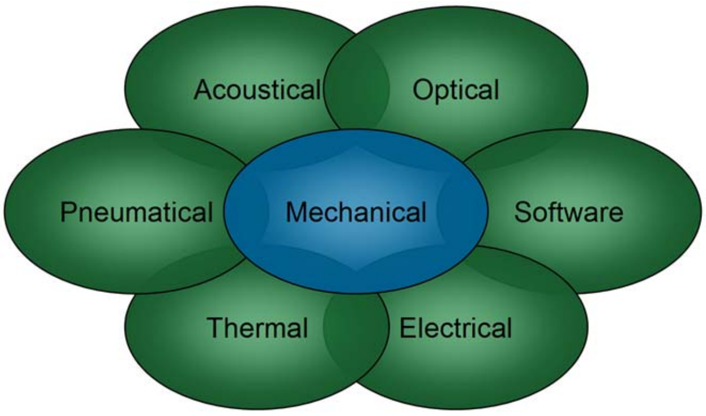
DEVELOPMENT PROCESS FOR MULTI-DISCIPLINARY EMBEDDED CONTROL SYSTEMS

Electrical and Computer Engineering
Technical Report ECE-TR-3



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Author: Sune Wolff, Department of Engineering – Electrical and Computer Engineering, Aarhus University

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DEVELOPMENT PROCESS FOR MULTI-DISCIPLINARY EMBEDDED CONTROL SYSTEMS

Sune Wolff — Aarhus University, Department of Engineering

Abstract

This report contains the progress report for the qualification exam for Industrial PhD student Sune Wolff. Initial work on describing a development process for multi-disciplinary systems using collaborative modelling and co-simulation is described.

Contents

Chapter 1

Introduction

This progress report describes the scientific work, which has been carried out as part of the first year and a half of my Industrial Ph.D. studies. The goal of the report is to give an overview of the work and give directions for future work.

The main focus of my work has been on combined simulation (called co-simulation) of models from different domains using different models of computation, in order to give a holistic description of an embedded system. The intended outcome of the PhD project is a methodology describing the work flow when utilising co-simulation in embedded systems development.

So far, the work has resulted in eight papers which have been submitted/published at international conferences or journals.

1.1 Structure of the Progress Report

In Chapter 2, a general introduction to the challenges in developing embedded systems is given based on [51]. Chapter 3 introduces different single-domain methodologies useful for developing software systems using abstract system level formal models. This chapter is based on the work presented in [31, 48, 32, 49, 39], and covers methods for developing models in the formal specification language VDM, as well as methods for combining agile development methodologies with the use of formal methods. Following this introduction, a case study is described where several subsystems of a self-defense system for fighter aircraft were modelled in VDM++, as presented in [50]. In Chapter 4 initial results of a multi-domain methodology making use of co-simulation is described, based on [17]. Finally, in Chapter 5 summary of work as well as future work, and current work not yet published, is outlined. In Appendix A my publications are listed, and Appendix B gives an overview of the courses I have completed in the first half of my Ph.D studies.

Chapter 2

Background

This chapter will introduce the reader to the background of the project and reasons why the work is needed. Various model-driven development techniques, both formal and informal languages and tools, will also be introduced in this chapter which is based on [51]. The systems of interest are multi-disciplinary embedded control systems, which are also called hybrid or cyber-physical systems – these names will be used interchangeably in this report.

2.1 Embedded Systems Design Challenges

The development of hybrid systems consisting of software, electronics and mechanical components which are operating in a physical world is a very complex challenge [23, 24]. These challenges arise from the need to develop complex, software-rich products that take the constraints of the physical world into account. The task is made even more challenging due to the fact that these types of systems often are developed out of phase – initially the mechanical parts are designed, followed by electronics and finally software is designed. Any problems discovered late in the development process, can really only be corrected in the software without causing huge delays to the complete project due to longer iterative cycles in electronics and mechanical development. These very late changes often increase the complexity of the software and the risk of introducing new bugs. Hence, an otherwise well thought-out software design can be compromised. In order to avoid situations like this, early feedback at a systems level is invaluable.

In order to develop hybrid systems, engineers from different backgrounds and with diverse fields of expertise are involved, making communication much harder than in mono-disciplinary projects. It is close to impossible for each individual engineer to foresee all the cross-discipline consequences of a given design decision.

Consider the system in Figure 2.1 describing a system controlling the level of bacteria in a water reservoir. A sample of the water and a reference fluid is passed through a micro capillary system (in order to obtain a very accurate output flow) and are mixed. An optoelectronic diode measures the result of the chemical reaction and sends this to a micro controller, which calculates a motor control signal. A reagent fluid is pumped into the water in order to lower the bacteria level below a predetermined threshold.

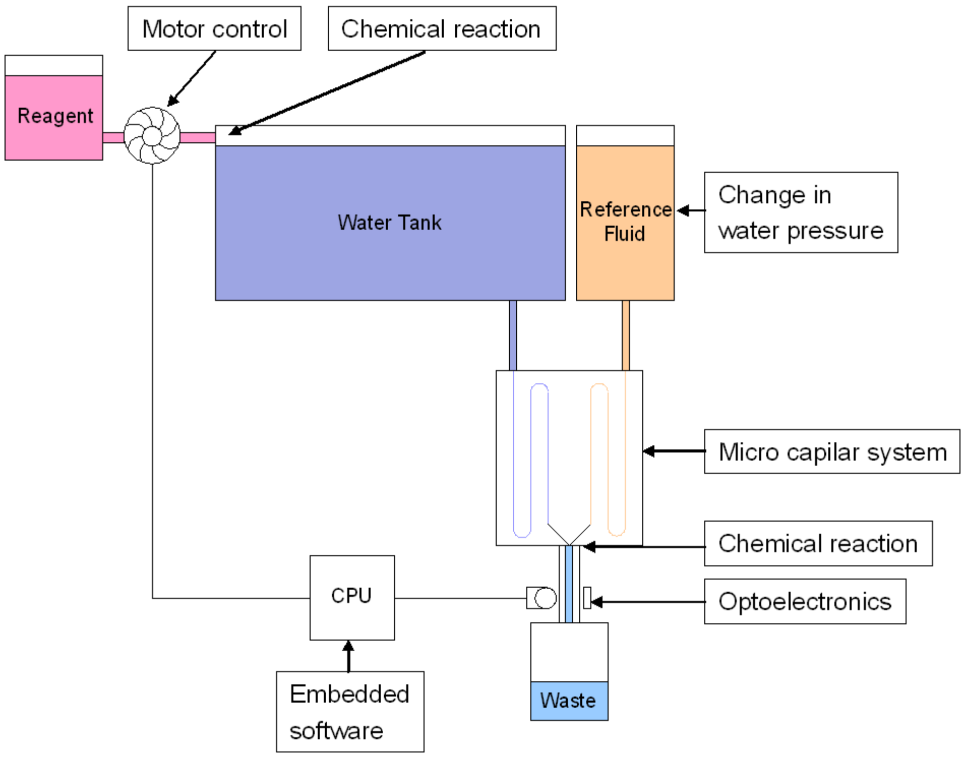


Figure 2.1: Example of multi-disciplinary system

A system like the one described above clearly needs a lot of different engineering disciplines with knowledge in areas like: physics, micro fluid systems, chemistry, optoelectronic, embedded software, machine engineering, etc. Lack of communication between these different disciplines, in order to solve cross discipline issues, can result in locally optimal subsystems but a globally suboptimal system, or even complex integration issues.

Mono-disciplinary problems are often well-defined and can be studied in depth with solutions based on mathematical rigor. Moving to multi-disciplinary problem solving introduces a lot of uncertainty. In order to evaluate the problem at hand and provide appropriate solutions different formalisms have to inter-operate, such as discrete (software) and continuous (mechanical) models. There is clearly a need for a framework that supports efficient evaluation of design choices over multiple disciplines.

2.1.1 Academic Research Projects

In the academic world, hybrid systems have been considered for more than a decade starting from a fuzzy logic perspective [20] to an automata perspective [22]. Since then, many academic research projects have attempted to tackle the challenges for developing such multi-disciplinary systems in predictable fashions. These include:

- AVACS investigates automatic verification and analysis of complex systems in particular hybrid systems using model checking.
- CREDO focuses on the development and application of an integrated suite of tools for compositional modeling, testing, and validation of software for evolving networks of dynamically reconfigurable components.
- DEPLOY is a major European FP7/IP addressing the industry deployment of formal methods for fault tolerant (discrete event) computing systems.
- INTERESTED focuses on creating a reference and open interoperable embedded systems tool-chain. The project's main focus is on discrete event tools for graphical overview and code generation, and not on co-simulation.
- MEDEIA aims to bridge the gap between engineering disciplines in the discrete engineering domain, by using containers that contain design models from various disciplines which can be seamlessly interconnected. Like the INTERESTED, MEDEIA aims to connect tools in the discrete event domain.
- PREDATOR aims to advance the state of the art in the development of safety-critical embedded systems focusing on timing aspects. systems.
- QUASIMODO aims to develop techniques and tools for model-driven design, analysis, testing and code-generation for embedded systems where ensuring quantitative bounds on resource consumption is a central problem. It focuses on formal notations for timed, probabilistic and hybrid systems that can be subjected to exhaustive state space analysis techniques such as model checking.
- SPEEDS focus on tool-supported collaborative modeling for embedded systems design.
- VERTIGO aims to develop a systematic methodology to enhance modeling, integration and verification of architectures targeting embedded systems. It will use a co-simulation strategy that allows the correctness of the interaction between HW and SW to be assessed by simulation and assertion checking.

In 2007 the major stakeholders for embedded systems in Europe have jointly started the organization ARTEMIS (Advanced Research & Technology in Embedded Intelligence and System). They have defined a Strategic Research Agenda (SRA) to focus on the main challenges for the future. In this SRA it is explicitly stated that there is a need for multidisciplinary, multi-objective, systems design techniques that will yield appropriate price/performance for acceptable power and with manageable temporal behavior.

One of the main concerns of my Industrial Ph.D. project is to bridge the gab between industry and academia by ensuring that the project outcome solves actual issues seen in industry. In addition, it is of great importance that the final methodology described fits into existing development methods used in industry, and hence can be applied with as few alterations as possible.

2.2 Model-Driven Development

Model driven development can address some of these challenges. Normally, the different types of engineers involved in the development of a hybrid system make use of domain specific tools in order to create models of the individual parts of the system. This enables the individual disciplines to optimize one specific part of the system. By creating abstract high-level multi-disciplinary models of the entire hybrid system and the ability to run a co-simulation of these, system engineers will be able to reason about system-level properties of the control system across multiple disciplines. This will ensure early feedback on system properties, as well as ease communication across different disciplines, since the impact of a given design decision can be made visible to the entire team.

A major challenge in model-driven development of hybrid systems, lies in the combination of the models used by the different disciplines involved in the development of the system. As long as the models lies within the same domain, this challenge is of limited complexity. When combining models from different domains like continuous-time and discrete-event models, the challenge is significant, and as will be argued this has not yet been done in a satisfying manner.

2.2.1 Discrete-Event Modelling

Software engineers can make use of discrete-event models when specifying the logic of the controller of an embedded system. Formal methods can be used to describe these models, where a mathematically based notation enables the engineer to rigorously describe and analyze the properties of the controller [47]. The motivation of using these models is to precisely describe the desired properties of the systems, while applying a higher level of abstraction to less important parts of the system. For example, device drivers and hardware components can be excluded from the model, enabling the software engineer to focus on the algorithmic challenges of the controller.

Several different discrete-event notations are used in industry and academia. Without a doubt, one of the most commonly used technique in industry is the graphical notation ”Unified Modeling Language” (UML) created by the Object Management Group. UML enables engineers to create several different views of the software under design. For example, requirement specification using use-case diagrams, static architecture using class diagrams and dynamic behavior using sequence diagrams. Industrial strength tools like IBM Rational Rhapsody enables the software engineer to code generate full C/C++ and Java code from a complete suite of UML diagrams, in order to uncover defects earlier in the product life cycle. An extension to UML called SysML [42] (System Modelling Language) has been created where system *blocks* can be defined without having to determine if it is a hardware or software entity.

In object-oriented formal languages, like VDM [16] (Vienna Development Method), the desired functionality of the controller can be described at the desired level of abstraction. This is a major advantage, since the model can describe the current problem at hand, and disregard all other parts of the system. Since VDM is used extensively in the project, it will be described in more details here.

VDM is a collection of techniques to formally specify and develop software. VDM originates from IBM's Laboratories in Vienna in the 1970s. The very first language supported by the VDM method was called Vienna Definition Language (VDL), which evolved into the meta-language Meta-IV [21, 4] and later into the specification language VDM-SL [40]. Over the years, extensions have been defined to model object-orientation (VDM++ [16]) and distributed real-time systems (VDM-RT [35, 45]). Two alternative tools exists; the commercial tool VDMTools [18] and the open source initiative Overture [29].

Data in VDM models can be described using simple abstract data types such as natural numbers, booleans and characters, as well as product and unions types and collection types such as sets, sequences and mappings. VDM has both a mathematical and an ASCII based syntax, where the latter is used in this report. The system state can be described using **`state`** in VDM-SL and **`instance variables`** in VDM++ and VDM-RT, the value of which can be restricted by invariants. To modify the state of the system, operations can be defined either explicitly by imperative statements, or implicitly by pre- and post-conditions. Functions which cannot use or modify the state can be defined in a similar fashion.

VDM has been used in several successful industrial applications e.g. [30] – examples of two recent applications in the Japanese industry is the TradeOne system developed by CSK systems for the Japanese stock exchange [16] and the FeliCa contactless chip firmware [28, 27]. Most of these applications have the common goal of providing rapid feedback on requirements and design early in the development cycle, by utilising executable models and doing lightweight formal analysis of these.

2.2.2 Continuous-Time Modelling

In classical physics, aspects like movement, acceleration and force are described using differential equations. Naturally, models of the environment in which an embedded system is operating is best described using differential equations as well. Whereas continuous-time models excel at describing physical movement, hydraulics and pneumatics, they generally lack the possibility to apply the correct level of abstraction to the discrete-event controller.

In industry Matlab/Simulink [34] created by MathWorks is possibly one of the most widely used tool for creating continuous-time models. Matlab is a high-level language and interactive environment which perform computationally intensive tasks very fast compared to traditional programming languages. Simulink is an environment for multi-domain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries which lets the user design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing.

20-sim [8], formerly CAMAS [7], is a tool for modelling and simulation of dynamic systems including electronics, mechanical and hydraulic systems. All models are based on Bond Graphs [26] which is a non-causal technology, where the underlying equations are specified as equalities. Hence variables do not initially need to be specified as inputs or outputs. In addition, the interface between Bond Graph elements is port-based where each port has two variables that are computed in opposite directions, for example voltage and current in the electrical domain. 20-sim also supports graphical representation of the mathematical relations between signals in the form of block diagrams and iconic diagrams (building blocks of physical systems like masses and springs) as more user friendly notations. Combination of notations is also possible, since Bond Graphs provide a common basis. It is possible to create sub-models of multiple components or even multiple sub-models allowing for a hierarchical model structure.

There are many other continuous-time modelling and simulation tools, including:

- Modelica – non-causal multi-domain modelling language [19]
- Scilab – open source version of MATLAB [53]
- Ptolemy – multi-domain modelling tool [10, 12, 13]
- SPICE – modelling of electrical systems [36]

A comparative survey of some of these tools have been carried out, described in Section 4.2.

2.2.3 Multi-Domain Modelling

Whereas the individual technologies and tools described above excel at creating models in their specific domain, few (if any) are suitable for modeling systems operating on both discrete-events and in continuous-time. The Stateflow application from MathWorks extends Simulink by allowing the use of language elements to describe complex logic. It is tightly integrated with Matlab and Simulink, and provides an environment for designing embedded hybrid systems. Matlab is a very efficient tool for algorithm development and large calculations, but lacks the possibility of using object-oriented architecture. The tool chain is also limited in the inability to apply a higher level of abstraction to parts of the system not currently in focus.

Another approach to combine discrete events and continuous time is to use discrete abstractions of the continuous elements. This approach was originally proposed by Alur et al. [2] who uses the first derivative of a continuous signal as well as state changes as discrete events which can be simulated with the remaining discrete parts of the system. An example of this can be seen in Figure 2.2. Every time the signal crosses a threshold, and at every local maximum and minimum a discrete event is generated. This has the unfortunate side effect that all notions of time is lost in the continuous time model. If this is acceptable for the problem at hand, this method can be used to great success. But especially if real-time aspects of the system is of interest, valuable information is lost.

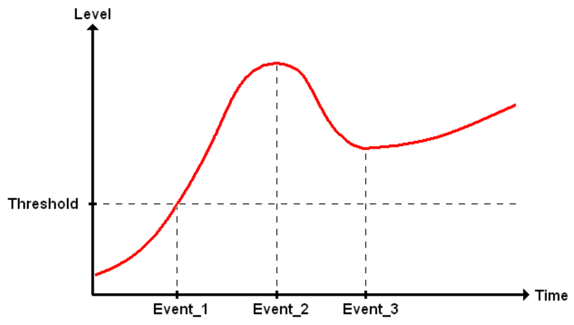


Figure 2.2: Discrete abstraction of continuous-time

The project ”Ptolemy2” [10] from University of California, Berkeley allows modeling, simulation and design of concurrent real-time embedded systems within multiple domains such as discrete-time, continuous-time, dynamic data flow, state machines and more [9, 13]. Hierarchical models can be described, where each level in the hierarchy can have a different model of computation defined by the type of *Director* chosen. For example, continuous-time elements of an embedded system can be described using block diagrams similar to the Simulink style, and discrete-event controllers can be described using modal-models. The controller model can again be hierarchical described in order to define different modes of operation. These notation forms are a huge advantage of Ptolemy, since many embedded systems software developers are used to designing controllers using state machines, while the block diagram notation is very similar to Simulink which must be the most commonly used continuous-time modelling tool.

The project ”Design Support and Tooling for Embedded Control Software” (abbreviated as DESTECS) [6]* aims at creating a methodology and open tools platform for the collaborative and multidisciplinary development of dependable embedded real-time control systems. The methodology combines continuous-time and discrete-event modeling

*http://www.destecs.org/

via co-simulation, allowing explicit modeling of faults and fault-tolerance mechanisms from the outset. Continuous-time models are expressed using bond graphs supported by the 20-sim tool while discrete-event controllers are modeled using VDM supported by the Overture tools. This project holds great promise both regarding tools and methodology, and will be followed closely throughout this project.

2.3 Summary

Designing multi-disciplinary systems consisting of software, electronics and mechanical components is a highly complex affair, and existing mono-disciplinary development methods cannot be applied directly to these types of systems. Even though a lot of academic projects has been carried out in this area of research, few - if any - has gained acceptance in industry.

The aim of the project ”Development Process for Multi-Disciplinary Embedded Control Systems” is to describe a model-driven development methodology, which can be used as a golden reference when creating system-level models in multi-disciplinary projects. It is of great importance that the method fits into existing classic development processes, as well as support dialog across disciplines. The methodology will be tested on case studies of safety-critical hybrid systems. It is imperative that the developed method can be widely accepted by engineers with different fields of expertise such as electronics, mechanics and software.

Chapter 3

Development Process for Discrete-Event Systems

As a natural first step towards describing a methodology for multi-domain systems, significant work has been put into describing a development process for discrete-event systems. A development methodology for VDM-RT models is describes in [31] and with an alternative case study in [39].

Agile methods have gained acceptance in the software industry as a means to incorporate the customer more in the development process by releasing several working version of the system in an iterative manner. In [32] the agile manifesto and the 12 agile principles are analysed in order to investigate if agile principles are compatible with formal modelling techniques. In [49] a concrete example of adding the use of formal methods to the agile development process Scrum is described.

In [50] an industrial case is described where a VDM model was created in order to investigate the impact of a suggested update to the interface between two subsystems of a self-defense system for fighter aircraft. This case serves as an example of using the development processes described above.

3.1 VDM-RT Model Development Methodology

The development of distributed embedded systems presents a considerable challenge. Designs for such systems are typically complex because of the need to address timing, concurrency and distribution aspects in addition to functionality. This complexity hinders the validation of designs and the exploration of alternatives. As a consequence design errors can prove expensive to correct if not detected early. The problem is made worse by the characteristics of the embedded systems business, in which sound design decisions have to be made early and rapidly in order to achieve a short time to market.

Formal models have a potentially valuable role to play in managing the complexity of embedded systems design. Rapid feedback from the machine-assisted analysis of such models has the potential to reduce the risk of expensive re-working as a consequence of the late detection of defects. However, models that incorporate the description of functionality alongside timing behaviour and distribution across shared computing resources are themselves potentially complex. Moving too rapidly to such a complex model can increase modelling and design costs in the long run.

While there are many formal notations for the representation of distributed and real-time systems, guides to practical methods for model construction and analysis are essential if these approaches are to be deployed successfully in industrial settings. Such methods should be incremental, allowing the staged introduction of detail. They should also allow the decomposition of the validation task by permitting tool- supported analysis of the models produced at each stage. They should use tools that maximise the value gained in return for sustainable levels of investment in training as well as in creating and analysing formal models.

A pragmatic and tool-supported method for the stepwise development of models of distributed embedded systems is summarised in the following. At each step in our method, we develop a model that considers an additional aspect of the design problem, such as distribution or concurrency. Our approach uses and extends the Vienna Development Method (VDM) [4, 25, 15, 16] and its tools: VDMTools [18] and Overture [37]). A comprehensive description of the method of model derivation and forms a contribution to the methodological guidelines accompanying VDMTools [11] is provided.

3.1.1 An Incremental Approach to Model Construction

The goal is to describe a method for developing formal models of distributed real-time systems that is incremental and allows tool-supported validation of the models produced at each stage. We propose a stepwise approach [11] which exploits the capabilities of each of the VDM modelling language extensions described in Section 2.2.1. Our approach aims to assist the management of complexity by enabling the developer to consider a different facet of the modelled system at each stage. The steps themselves are as follows:

1. System Boundary Definition
2. Sequential Design Modelling
3. Concurrent Design Modelling
4. Distributed Real-time Design Modelling

In the design of embedded systems, a key early decision is the drawing of the boundary between the environment, which consists of elements that can not be controlled by the designer, and the controller that is to be developed. In particular, this allows the developer to state assumptions about environment behaviour and the guarantees that describe the correct operation of the controller in a valid environment. The first stage of our method involves making the system boundary, assumptions and guarantees explicit. Such an explicit abstract description can be given informally or using both formal and informal elements side by side. It may also be given purely formally, often using domain-specific notations, though we will not illustrate that aspect here.

Based on this abstract description, an object-oriented architecture is introduced, creating a sequential model with structure expressed using the features of VDM++. Consideration of the synchronisation of concurrent activities is deferred in order to focus on functional aspects. In the next stage, this sequential model is extended to encompass concurrency and thread synchronisation (still using the VDM++ language, which includes concurrency modelling features). Subsequently, the concurrent design model may be extended with real-time information using the VDM-RT extensions. Finally, distribution over a distributed embedded architecture can be described, using the VDM-RT extensions. At this stage it may prove necessary to revisit the concurrent design model, since design decisions made at that stage may prove to be infeasible when real-time information is added to the model (for instance, the model may not be able to meet its deadlines). From the concurrent and distributed real-time VDM++ design model an implementation may subsequently be developed. Testing of the final implementation and the various design-oriented models may be able to exploit the more abstract models as a test oracle. Note that the approach suggested here enables continuous validation of the models if these are written in executable subsets of the different VDM dialects.

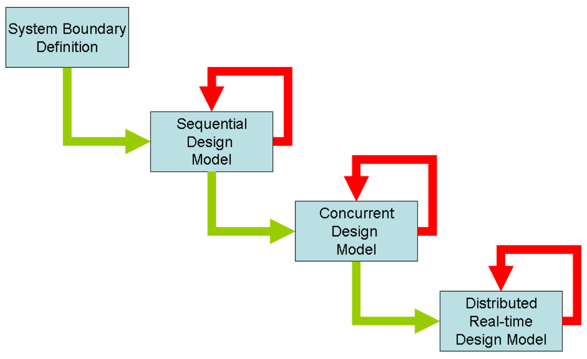

System Boundary Definition
Sequential Design Model
Concurrent Design Model
Distributed Real-time Design Model

Figure 3.1: Overview of Models Produced

Figure 3.1 gives an overview of the relationships between the products in our proposed method. The downward arrows indicate the primary flow of information whenever a phase has been completed whereas the upward arrows show iteration that might follow the detection of modelling errors in the validation of the model produced at each stage. Note that this is not intended as a process model, but rather a rational structure for the relationships between the models produced. Internal iterations, and even iterations between models, are likely to occur in practice.

We do not claim that the models introduced at each stage in our approach are necessarily formal refinements of their predecessors. Our intended output is a comprehensive model of the target system that can serve as a basis for subsequent development, possibly using refinement. We are therefore introducing detail in a staged manner, where the executions at each level might, informally, be seen as providing a finer level of granularity than its predecessor.

Detailed description of the method as well as a small case study where the method has been applied can be seen in the paper [31].

3.2 Using Formal Methods in Agile System Development

Formal methods are a response to the challenge of complexity in computer-based systems, and the defects that arise as a result. They are techniques used to model and analyse complex computer-based systems as mathematical entities. Producing a mathematically rigorous model of a complex system enables developers to verify or refute claims about the putative system at various stages in its development. Formal methods can be applied to models produced at any stage of a system's development, from high-level models of abstract requirements to models of the characteristics of running code, such as memory usage [52]. The motivations for including formal methods in software development are to minimise defects in the delivered system by identifying them as soon as they arise, and also to provide evidence of the verification of critical system elements. Formal methods are highly diverse, in part because of the variety of domains in which they have been applied. Notable applications have been in the areas of communications, operating system and driver verification, processor design, the power and transportation sectors.

In spite of their successful application in a variety of industry sectors, formal methods have been perceived as expensive, niche technology requiring highly capable engineers [41]. The development of stronger and more automated formal analysis techniques in the last decade has led to renewed interest in the extent to which formal techniques can contribute to evolving software development practices.

3.2.1 Are Formal Methods Ready for Agility?

The principles of agile software development emerged as a reaction to the perceived failure of more conventional methodologies to cope with the realities of software development in a volatile and competitive market. In contrast with some established development approaches, which had come to be seen as necessary fictions [38], agile methods were characterised as incremental (small software releases on a rapid cycle), cooperative (emphasising close communication between customers and developers), straightforward to learn and modify, and adaptive to changes in the requirements or environment [1]. Four value statements[*] summarise the principles of the approach. Proponents

[*] http://agilemanifesto.org/

of agile techniques value *Individuals and interactions* over processes and tools, *working software* over comprehensive documentation, *customer collaboration* over contract negotiation and *responding to change* over following a plan.

Agile methods have received considerable attention, but as Turk et al. have pointed out, they do appear to make some underlying assumptions [43]. For example, close customer interaction assumes the ready availability of an authoritative customer; a lower value placed on documentation assumes that documentation and software models are not themselves first-class products of the process; the emphasis on adaptation to changing conditions assumes a level of experience among developers. Since not all projects satisfy these assumptions, it has been suggested that agile approaches are unsuited for distributed development environments, for developments that make extensive use of subcontracting or that require to develop reusable artifacts, that involve large teams or involve the development of critical, large or complex software.

Two of the 12 principles do not fit the value statements quite so easily as the others listed above. Both of them deal with aspects of the technical quality of the product:

- Continuous attention to technical excellence and good design enhances agility.
- The best architectures, requirements, and designs emerge from self-organizing teams.

Formal techniques certainly support this focus on quality. Black et al. [5] also mention the potential synergy between agile and formal methods, opening up the possibility of agile methods being applied to more safety critical domains – something which is currently, to a large extent, off limits to pure agile methods. We conjecture that the second value statement of the original agile manifesto (working software over documentation) has provided a pretext for hack-fixing and ad-hoc programming to call itself an agile process. This has hurt the reputation of agile development, and we would suggest that the addition of a fifth principle favouring quality of the end product over ad-hoc solutions could prevent some of the abuses of agility.

3.2.2 Adding Formal Methods to Scrum

In order to give concrete examples of how formal and agile methods can be combined, two different approaches, called the parallel and sequential strategy, were described in [49] and compared. Both approaches extend the agile development method Scrum by adding the use of formal methods in order to validate key concepts of the system under constriction. The two different strategies presented in the paper are quite different and it is apparent that the advantages of one strategy are the drawbacks of the other and vice versa.

The parallel strategy reduces some of the agile properties of traditional Scrum by decreasing the readiness of adapting to changes, since changes imposed by one sprint cannot be added to the following sprint. The reason for this is that optimally the content

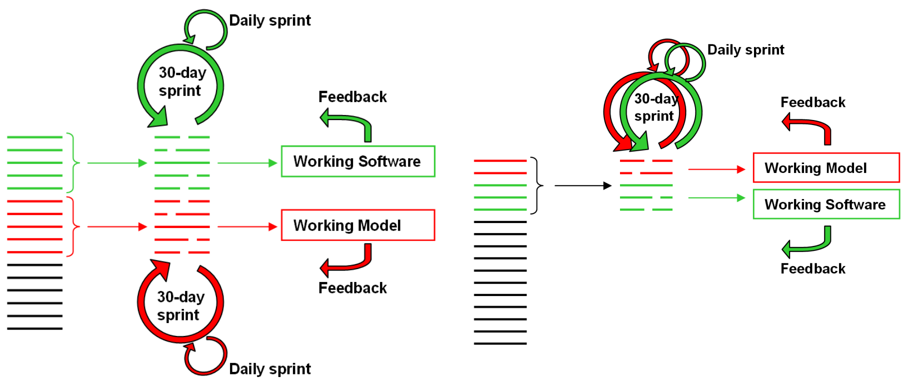


Figure 3.2: (a) schematic overview of the parallel (left) and (b) sequential (right) strategies.

of two consecutive sprints should be kept constant, to ensure that the tasks of the software sprint already have been formally validated in the previous formal modelling sprint. The sequential strategy has better support for change, and hence is more agile. Since the same team needs to do both formal modelling as well as software implementation less progress will be made on the working software though, which can give a bad impression for the customer.

The need for two separate teams in the parallel strategy introduces a resource overhead. Since the workload of the sequential strategy is comparable, it is reasonable to assume that a comparable resource overhead is imposed using this strategy as well. The formal community will argue that the added time spent on formal validation is gained in the implementation and integration phases since the system will have fewer errors.

One of the main benefits of adding the use of formal methods is to give valuable input to the implementation phase, or to enable reuse of test cases, which in turn will lessen the overall workload. Tool support for some formal methods include code generation from the formal model to a target programming language. The generated code can rarely be seamlessly deployed without further alterations but can at least be used as a skeleton for further development and thereby decreasing the workload.

A general observation for both strategies is the need of additional meetings during each sprint to synchronize the progress of the team(s) and demonstrate both the formal model as well as the final software implementation. This is hard to avoid since additional people are involved in the project (at least for the parallel strategy) and additional artifacts are generated (mainly formal models). Traditional Scrum can scale using several Scrum teams, and by making use of Scrum-of-Scrums where the Scrum masters synchronise the work done by the different groups involved in the project. A similar approach is proposed for the parallel strategy in order to synchronise the work of the two teams.

Using separate teams to do the formal model and the final software implementation in the parallel strategy has another main benefit; if a team is under time pressure, there is a danger of neglecting the formal modelling phase in order to ensure that enough time is left for finishing the final implementation in each sprint. This danger is avoided when having separate teams doing the formal model and the software implementation. On the other hand, having two separate teams working on the implementation and investigation tasks works against the agile principles of having self-contained teams.

3.2.3 Concluding Remarks

The improved analytic power of formal methods tools and greater understanding of the role of rigorous modelling in development processes are gradually improving software practice. However, the claim that formal methods can be part of agile processes should not be made lightly. We have examined the value statements and supporting principles of the agile manifesto and have identified areas in which formal methods and tools are hard-pressed to live up to the claim that they can work with agile techniques. In doing so, we have drawn on our own experience of developing and deploying a tool-supported formal method in industrial settings.

Formal methods should not be thought of as development *processes*, but are better seen as collections of techniques that can be deployed as appropriate. For the agile developer, it is not possible to get benefits from formalism unless the formal notation or technique is focused and easy to learn and apply. Luckily, formal modelling and analysis does not *have* to be burdensome. For example, forms of static analysis and automatic verification can be used to ensure that key properties are preserved from one iteration to the next. For this to be efficient, and to fit into the agile mindset, analysis must have automated tool support. Formalists should stop worrying about development processes if they want to support agility. Instead, they should start adjusting their ”only perfect is good enough” mindset, and try a more lightweight approach to formal modelling if their goal is to become more agile.

Formalists may need to remember that most engineers, even good ones, have no prior experience of formal methods technology and demand tools that give answers to analyses in seconds. Developers of formal methods must give serious attention to their ease of use if they are to claim any link with agile software development.

Tools must integrate almost seamlessly with existing development environments if they are to support agile processes and there is considerable research required to make this a reality. Progress can certainly be made by improving tools, in particular in combining with GUI building tools and for automation of different forms of analysis. In fact we would like the agile thinking to go beyond the software to encompass collaboration between different engineering disciplines involved in a complex product development, as in the embedded systems domain [6].

The agile manifesto is not necessarily consistent with a view of formal methods as correct-by-construction development processes. However, there are good reasons for combining agile principles with the formal techniques. Formal methods researchers and tool builders must, however, address some deficiencies if the benefits of such a collaborative approach are to be realised.

3.3 Industrial Case - VDM Model Development

A lightweight version of the parallel strategy mentioned above has already been tried out in practice [50], where the author worked as the only member of the formal modelling team working in parallel with a large team of more than 25 software engineers implementing a significant upgrade to a self-defense system for fighter aircraft. The project involved many upgrades to an existing system, whereas the formal modelling focused on an upgrade to the interpretation of messages sent between two subsystems using an existing communication protocol. Executable models of both subsystems were modelled in VDM++ and a large test suite was used in order to exercise the use of the communication protocol. The result of these numerous tests were used to show the implications of the upgrade to the customer, and to ensure that no unfortunate side effects were introduced.

3.3.1 Case Description

When fighter pilots are flying missions in hostile territory, there is a risk of encountering enemy anti-aircraft systems. To respond to these threats, the pilot can deploy different countermeasures. Since opposing anti aircraft systems are becoming increasingly sophisticated, and on-board self-defense systems are also becoming more sophisticated, the fighter pilot is in need of assistance in choosing the optimal countermeasures strategy.

A system called *Electronic Combat Adaptive Processor* (ECAP) has been developed to assist the pilot in choosing the most optimal response to incoming threats. The system is a programmable unit that provides threat adaptive processing, threat evaluation and countermeasures strategy to counter incoming threats. From a multitude of sensor inputs (aircraft position, orientation, speed, altitude and threat type and incoming angle to name a few) the system chooses an effective combination of countermeasures against the incoming threat. The different sensors attached to ECAP can detect different types of threats, and will report data of any incoming threat of that specific type to ECAP. The chosen threat response, which can consist of one or more countermeasure programs, is sent to a Dispenser subsystem which administers the deployment of the correct types of dispense payloads with the correct timing. An overview of the system can be seen in Fig. 3.3.

The subsystem of interest for this paper, is a special Advanced Sensor (AS). This sensor not only detects incoming threats, but also calculates the countermeasures needed to avoid the threat. AS is running in parallel with the rest of the system, and relies on ECAP to accept and execute generated threat responses. Hence, ECAP needs to check the RT and IAT of the proposed response for conflicts, and accept/reject the response based on this. A robust protocol has been specified, defining the communication between

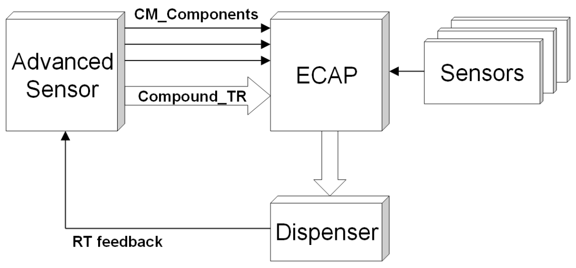


Figure 3.3: Self-defense system overview.

ECAP and AS. A threat response consists of several components, which can be either a dispense routine of countermeasure payloads, a command to a subsystem or audio feedback to the pilot. Initially, ECAP treated all components separately which resulted in the need for several pilot consent actions in order to execute a response when the system was running in semi-automatic mode. Not only did this put unnecessary strain on the pilot, but it also resulted in delays between the different countermeasure programs.

The main focus of this case study was an update to the way ECAP interprets messages from the AS system. The protocol itself has undergone military certification, hence no changes to the protocol were possible, since this would involve re-certification of the protocol, which is both a costly and time consuming task. Instead, in addition to the individual components of the threat response, AS will also generate a compound threat response message which is the concatenation of the sequence of components. The only thing distinguishing a component from the compound threat response is the position in the complete AS message – in a message of length = n, all sub-messages [1..n-1] are components and the n'th message is the compound threat response.

For a more in-depth description of the VDM model, please see [50].

3.3.2 Discussion of Results

In total, the complete model of ECAP and the AS subsystem consists of more than 1800 lines of VDM++ specification. In addition, more than 1500 lines of test were created to run the many scenarios needed to exercise the new use of the protocol. Built into the Overture tool is the ability to generate test coverage of a model, which gives an indication of parts of the model which are exercised less than other parts. The AP subsystem has a test coverage of 100%, meaning that every line of specification has been exercised by the scenarios. On average, the complete model of ECAP, AP and all other subsystems has a test coverage of 94%. The focus of the scenarios was on testing the new interpretation of the protocol, and testing combinations of ECAP system state with different AP input. This is the reason why every branch of the complete model has not been completely covered by the tests, but only the parts of the system concerned with the communication between ECAP and AS.

The ECAP and AS model made use of extensive logging, so at any point in time the system state was available for post-execution analysis. The logfiles from the many scenarios were used directly in the communication with the customer, to give a precise description of how the systems should react in the different situations. This was a great aid in agreeing on the way ECAP should interpret the countermeasure components and compound threat response. In addition to these logs built directly into the model, a certain amount of logging is available in the Overture tool. The main focus of these automatically created logs is multi-threaded models, so mainly the scheduling of threads is logged. If this automatic logging feature was to be extended into a more useful tool, it could be very beneficial for the Overture tool in general, since users could avoid writing their own logging mechanism for each model.

The end customer was very impressed by the extensive tests which had been carried out on the model, and the log files from the test proved to be a great communication tool between the customer and the systems engineers in charge of the project. The test results also increased the confidence in the proposed solution for the development team.

For a system the size and complexity of the one presented here, it is very difficult (if not impossible) to analyse the many combinations of system state and AS input by hand. In addition the manual approach is very error prone, which could result in agreeing on erroneous behaviour and not discovering critical design flaws in the protocol. The test suite composed for this project does not ensure complete coverage of the state-space of the system, but provided a simple framework enabling extension of other scenarios to analyse some newly discovered corner-case. This ensured a short duration of the iterative cycles internally in the company when new corner cases had to be tested.

For the systems engineers leading the project, this was their first experience with formal methods, and in using executable models to specify functional requirements in general:

> *"The possibility to run numerous scenarios to analyse different combinations of ECAP system state and AS input was invaluable, and the rapid feedback from the model designer was very useful due to the time constraints of the project. We are extremely happy with the results obtained from this case study, which helped us in reaching an agreement with the customer within a very limited period of time."*

The models of ECAP, AS and the protocol were developed by a single person over a period of just two months including knowledge gathering of the systems involved. This was only possible due to the fact that a lot of details of the real system was abstracted away, and only the main functionality of the systems was included in the model. The different subsystems are connected by a military standard communication bus, which could have been modelled in detail to test package collision etc. In addition, several subsystem commands to enable and disable various subsystems were omitted. This is indeed one of the main advantages of using system modelling in the early phases of system development; describe the parts of the system of interest in detail and abstract away from any unneeded details. For example, low level implementation details of the desired logic of various drivers is not needed to understand the overall functionality of the system – hence abstracting away from such details helps creating more readable models giving a better system overview.

3.4 Summary of Discrete-Event Work

The work presented in this chapter is focused on development of discrete-event models, which is a natural first step before adding the complexity of multi-domain models and co-simulation. On the methodology side of things, the step-wise development of VDM-RT models is described. In addition, the agile manifesto has been analysed in order to determine how well formal methods support these principles and to discuss to what extent the two different approaches to software development can be combined. A concrete example of how formal methods can be used in the agile development framework Scrum has been described, and a lightweight version of this strategy has been tried in an industrial case.

Chapter 4

Development Process for Multi-Disciplinary Systems

Traditional development approaches are mono-disciplinary in style, in that separate mechanical, electronic and software engineering groups handle distinct aspects of product development and often do so in sequence. Contemporary concurrent engineering strategies aim to improve the time to market by performing these activities in parallel. However, cross-cutting system-level requirements that cannot be assigned to a single discipline, such as performance and dependability, can cause great problems, because their impact on each discipline is exposed late in the development process, usually during integration. Embedded systems, in which the viability of the product depends on the close coupling between the physical and computing disciplines, therefore calls for a more multidisciplinary approach. My work in this area (so far) is described in [17].

4.1 Collaborative Modelling and Co-simulation

We conjecture that a collaborative methodology based on lightweight formal modelling improves the chances of closing the design loop early, encouraging dialogue between disciplines and reducing errors, saving cost and time. Throughout the paper, we term this approach ”collaborative modelling” or ”co-modelling”. In previous work [44], Verhoef has demonstrated that significant gains are feasible by combining VDM and Bond Graphs, using co-simulation as the means of model assessment. Andrews et al. have suggested that collaborative models are suited to exploring fault behaviours [3]. We build upon these results, indicating how a collaborative modelling approach can be realised in existing formally-based technology, how models can be extended to describe forms of faulty behaviour, and identifying requirements for design space exploration in this context.

A *co-model* (Figure 4.1 (a)) is a model composed of:

- Two component models, normally one describing a computing subsystem and one describing the plant or environment with which it interacts. The former model is typically expressed in a discrete event (DE) formalism and the latter using a continuous-time (CT) formalism.

- A *contract*, which identifies shared design parameters, shared variables, and common events used to effect communication between the subsystems represented by the models.

A co-model is itself a model and may be simulated under the control of a script. The simulation of a co-model is termed *co-simulation*. A co-model offers an interface that can be used to set design parameters and to run scripts to set initial values, trigger faulty behaviour, provide external inputs and observe selected values as the simulation progresses. Our goal is to provide modelling and simulation techniques that support *design space exploration*, by which we mean the (iterative) process of constructing co-models, co-simulation and interpretation of test results governing the selection of alternative models and co-models as the basis for further design steps.

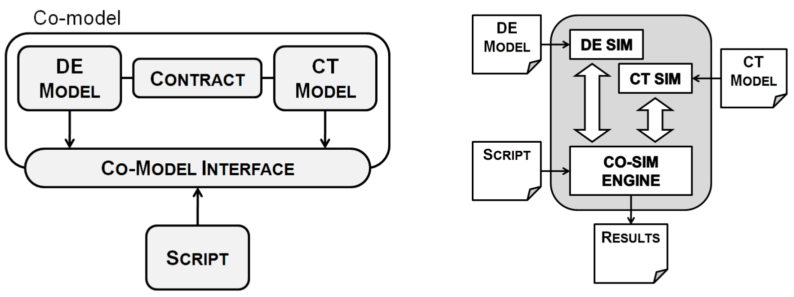


Figure 4.1: (a) conceptual view of a co-model (left) and (b) execution of a co-model realised using a co-simulation engine (right).

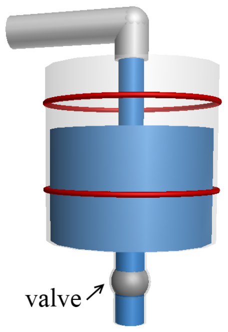
In a co-simulation, a *shared variable* is a variable that appears in and can be accessed from both component models. Predicates over the variables in the component models may be stated and may change value as the co-simulation progresses. The changing of the logical value of a predicate at a certain time is termed an *event*. Events are referred to by name and can be propagated from one component model to another within a co-model during co-simulation. The semantics of a co-simulation is defined in terms of the evolution of these shared variable changes and event occurrences while co-model time is passing. In a co-simulation, the CT and DE models execute as interleaved threads of control in their respective simulators under the supervision of a *co-simulation engine* (Figure 4.1 (b)). The DE simulator calculates the smallest time Δt it can run before it can perform the next possible action. This time step is used by the co-simulation engine in the communication to the CT simulator which then runs the solver forward by up to Δt.

If the CT simulator observes an event, for example when a continuously varying value passes a threshold, this is communicated back to the DE simulator by the co-simulation engine. If this event occurred prior to Δt, then the DE simulator does not complete the full time step, but it runs forward to this shorter time step and then re-evaluates its simulator state. Note that it is not possible (in general) to roll the DE simulation back, owing to the expense of saving the full state history, whereas the CT solver can work to specified times analytically. Verhoef et al. [46] provide an integrated operational semantics for the co-simulation of DE models with CT models. Co-simulation soundness is ensured by enforcing strict monotonically increasing model time and a transaction mechanism that manages time triggered modification of shared variables.

The work reported in this paper is aimed at demonstrating the feasibility of multidisciplinary collaborative modelling for early-stage design space exploration. As a proof of concept, methods and an open tools platform are being developed to support modelling and co-simulation, with explicit modelling of faults and fault-tolerance mechanisms from the outset. This activity is undertaken as part of the EU FP7 Project DESTECS.

The proof of concept work uses continuous-time models expressed as differential equations in Bond Graphs [26] and discrete event models expressed using the Vienna Development Method (VDM) [14, 15] notation. The simulation engines supporting the two notations are, respectively, 20-sim [8] [*] and Overture [29] [†].

4.1.1 Basic Co-simulation in 20-sim and VDM



$$\frac{dV}{dt} = \varphi_{in}\text{-}\varphi_{out} \tag{4.1}$$

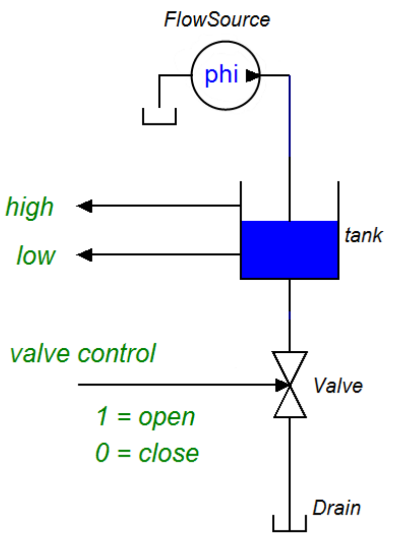
$$\varphi_{out} = \begin{cases} \frac{\rho * g}{A * R} * V & \text{if valve open} \\ 0 & \text{if valve closed} \end{cases} \tag{4.2}$$

Figure 4.2: Water tank level controller case study system overview

Co-simulation between a VDM and 20-sim model is illustrated by means of a simple example based on the level controller of a water tank (Figure 4.2). The tank is continuously filled by the input flow φ_{in}, and can be drained by opening the valve, resulting in the output flow φ_{out}. The output flow through the valve when this is opened or closed is described by Equation 2 in Figure 4.2, where ρ is the density of the water, g is acceleration due to gravity, A is the surface area of the water tank, R is the resistance in

[*] http://www.20sim.com/
[†] http://www.overturetool.org/

the valve and V is the volume. An iconic diagram model of this system created in 20-sim is shown in Figure 4.3 (a). There are two simple requirements for the discrete-event controller: when the water reaches the ”high” level mark the valve must be opened, and when the water reaches the ”low” level mark, the valve must be closed. A VDM model of the controller is in Figure 4.3 (b).



```
class Controller

instance variables
 private i : 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
```

Figure 4.3: (a) 20-Sim model (left) and (b) event-driven controller in VDM (right).

The controller model is expressed in VDM-RT. An instance variable represents the state of the valve and the asynchronous `Open` and `Close` operations set its value. Both operations are specified explicitly in the sense that they are directly executable. In order to illustrate the recording of timing constraints in VDM-RT, the **`duration`** and **`cycles`** statements constrain the time taken by the operations to 50 ms in the case of `Open` and 1000 processor cycles in the case of `Close`. The time taken for a `Close` operation is therefore dependent on the defined speed of the computation unit (CPU) on which it is deployed (described elsewhere in the model). The synchronisation constraints state that the two operations are mutually exclusive.

Using the DESTECS tool a co-model can be constructed consisting of the 20-sim model and VDM model shown above. The co-simulation contract between them identifies the events from the CT model that are coupled to the operations in the DE model and indicates that `valve` is shared between the two models. The contract indicates which state event triggers which operations. In the case the water level rises above the upper sensor, the `Open` operation shall be triggered and respectively when the water level drops below the lower sensor, the `Close` operation shall be called. Note that `valve` represents the actual state of the valve, not merely the controller's view of it.

4.2 Tools

In addition to the DESTECS tool described above, multiple other tools have been tested and compared in order to find limitations in their co-simulation capabilities. Initially, four mainly continuous-time simulation tools were compared in order to investigate initial learning curve and usability. The four different tools were chosen based on the following criteria. Matlab/Simulink was chosen since it is widely used in the industry – MathWorks claim that more than 1million engineers worldwide use the tool. As a free alternative, the open-source tool Scilab/Xcos was chosen. This tool is by many known as the "Open-source version of Matlab". 20-sim has its roots in academia but is now maintained by the company Controllab Products B.V. which is an off-spring company from the Control Engineering Group at Twente University. It was chosen as an example of an academic tool which has successfully moved into industry. Finally, Ptolemy II was chosen as a purely academic tool developed and maintained by the Center for Hybrid and Embedded Software Systems (CHESS) at University of California at Berkeley.

The watertank case described above was modelled in all four tools. In addition, the model was extended with an additional cascade coupled watertank where the output of one tank is the input to the other. This addition was created in order to test how well the different tools support model reuse and extensions to existing models.

Each of the four tools were evaluated based on a number of criteria, like: learning curve, usability, model extension support, model component reuse, simulation result visualisation and accessibility of tutorials and model examples. As is clear, there was great focus on usability aspects in this initial survey.

Of the four tools, only Ptolemy is really suited for stand-alone co-simulation, so a more in-depth investigation has been initiated comparing the co-simulation capabilities of the DESTECS and the Ptolemy tools. In this comparison a model of a fuel system for aircrafts will be modelled, where fuel will be transfered between several on-board fuel tanks. This comparison will focus less on usability and more on co-simulation capabilities like:

Simulation speed: Running the same simulation on the two tools, which is the fastest?

Continuous-time simulation settings: Which ordinary differential equation (ODE) solvers can be chosen? Can the stepsize of the solver be changed freely?

Discrete-event controller expressiveness: How well does the discrete-event part of the tools support abstraction? Is it possible to describe a hierarchical or object oriented controller?

Fault modelling: How well do the tools support modelling faults and error correcting controllers?

This work is far from concluded, and only the initial modelling work has begun. Collaborating with post-docs from Berkeley University and Newcastle University will ensure that the comparison is fair and that the results are validated by both Ptolemy and DESTECS representatives.

4.3 Casework

Even though both tools and methodology supporting co-simulation still are in the early phases of development, a few case studies have already been created investigating the maturity of both tools and methods. One such project was made in collaboration with the DESTECS project. A co-model a self-defense system (similar to the one described in Section 3.3) and the continuous movement of the aircraft and decoys was created in a collaboration between Terma A/S and the project. The purpose of the model was twofold:

1. Analyze how much the thermal picture is distorted during different maneuvers
   - Which maneuver distorts the thermal picture the most?
   - Is there any need for changing the sequence?
2. Develop algorithm that changes the sequence of flares at run-time to counter the distortion
   - Can the algorithm ensure that the decoys deployed draw a pattern which looks more like the original picture?
   - Can the algorithm draw ”any” picture? Ex. make it look like the aircraft is flying in another direction?

The dynamics of the individual flares including drag force, gravity and release force was modelled in 20-sim, and the controller determining the optimal counter measure to a given threat was modelled in VDM. An algorithm was developed which, based on the orientation of the aircraft, takes corrective measures in order to ensure that the flare pattern looks more like the intended level flight pattern. In Figure 4.4 the result of the algorithm can be seen.

This project is still work in progress, and the impact of the co-simulation results are still being discussed at Terma A/S, and more domain experts need to see the project in order to determine the significance of the results.

4.4 Summary of Multi-Disciplinary Work

Most of the multi-disciplinary modelling has been carried out in context of the DESTECS project using the tools developed by the project. The comparative work of this tool with

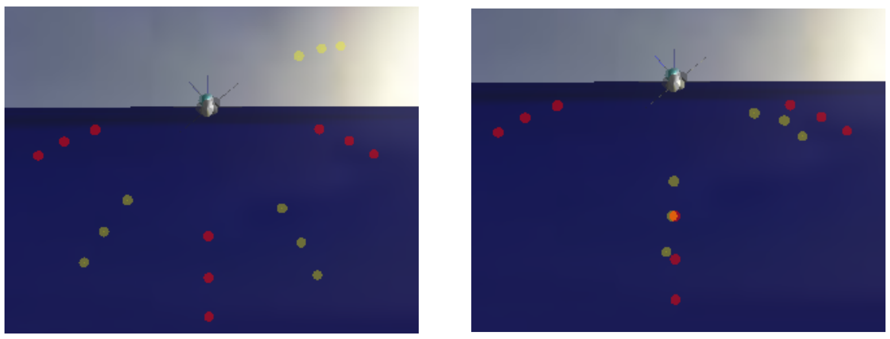


Figure 4.4: (a) comparing dispense pattern of level and rolling flight (left) and (b) same comparison using the correcting algorithm (right). In both pictures, the decoys in level flight are red and the decoys in rolling flight are yellow.

the Ptolemy tool will provide valuable input as to which is the strongest in several aspects of co-simulation, and hence will be an important factor for the continued work of the project. The results from the case work done on the DESTECS IFG challenge described above has been well received by Terma, and will hopefully be the first of many interesting co-simulation projects for the remainder of the PhD project.

Chapter 5

Summary and Future Work

The main goal of the PhD project is to describe and validate a development process for multi-disciplinary embedded systems. This chapter gives a summary of the work carried out so far, as well as an outline of the work planned for the remainder of the project.

5.1 Summary of Work

As an Industrial PhD student, the interests of the company (Terma A/S) needs to be taken into account. Since Terma has no experience in using a model driven development process, it was clear that moving directly to co-simulation of both discrete-event and continuous-time models was to big a jump. Instead the modelling concepts were initially introduced in the discrete domain only.

5.1.1 Discrete-event Modelling

A methodology of how to develop and refine VDM models was initially described in [31]. Here requirements are captured in a VDM-SL model, describing only the key functionality of the system. Following this, an object oriented architecture is described in a sequential VDM++ model, and concurrency constraints are described in a concurrent VDM++ model. Finally, a VDM-RT model is created in order to describe distribution and real-time constraints of the system.

Since agile methods have gained a lot of acceptance in industry (Terma uses a heavily tailored Scrum process in their day-to-day software development) this topic were also investigated. In [32] we discussed how different agile methods and light weight formal methods really are, and argue that the two approaches to software development can be combined if both the agile and formal community are ready to adjust their ideals slightly. Each of the 12 agile principles are analysed and it is argued how light weight formal models can be used to support these principles. In [49] a concrete example of adding the use of formal methods to the agile development process Scrum is described.

The work on the discrete-event model development methodologies is supported by the case work on the self-defense system for fighter aircraft described in [50]. In this case, a concurrent VDM++ model was used to describe the behaviour of a proposed extension to a complex counter measure system. The incremental model development process was used, moving from a sequential to a concurrent model, and one of the strategies of combining formal methods with Scrum described in [49] was used. This case work gave good confidence in the methods described.

5.1.2 Multi-domain Modelling

There is only a limited choice when it comes to co-simulation tools. I have used the tools developed in the DESTECS project the most for multi domain modelling, but a two week visit to Berkeley University has also given a good understanding of the Ptolemy tool. In order to determine pros and cons of the two tools, an in depth comparison has been initiated with collaboration from Berkeley and the DESTECS project.

Numerous smaller co-simulation models have been developed in order to get comfortable with the tools, and in order to take the initial steps towards describing a first version of a multi-disciplinary development process. The DESTECS IFG challenge described in Section 4.3 is the most extensive co-model created.

5.2 Future Work

This section gives a brief overview of some of the projects planned for the second half of the PhD project. Some of this work has already been initiated, while other areas are mainly suggested areas of interest.

5.2.1 Methodology

The main focus of the second half of the PhD project is on describing and testing a multi-domain development process utilising co-simulation of different domain specific models. This work has already been initiated, and a brief overview of the initial phases is given below. It is important to note that this is very early work in progress which might be changed later in the project.

Model purpose It is very important to have a well defined purpose of a model, in order to determine which details are important and which can be abstracted away. In order to make a systematic progression from the model purpose to an initial system model, the Requirement Diagrams of the system modelling language SysML [42] is used for this. A single main purpose of the system model is defined, and several sub-purposes can be derived or refined from this in a hierarchical manner. This will help defining the necessary main parts of the system model in the following phase.

System overview Using the SysML Block Definition Diagrams the main blocks of the system are derived from the Requirement Diagram from the previous phase. The different blocks are connected using flowports in order to define the direction of data flow between the different blocks.

Detailed view For each of the main parts of the system overview model, a SysML Internal Block Diagram is created in order to describe more details of the sub-systems. Here it is very important to define the interface between the different models in great details, since this will be the basis of the contract describing the interface between models from different domains. At this point, it should also be made explicit which blocks are software (to be modelled in the discrete-event domain) and which blocks are mechanics or physical phenomena (to be modelled in the continuous-time domain).

These initial phases will help translating system requirements into more detailed mono-disciplinary design decisions which is often a huge challenge when developing multi-disciplinary systems. Dividing the complete system overview into several subsystems also ensures that smaller incremental steps can be taken in the model development.

A lot of work is still needed, and as said above this is the main focus of the remainder of the PhD project. It is also the plan to have students try out and evaluate the method in small multi-disciplinary groups consisting of IT and mechanics engineers for example.

5.2.2 Tools

As already mentioned a comparison of the DESTECS and the Ptolemy tools has been initiated. In addition, a Danish developed game engine called Unity[*] will be tested as an alternative low-fidelity modelling tool using the build-in PhysX engine for simple real-time rigid body simulations. Comparing this approach to a high-fidelity simulation engine like 20-sim will determine if the results of the real-time simulations made by PhysX are "good enough" for certain continuous systems, like the modelling of the trajectory of decoys in the DESTECS IFG challenge. Early results, comparing the output of a simple gravity model and a spring/damper system, shows great promise (only about 3% inaccuracy close to signal peaks), but more in-depth work is still needed.

5.2.3 Case work

A new industrial case for Terma A/S has been started June 2011. Here a large combination of several discrete-event and continuous-time models will be combined in order

[*]http://www.unity3d.com/

to model a self-defense system for battleships. This co-model will include the following components:

Missile A continuous-time model of the movement of the missile describing maximum speed and minimum turn radius, and a discrete-event model of the tracking algorithm trying to lead the missile to its target.

Battleship A continuous-time model of the movement of the ship describing maximum speed and maneuverability, and a discrete-event model of the counter measure software onboard, calculating most optimal response to an incoming threat.

Decoys A continuous-time model describing the trajectory of dispensed decoys, and how the wind affects this.

This will be a large and complex model including a lot of interesting issues, and will be perfect for trying out the methodology defined.

5.3 Concluding Remarks

This report describes the main activities of the first half of my PhD studies, which is concerned with co-simulation of multi-domain models using in embedded system development. I have given concrete examples of the work done as well as the eight papers produced during the first year and a half. A lot of this work has been centered around single-domain modelling mainly in the discrete-event domain, since it was decided that this was a necessary first step towards multi-domain modelling.

In addition, I have outlined possible future research areas. Here it is the plan to leave the single-domain modelling and focus on co-simulation methodology and case studies.

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Appendices

Appendix A

My Publications

A.1 Methodology

1. Methods for the Development of Distributed Real-Time Systems using VDM [31]
2. Development Process for Multi-Disciplinary Embedded Control Systems [51]
3. Formalising Agility – Scrum Goes Formal [49]

A.2 Cases

4. Using Executable VDM++ Models in an Industrial Application – Self-defense System for Fighter Aircraft [50]

A.3 Overture

5. Development Process of Distributed Embedded Systems using VDM [39]
6. Overture VDM-10 Tool Support: User Guide [33]

A.4 Misc

7. Formalising Concurrent and Distributed Design Patters with VDM [48]
8. Are Formal Methods Ready for Agility? A Reality Check [32]
9. Collaborative Modelling and Co-simulation in the Development of Dependable Embedded Systems [17]

Appendix B

Courses Completed

During the first half of my Ph.D. studies I have completed the following courses (a total of 33.2 ECTS points):

Business Course: Mandatory 7.5 ECTS point course that all Industrial Ph.D. students have to complete. The course was arranged by the consulting company *Haslund & Alsted* in collaboration with the *Danish Agency for Science Technology and Innovation* and gave a broad introduction to topics like intellectual property rights, innovation, management strategies, etc.

Writing and Reviewing Scentific Papers: A 3.7 ECTS point course held by Aalborg University. Theory like the IMRAD structure (introduction, method, results and discussion) was tried out in practice where all course participants had to provide a short paper describing the topic of their Ph.D. project.

Compiler: A 10 ECTS point course held at the Computer Science department of Aarhus University. A compiler for a sub-set of Java was developed including parser, type checker, static analysis, code generation and code optimization. This course gave a very in-depth understanding of the structure of object-oriented languages.

Systems Engineering: A 5 ECTS point course held at Aarhus School of Engineering. Topics like requirements, development cycle, design synthesis, system verification, project planning, resource management and risk management were included in the curriculum of this course. Since I have worked with several systems engineers at Terma A/S I found it important to understand their world better.

Hardware/Software Co-design: A 5 ECTS point course held at Aarhus School of Engineering. The course provides a thorough introduction to the methods and techniques for hardware-software co-design to modern digital electronics such as FPGAs.

Modelchecking: A short 2 ECTS point course arranged by the Computer Science department of Aalborg University. The course gave a short introduction to modelchecking with a practical approach where several exercises had to be completed using the SPIN model checker.

Sune Wolff:
Development Process for Multidisciplinary Embedded Control Systems, 2012

Department of Engineering
Aarhus University
Edison, Finlandsgade 22
8200 Aarhus N
Denmark

Tel.: +45 4189 3000