122             Vtbi_Upper_Hard : PCA_Types::Drug_Volume;    --Upper hard limit of drug volume to be infused
123             Basal_Rate_Lower_Soft : PCA_Types::Flow_Rate; --Lower soft limit of basal drug dose rate
124             Basal_Rate_Lower_Hard : PCA_Types::Flow_Rate; --Lower hard limit of basal drug dose rate
125             Basal_Rate_Typical : PCA_Types::Flow_Rate;   --Typical basal drug dose rate
126             Basal_Rate_Upper_Soft : PCA_Types::Flow_Rate; --Upper soft limit of basal drug dose rate
127             Basal_Rate_Upper_Hard : PCA_Types::Flow_Rate; --Upper hard limit of basal drug dose rate
128             Bolus_Typical : PCA_Types::Drug_Volume;      --Typical Value of Bolus Volume
129             Square_Bolus_rate_typical : PCA_Types::Flow_Rate; --Typical duration of clinician commanded
130             bolus

```

```

130     );
131 Data_Model::Data_Representation => Struct;
132 Data_Model::Element_Names =>
133   ( "Amount",           --The weight of the drug dissolved in the diluent (mg)
134     "Concentration",     --Drug concentration; as prescribed
135     "Vtbi_Lower_Soft",   --Lower soft limit of drug volume to be infused
136     "Vtbi_Lower_Hard",   --Lower hard limit of drug volume to be infused
137     "Vtbi_Typical",      --Typical drug volume to be infused
138     "Vtbi_Upper_Soft",   --Upper soft limit of drug volume to be infused
139     "Vtbi_Upper_Hard",   --Upper hard limit of drug volume to be infused
140     "Basal_Rate_Lower_Soft", --Lower soft limit of basal drug dose rate
141     "Basal_Rate_Lower_Hard", --Lower hard limit of basal drug dose rate
142     "Basal_Rate_Typical", --Typical basal drug dose rate
143     "Basal_Rate_Upper_Soft", --Upper soft limit of basal drug dose rate
144     "Basal_Rate_Upper_Hard", --Upper hard limit of basal drug dose rate
145     "Bolus_Typical",      --Typical Value of Bolus Volume
146     "Square_Bolus_Rate_Typical" --Typical rate of clinician commanded bolus
147   );
148 Data_Model::Base_Type =>
149   ( classifier(Drug_Weight),      --amount
150     classifier(Drug_Concentration), --concentration
151     classifier(Drug_Volume),      --vtbi_lower_soft
152     classifier(Drug_Volume),      --vtbi_lower_hard
153     classifier(Drug_Volume),      --vtbi_typical
154     classifier(Drug_Volume),      --vtbi_upper_soft
155     classifier(Drug_Volume),      --vtbi_upper_hard
156     classifier(Flow_Rate),         --basal_rate_lower_soft
157     classifier(Flow_Rate),         --basal_rate_lower_hard
158     classifier(Flow_Rate),         --basal_rate_typical
159     classifier(Flow_Rate),         --basal_rate_upper_soft
160     classifier(Flow_Rate),         --basal_rate_upper_hard
161     classifier(Drug_Volume),       --bolus_typical
162     classifier(Flow_Rate)         --ssquare_bolus_rate_typical
163   );
164 end Drug_Record;
165
166
167 data Drug_Library --holds drug records for all drugs approved by the hospital pharmacy
168 properties
169   BLESS::Typed => "array [PCA_Properties::Drug_Library_Size] of PCA_Types::Drug_Record";
170   Data_Model::Data_Representation => Array;
171   Data_Model::Base_Type => (classifier(Drug_Record));
172   Data_Model::Dimension => (PCA_Properties::Drug_Library_Size);
173 end Drug_Library;
174
175 data Prescription
176 properties
177   BLESS::Typed =>
178     "record (
179       Concentration : Drug_Concentration;
180       Initial_Volume : Drug_Volume;
181       Basal_Flow_Rate : Flow_Rate;
182       Vtbi : Drug_Volume;
183       Max_Drug_Per_Hour : Drug_Volume;
184       Minimum_Time_Between_Bolus : ICE_Types::Minute;
185     )";
186   Data_Model::Data_Representation => Struct;
187   Data_Model::Element_Names =>
188     ( "Concentration",
189       "Initial_Volume",
190       "Basal_Flow_Rate",
191       "Vtbi",
192       "Max_Drug_Per_Hour",
193       "Minimum_Time_Between_Bolus"
194     );

```

```

195     Data_Model::Base_Type =>
196     ( classifier(Drug_Concentration),    --concentration
197       classifier(Drug_Volume),          --initial volume
198       classifier(Flow_Rate),            --basal flow rate
199       classifier(Drug_Volume),          --VTBI
200       classifier(Drug_Volume),          --maximum drug allowed per hour
201       classifier(ICE_Types::Minute)     --min time between bolus doses
202     );
203 end Prescription;
204
205 data Fault_Record --record of fault for log
206 properties
207   BLESS::Typed => "record (Alarm:Alarm_Type; Warning:Warning_Type; Occurrence_Time:BLESS_Types::Time)";
208   Data_Model::Data_Representation => Struct;
209   Data_Model::Element_Names => ("Alarm","Warning","Occurrence_Time");
210   Data_Model::Base_Type => ( classifier(Alarm_Type),classifier(Warning_Type),classifier(BLESS_Types::Time))
211   ;
212 end Fault_Record;
213
214 data Fault_Log --holds records of faults
215 properties
216   BLESS::Typed => "array [PCA_Properties::Fault_Log_Size] of PCA_Types::Fault_Record";
217   Data_Model::Data_Representation => Array;
218   Data_Model::Base_Type => (classifier(Fault_Record));
219   Data_Model::Dimension => (PCA_Properties::Fault_Log_Size);
220 end Fault_Log;
221
222 data Event_Record --record of event for log
223 properties
224   BLESS::Typed => "record ( Time : BLESS_Types::Time)";
225   Data_Model::Data_Representation => Struct;
226   Data_Model::Element_Names => ( "Time" );
227   Data_Model::Base_Type => (classifier(BLESS_Types::Time));
228 end Event_Record;
229
230 data Event_Log --holds records of events
231 properties
232   BLESS::Typed => "array [PCA_Properties::Event_Log_Size] of PCA_Types::Event_Record";
233   Data_Model::Data_Representation => Array;
234   Data_Model::Base_Type => (classifier(Event_Record));
235   Data_Model::Dimension => (PCA_Properties::Event_Log_Size);
236 end Event_Log;
237
238 data Infusion_Type --used for over- and under-infusion alarms
239 properties
240   BLESS::Typed=>"enumeration(Bolus_Infusion, Square_Infusion, Basal_Infusion, KVO_Infusion)";
241   Data_Model::Data_Representation => Enum;
242   Data_Model::Enumerators => ("Bolus_Infusion","Square_Infusion","Basal_Infusion","KVO_Infusion");
243 end Infusion_Type;
244
245 data Pump_Fault_Type
246 properties
247   BLESS::Typed=>"enumeration(Prime_Failure, Pump_Hot, Bubble, Upstream_Occlusion_Fault,
248     Downstream_Occlusion_Fault, Overinfusion, Underinfusion)";
249   Data_Model::Data_Representation => Enum;
250   Data_Model::Enumerators => ("Prime_Failure","Pump_Hot","Bubble","Upstream_Occlusion_Fault","
251     Downstream_Occlusion_Fault","Overinfusion","Underinfusion" );
252 end Pump_Fault_Type;
253
254 end PCA_Types;

```

Listing E.6: PCA\_Types package



```

1 package PCA_Operation
2 public
3   with PCA_Properties, Base_Types, BLESS, BLESS_Types, ICE_Types, PCA_Types;
4
5 system operation
6   features
7     Start_Button_Pressed: in event port;
8     Stop_Button_Pressed: in event port;
9     Patient_Request_Bolus: in event port;
10    Clinician_Request_Bolus: in event port;
11    Bolus_Duration: in event data port ICE_Types::Minute;
12    Infusion_Flow_Rate: out data port PCA_Types::Flow_Rate;
13    System_Status: out data port PCA_Types::Status_Type;
14    Rx: in event data port PCA_Types::Prescription;
15 end operation;
16
17 system implementation operation.imp
18   subcomponents
19     operation_process: process operation_process.imp;
20   connections
21     start: port Start_Button_Pressed -> operation_process.Start_Button_Pressed;
22     stop: port Stop_Button_Pressed -> operation_process.Stop_Button_Pressed;
23     pbp: port Patient_Request_Bolus -> operation_process.Patient_Request_Bolus;
24     crb: port Clinician_Request_Bolus -> operation_process.Clinician_Request_Bolus;
25     bd: port Bolus_Duration -> operation_process.Bolus_Duration;
26     pfr: port operation_process.Infusion_Flow_Rate -> Infusion_Flow_Rate;
27     stat: port operation_process.System_Status -> System_Status;
28     rxo: port Rx->operation_process.Rx;
29 end operation.imp;
30
31 process operation_process
32   features
33     Start_Button_Pressed: in event port;
34     Stop_Button_Pressed: in event port;
35     Patient_Request_Bolus: in event port;
36     Clinician_Request_Bolus: in event port;
37     Bolus_Duration: in event data port ICE_Types::Minute;
38     Infusion_Flow_Rate: out data port PCA_Types::Flow_Rate;
39     System_Status: out data port PCA_Types::Status_Type;
40     Rx: in event data port PCA_Types::Prescription;
41 end operation_process;
42
43 process implementation operation_process.imp
44   subcomponents
45     Max_Drug_Per_Hour_Watcher : thread Max_Drug_Per_Hour_Watcher.imp;
46     Rate_Controller : thread Rate_Controller.imp;
47     Patient_Bolus_Checker : thread Patient_Bolus_Checker.imp;
48   connections
49     start: port Start_Button_Pressed -> Rate_Controller.Start_Button_Pressed;
50     stop: port Stop_Button_Pressed -> Rate_Controller.Stop_Button_Pressed;
51     pb: port Patient_Request_Bolus -> Patient_Bolus_Checker.Patient_Request_Bolus;
52     crb: port Clinician_Request_Bolus -> Rate_Controller.Clinician_Request_Bolus;
53     bd: port Bolus_Duration -> Rate_Controller.Bolus_Duration;
54     pfr: port Rate_Controller.Infusion_Flow_Rate -> Infusion_Flow_Rate;
55     ss: port Rate_Controller.System_Status -> System_Status;
56     rxrc: port Rx->Rate_Controller.Rx;
57 end operation_process.imp;
58
59 thread Max_Drug_Per_Hour_Watcher
60   features
61     Infusion_Flow_Rate: in data port PCA_Types::Flow_Rate
62       {BLESS::Assertion => "<<:=PUMP_RATE()>>"};
63     Max_Drug_Per_Hour: in data port PCA_Types::Drug_Volume
64       {BLESS::Assertion => "<<:=MAX_DRUG_PER_HOUR>>"};
65 end Max_Drug_Per_Hour_Watcher;

```

```

66
67 thread implementation Max_Drug_Per_Hour_Watcher.imp
68 end Max_Drug_Per_Hour_Watcher.imp;
69
70 thread Rate_Controller
71 features
72   Start_Button_Pressed: in event port;
73   Stop_Button_Pressed: in event port;
74   Rx: in event data port PCA_Types::Prescription
75   {BLESS::Assertion => "<<:=Rx_APPROVED()>>"};
76   Clinician_Request_Bolus: in event port;
77   Bolus_Duration: in event data port ICE_Types::Minute;
78   Infusion_Flow_Rate: out data port PCA_Types::Flow_Rate
79   {BLESS::Assertion => "<<:=PUMP_RATE()>>"};
80   System_Status: out event data port PCA_Types::Status_Type;
81 end Rate_Controller;
82
83 thread implementation Rate_Controller.imp
84 annex BLESS
85 {**
86 assert
87 <<HALT : :(la=StopButton) >>                --pump at 0 if stop button
88 <<KVO_RATE : :(la=TooMuchJuice)>>            --pump at KVO rate when commanded, some alarms, or
      exceeded hourly limit
89 <<PB_RATE : :la=PatientButton>>              --patient button pressed, and allowed
90 <<CCB_RATE : :(la=StartSquareBolus) or (la=ResumeSquareBolus)>>  --clinician-commanded bolus start or
      resumption after patient bolus
91 <<BASAL_RATE : :(la=StartButton) or (la=ResumeBasal) or (la=SquareBolusDone)>> --regular infusion
92 <<PUMP_RATE : :=
93   (HALT()) -> 0,                                --no flow
94   (KVO_RATE()) -> PCA_Properties::KVO_Rate,      --KVO rate
95   (PB_RATE()) -> Patient_Bolus_Rate,            --maximum infusion upon patient request
96   (CCB_RATE()) -> Square_Bolus_Rate,            --square bolus rate=VTBI/duration, from data port
97   (BASAL_RATE()) -> Basal_Rate                  --basal rate, from data port
98 >>
99 invariant <<true>>
100 variables
101   la : --last action
102   enumeration (
103     StopButton,      --clinician pressed stop button
104     TooMuchJuice,    --exceeded max drug per hour, pump at KVO until prescription and patient are re-
      authenticated
105     PatientButton,   --patient requested drug
106     ResumeSquareBolus, --infusion of VTBI finished, resume clinician-commanded bolus
107     ResumeBasal,     --infusion of VTBI finished, resume basal-rate
108     StartSquareBolus, --begin clinician-commanded bolus
109     SquareBolusDone,  --infusion of VTBI finished
110     StartButton      --start pumping at basal rate
111   );
112 **};
113 end Rate_Controller.imp;
114
115 thread Patient_Bolus_Checker
116 features
117   Patient_Request_Bolus: in event port;
118 end Patient_Bolus_Checker;
119
120 thread implementation Patient_Bolus_Checker.imp
121 end Patient_Bolus_Checker.imp;
122
123 end PCA_Operation;

```

Listing E.7: PCA\_Operation package

# Appendix F

## Simplified PCA pump - translated from simplified AADL models

This appendix presents PCA pump prototype, which was created by direct translation from simplified AADL/BLESS models presented in [appendix E](#).

```
1 package Base_Types
2 is
3   protected type Boolean_Store
4   is
5     pragma Priority (10);
6
7     function Get return Boolean;
8     --# global in Boolean_Store;
9
10    procedure Put(X : in Boolean);
11    --# global out Boolean_Store;
12    --# derives Boolean_Store from X;
13  private
14    TheStoredData : Boolean := False;
15  end Boolean_Store;
16
17  protected type Integer_Store
18  is
19    pragma Priority (10);
20
21    function Get return Integer;
22    --# global in Integer_Store;
23
24    procedure Put(X : in Integer);
25    --# global out Integer_Store;
26    --# derives Integer_Store from X;
27  private
28    TheStoredData : Integer := 0;
29  end Integer_Store;
```

```

30
31 protected type Natural_Store
32 is
33     pragma Priority (10);
34
35     function Get return Natural;
36     --# global in Natural_Store;
37
38     procedure Put(X : in Natural);
39     --# global out Natural_Store;
40     --# derives Natural_Store from X;
41 private
42     TheStoredData : Natural := 0;
43 end Natural_Store;
44
45 type Integer_8 is new Integer range -2**(1*8-1) .. 2**(1*8-1)-1;
46
47 protected type Integer_8_Store
48 is
49     pragma Priority (10);
50
51     function Get return Integer_8;
52     --# global in Integer_8_Store;
53
54     procedure Put(X : in Integer_8);
55     --# global out Integer_8_Store;
56     --# derives Integer_8_Store from X;
57 private
58     TheStoredData : Integer_8 := 0;
59 end Integer_8_Store;
60
61 type Integer_16 is new Integer range -2**(2*8-1) .. 2**(2*8-1)-1;
62
63 protected type Integer_16_Store
64 is
65     pragma Priority (10);
66
67     function Get return Integer_16;
68     --# global in Integer_16_Store;
69
70     procedure Put(X : in Integer_16);
71     --# global out Integer_16_Store;
72     --# derives Integer_16_Store from X;
73 private
74     TheStoredData : Integer_16 := 0;
75 end Integer_16_Store;
76
77 type Integer_32 is new Integer range -2**(4*8-1) .. 2**(4*8-1)-1;
78
79 protected type Integer_32_Store
80 is
81     pragma Priority (10);
82
83     function Get return Integer_32;
84     --# global in Integer_32_Store;
85
86     procedure Put(X : in Integer_32);
87     --# global out Integer_32_Store;
88     --# derives Integer_32_Store from X;
89 private
90     TheStoredData : Integer_32 := 0;
91 end Integer_32_Store;
92
93 type Integer_64 is range -2**(8*8-1) .. 2**(8*8-1)-1; -- with new Integer gnat compiler error: value not
    in range of type "Standard.Integer"

```

```

94
95 protected type Integer_64_Store
96 is
97     pragma Priority (10);
98
99     function Get return Integer_64;
100     --# global in Integer_64_Store;
101
102     procedure Put(X : in Integer_64);
103     --# global out Integer_64_Store;
104     --# derives Integer_64_Store from X;
105 private
106     TheStoredData : Integer_64 := 0;
107 end Integer_64_Store;
108
109 type Unsigned_8 is new Integer range 0 .. 2**(1*8)-1;
110
111 protected type Unsigned_8_Store
112 is
113     pragma Priority (10);
114
115     function Get return Unsigned_8;
116     --# global in Unsigned_8_Store;
117
118     procedure Put(X : in Unsigned_8);
119     --# global out Unsigned_8_Store;
120     --# derives Unsigned_8_Store from X;
121 private
122     TheStoredData : Unsigned_8 := 0;
123 end Unsigned_8_Store;
124
125 type Unsigned_16 is new Integer range 0 .. 2**(2*8)-1;
126
127 protected type Unsigned_16_Store
128 is
129     pragma Priority (10);
130
131     function Get return Unsigned_16;
132     --# global in Unsigned_16_Store;
133
134     procedure Put(X : in Unsigned_16);
135     --# global out Unsigned_16_Store;
136     --# derives Unsigned_16_Store from X;
137 private
138     TheStoredData : Unsigned_16 := 0;
139 end Unsigned_16_Store;
140
141 type Unsigned_32 is range 0 .. 2**(4*8)-1; -- with new Integer gnat compiler error: value not in range of
142     type "Standard.Integer"
143
144 protected type Unsigned_32_Store
145 is
146     pragma Priority (10);
147
148     function Get return Unsigned_32;
149     --# global in Unsigned_32_Store;
150
151     procedure Put(X : in Unsigned_32);
152     --# global out Unsigned_32_Store;
153     --# derives Unsigned_32_Store from X;
154 private
155     TheStoredData : Unsigned_32 := 0;
156 end Unsigned_32_Store;

```

```

157  --type Unsigned_64 is range 0 .. 2**64-1; -- gnat compiler error: integer type definition bounds out of
      range
158
159  end Base_Types;
160
161  package body Base_Types
162  is
163      protected body Boolean_Store is
164          function Get return Boolean
165              --# global in TheStoredData;
166          is
167              begin
168                  return TheStoredData;
169              end Get;
170
171          procedure Put(X : in Boolean)
172              --# global out TheStoredData;
173              --# derives TheStoredData from X;
174          is
175              begin
176                  TheStoredData := X;
177              end Put;
178      end Boolean_Store;
179
180      protected body Integer_Store is
181          function Get return Integer
182              --# global in TheStoredData;
183          is
184              begin
185                  return TheStoredData;
186              end Get;
187
188          procedure Put(X : in Integer)
189              --# global out TheStoredData;
190              --# derives TheStoredData from X;
191          is
192              begin
193                  TheStoredData := X;
194              end Put;
195      end Integer_Store;
196
197      protected body Natural_Store is
198          function Get return Natural
199              --# global in TheStoredData;
200          is
201              begin
202                  return TheStoredData;
203              end Get;
204
205          procedure Put(X : in Natural)
206              --# global out TheStoredData;
207              --# derives TheStoredData from X;
208          is
209              begin
210                  TheStoredData := X;
211              end Put;
212      end Natural_Store;
213
214      protected body Integer_8_Store is
215          function Get return Integer_8
216              --# global in TheStoredData;
217          is
218              begin
219                  return TheStoredData;
220              end Get;

```

```

221
222     procedure Put(X : in Integer_8)
223         --# global out TheStoredData;
224         --# derives TheStoredData from X;
225     is
226     begin
227         TheStoredData := X;
228     end Put;
229 end Integer_8_Store;
230
231 protected body Integer_16_Store is
232     function Get return Integer_16
233         --# global in TheStoredData;
234     is
235     begin
236         return TheStoredData;
237     end Get;
238
239     procedure Put(X : in Integer_16)
240         --# global out TheStoredData;
241         --# derives TheStoredData from X;
242     is
243     begin
244         TheStoredData := X;
245     end Put;
246 end Integer_16_Store;
247
248 protected body Integer_32_Store is
249     function Get return Integer_32
250         --# global in TheStoredData;
251     is
252     begin
253         return TheStoredData;
254     end Get;
255
256     procedure Put(X : in Integer_32)
257         --# global out TheStoredData;
258         --# derives TheStoredData from X;
259     is
260     begin
261         TheStoredData := X;
262     end Put;
263 end Integer_32_Store;
264
265 protected body Integer_64_Store is
266     function Get return Integer_64
267         --# global in TheStoredData;
268     is
269     begin
270         return TheStoredData;
271     end Get;
272
273     procedure Put(X : in Integer_64)
274         --# global out TheStoredData;
275         --# derives TheStoredData from X;
276     is
277     begin
278         TheStoredData := X;
279     end Put;
280 end Integer_64_Store;
281
282 protected body Unsigned_8_Store is
283     function Get return Unsigned_8
284         --# global in TheStoredData;
285     is

```

```

286     begin
287         return TheStoredData;
288     end Get;
289
290     procedure Put(X : in Unsigned_8)
291         --# global out TheStoredData;
292         --# derives TheStoredData from X;
293     is
294     begin
295         TheStoredData := X;
296     end Put;
297 end Unsigned_8_Store;
298
299 protected body Unsigned_16_Store is
300     function Get return Unsigned_16
301         --# global in TheStoredData;
302     is
303     begin
304         return TheStoredData;
305     end Get;
306
307     procedure Put(X : in Unsigned_16)
308         --# global out TheStoredData;
309         --# derives TheStoredData from X;
310     is
311     begin
312         TheStoredData := X;
313     end Put;
314 end Unsigned_16_Store;
315
316 protected body Unsigned_32_Store is
317     function Get return Unsigned_32
318         --# global in TheStoredData;
319     is
320     begin
321         return TheStoredData;
322     end Get;
323
324     procedure Put(X : in Unsigned_32)
325         --# global out TheStoredData;
326         --# derives TheStoredData from X;
327     is
328     begin
329         TheStoredData := X;
330     end Put;
331 end Unsigned_32_Store;
332
333 end Base_Types;

```

**Listing F.1:** Base\_Types package



```

1 with Base_Types;
2 --# inherit Base_Types;
3 package Bless_Types
4 is
5     subtype Fixed_Point is Integer;
6     protected type Fixed_Point_Store
7     is
8         pragma Priority (10);
9         function Get return Fixed_Point;
10        --# global in Fixed_Point_Store;
11        procedure Put(X : in Fixed_Point);
12        --# global out Fixed_Point_Store;
13        --# derives Fixed_Point_Store from X;
14    private
15        TheStoredData : Fixed_Point := 0;
16    end Fixed_Point_Store;
17
18    subtype Time is Base_Types.Integer_64;
19    protected type Time_Store
20    is
21        pragma Priority (10);
22        function Get return Time;
23        --# global in Time_Store;
24        procedure Put(X : in Time);
25        --# global out Time_Store;
26        --# derives Time_Store from X;
27    private
28        TheStoredData : Time := 0;
29    end Time_Store;
30 end Bless_Types;
31
32 package body Bless_Types
33 is
34     protected body Fixed_Point_Store is
35         function Get return Fixed_Point
36         --# global in TheStoredData;
37         is begin
38             return TheStoredData;
39         end Get;
40         procedure Put(X : in Fixed_Point)
41         --# global out TheStoredData;
42         --# derives TheStoredData from X;
43         is begin
44             TheStoredData := X;
45         end Put;
46     end Fixed_Point_Store;
47
48     protected body Time_Store is
49         function Get return Time
50         --# global in TheStoredData;
51         is begin
52             return TheStoredData;
53         end Get;
54         procedure Put(X : in Time)
55         --# global out TheStoredData;
56         --# derives TheStoredData from X;
57         is begin
58             TheStoredData := X;
59         end Put;
60     end Time_Store;
61 end Bless_Types;

```

Listing F.2: Bless\_Types package

```

1 with Base_Types;
2 --# inherit Base_Types;
3 package Ice_Types
4 is
5     subtype Milliliter is Base_Types.Unsigned_16 range 0 .. 1000;
6
7     protected type Milliliter_Store
8     is
9         pragma Priority (10);
10
11         function Get return Milliliter;
12         --# global in Milliliter_Store;
13
14         procedure Put(X : in Milliliter);
15         --# global out Milliliter_Store;
16         --# derives Milliliter_Store from X;
17     private
18         TheStoredData : Milliliter := 0;
19     end Milliliter_Store;
20
21
22     subtype Milliliter_Per_Hour is Base_Types.Unsigned_16 range 0 .. 1000;
23
24     protected type Milliliter_Per_Hour_Store
25     is
26         pragma Priority (10);
27
28         function Get return Milliliter_Per_Hour;
29         --# global in Milliliter_Per_Hour_Store;
30
31         procedure Put(X : in Milliliter_Per_Hour);
32         --# global out Milliliter_Per_Hour_Store;
33         --# derives Milliliter_Per_Hour_Store from X;
34     private
35         TheStoredData : Milliliter_Per_Hour := 0;
36     end Milliliter_Per_Hour_Store;
37
38
39     subtype Microliter_Per_Hour is Base_Types.Unsigned_16 range 0 .. 1000;
40
41     protected type Microliter_Per_Hour_Store
42     is
43         pragma Priority (10);
44
45         function Get return Microliter_Per_Hour;
46         --# global in Microliter_Per_Hour_Store;
47
48         procedure Put(X : in Microliter_Per_Hour);
49         --# global out Microliter_Per_Hour_Store;
50         --# derives Microliter_Per_Hour_Store from X;
51     private
52         TheStoredData : Microliter_Per_Hour := 0;
53     end Microliter_Per_Hour_Store;
54
55
56     subtype Minute is Base_Types.Unsigned_16 range 0 .. 1000;
57
58     protected type Minute_Store
59     is
60         pragma Priority (10);
61
62         function Get return Minute;
63         --# global in Minute_Store;
64
65         procedure Put(X : in Minute);

```

```

66     --# global out Minute_Store;
67     --# derives Minute_Store from X;
68 private
69     TheStoredData : Minute := 0;
70 end Minute_Store;
71
72
73 type Alarm_Signal is (On, Alarm_Off, Alarm_Paused, Audio_Off, Audio_Paused);
74
75 protected type Alarm_Signal_Store
76 is
77     pragma Priority (10);
78
79     function Get return Alarm_Signal;
80     --# global in Alarm_Signal_Store;
81
82     procedure Put(X : in Alarm_Signal);
83     --# global out Alarm_Signal_Store;
84     --# derives Alarm_Signal_Store from X;
85 private
86     TheStoredData : Alarm_Signal := Alarm_Signal'First;
87 end Alarm_Signal_Store;
88
89
90 subtype Percent is Base_Types.Unsigned_8 range 0 .. 100;
91
92 protected type Percent_Store
93 is
94     pragma Priority (10);
95
96     function Get return Percent;
97     --# global in Percent_Store;
98
99     procedure Put(X : in Percent);
100    --# global out Percent_Store;
101    --# derives Percent_Store from X;
102 private
103     TheStoredData : Percent := 0;
104 end Percent_Store;
105
106
107 type Minute_Count is new Integer;
108
109 protected type Minute_Count_Store
110 is
111     pragma Priority (10);
112
113     function Get return Minute_Count;
114     --# global in Minute_Count_Store;
115
116     procedure Put(X : in Minute_Count);
117     --# global out Minute_Count_Store;
118     --# derives Minute_Count_Store from X;
119 private
120     TheStoredData : Minute_Count := 0;
121 end Minute_Count_Store;
122
123
124 type Second_Count is new Integer;
125
126 protected type Second_Count_Store
127 is
128     pragma Priority (10);
129
130     function Get return Second_Count;

```

```

131     --# global in Second_Count_Store;
132
133     procedure Put(X : in Second_Count);
134     --# global out Second_Count_Store;
135     --# derives Second_Count_Store from X;
136 private
137     TheStoredData : Second_Count := 0;
138 end Second_Count_Store;
139 end Ice_Types;
140
141 package body Ice_Types
142 is
143     protected body Milliliter_Store is
144         function Get return Milliliter
145         --# global in TheStoredData;
146         is
147         begin
148             return TheStoredData;
149         end Get;
150
151         procedure Put(X : in Milliliter)
152         --# global out TheStoredData;
153         --# derives TheStoredData from X;
154         is
155         begin
156             TheStoredData := X;
157         end Put;
158     end Milliliter_Store;
159
160     protected body Milliliter_Per_Hour_Store is
161         function Get return Milliliter_Per_Hour
162         --# global in TheStoredData;
163         is
164         begin
165             return TheStoredData;
166         end Get;
167
168         procedure Put(X : in Milliliter_Per_Hour)
169         --# global out TheStoredData;
170         --# derives TheStoredData from X;
171         is
172         begin
173             TheStoredData := X;
174         end Put;
175     end Milliliter_Per_Hour_Store;
176
177     protected body Microliter_Per_Hour_Store is
178         function Get return Microliter_Per_Hour
179         --# global in TheStoredData;
180         is
181         begin
182             return TheStoredData;
183         end Get;
184
185         procedure Put(X : in Microliter_Per_Hour)
186         --# global out TheStoredData;
187         --# derives TheStoredData from X;
188         is
189         begin
190             TheStoredData := X;
191         end Put;
192     end Microliter_Per_Hour_Store;
193
194     protected body Minute_Store is
195         function Get return Minute

```

```

196     --# global in TheStoredData;
197     is
198     begin
199         return TheStoredData;
200     end Get;
201
202     procedure Put(X : in Minute)
203         --# global out TheStoredData;
204         --# derives TheStoredData from X;
205     is
206     begin
207         TheStoredData := X;
208     end Put;
209 end Minute_Store;
210
211 protected body Alarm_Signal_Store is
212     function Get return Alarm_Signal
213         --# global in TheStoredData;
214     is
215     begin
216         return TheStoredData;
217     end Get;
218
219     procedure Put(X : in Alarm_Signal)
220         --# global out TheStoredData;
221         --# derives TheStoredData from X;
222     is
223     begin
224         TheStoredData := X;
225     end Put;
226 end Alarm_Signal_Store;
227
228 protected body Percent_Store is
229     function Get return Percent
230         --# global in TheStoredData;
231     is
232     begin
233         return TheStoredData;
234     end Get;
235
236     procedure Put(X : in Percent)
237         --# global out TheStoredData;
238         --# derives TheStoredData from X;
239     is
240     begin
241         TheStoredData := X;
242     end Put;
243 end Percent_Store;
244
245 protected body Minute_Count_Store is
246     function Get return Minute_Count
247         --# global in TheStoredData;
248     is
249     begin
250         return TheStoredData;
251     end Get;
252
253     procedure Put(X : in Minute_Count)
254         --# global out TheStoredData;
255         --# derives TheStoredData from X;
256     is
257     begin
258         TheStoredData := X;
259     end Put;
260 end Minute_Count_Store;

```

```

261
262     protected body Second_Count_Store is
263         function Get return Second_Count
264             --# global in TheStoredData;
265         is
266         begin
267             return TheStoredData;
268         end Get;
269
270         procedure Put(X : in Second_Count)
271             --# global out TheStoredData;
272             --# derives TheStoredData from X;
273         is
274         begin
275             TheStoredData := X;
276         end Put;
277     end Second_Count_Store;
278
279 end Ice_Types;

```

Listing F.3: Ice\_Types package

```

1 with Base_Types;
2 with Bless_Types;
3 with Ice_Types;
4 with Pca_Properties;
5 --# inherit Base_Types,
6 --#         Bless_Types,
7 --#         Ice_Types,
8 --#         Pca_Properties;
9 package Pca_Types
10 is
11     type Alarm_Type is (
12         No_Alarm,
13         Pump_Overheated,
14         Defective_Battery,
15         Low_Battery,
16         POST_Failure,
17         RAM_Failure,
18         ROM_failure,
19         CPU_Failure,
20         Thread_Monitor_Failure,
21         Air_In_Line,
22         Upstream_Occlusion,
23         Downstream_Occlusion,
24         Empty_Reservoir,
25         Basal_Overinfusion,
26         Bolus_Overinfusion,
27         Square_Bolus_Overinfusion
28     );
29
30     protected type Alarm_Type_Store
31     is
32         pragma Priority (10);
33
34         function Get return Alarm_Type;
35         --# global in Alarm_Type_Store;
36
37         procedure Put(X : in Alarm_Type);
38         --# global out Alarm_Type_Store;
39         --# derives Alarm_Type_Store from X;
40     private
41         TheStoredData : Alarm_Type := Alarm_Type'First;

```

```

42  end Alarm_Type_Store;
43
44
45  type Warning_Type is (No_Warning,
46                        Over_Max_Drug_Per_Hour,
47                        Soft_Limit,
48                        Low_Reservoir,
49                        Priming_Failure,
50                        Basal_Underinfusion,
51                        Bolus_Underinfusion,
52                        Square_Bolus_Underinfusion,
53                        Input_Needed,
54                        Long_Pause,
55                        Drug_Not_In_Library,
56                        Hard_Limit_Violated,
57                        Voltage_OOR
58                        );
59
60  protected type Warning_Type_Store
61  is
62      pragma Priority (10);
63
64      function Get return Warning_Type;
65      --# global in Warning_Type_Store;
66
67      procedure Put(X : in Warning_Type);
68      --# global out Warning_Type_Store;
69      --# derives Warning_Type_Store from X;
70  private
71      TheStoredData : Warning_Type := Warning_Type'First;
72  end Warning_Type_Store;
73
74
75  type Status_Type is (Stopped, Bolus, Basal, KVO, Square_Bolus);
76
77  protected type Status_Type_Store
78  is
79      pragma Priority (10);
80
81      function Get return Status_Type;
82      --# global in Status_Type_Store;
83
84      procedure Put(X : in Status_Type);
85      --# global out Status_Type_Store;
86      --# derives Status_Type_Store from X;
87  private
88      TheStoredData : Status_Type := Status_Type'First;
89  end Status_Type_Store;
90
91
92  subtype Flow_Rate is Base_Types.Integer_16;
93
94  protected type Flow_Rate_Store
95  is
96      pragma Priority (10);
97
98      function Get return Flow_Rate;
99      --# global in Flow_Rate_Store;
100
101      procedure Put(X : in Flow_Rate);
102      --# global out Flow_Rate_Store;
103      --# derives Flow_Rate_Store from X;
104  private
105      TheStoredData : Flow_Rate := 0;
106  end Flow_Rate_Store;

```

```

107
108
109 subtype Drug_Volume is Base_Types.Integer_16;
110
111 protected type Drug_Volume_Store
112 is
113     pragma Priority (10);
114
115     function Get return Drug_Volume;
116     --# global in Drug_Volume_Store;
117
118     procedure Put(X : in Drug_Volume);
119     --# global out Drug_Volume_Store;
120     --# derives Drug_Volume_Store from X;
121 private
122     TheStoredData : Drug_Volume := 0;
123 end Drug_Volume_Store;
124
125
126 subtype Drug_Weight is Base_Types.Integer_16;
127
128 protected type Drug_Weight_Store
129 is
130     pragma Priority (10);
131
132     function Get return Drug_Weight;
133     --# global in Drug_Weight_Store;
134
135     procedure Put(X : in Drug_Weight);
136     --# global out Drug_Weight_Store;
137     --# derives Drug_Weight_Store from X;
138 private
139     TheStoredData : Drug_Weight := 0;
140 end Drug_Weight_Store;
141
142
143 type Drug_Concentration is new Integer;
144
145 protected type Drug_Concentration_Store
146 is
147     pragma Priority (10);
148
149     function Get return Drug_Concentration;
150     --# global in Drug_Concentration_Store;
151
152     procedure Put(X : in Drug_Concentration);
153     --# global out Drug_Concentration_Store;
154     --# derives Drug_Concentration_Store from X;
155 private
156     TheStoredData : Drug_Concentration := 0;
157 end Drug_Concentration_Store;
158
159
160 type Drug_Record is record
161     Amount : Drug_Weight;
162     Concentration : Drug_Concentration;
163     Vtbi_Lower_Soft : Drug_Volume;
164     Vtbi_Lower_Hard : Drug_Volume;
165     Vtbi_Typical : Drug_Volume;
166     Vtbi_Upper_Soft : Drug_Volume;
167     Vtbi_Upper_Hard : Drug_Volume;
168     Basal_Rate_Lower_Soft : Flow_Rate;
169     Basal_Rate_Lower_Hard : Flow_Rate;
170     Basal_Rate_Typical : Flow_Rate;
171     Basal_Rate_Upper_Soft : Flow_Rate;

```



```

172     Basal_Rate_Upper_Hard : Flow_Rate;
173     Bolus_Typical : Drug_Volume;
174     Bolus_Time_Typical : Ice_Types.Minute;
175 end record;
176
177 protected type Drug_Record_Store
178 is
179     pragma Priority (10);
180
181     function Get return Drug_Record;
182     --# global in Drug_Record_Store;
183
184     procedure Put(X : in Drug_Record);
185     --# global out Drug_Record_Store;
186     --# derives Drug_Record_Store from X;
187 private
188     TheStoredData : Drug_Record :=
189         Drug_Record'(Amount => Drug_Weight'First,
190             Concentration => Drug_Concentration'First,
191             Vtbi_Lower_Soft => Drug_Volume'First,
192             Vtbi_Lower_Hard => Drug_Volume'First,
193             Vtbi_Typical => Drug_Volume'First,
194             Vtbi_Upper_Soft => Drug_Volume'First,
195             Vtbi_Upper_Hard => Drug_Volume'First,
196             Basal_Rate_Lower_Soft => Flow_Rate'First,
197             Basal_Rate_Lower_Hard => Flow_Rate'First,
198             Basal_Rate_Typical => Flow_Rate'First,
199             Basal_Rate_Upper_Soft => Flow_Rate'First,
200             Basal_Rate_Upper_Hard => Flow_Rate'First,
201             Bolus_Typical => Drug_Volume'First,
202             Bolus_Time_Typical => Ice_Types.Minute'First
203         );
204 end Drug_Record_Store;
205
206
207 subtype Drug_Library_Index is Integer range 1 .. Pca_Properties.Drug_Library_Size;
208 type Drug_Library is array (Drug_Library_Index) of Drug_Record;
209
210 protected type Drug_Library_Store
211 is
212     pragma Priority (10);
213
214     function Get(Ind : in Integer) return Drug_Record;
215     --# global in Drug_Library_Store;
216
217     procedure Put(Ind : in Integer; Val : in Drug_Record);
218     --# global in out Drug_Library_Store;
219     --# derives Drug_Library_Store from Drug_Library_Store, Ind, Val;
220 private
221     TheStoredData : Drug_Library := Drug_Library'(others =>
222         Drug_Record'(Amount => Drug_Weight'First,
223             Concentration => Drug_Concentration'First,
224             Vtbi_Lower_Soft => Drug_Volume'First,
225             Vtbi_Lower_Hard => Drug_Volume'First,
226             Vtbi_Typical => Drug_Volume'First,
227             Vtbi_Upper_Soft => Drug_Volume'First,
228             Vtbi_Upper_Hard => Drug_Volume'First,
229             Basal_Rate_Lower_Soft => Flow_Rate'First,
230             Basal_Rate_Lower_Hard => Flow_Rate'First,
231             Basal_Rate_Typical => Flow_Rate'First,
232             Basal_Rate_Upper_Soft => Flow_Rate'First,
233             Basal_Rate_Upper_Hard => Flow_Rate'First,
234             Bolus_Typical => Drug_Volume'First,
235             Bolus_Time_Typical => Ice_Types.Minute'First
236         ));

```

```

237 end Drug_Library_Store;
238
239 type Prescription is record
240     Concentration : Drug_Concentration;
241     Initial_Volume : Drug_Volume;
242     Basal_Flow_Rate : Flow_Rate;
243     Vtbi : Drug_Volume;
244     Max_Drug_Per_Hour : Drug_Volume;
245     Minimum_Time_Between_Bolus : Ice_Types.Minute;
246 end record;
247
248 protected type Prescription_Store
249 is
250     pragma Priority (10);
251
252     function Get return Prescription;
253     --# global in Prescription_Store;
254
255     procedure Put(Prescription_In : in Prescription);
256     --# global out Prescription_Store;
257     --# derives Prescription_Store from Prescription_In;
258
259 private
260     TheStoredData : Prescription :=
261         Prescription'(Concentration => 0,
262             Initial_Volume => 0,
263             Basal_Flow_Rate => 0,
264             Vtbi => 0,
265             Max_Drug_Per_Hour => 0,
266             Minimum_Time_Between_Bolus => 0
267         );
268
269 end Prescription_Store;
270
271 type Fault_Record is record
272     Alarm : Alarm_Type;
273     Warning : Warning_Type;
274     Time : Bless_Types.Time;
275 end record;
276
277 protected type Fault_Record_Store
278 is
279     pragma Priority (10);
280
281     function Get return Fault_Record;
282     --# global in Fault_Record_Store;
283
284     procedure Put(X : in Fault_Record);
285     --# global out Fault_Record_Store;
286     --# derives Fault_Record_Store from X;
287 private
288     TheStoredData : Fault_Record := Fault_Record'(Alarm => Alarm_Type'First,
289         Warning => Warning_Type'First,
290         Time => Bless_Types.Time'First
291     );
292 end Fault_Record_Store;
293
294
295 subtype Fault_Log_Index is Integer range 1 .. Pca_Properties.Fault_Log_Size;
296 type Fault_Log is array (Fault_Log_Index) of Fault_Record;
297
298 protected type Fault_Log_Store
299 is
300     pragma Priority (10);
301

```

```

302     function Get(Ind : in Integer) return Fault_Record;
303     --# global in Fault_Log_Store;
304
305     procedure Put(Ind : in Integer; Val : in Fault_Record);
306     --# global in out Fault_Log_Store;
307     --# derives Fault_Log_Store from Fault_Log_Store, Ind, Val;
308 private
309     TheStoredData : Fault_Log := Fault_Log'(others =>
310         Fault_Record'(Alarm => Alarm_Type'First,
311             Warning => Warning_Type'First,
312             Time => Bless_Types.Time'First
313         ));
314 end Fault_Log_Store;
315
316
317 type Event_Record is record
318     Time : Bless_Types.Time;
319 end record;
320
321 protected type Event_Record_Store
322 is
323     pragma Priority (10);
324
325     function Get return Event_Record;
326     --# global in Event_Record_Store;
327
328     procedure Put(X : in Event_Record);
329     --# global out Event_Record_Store;
330     --# derives Event_Record_Store from X;
331 private
332     TheStoredData : Event_Record := Event_Record'(Time => Bless_Types.Time'First);
333 end Event_Record_Store;
334
335
336 subtype Event_Log_Index is Integer range 1 .. Pca_Properties.Event_Log_Size;
337 type Event_Log is array (Event_Log_Index) of Event_Record;
338
339 protected type Event_Log_Store
340 is
341     pragma Priority (10);
342
343     function Get(Ind : in Integer) return Event_Record;
344     --# global in Event_Log_Store;
345
346     procedure Put(Ind : in Integer; Val : in Event_Record);
347     --# global in out Event_Log_Store;
348     --# derives Event_Log_Store from Event_Log_Store, Ind, Val;
349 private
350     TheStoredData : Event_Log := Event_Log'(others => Event_Record'(Time => Bless_Types.Time'First));
351 end Event_Log_Store;
352
353
354 type Infusion_Type is (Bolus_Infusion, Square_Infusion, Basal_Infusion, KVO_Infusion);
355
356 protected type Infusion_Type_Store
357 is
358     pragma Priority (10);
359
360     function Get return Infusion_Type;
361     --# global in Infusion_Type_Store;
362
363     procedure Put(X : in Infusion_Type);
364     --# global out Infusion_Type_Store;
365     --# derives Infusion_Type_Store from X;
366 private

```

```

367     TheStoredData : Infusion_Type := Infusion_Type'First;
368 end Infusion_Type_Store;
369
370
371 type Pump_Fault_Type is (Prime_Failure, Pump_Hot, Bubble, Upstream_Occlusion_Fault,
    Downstream_Occlusion_Fault, Overinfusion, Underinfusion);
372
373 protected type Pump_Fault_Type_Store
374 is
375     pragma Priority (10);
376
377     function Get return Pump_Fault_Type;
378     --# global in Pump_Fault_Type_Store;
379
380     procedure Put(X : in Pump_Fault_Type);
381     --# global out Pump_Fault_Type_Store;
382     --# derives Pump_Fault_Type_Store from X;
383 private
384     TheStoredData : Pump_Fault_Type := Pump_Fault_Type'First;
385 end Pump_Fault_Type_Store;
386
387 end Pca_Types;
388
389 package body Pca_Types
390 is
391     protected body Alarm_Type_Store is
392     function Get return Alarm_Type
393     --# global in TheStoredData;
394     is
395     begin
396         return TheStoredData;
397     end Get;
398
399     procedure Put(X : in Alarm_Type)
400     --# global out TheStoredData;
401     --# derives TheStoredData from X;
402     is
403     begin
404         TheStoredData := X;
405     end Put;
406 end Alarm_Type_Store;
407
408     protected body Warning_Type_Store is
409     function Get return Warning_Type
410     --# global in TheStoredData;
411     is
412     begin
413         return TheStoredData;
414     end Get;
415
416     procedure Put(X : in Warning_Type)
417     --# global out TheStoredData;
418     --# derives TheStoredData from X;
419     is
420     begin
421         TheStoredData := X;
422     end Put;
423 end Warning_Type_Store;
424
425     protected body Status_Type_Store is
426     function Get return Status_Type
427     --# global in TheStoredData;
428     is
429     begin
430         return TheStoredData;

```

```

431     end Get;
432
433     procedure Put(X : in Status_Type)
434         --# global out TheStoredData;
435         --# derives TheStoredData from X;
436     is
437     begin
438         TheStoredData := X;
439     end Put;
440 end Status_Type_Store;
441
442 protected body Flow_Rate_Store is
443     function Get return Flow_Rate
444         --# global in TheStoredData;
445     is
446     begin
447         return TheStoredData;
448     end Get;
449
450     procedure Put(X : in Flow_Rate)
451         --# global out TheStoredData;
452         --# derives TheStoredData from X;
453     is
454     begin
455         TheStoredData := X;
456     end Put;
457 end Flow_Rate_Store;
458
459 protected body Drug_Volume_Store is
460     function Get return Drug_Volume
461         --# global in TheStoredData;
462     is
463     begin
464         return TheStoredData;
465     end Get;
466
467     procedure Put(X : in Drug_Volume)
468         --# global out TheStoredData;
469         --# derives TheStoredData from X;
470     is
471     begin
472         TheStoredData := X;
473     end Put;
474 end Drug_Volume_Store;
475
476 protected body Drug_Weight_Store is
477     function Get return Drug_Weight
478         --# global in TheStoredData;
479     is
480     begin
481         return TheStoredData;
482     end Get;
483
484     procedure Put(X : in Drug_Weight)
485         --# global out TheStoredData;
486         --# derives TheStoredData from X;
487     is
488     begin
489         TheStoredData := X;
490     end Put;
491 end Drug_Weight_Store;
492
493 protected body Drug_Concentration_Store is
494     function Get return Drug_Concentration
495         --# global in TheStoredData;

```

```

496     is
497     begin
498         return TheStoredData;
499     end Get;
500
501     procedure Put(X : in Drug_Concentration)
502         --# global out TheStoredData;
503         --# derives TheStoredData from X;
504     is
505     begin
506         TheStoredData := X;
507     end Put;
508 end Drug_Concentration_Store;
509
510 protected body Drug_Record_Store is
511     function Get return Drug_Record
512         --# global in TheStoredData;
513     is
514     begin
515         return TheStoredData;
516     end Get;
517
518     procedure Put(X : in Drug_Record)
519         --# global out TheStoredData;
520         --# derives TheStoredData from X;
521     is
522     begin
523         TheStoredData := X;
524     end Put;
525 end Drug_Record_Store;
526
527 protected body Drug_Library_Store is
528     function Get(Ind : in Integer) return Drug_Record
529         --# global in TheStoredData;
530     is
531     begin
532         return TheStoredData(Ind);
533     end Get;
534
535     procedure Put(Ind : in Integer; Val : in Drug_Record)
536         --# global in out TheStoredData;
537         --# derives TheStoredData from TheStoredData, Ind, Val;
538     is
539     begin
540         TheStoredData(Ind) := Val;
541     end Put;
542 end Drug_Library_Store;
543
544 protected body Prescription_Store
545 is
546     function Get return Prescription
547         --# global in TheStoredData;
548     is
549     begin
550         return TheStoredData;
551     end Get;
552
553     procedure Put(Prescription_In : in Prescription)
554         --# global out TheStoredData;
555         --# derives TheStoredData from Prescription_In;
556     is
557     begin
558         TheStoredData := Prescription_In;
559     end Put;
560 end Prescription_Store;

```

```

561
562 protected body Fault_Record_Store is
563     function Get return Fault_Record
564         --# global in TheStoredData;
565     is
566     begin
567         return TheStoredData;
568     end Get;
569
570     procedure Put(X : in Fault_Record)
571         --# global out TheStoredData;
572         --# derives TheStoredData from X;
573     is
574     begin
575         TheStoredData := X;
576     end Put;
577 end Fault_Record_Store;
578
579 protected body Fault_Log_Store is
580     function Get(Ind : in Integer) return Fault_Record
581         --# global in TheStoredData;
582     is
583     begin
584         return TheStoredData(Ind);
585     end Get;
586
587     procedure Put(Ind : in Integer; Val : in Fault_Record)
588         --# global in out TheStoredData;
589         --# derives TheStoredData from TheStoredData, Ind, Val;
590     is
591     begin
592         TheStoredData(Ind) := Val;
593     end Put;
594 end Fault_Log_Store;
595
596 protected body Event_Record_Store is
597     function Get return Event_Record
598         --# global in TheStoredData;
599     is
600     begin
601         return TheStoredData;
602     end Get;
603
604     procedure Put(X : in Event_Record)
605         --# global out TheStoredData;
606         --# derives TheStoredData from X;
607     is
608     begin
609         TheStoredData := X;
610     end Put;
611 end Event_Record_Store;
612
613 protected body Event_Log_Store is
614     function Get(Ind : in Integer) return Event_Record
615         --# global in TheStoredData;
616     is
617     begin
618         return TheStoredData(Ind);
619     end Get;
620
621     procedure Put(Ind : in Integer; Val : in Event_Record)
622         --# global in out TheStoredData;
623         --# derives TheStoredData from TheStoredData, Ind, Val;
624     is
625     begin

```

```

626         TheStoredData(Ind) := Val;
627     end Put;
628 end Event_Log_Store;
629
630 protected body Infusion_Type_Store is
631     function Get return Infusion_Type
632         --# global in TheStoredData;
633     is
634     begin
635         return TheStoredData;
636     end Get;
637
638     procedure Put(X : in Infusion_Type)
639         --# global out TheStoredData;
640         --# derives TheStoredData from X;
641     is
642     begin
643         TheStoredData := X;
644     end Put;
645 end Infusion_Type_Store;
646
647 protected body Pump_Fault_Type_Store is
648     function Get return Pump_Fault_Type
649         --# global in TheStoredData;
650     is
651     begin
652         return TheStoredData;
653     end Get;
654
655     procedure Put(X : in Pump_Fault_Type)
656         --# global out TheStoredData;
657         --# derives TheStoredData from X;
658     is
659     begin
660         TheStoredData := X;
661     end Put;
662 end Pump_Fault_Type_Store;
663
664 end Pca_Types;

```

**Listing F.4:** Pca\_Types package

```

1 package Pca_Properties
2 is
3     Drug_Library_Size : constant Integer := 500;
4     Fault_Log_Size : constant Integer := 150;
5     Event_Log_Size : constant Integer := 1500;
6     KVO_Rate_Constant : constant Integer := 1;
7     KVO_Rate : constant Integer := KVO_Rate_Constant;
8     Max_Rate : constant Integer := 10;
9 end Pca_Properties;

```

**Listing F.5:** Pca\_Properties package



```

1 with Pca_Properties,
2     Base_Types,
3     Bless_Types,
4     Ice_Types,
5     Pca_Types;
6 --# inherit Pca_Properties,
7 --#         Base_Types,
8 --#         Bless_Types,
9 --#         Ice_Types,
10 --#        Pca_Types;
11 package Pca_Operation
12 --# own protected Bolus_Duration : Ice_Types.Minute_Store (Priority=>10);
13 --#     protected Infusion_Flow_Rate : PCA_Types.Flow_Rate_Store (Priority=>10);
14 --#     protected System_Status : Pca_Types.Status_Type_Store (Priority=>10);
15 --#     protected Rx : Pca_Types.Prescription_Store (Priority=>10);
16 --#     task mdphw : Max_Drug_Per_Hour_Watcher;
17 --#     task rc : Rate_Controller;
18 --#     task pbc : Patient_Bolus_Checker;
19 is
20     procedure Put_Start_Button_Pressed;
21
22     procedure Put_Stop_Button_Pressed;
23
24     procedure Put_Patient_Request_Bolus;
25
26     procedure Put_Clinician_Request_Bolus;
27
28     procedure Put_Bolus_Duration (Bolus_Duration_In : Ice_Types.Minute);
29     --# global out Bolus_Duration;
30     --# derives Bolus_Duration from Bolus_Duration_In;
31
32     procedure Get_Infusion_Flow_Rate (Infusion_Flow_Rate_Out : out Pca_Types.Flow_Rate);
33     --# global in Infusion_Flow_Rate;
34     --# derives Infusion_Flow_Rate_Out from Infusion_Flow_Rate;
35
36     procedure Get_System_Status (System_Status_Out : out Pca_Types.Status_Type);
37     --# global in System_Status;
38     --# derives System_Status_Out from System_Status;
39
40     procedure Put_Rx (Rx_In : Pca_Types.Prescription);
41     --# global out Rx;
42     --# derives Rx from Rx_In;
43
44
45     task type Max_Drug_Per_Hour_Watcher
46     --# global in Infusion_Flow_Rate;
47     is
48         pragma Priority(10);
49     end Max_Drug_Per_Hour_Watcher;
50
51     task type Rate_Controller
52     --# global in Rx;
53     --#     in Bolus_Duration;
54     --#     out Infusion_Flow_Rate;
55     --#     out System_Status;
56     is
57         pragma Priority(10);
58     end Rate_Controller;
59
60     task type Patient_Bolus_Checker
61     is
62         pragma Priority(10);
63     end Patient_Bolus_Checker;
64
65 end Pca_Operation;

```

```

66
67 package body Pca_Operation
68 is
69     type la_type is (
70         StopButton,
71         TooMuchJuice,
72         PatientButton,
73         ResumeSquareBolus,
74         ResumeBasal,
75         StartSquareBolus,
76         SquareBolusDone,
77         StartButton);
78
79     Bolus_Duration : Ice_Types.Minute_Store;
80     Infusion_Flow_Rate : PCA_Types.Flow_Rate_Store;
81     System_Status : Pca_Types.Status_Type_Store;
82     Rx : Pca_Types.Prescription_Store;
83
84     mdphw : Max_Drug_Per_Hour_Watcher;
85     rc : Rate_Controller;
86     pbc : Patient_Bolus_Checker;
87
88     procedure Put_Start_Button_Pressed
89     is
90     begin
91         -- TODO: implement event handler
92         null;
93     end Put_Start_Button_Pressed;
94
95     procedure Put_Stop_Button_Pressed
96     is
97     begin
98         -- TODO: implement event handler
99         null;
100    end Put_Stop_Button_Pressed;
101
102    procedure Put_Patient_Request_Bolus
103    is
104    begin
105        -- TODO: implement event handler
106        null;
107    end Put_Patient_Request_Bolus;
108
109    procedure Put_Clinician_Request_Bolus
110    is
111    begin
112        -- TODO: implement event handler
113        null;
114    end Put_Clinician_Request_Bolus;
115
116    procedure Put_Bolus_Duration (Bolus_Duration_In : ICE_Types.Minute)
117    is
118    begin
119        Bolus_Duration.Put(Bolus_Duration_In);
120    end Put_Bolus_Duration;
121
122    procedure Get_Infusion_Flow_Rate (Infusion_Flow_Rate_Out : out Pca_Types.Flow_Rate)
123    is
124    begin
125        Infusion_Flow_Rate_Out := Infusion_Flow_Rate.Get;
126    end Get_Infusion_Flow_Rate;
127
128    procedure Get_System_Status (System_Status_Out : out Pca_Types.Status_Type)
129    is
130    begin

```

```

131     System_Status_Out := System_Status.Get;
132 end Get_System_Status;
133
134 procedure Put_Rx (Rx_In : Pca_Types.Prescription)
135 is
136 begin
137     Rx.Put(Rx_In);
138 end Put_Rx;
139
140
141 task body Max_Drug_Per_Hour_Watcher
142 is
143 begin
144     loop
145         --# assert PUMP_RATE;
146         null;
147     end loop;
148 end Max_Drug_Per_Hour_Watcher;
149
150 task body Rate_Controller
151 is
152     la : la_type;
153 begin
154     loop
155         --# assert true;
156         --# assert Rx_APPROVED;
157         --# assert PUMP_RATE;
158         --# assert (la=StopButton) -> HALT;
159         --# assert (la=TooMuchJuice) -> KVO_RATE;
160         --# assert (la=PatientButton) -> PB_RATE;
161         --# assert ((la=StartSquareBolus) or (la=ResumeSquareBolus)) -> CCB_RATE;
162         --# assert ((la=StartButton) or (la=ResumeBasal) or (la=SquareBolusDone)) -> BASAL_RATE;
163         --# assert (PUMP_RATE = 0) -> HALT;
164         --# assert (PUMP_RATE = Pca_Properties.KVO_Rate) -> KVO_RATE;
165         --# assert (PUMP_RATE = Patient_Bolus_Rate) -> PB_RATE;
166         --# assert (PUMP_RATE = Square_Bolus_Rate) -> CCB_RRATE;
167         --# assert (PUMP_RATE = Basal_Rate) -> BASAL_RATE;
168         null;
169     end loop;
170 end Rate_Controller;
171
172 task body Patient_Bolus_Checker
173 is
174 begin
175     loop
176         --# assert true;
177         null;
178     end loop;
179 end Patient_Bolus_Checker;
180
181 end Pca_Operation;

```

**Listing F.6:** Pca\_Operation package

# Appendix G

## AUnit tests for PCA pump dose monitor module

This appendix presents AUnit tests for isolated, sequential module for PCA pump dose monitoring.

```
1 with AUnit.Test_Fixtures;
2
3 package Pca_Pump.Test_Data is
4
5     type Test is new AUnit.Test_Fixtures.Test_Fixture
6     with null record;
7
8     procedure Set_Up (Gnattest_T : in out Test);
9     procedure Tear_Down (Gnattest_T : in out Test);
10
11 end Pca_Pump.Test_Data;
12
13 package body Pca_Pump.Test_Data is
14
15     procedure Set_Up (Gnattest_T : in out Test) is
16         pragma Unreferenced (Gnattest_T);
17     begin
18         null;
19     end Set_Up;
20
21     procedure Tear_Down (Gnattest_T : in out Test) is
22         pragma Unreferenced (Gnattest_T);
23     begin
24         null;
25     end Tear_Down;
26
27 end Pca_Pump.Test_Data;
```

**Listing G.1:** Package `Pca_Pump.Test_Data`

```

1 with Gnattest_Generated;
2
3 package Pca_Pump.Test_Data.Tests is
4
5     type Test is new GNATtest_Generated.GNATtest_Standard.Pca_Pump.Test_Data.Test
6     with null record;
7
8     procedure Test_Sum_Zero (Gnattest_T : in out Test);
9
10    procedure Test_Sum_100 (Gnattest_T : in out Test);
11
12    procedure Test_Read_Dosed_Zero (Gnattest_T : in out Test);
13
14    procedure Test_Increase_Dosed_By_1 (Gnattest_T : in out Test);
15
16    procedure Test_Move_Dosed_First_Element_Zero (Gnattest_T : in out Test);
17
18    procedure Test_Move_Dosed_First_Element_Not_Zero (Gnattest_T : in out Test);
19
20 end Pca_Pump.Test_Data.Tests;
21
22 with AUnit.Assertions; use AUnit.Assertions;
23 with Pca_Pump;
24
25 package body Pca_Pump.Test_Data.Tests is
26
27     procedure Test_Sum_Zero (Gnattest_T : in out Test) is
28         pragma Unreferenced (Gnattest_T);
29         Arr : Pca_Pump.Doses_Array := Pca_Pump.Doses_Array'(others => 0);
30         Result : Pca_Pump.Drug_Volume := 0;
31     begin
32         -- Arrange
33
34         -- Act
35         Result := Pca_Pump.Sum(Arr);
36
37         -- Assert
38         AUnit.Assertions.Assert
39             (Result = 0,
40              "Sum function result is incorrect.");
41     end Test_Sum_Zero;
42
43     procedure Test_Sum_100 (Gnattest_T : in out Test) is
44         pragma Unreferenced (Gnattest_T);
45         Arr : Pca_Pump.Doses_Array := Pca_Pump.Doses_Array'(others => 0);
46         Result : Pca_Pump.Drug_Volume := 0;
47     begin
48         -- Arrange
49         Arr(Pca_Pump.Doses_Array_Index'First) := 51;
50         Arr(Pca_Pump.Doses_Array_Index'Last) := 49;
51
52         -- Act
53         Result := Pca_Pump.Sum(Arr);
54
55         -- Assert
56         AUnit.Assertions.Assert
57             (Result = 100,
58              "Sum function result is incorrect:" & Pca_Pump.Drug_Volume'Image(Result) & " /= 100");
59     end Test_Sum_100;
60
61
62     procedure Test_Read_Dosed_Zero (Gnattest_T : in out Test) is
63         pragma Unreferenced (Gnattest_T);
64         Result : Pca_Pump.Drug_Volume;
65         Expected : Pca_Pump.Drug_Volume;

```

```

66 begin
67   -- Arrange
68   Expected := 0;
69
70   -- Act
71   Result := Pca_Pump.Read_Dosed;
72
73   -- Assert
74   AUnit.Assertions.Assert
75     (Expected = Result,
76     "Readed dose incorrect: " & Pca_Pump.Drug_Volume'Image(Expected) & " /= " & Pca_Pump.Drug_Volume'
Image(Result));
77
78 end Test_Read_Dosed_Zero;
79
80 procedure Test_Increase_Dosed_By_1 (Gnatatest_T : in out Test) is
81   pragma Unreferenced (Gnatatest_T);
82   Pre_Sum : Pca_Pump.Drug_Volume := 0;
83   Post_Sum : Pca_Pump.Drug_Volume := 0;
84 begin
85   -- Arrange
86   Pre_Sum := Pca_Pump.Read_Dosed;
87
88   -- Act
89   Pca_Pump.Increase_Dosed;
90   Post_Sum := Pca_Pump.Read_Dosed;
91
92   -- Assert
93   AUnit.Assertions.Assert
94     (Post_Sum = Pre_Sum + 1,
95     "Total dose not increased properly: " & Pca_Pump.Drug_Volume'Image(Post_Sum) & " /= " & Pca_Pump.
Drug_Volume'Image(Pre_Sum+1));
96 end Test_Increase_Dosed_By_1;
97
98 procedure Test_Move_Dosed_First_Element_Zero (Gnatatest_T : in out Test) is
99   pragma Unreferenced (Gnatatest_T);
100   Pre_Sum : Pca_Pump.Drug_Volume := 0;
101   Post_Sum : Pca_Pump.Drug_Volume := 0;
102 begin
103   -- Arrange
104   Pre_Sum := Pca_Pump.Read_Dosed;
105
106   -- Act
107   Pca_Pump.Move_Dosed;
108   Post_Sum := Pca_Pump.Read_Dosed;
109
110   -- Assert
111   AUnit.Assertions.Assert
112     (Post_Sum = Pre_Sum,
113     "Total dose changed: " & Pca_Pump.Drug_Volume'Image(Pre_Sum) & " /= " & Pca_Pump.Drug_Volume'Image
(Post_Sum));
114 end Test_Move_Dosed_First_Element_Zero;
115
116 procedure Test_Move_Dosed_First_Element_Not_Zero (Gnatatest_T : in out Test) is
117   pragma Unreferenced (Gnatatest_T);
118   Pre_Sum : Pca_Pump.Drug_Volume := 0;
119   Post_Sum : Pca_Pump.Drug_Volume := 0;
120 begin
121   -- Arrange
122   Pca_Pump.Increase_Dosed;
123   for I in Pca_Pump.Doses_Array_Index range 1 .. Pca_Pump.Doses_Array_Index'Last-1 loop
124     Pca_Pump.Move_Dosed;
125   end loop;
126   Pre_Sum := Pca_Pump.Read_Dosed;
127

```

```

128     -- Act
129     Pca_Pump.Move_Dosed;
130     Post_Sum := Pca_Pump.Read_Dosed;
131
132     -- Assert
133     AUnit.Assertions.Assert
134       (Post_Sum < Pre_Sum,
135        "Total dose changed: " & Pca_Pump.Drug_Volume'Image(Pre_Sum) & " should be greater than " &
136        Pca_Pump.Drug_Volume'Image(Post_Sum));
137   end Test_Move_Dosed_First_Element_Not_Zero;
138 end Pca_Pump.Test_Data.Tests;

```

**Listing G.2:** Package `Pca_Pump.Test_Data.Tests`