Collaborative Design of Embedded Systems –
co-modelling and co-simulation
FBK seminar 15-12-2016

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Contents

• Roots of the methodology
• Applications
• The family of languages
• A flavor of VDM
• Tool support
• Beyond VDM – co-modelling and co-simulation
• Some examples
Roots of the method

- Invented at IBM’s labs in Vienna in the (19)70’s

- Originally designed to define semantics of other programming languages: CHILL, ADA, MODULA-2, ...

- Evolved into a family of general purpose formal specification languages

- Intuitive model-oriented notational style:
  - Simple and abstract data types (including collections)
  - Invariants to restrict membership
  - Focus on specification of functionality:
    - Referentially transparent functions
    - Operations with side effects on state variables
    - Implicit specification (pre/post conditions)
    - Explicit specification (functional or imperative, with optional pre/post)
  - Refinement as principle technique to elaborate specifications to design
Some (large scale) Applications of VDM

• British Aerospace (UK) : secure gateway
• GAO Gmbh (D) : bank note processing system
• JFITS (JP) : trading room application specification
• Flower auction Aalsmeer (NL) : auction clock system
• DoD (NL) : complex data handling subsystem
• Sony / Felica (JP) : firmware for NFC chip
• Specification of SPOT-4 payload software
• RTRI (JP) : railway interlocking specification
• Lockheed-Martin (USA) : JSF ground support equipment
• Rijkswaterstaat (NL): road congestion warning system
Key success factor(s)

• Notation is easy to learn
• Robust tool support and (a lot of) documentation
• Active research and user community (albeit small)
• Formal methods “light”: focus on prototyping and test rather than proof (get results fast)
• Simple to adopt and embed in current practice
• Support design dialogue very early in life-cycle
• Use *abstraction* as primary technique to focus on essential elements of the problem (requirements)
Definition of Abstraction

• the act of *withdrawing* or *removing* something

• the act or process of *leaving out* of consideration one or more properties of a complex object so as to attend to others

=> *Remove detail (simplify) and focus (selection)*

• a *general concept* formed by extracting *common* features from specific examples

• the process of formulating *general concepts* by abstracting *common* properties of instances

=> *generalisation (core or essence)*
Models and Modelling

• A model is a description from which detail has been removed in a systematic manner and for a particular purpose.

• A simplification of reality intended to promote understanding, reasoning and analysis.

• Models are the most important engineering tool; they allow us to understand and analyze large and complex problems.
Abstract models (1)
Abstract models (2)
Abstract models of software (?)
Validation Techniques (gaining model trust)

- **Inspection**: organized process of examining the model alongside domain experts (build up domain knowledge explicitly – terms of reference)

- **Static Analysis**: automatic checks of syntax & type correctness, detect unusual features (assess intrinsic model quality)

- **Prototyping**: execute the model and interact / explore to validate modelling assumptions (i.e. connecting a UI mock-up)

- **Testing**: execute the model and check outcomes against explicitly formulated expectations (and easily perform regression testing when model is changed)

- **Model Checking**: search the state space of the model exhaustively to find states that violate the properties we are checking; presents a counter example in such case

- **Proof**: use a logic to reason symbolically about whole classes of states at once.

*Caveat: use last two techniques only when sufficient confidence is built with first four as investment required to perform these steps is typically higher*
Family of Languages

- **VDM-SL**
  - Formal syntax, static and denotational semantics

- **VDM++**
  - Object-orientation
  - Concurrency / synchronization

- **VDM-RT**
  - Asynchronous operations
  - Timing
  - Deployment

- Caveat: $\text{VDM-SL} \subset \text{VDM++} \subset \text{VDM-RT}$
VDM-SL in a nutshell

module <module-name>
    imports
    exports
    ...
end <module-name>

Interface

Definitions

state
types
values
functions
operations
...

VDM-SL in a nutshell
## VDM-SL : basic types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>bool</code></td>
<td>Boolean datatype</td>
<td><code>false, true</code></td>
</tr>
<tr>
<td><code>nat</code></td>
<td>Natural numbers (including zero)</td>
<td><code>0, 1, 2, 3, ...</code></td>
</tr>
<tr>
<td><code>nat1</code></td>
<td>Natural numbers (excluding zero)</td>
<td><code>1, 2, 3, 4, ...</code></td>
</tr>
<tr>
<td><code>int</code></td>
<td>Integers</td>
<td><code>..., -3, -2, -1, 0, 1, 2, 3, ...</code></td>
</tr>
<tr>
<td><code>rat</code></td>
<td>Rational numbers</td>
<td><code>a/b, where a and b are integers, b is not 0</code></td>
</tr>
<tr>
<td><code>real</code></td>
<td>Real numbers</td>
<td><code>...</code></td>
</tr>
<tr>
<td><code>char</code></td>
<td>Characters</td>
<td><code>A, B, C, ...</code></td>
</tr>
<tr>
<td><code>token</code></td>
<td>Structureless tokens</td>
<td><code>...</code></td>
</tr>
<tr>
<td><code>&lt;A&gt;</code></td>
<td>The quote type containing the value</td>
<td><code>&lt;A&gt;</code></td>
</tr>
</tbody>
</table>
VDM-SL: sets

- Set enumeration: the set of elements \( a, b \) and \( c \): \( \{a, b, c\} \)
- Set comprehension: the set of \( x \) from type \( T \) such that \( P(x) : \{x \mid x : T \land P(x)\} \)
- The set of integers in the range \( i \) to \( j \): \( \{i, \ldots, j\} \)
- Set membership, \( e \) is an element of set \( s \): \( e \text{ in set } s \)
- Not a member of, \( e \) is not an element of set \( s \): \( e \text{ not in set } s \)
- Union of sets \( s_1 \) and \( s_2 \): \( s_1 \cup s_2 \)
- Intersection of sets \( s_1 \) and \( s_2 \): \( s_1 \cap s_2 \)
- Set difference of sets \( s_1 \) and \( s_2 \): \( s_1 \setminus s_2 \)
- Distributed union of set of sets \( s \): \( \text{dunion } s \)
- Proper subset, \( s_1 \) is a (proper) subset of \( s_2 \): \( s_1 \text{ psubset } s_2 \)
- (weak) subset, \( s_1 \) is a (weak) subset of \( s_2 \): \( s_1 \text{ subset } s_2 \)
- The cardinality of set \( s \): \( \text{card } s \)
VDM-SL : sequences

String = seq of char

- Sequence enumeration: the sequence of elements \( a, b \) and \( c \): \([a, b, c]\)
- Sequence comprehension: sequence of expressions \( f(x) \) for each \( x \) of (numeric) type \( T \) such that \( P(x) \) holds (\( x \) values taken in numeric order): \([f(x) \mid x:T \& P(x)]\)
- The head (first element) of \( s \): \( \text{hd } s \)
- The tail (remaining sequence after head is removed) of \( s \): \( \text{tl } s \)
- The length of \( s \): \( \text{len } s \)
- The set of elements of \( s \): \( \text{elems } s \)
- The \( i \)\(^{th}\) element of \( s \): \( s(i) \)
- The set of indices for the sequence \( s \): \( \text{inds } s \)
- The sequence formed by concatenating sequences \( s_1 \) and \( s_2 \): \( s_1 \& s_2 \)
Birthdays = map String to Date

- Mapping enumeration: \( a \) maps to \( r \), \( b \) maps to \( s \): \( \{ a \mapsto r, b \mapsto s \} \)
- Mapping comprehension: \( x \) maps to \( f(x) \) for all \( x \) of type \( T \) such that \( P(x) \): \( \{ x \mapsto f(x) \mid x: T \land P(x) \} \)
- The domain of \( m \): \( \text{dom} \ m \)
- The range of \( m \): \( \text{rng} \ m \)
- Application, \( m \) applied to \( x \): \( m(x) \)
- Union of mappings \( m_1 \) and \( m_2 \) (\( m_1, m_2 \) must be consistent where they overlap): \( m_1 \text{ union } m_2 \)
- Override, \( m_1 \) overwritten by \( m_2 \): \( m_1 ++ m_2 \)
VDM-SL: unions, tuple, records

- Union of types: $T_1, \ldots, T_n : T_2 \mid \ldots \mid T_n$
- Cartesian product of types: $T_1, \ldots, T_n : T_1 \times T_2 \times \ldots \times T_n$
- Composite (Record) type: $T :: f_1 : T_1 \mid \ldots \mid f_n : T_n$

```plaintext
SignalColour = <Red> | <Amber> | <FlashingAmber> | <Green>
```

```plaintext
Date :: day:nat1 month:nat1 year:nat inv mk_Date(d,m,y) == d \leq 31 and m \leq 12
```
VDM-SL: specifying functions

Implicit style (1) – *just focus on interface and properties*

```plaintext
SQRTP(x:real) r:real
pre x >=0
post r*r = x and r >= 0
```

Implicit style (2) – *pre- and post conditions can be arbitrarily complex*

```plaintext
SqListImp(s:seq of nat)r:seq of nat
post len r = len s and forall i in set inds s & r(i) = s(i)**2
```

Explicit style (2) – *executable specification (can still have pre- and postconditions!)*

```plaintext
SqList: seq of nat -> seq of nat
SqList(s) ==
  if s = []
  then []
  else [(hd s)**2] ^ SqList(tl s)
```
VDM-SL: specifying state and operations

Definition of the global state

```vdm-slx
state Register of
 someStateRegister : nat
end
```

Implicit style (showing side effect – state is modified)

*caveat: postcondition is a logical expression, not an assignment*

```vdm-slx
LOAD(i: nat)
  ext wr someStateRegister: nat
  post someStateRegister = i
```

Implicit style (showing side effect – state is modified)

*caveat: postcondition is referring to the previous state: someStateRegister~*

```vdm-slx
ADD(i: nat)
  ext wr someStateRegister : nat
  post someStateRegister = someStateRegister~ + i
```

Explicit style not shown here for brevity
VDM-SL : advanced features

- Optional and function types
- Polymorphic and higher-order functions
- Conditional, Lambda, let-be, let-be-such-that expressions
- Undefined expression
- Type judgement expression
- Pattern matching
- Type bindings
- Block, assignment, loop and conditional statements
- Exception handling, error and non-deterministic choice
- And much more ... see language reference manual
VDM++ in a nutshell

class  <class-name>

  instance variables
  ...

  types
  values
  functions
  operations

  thread
  ...

  sync
  ...

  traces
  ...

end  <class-name>

Internal object state

Definitions

Dynamic behavior

Synchronization control

Test automation support
class Controller

instance variables
  private i : Interface := new Interface()

operations
  async public Open:() ==> ()
  Open() == duration (50) i.SetValve(true);

  async public Close:() ==> ()
  Close() == cycles (1000) i.SetValve(false);

sync
  mutex (Open, Close);
  mutex (Open);
  mutex (Close)

end Controller
system WaterTank

instance variables
  public static controller : [Controller] := nil;

  -- architecture definition
  cpu1 : CPU := new CPU(<FP>, 20);

operations

  public WaterTank : () ==> WaterTank
  WaterTank() == (  
    controller := new Controller();
    cpu1.deploy(controller, "Controller");
  );

end WaterTank
Tool support (1)

FMVDM

[English] [日本語]

VDMTools

- Dev version (9.0.7)
  - VDM++ Windows MacOSX 10.0.7 Linux
  - VDM-SL Windows MacOSX 10.0.7 Linux
- How to install VDM++ VDM-SL
- Documentation
- Source repository

Return to the top of this page
Tool support (2)

Overture Tool

Formal Modelling in VDM

Home
The Method
Languages
Download
Examples
Documentation
Community
Contact
Institutional Supporters
Contributors
Core Net-Meetings
Workshops
Language Board
Related Tools
Publications
Planned
Books
Training

Go to our GitHub Profile
Follow @overturetool

Overview

The Overture community supports the modelling method The Vienna Development Method (VDM) which is a set of modelling techniques that have a long and successful history in both research and industrial application in the development of computer-based systems.

The Overture Tool is an open-source integrated development environment (IDE) for developing and analysing VDM models. The tool suite is written entirely in Java and built on top of the Eclipse platform.

The current stable version is 2.4.4 (Dec 2016) which you can download here.

Extensions:

- **Cresendo Tool** uses the Overture platform and Controlab’s 20-sim to perform co-simulations that can be used in the analysis and development of cyber-physical systems.

- **Symphony Tool** extends part of the Overture Tool in order to support the CML language, which is aimed at describing and analysing Systems of Systems.
Tool support (3) - Overture
Useful features – enhanced static analysis

Caveat: VDM is a strongly typed language, but not always compile time analyzable due to its fundamental set-theoretic basis: three valued logic and logic of partial functions. A specification is considered correct if there exists at least one valid interpretation of the model. The enhanced static analysis identifies possible weaknesses that can be addressed by either reinforcing the model or by proving that the some assumption will always hold at run-time.
Useful features – test coverage
Useful features – combinatorial testing

Traces specifications can be used to describe a large number of test cases that are used to feed a small piece of specification (here a statement block). The tool executes each individual test case and reports the result. Failing test cases can be isolated and loaded in the interpreter for later analysis. Moreover, a JUNIT like framework exists to allow another style of testing.
Usefull features – specifications in-line in deliverables

3.8 Test coverage

It is often useful to know how much of a model has been exercised by a set of tests. This gives some insight into the thoroughness of a test suite and may also help to identify parts of the model that have not been assessed, allowing new tests to be devised to cover these. When any evaluation is performed on a VDM++ model, the interpreter records the lines of the VDM++ model that are executed. This permits the line coverage to be examined after a test to identify parts of the VDM++ model that have not yet been exercised—coverage is cumulative, so a set of tests can be executed and their total coverage examined at the end.

In our simple example, the different tests in the exercise above does cause the majority of the VDM++ model to be executed, but for demonstration purposes let us start by cleaning the model (select “Project” at the top and select “Clean...” in the menu). If we simply take the AlarmPP2 debug launch configuration the Expert = Duty and expertToDuty operations in plant.vdmpp are called by the Run function. Remember that whenever test coverage information is desired the Generate Coverage option must be selected as shown in Figure 3.11[10]. Once the debugger has completed and the result is written out in the console it is possible to right click on the AlarmPP project and select “Debug As” → “Debug C++”. The coverage information that have been gathered in any expressions that have been debugged since the last change to a file have been saved or the project has been cleaned will be turned into a pdf file. The AlarmPP.pdf file is placed in the generated/latex directory as shown in Figure 3.15 and it includes the VDM definitions from all the files included in the project including coverage information. Note that whenever the model is adjusted or it is cleaned so it gets type checked again all the files in the generated directory are deleted.

The coverage information is provided in a way where uncovered expressions are shown in red in the generated pdf file. In addition to the content of each VDM++ source file a table with coverage overview is provided in tabular form. For the plant.vdmpp file this looks like:

<table>
<thead>
<tr>
<th>Function or operation</th>
<th>Coverage</th>
<th>Calls</th>
</tr>
</thead>
<tbody>
<tr>
<td>ExpertsOnDuty</td>
<td>100.0%</td>
<td>1</td>
</tr>
<tr>
<td>ExpertToDuty</td>
<td>100.0%</td>
<td>1</td>
</tr>
<tr>
<td>NumberOfExperts</td>
<td>100.0%</td>
<td>2</td>
</tr>
<tr>
<td>Plant</td>
<td>100.0%</td>
<td>1</td>
</tr>
<tr>
<td>PlantInv</td>
<td>100.0%</td>
<td>2</td>
</tr>
<tr>
<td>plant.vdmpp</td>
<td>89.0%</td>
<td>5</td>
</tr>
</tbody>
</table>

\[10\] Note that this feature is not yet supported for models using unicode characters such as Japanese identifiers.

\[11\] Note that using this feature required plugins to be installed.

3.9 Combinatorial Testing

The previous sections have shown how to test and debug models manually. However, Overturn also contains a feature enabling more automation in the testing process, making more comprehensive high-volume testing feasible. It is possible to write regular expressions, as traces, that one would like to expand into a large set of individual tests. When new traces are incorporated in a VDM model you may need to press the Refresh button (§) in the CT Overview view.

In order to illustrate how this can be used, we extend the Plant class with two additional operations for adding and removing experts from a given schedule. Both operations take a given Period and an Expert and then update the schedule instance variable from the Plant class.

\[\text{AddExpertToSchedule} \text{ and } \text{RemoveExpertFromSchedule} \text{ operations can be defined as:}\]

\[\text{public AddExpertToSchedule} \text{ Period } \times \text{ Expert } \rightarrow () \]
\[\text{AddExpertToSchedule}(p, ox) \rightarrow \]
\[\text{schedule}(p) = \begin{cases} \text{if } p \in \text{ set dom schedule} & \text{then } \text{ schedule}(p) \cup \{ox\} \\ \text{else } \{ox\} \end{cases} \]

\[\text{and the RemoveExpertFromSchedule} \text{ operation can be expressed as:}\]

\[\text{public RemoveExpertFromSchedule} \text{ Period } \times \text{ Expert } \rightarrow () \]
\[\text{RemoveExpertFromSchedule}(p, ox) \rightarrow \]
\[\text{let } exs = \text{ schedule}(p) \text{ in} \]
\[\text{schedule } \begin{cases} \text{if } \text{ card } exs = 1 & \text{then } [p] \not\in \text{ schedule} \\ \text{else } \text{ schedule} + (p \rightarrow \{exs \setminus \{ox\}\}) \end{cases} \]

\[\text{Note that RemoveExpertFromSchedule} \text{ contains a deliberate error. It fails to take account of the invariant so the operation can leave the Plant in a state where it cannot be guaranteed that experts with the right qualifications are available in the periods that have been scheduled. AddExpertToSchedule} \text{ has a similar error. If nobody is scheduled at the period provided as an argument, and the expert added for the schedule at this period does not have all the necessary qualifications, the invariant will again be violated. In fact this means that one would probably have to change the signature of this operation such that it instead of taking a simple expert would take a collection of experts. Instead of adding the two operations manually, use the AlarmPP project. We could use the debugger presented above to test these two new operations manually, but we can also automate a part of this process. In order to do the automation, Overturn needs to know about the combinations of operation calls that you would like to have carried out, so it is necessary to write a kind of regular expression called a trace. VDM++ has been extended such that traces can be written directly as a part of a VDM++ model. In our case, inside the Test class one can}\]
Useful features – VDM-RT runtime analysis (1)
Useful features – VDM-RT runtime analysis (2)
Beyond VDM – co-simulation

VDM (Overture)

Fault/Error Modelling

Discrete Event (DE)

Continuous Time (CT)

Bond Graphs (20-sim)
Crescendo: co-simulation (1)
Crescendo: co-simulation (2)

Language: VDM-RT
Time
Concurrency
Architecture
Deployment

Language: Bond Graphs
Mechanics
Electronics
Hydraulics
Pneumatics
Thermodynamics
Crescendo: co-simulation (3)
Illustrative Case Study: Line-Follow Robot

- IR distance sensors
- wheel encoder
- servo motor
- contact switch
- IR line-follow sensors
- example path
Fault Modelling

- Initial model behaviour is **ideal**
- Add **realistic** and **faulty** behaviour
  - Ambient light levels affect readings (black level)
  - Realistic sensor noise
  - Total failure

<table>
<thead>
<tr>
<th></th>
<th>Ideal</th>
<th>Ambient light</th>
<th>Noise</th>
<th>Total failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
</tr>
<tr>
<td>Black</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
</tr>
<tr>
<td>Line</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
</tr>
</tbody>
</table>
Fault Tolerance

- Light levels: calibration mode
- Sensor failure: one-sensor mode
- Noise: filtering
Design Space Exploration (DSE)

- Building and evaluating models to reach a design
- Design choices restrict the design space

Choice: Two Sensors
Automated Co-model Analysis (ACA)

• Tool-support for DSE
• Run multiple co-simulations to gather results

<table>
<thead>
<tr>
<th>Lateral sensor offset</th>
<th>Longitudinal sensor offset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.01m</td>
</tr>
<tr>
<td>0.01m</td>
<td>(a)</td>
</tr>
<tr>
<td>0.03m</td>
<td>(d)</td>
</tr>
<tr>
<td>0.05m</td>
<td>(g)</td>
</tr>
</tbody>
</table>
Results and Rankings

• Results can be graphical or numerical
• Designs can be evaluated by ranking functions

<table>
<thead>
<tr>
<th>Rank</th>
<th>Design</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Mean Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(b)</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>(f)</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>(a)</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>(e)</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>4.2</td>
</tr>
<tr>
<td>5</td>
<td>(i)</td>
<td>9</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>4.5</td>
</tr>
<tr>
<td>6</td>
<td>(c)</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>5.5</td>
</tr>
<tr>
<td>7</td>
<td>(d)</td>
<td>6</td>
<td>4</td>
<td>7</td>
<td>7</td>
<td>6.0</td>
</tr>
<tr>
<td>8</td>
<td>(h)</td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>7.0</td>
</tr>
<tr>
<td>9</td>
<td>(j)</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>8.0</td>
</tr>
</tbody>
</table>

* A = distance, B = energy, C = deviation area, D = maximum deviation
Summary (1)

- Pragmatic approach to formal specification (no *all-or-nothing* paradigm)
- Focus on capturing requirements succinctly
- Small abstract models – easy to understand, maintain and explain
- Support design dialogue – get value for money fast
  - gain better problem domain understanding
  - fewer residual errors in downstream design artifacts (hence: less rework)
  - early validation and test creates opportunity to reuse test cases
- Not a panacea or “silver bullet”; abstraction still requires skill!

- Similar techniques: Z, B-method, Event-B, ASM
  (but these focus more on proof and refinement)
- Many of the VDM language concepts now “available” in high-level languages: (OCA)ML, Haskell, Python, Java, Ada, Eiffel
- Nevertheless modelling ≠ coding!
Summary (2) – useful links

• TOOLS:
  – (open source) Overture (all VDM dialects): [www.overturetool.org](http://www.overturetool.org) (tools, manuals, examples, books)
  – (open source) Crescendo (co-sim): [www.crescendotool.org](http://www.crescendotool.org)
  – (open source) Modelica: [https://www.modelica.org/](https://www.modelica.org/)

• PROJECTS:
  – DESTECS (completed in 2012): [www.destecs.org](http://www.destecs.org)