Dina Research School:

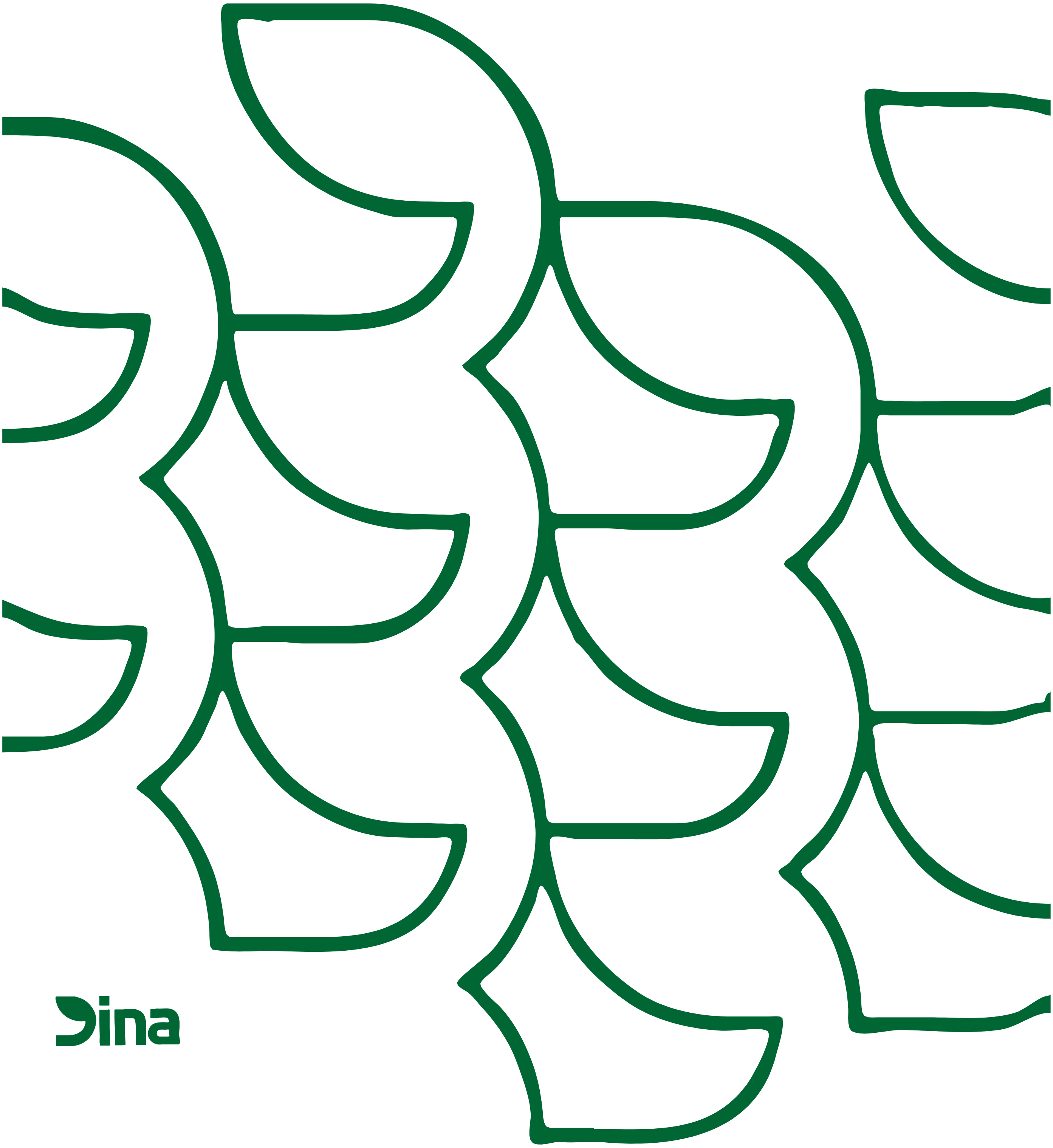
Nina Workshop November 28-29, 2002

Hybrid Systems

Tune Landboskole.

Edited by Erik Jørgensen & A. P. Ravn

Dina Notat No. 103 · November 2002



Dina

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This note is also available on www at URL:
http://www.dina.dk/phd/w/w11/notat103.pdf

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Contents

1 Introduction

The workshop is aimed at research students and researchers which study complex dynamical phenomena as found in life sciences and in highly non-linear and multimodal control tasks. The purpose is to introduce *hybrid systems*, a novel modelling framework for such systems.

Hybrid Systems are dynamical systems which change irregularly between smooth evolutions and discrete transitions. Some examples from the control domain are a driving wheel hitting black ice, a robot detecting an obstacle, or a gearbox with quick shifts; examples from biology are protein synthesis and cell transformations, e.g. within the immune system. Typically, the smooth evolutions are modelled by differential equations and the discrete transitions by state machines (automata).

The basic theory has evolved during the recent decade in an interplay between control theory and computer science. Control theory has supplied the framework for modelling smooth evolutions by means of differential equations with algebraic constraints, while computer science has supplied automata theory that gives a framework for modelling discrete transitions. In recent years, modelling tools have been developed together with techniques for determining interesting properties such as stability or optimality.

The workshop introduces the fundamental theory, starting with automata, then quickly proceeds to examples and exercises using modelling tools, such that participants get an operational understanding of the framework. We assume that participants are familiar with modelling of dynamical systems by means of ordinary differential equations.

The workshop is directed to:

- PhD students in agricultural, biological or biochemical sciences who have to model complex phenomena.
- PhD students in control engineering or theory who wants to apply hybrid systems in their work.

The workshop is organised by the DINA Research School as part of the Nordic cooperation in NINA, Nordic Informatic Network in Agricultural Sciences. The workshop language is English.

Anders. P. Ravn
Aalborg University

Erik Jørgensen
Peter Sestoft
Dina Research School

2 Program

2.1 Thursday, November 28

11.00 Arrival and accommodation.
12.00 Lunch

13.00 **Introduction and presentation of participants**
Erik Jørgensen, Dina Research School.

13.15 **Lecture: Hybrid Systems.**
A quick introduction by example to: automata, timed automata and hybrid automata
Anders P. Ravn, Aalborg University

We introduce the concept of a state machine or automaton and illustrate how it is used to model simple systems , where the dynamic behaviour consists of discrete state transitions. The model is then extended with timers or local clocks that measure the time spent in states. They can be reset at a transition, and a transition can be dependent on a clock value. Finally we generalize the concept of timers to flow variables that evolve according to a differential or differential algebraic set of equations.
At the end of the lecture, we shall briefly indicate constructs for hierarchical composition of state machines: Substates and Superstates, Sequential composition, and Parallel Composition with communication.

13.50 Break.

14.00 **Lecture: An Application Case Study from Control Engineering**
An application to a trajectory following problem for an outdoor vehicle.
Jan Dimon Bendtsen, Aalborg University

This lecture discusses an application of hybrid systems design taken from nonlinear control, namely the problem of trajectory tracking for a four-wheel steered, four-wheel driven mobile robot. The purpose of the robot is to drive autonomously between waypoints, starting from rest and stopping when the next waypoint is reached. The robot is modelled as a non-holonomic dynamic system subject to pure rolling, no-slip constraints. Under normal driving conditions, a nonlinear trajectory tracking feedback control law based on dynamic feedback linearization is sufficient to stabilize the system and ensure asymptotically stable tracking. However, when the velocity of the robot becomes very small, or the wheel configurations approach certain singular points, the feedback linearization scheme tends to fail due to these singularities. It is therefore necessary to switch to other modes of control when the robot is sufficiently close to the singularities. We will show how these transitions are derived systematically from the model, and present a hybrid automaton containing the different continuous-time control laws derived above in each mode

14.30 **Lecture: An Application Case Study from Biology**
Application of automata to modelling of a T cell in immunology
Na'aman Kam, Weizmann Institute, Israel

The construction of reliable reactive systems is considered to be one of the most challenging goals in the fields of software and system engineering.
The definition of a reactive system definitely suits biological systems at different levels, ranging from gene networks, developing embryos and the immune system of the adult. This talk will discuss the application of a tool developed for constructing computerized systems to the modeling and analysis of a biological system, the immune system. We use the language of statecharts within the framework of object-oriented modeling. The results described here indicate that this modeling strategy can contribute to the transition of biology from the phase of analysis to the phase of synthesis.

15.30 Coffee and Tea.

16.00 **Modelling Exercises on Computers.**

17.30 **Discussion of results**

17.45 Dinner.

19.00 **Lecture: Analyzing Properties of Hybrid Systems**
Analyzing automata: reachability, invariants, timed and hybrid extensions.
Rafael Wiesniewski, Aalborg University

In this lecture we shall continue with the notion of hybrid automaton. The focus is on a class of rectangular automata, which is a generalization of timed automata. In particular we shall analyse the following control problem. Given a set of possible control modes, together with the plant behaviour resulting from each model the control problem is to find a switching strategy between control modes that keeps the plant output out of unsafe state. The central issue is whether such a control problem can be solved algorithmically.

19.35 **Modelling Exercises, (continued)**.

21.45 Coffee, tea and sandwiches.

2.2 Friday, November 29

7.30 Breakfast.

8.00 **Discussion of Results from Exercises** .

8.35 Break.

8.50 **Lecture: Advanced Modelling of Biological Systems**
Application in genetics - studying *Caenorhabditis elegans*
Na'aman Kam, Weizmann Institute, Israel

Our understanding of biology is reaching a new phase that increasingly requires the synthesis of information from many sources to gain deeper insights into how functional organisms are assembled. To assist in the integration of this information, we have begun to model the development and function of biological systems using the languages and methodologies designed for computer modeling of highly reactive man-made systems. We are currently developing a model of the highly characterized and well-defined egg-laying system of the nematode Caenorhabditis elegans. We have begun to incorporate into our model all existing data pertaining to the coordinated development of the four tissues that enable C. elegans hermaphrodites to lay eggs. These data sets span a large spectrum of complex biological phenomena, including cell fate determination, cell cycle control, cell migration and apoptosis. Our modeling tools use various visual formalisms including statecharts and live sequence charts (LSCs) for specifying the behaviors of the system, model execution and analysis. This effort will serve to develop the tools, technology and expertise to expand this model for use by the entire C. elegans community and to allow the application of these methodologies to other biological systems.

9.30 Coffee and tea.

10.00 **Lecture: Abstraction and Refinement of Models**
Anders P. Ravn, Aalborg University

When models get too complex, we need to abstract from detail, and conversely, when the model is too superficial we have to refine some part of it.
Abstraction and refinement are introduced as a precise notion of a simulation relation between automata. The intuition is, that whenever the refined or detailed automaton does a transition to a target state, then the corresponding abstract state makes a transition to a new abstract state corresponding with the target state. Note that the abstract automaton may stay in a state, while the detailed automaton does a number of steps, as long as the states passed, all correspond to the abstract state

10.45 Break.

11.10 **Discussion and Closing**
Erik Jørgensen, Dina Research School.

12.00 Lunch and Departure.

3 List of participants

List of participants for workshop on Hybrid Systems

Tune Landboskole, November 28-29 2002.

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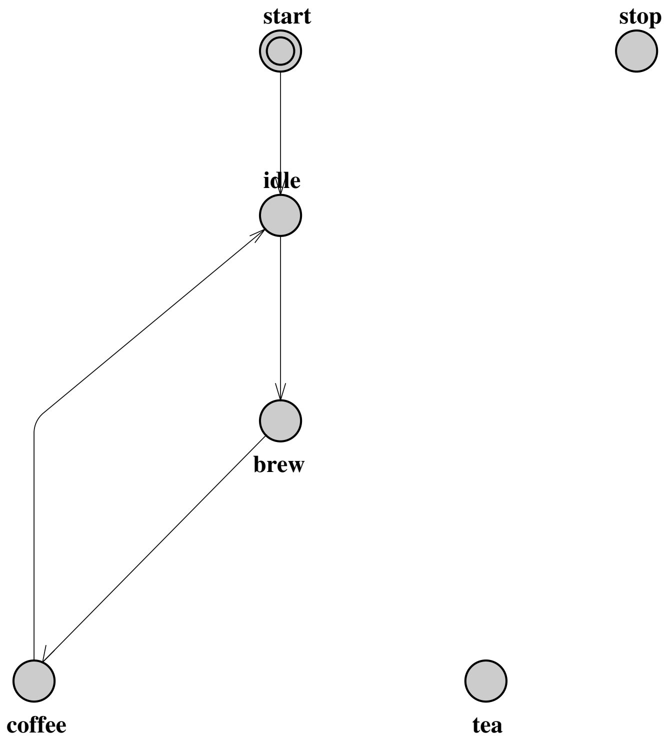
4 Exercises

4.1 A simple Coffee Machine

The purpose of this exercise is to familiarize you with the UppAal tool kit and to get a feeling for modelling of reactive systems.

The task is to model a simple coffee machine. Part of the job has already been done, because there is a system *Coffemaker* stored in the folder *Dina* in the UppAal tool. It is a simple finite state machine, which looks as follows:



1. Load the system and try a simulation to see that it actually goes through the motions.
2. Try checking the following properties with the verifier:
   (a) A[] not deadlock
   (b) A<> CoffeeMaker.coffee
   (c) E <> CoffeeMaker.coffee
   (d) CoffeeMaker.brew $--$ > CoffeeMaker.coffee
   (e) E <> CoffeeMaker.tea
3. Our coffee machine is sometimes a bit unpredictable and produces tea (thin coffee) and then refuses to move further. Add a transition (brew to tea) to this effect. And repeat the simulation and verification.

4. After complaints from our costumers, we manage to get the machine to return to idle, when tea has been brewed. Model this improved version.

5. The model is very abstract; it takes no resources to brew coffee. We want to model this by introducing state variables *amount* and *oldamount*. (These have already been added to the global declarations). We now stipulate that at the transition from start, *amount* gets the initial value 50 (assignment $amount := 50$). Coffee costs 4 units (assignment $amount := amount - 4$). and tea costs 2 units. Modify the model and simulate it. What happens when *amount* becomes negative? Check the invariant A[] $amount >= 0$.

6. To really check *amount*, we use *oldamount*, and introduce a guard $amount < oldamount$ on the transitions from coffee and tea to idle. We also need to assign $oldamount := amount$, just before brewing. Modify the model and recheck properties.

7. We should be able to resupply. When in idle, we should not brew unless $amount >= 4$, otherwise we should go to stop, and from there return to start. Remember to check properties! Perhaps it is a good idea also to check :

   A[] CoffeeMaker.stop imply $amount <= 4$.

8. It is still a bit strange that property 2.d does not hold in the weaker form:

   CoffeeMaker.brew $-- >$ CoffeeMaker.coffee or CoffeeMaker.tea

   We need to limit the duration of brewing. Introduce a clock c in the global declarations, reset it before brewing and give brew an invariant c < 10.

9. We have a similar problem with 2 b (in a weaker form). Try committing the states that should take no time. until the property:

   A<> CoffeeMaker.coffee or CoffeeMaker.tea

   holds.

10. What about guards that ensure proper brewing: $c > 8$ for coffee and $c > 15$ for tea? Check the properties!

We have completed building a coffee machine.

4.2 The Coffee Vending Machine

We have success with our coffee machine, so we want payment for each cup of coffee. We buy a *MoneyBox* from an independent vendor, it has a dangling wire (a channel), so we make it a *Box* connected to a channel *link*. See the system *VendingMachine*.

1. Check the properties! Suddenly there seems to be a problem with an infinite loop in the Box. Please repair it by inserting a delay!

2. Synchronize the money box and the CoffeeMaker; it should start to brew on an *ok* signal. There is a problem, the system deadlocks, because idle can no longer be committed; but it can be urgent. What is the difference?

3. Modify the MoneyBox so it has a local counter amount which counts the number of good coins. You can find a solution as *VendingMachine1*.

4. Make a new template representing a toggle switch. It should change a boolean parameter X between 0 and 1, whenever it receives a signal on a channel parameter *toggle*. A solution is found in *Toggle*.

5. Modify the Vending Machine such that it instantiates a toggle with a channel switch and a variable *COFFEE*. Remember to check properties.

6. Modify the coffee machine so it makes tea when $COFFEE == 0$ or otherwise coffee. Check the properties.
7. Modify the MoneyBox so it first start when it gets a signal on a coin channel. Declare such a global channel and introduce a user process that first flips the switch a number of times and then drops a coin. Check the properties! The system is in *VendingMachine_final*.

4.3 Building Models

For the remaining part of the exercises, we suggest that you get together according to preferences and try to model aspects of either the API control [BBR02] or the T-cell. [KCH01].

5 Material

Hybrid Systems

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