ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

BIOLOGICALLY INSPIRED
ROBOTICS GROUP (BIRG)

Ordinary Differential Equations Framework for the Robotic Dog Aibo

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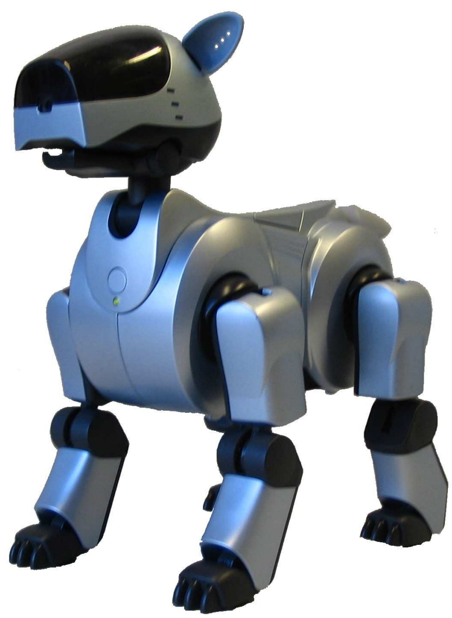
14th February 2005



Semester project winter 2004-2005
Supervisors: Jonas Buchli & Prof. Auke Jan Ijspeert

Summary

This document is a semester project report. It presents the work done to develop a software framework to control an Aibo robot with a set of ordinary differential equations. The first chapter explores the ideas and the tools which gave birth to this project. Project goals are also defined. The second chapter describes the software engineering process that was used throughout the project. This process follows the guidelines of the Fondue method. This chapter also serves as developer documentation for future refactoring of the software. The third chapter presents an example dynamical system which was used to test and demonstrate the software. Simulation and real world results are shown and discussed. Chapter four draws a conclusion of this project and looks at future improvements. Finally, two appendices are provided to bootstrap the new user into using the resulting work of this project.

Copyright information

About this document

The author believes knowledge — especially scientific knowledge — should be free (as in freedom) that is why this document is released under a license that guarantees it will remain free.

About the software provided

Trademarks

Acknowledgments

The author would like to thank Jonas Buchli and Prof. Auke Jan Ijspeert for their support, hints and overall great help.

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Chapter 1

Introduction

In this chapter, we briefly explore the ideas and the tools which gave birth to this project. Project goals are also defined here.

1.1 Motivation

From equations to life

Non-linear dynamical systems offer new and creative possibilities for the control of locomotion in legged robots. Their interesting properties include resistance to perturbations, attractors and synchronization with other systems or external input. These properties can be exploited to design a new generation of robot controllers: "online" controllers. These are truly reactive and can adapt themselves to their environment, as opposed to programmed controllers. They can react to every situation, even unplanned ones.

However, the search space of dynamical system parameters is huge. So finding the right system parameters to obtain a given property is far from being trivial. To explore the immense space of possible configuration, it would be desirable to have software tools to test one's ideas both in simulation and on a real robot.

The structure of non-linear dynamical systems bears some level of similarity with the neural structure of living beings. A dynamical system itself can be a collection of many dynamical systems. These systems are linked together and with the robot's sensors and actuators. They can be thought of as a collection of neurons, a "brain", which generates signal patterns in response to sensory input. This approach might be useful to understand how the neural system of animals and humans work. Or it can be used to produce very animal-like robot behavior, featuring adaptive locomotion and learning capabilities.

A sympathetic yet powerful dog

The robotic dog Aibo is made by Sony. It is marketed both as an entertainment system and as a research platform. Aibo features plenty of sensors (color camera, infrared distance sensor, chin, back and paw touch sensors) and actuators (LEDs and head, leg, ear, and tails joints). Sony provides a free development kit, the OPEN-R SDK, based on the GNU Compiler Collection (gcc) to write software for the Aibo. OPEN-R allows cross-compiling programs on a PC to run them on the Aibo.

Simulators are helpful to try new software without taking the risk of breaking real robots. Simulation is also faster than real world experiments. Webots, a commercial mobile robot simulation software developed by Cyberbotics Ltd [1] includes support for the Aibo. It features an Aibo model and a graphical user interface to observe and control the robot's parameters (both in simulation and on the real Aibo via a wireless link). One can also transfer programs from the PC to Aibo's memory with a single click.

1.2 Related work

Previous work in the field of biologically-inspired robotics contribute to the initial spark of this project.

Central pattern generators and quadrupedal locomotion In their article "Hard-wired central pattern generators for quadrupedal locomotion" [2] Collins and Richmond set the grounds of central pattern generators (CPG) used to control the locomotion of quadrupeds. Jonas Buchli and Auke Jan Ijspeert further extend the topic to differential systems in [3]. A system made of amplitude controlled phase oscillators (ACPO) will be implemented to test and demonstrate the final program.

Aibo simulation and transfer to real robot First and foremost, the two semester projects made by Lukas Hohl during the previous year provide the toolbox needed to develop control software for the Aibo. In [4] he presents the "Remote Control System" which allows monitoring and controlling an Aibo robot from a PC over a wireless connection. Then he integrated this software into Webots allowing the same monitoring to be performed both on a simulated and a real Aibo. Moreover, in [5], he added the cross-compiling function of OPEN-R to the graphical interface of Webots. This greatly helps the development of Aibo control software, as one is now able to write a single program which runs both in Webots and on the real Aibo using the Webots Controller API.

Quadruped locomotion controllers based on non-linear oscillators Mathieu Salzmann explored controllers based on non-linear oscillators to generate different gaits in quadruped locomotion. In [6] he shows how to have transitions between the different gaits by changing only one parameter in the differential equations of the controllers. He used a simulated Aibo in Webots in his experiments. His work shows that it is possible to implement natural movements (e.g. walk, trot and bound) with non-linear oscillators.

Self-organization of locomotion In his study of "Self-Organization of Locomotion in Modular Robots" [7], Bertrand Mesot uses genetic algorithms to tune oscillators toward sensible movement patterns. This suggests we could do the same to find interesting parameters of dynamical systems.

1.3 Goals

Up to now, only simulation and pre-calculated trajectories have been used to test non-linear systems in quadruped locomotion. We now have the tools to test the same controller program in both simulated and real environment.

The aim of this project is to develop a software framework allowing to control the Aibo robot with a set of dynamical systems. The robot running this system shall be independent of any other external processor, in particular it shall not get any help from a PC to solve differential equations. The same code must be used both in simulation and on the real robot.

1.4 Outline

The initial plan for this project was:

- Test Webots & OPEN-R integration and cross-compilation. This amounts to using and testing Lukas Hohl's software (see [4, 5]).
- Develop an ordinary differential equations (ODE) framework to allow control of Aibo via non-linear dynamical systems. The code should be the same for simulation and real world runs.
- Interactively demonstrate that the Aibo is controlled by a dynamical system.

- Write a user manual of the developed software.

Chapter 2

Software architecture

This chapter describes the software engineering process that I have used throughout my project. This process follows the guidelines of the Fondue method I learned in a software engineering course given by Prof. Alfred Strohmeier. I choose to use this method because writing code without planning first is a bad thing and it is the only method I already know since I practiced it during the software engineering project. Employing this method also has the advantage of documenting the software itself while designing it, which is important for users and future developments.

2.1 The Fondue method

What is Fondue? From [8]:

> *Fondue* is a software development method for reactive systems. Fondue evolved from the Fusion method, originally defined by Derek Coleman. It keeps the process and the models of the original Fusion method but uses the UML for the notation.

The Fondue process has four phases: requirements elicitation, analysis, design and implementation. The first phase defines what the software is required to do. The analysis phase turns the requirements into a specification. The design phase turns this specification into an architecture. And finally the implementation phase maps this architecture to a programming language. I will briefly explain these phases to give the reader enough background to understand the following models. The interested reader might want to read [9] for a detailed description of the method.

2.1.1 Requirements

The requirements phase produces two models: *use cases* and the *domain model* out of a textual or oral description of the software. A use case describes possible situations that can arise when a user has a particular goal against the system. It is an informal, mainly textual, goal-based description which captures the behavioral requirements of the software system. The domain model captures the concepts in the domain of the problem, and the relationships between them. It uses a class diagram notation.

I have skipped this phase in my project because my system is not an interactive one in the sense that its actions are not triggered by an input from a human user. Of course the AIBO robot has be able to react to sensory perception such as the activation of a paw touch sensor (which might be triggered by human intervention) but there is no real user interface to a human user. Classifying my system as "non reactive" makes it degenerated from the point of view of Fondue. Some models loose their *raison d'être* because they are intended to describe user-system interaction or depend on user input.

The only user intervention at run time is switching on the robot or launching a simulation in Webots. Then all inputs happen through the robot's devices. There would be only a single use case, boiling down to "switch robot on". Therefore, use cases are not needed. The domain model closely, if not exactly, resembles the concept model to be seen in the next phase. I decided to draw it only once.

2.1.2 Analysis

The analysis phase generates five models:

Environment model The environment is the set of actors with which the system communicates, via messages. This model uses a collaboration diagram to model the interactions between the actors and the system. It is defined by the set of input messages the system can receive, the set of time-triggered input events, the set of operations the system can perform and the set of it can output.

Concept model The concept model is a subset of the domain model. It keeps only what is part of the system. Everything else belonging to the environment is left out. It contains the set of classes and associations modeling the system state.

Behavior model The behavior model is the addition of the protocol model and the operation model.

Operation model The operation model uses the Object Constraint Language (OCL, see [10]) to specify the effects of operations in terms of system state changes and output messages sent.

Protocol model The protocol model defines the allowable sequence of operations during the lifetime of the system. It is a state diagram.

2.1.3 Design

The design phase aims to develop an object-oriented system architecture that satisfies the requirements defined during the analysis phase. It also provides the foundations of the implementation, testing and maintenance. All information and relationships defined in the concept model must be preserved. This results in a collection of interacting objects which realizes the operation model. This phase yields four models:

Interaction model The interaction model shows how objects interact at run-time to support the functionality specified in the operation model.

Dependency model The dependency model describes dependencies between classes and communication paths between interacting objects.

Inheritance model The inheritance model describes the superclass/subclass inheritance design structure.

Design class model The design class model is composed of the contents of all design classes (their attributes and methods), all the navigable associations between design classes and the inheritance structure.

2.1.4 Implementation

The work to be done in this phase relies on the interaction model and the design class model. The class interface has to be defined as well as the visibility of attributes/methods and whether a method or class is abstract or not. This will yield the implementation class model.

Finally code writing can take place. One has just to follow the implementation class model using an object-oriented programming language.

2.2 Environment model

The environment is very simplified because the system is not interactive. There is one user actor, only one input message *run* and one time-triggered message *tick*.

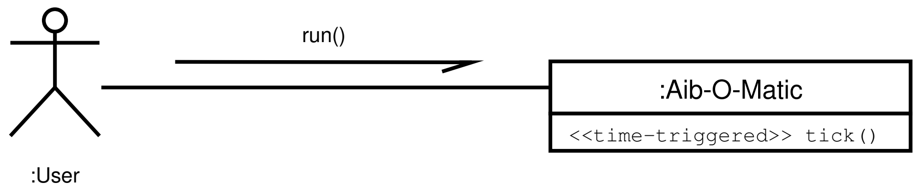

Figure 2.1: Environment diagram The environment diagram is very simple because there are only two messages: *run* and *tick*. The user starts the system and then the system runs on its own at the beat of *tick* messages.

run() Launches the system[1].

tick() Updates readings from devices, solves dynamical systems and applies results to devices. This message is triggered at each simulation step.

2.3 Concept model

As already said, the concept model is similar to the domain model. Note that there are no actors, nor classes representing actors inside the system. Everything is in the system, it is called a *simulation model*. Figure 2.3 shows the full concept model and Figure 2.2 shows the same model without inheritance which makes it (hopefully) easier to read.

2.3.1 Description of analysis classes

Here is the verbal description of the classes depicted on Figures 2.2 and 2.3 (pages 10–11).

Class *TimeKeeper* Knowing the current time is essential to the operation of the *NumericalSolver* from where the existence of the *TimeKeeper* class. It maintains a clock reference and takes care of updating the *Device*s and the *DynamicalSystem*s regularly, that is at each time step.

Class *Device* The *Device* class is a generic representation of all the sensors and actuators of the robot. It offers basic capabilities like reading, writing,

[1]Starting the system is not covered by Fondue. From this point of view, *run* is not really a message so it won't be covered in the analysis phase. Of course objects have to be created at system startup thus *run* will appear again in the implementation phase.

buffering, normalizing values, and enabling/disabling. It is meant to be extended via subclasses to represent more precise peripherals like servos and sensors.

Class *DynamicalSystem* The *DynamicalSystem* class is burdened with the representation of ODE systems: equations, state variables, parameters, initial conditions, names and a selection of variables to export for external use. There will be one instance of this class per differential system to facilitate the definition of the systems by the user. But, mathematically, the collection of differential systems can be seen as one single system and will be treated as such at the time of numerical solving. It has the ability to read and write to any *Device*. It can also read other *DynamicalSystem*'s state variables. This serves the need of introducing coupling between systems and also between the robot's devices and the various dynamical systems. Finally, *DynamicalSystem*s employ the *NumericalSolver* class to solve their equations.

Class *Logger* The *Logger* class has no associations leading to it because it has only a single instance and thus enjoys system-wide visibility. In the other direction, it also doesn't need any association with other classes because it won't use them. The *Logger*'s purpose is to provide a facility to log error or information messages and to output system data (i.e. the *DynamicalSystem*s' state variables) for external use.

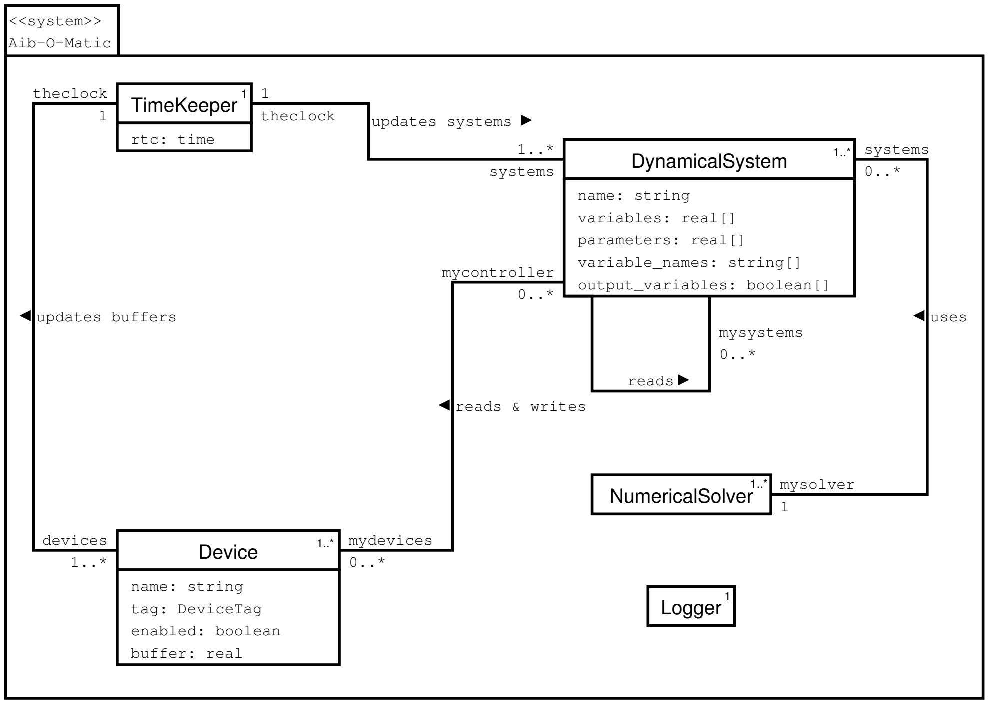

Figure 2.2: Simplified concept diagram Concept diagram shown without inheritance relationships. This model captures the initial idea of the system's classes and their interaction.
Knowing the current time is essential to the *NumericalSolver* from where the existence of the *TimeKeeper* class. It maintains a clock reference and takes care of updating the *Device*s and the *DynamicalSystems* regularly. The *Device* class represents all the sensors and actuators of the robot. It offers basic capabilities like reading, writing, buffering, normalizing values, and enabling/disabling. The *DynamicalSystem* class is burdened with the representation of differential systems. It has the ability to read and write to any *Device*, it can also read other *DynamicalSystem*'s state variables. Finally, it employs the *NumericalSolver* class to solve it's equations. The *Logger* class has no associations leading to it because it enjoys system-wide visibility. It's purpose is to provide a facility to log error or information messages and to output system data for external use.

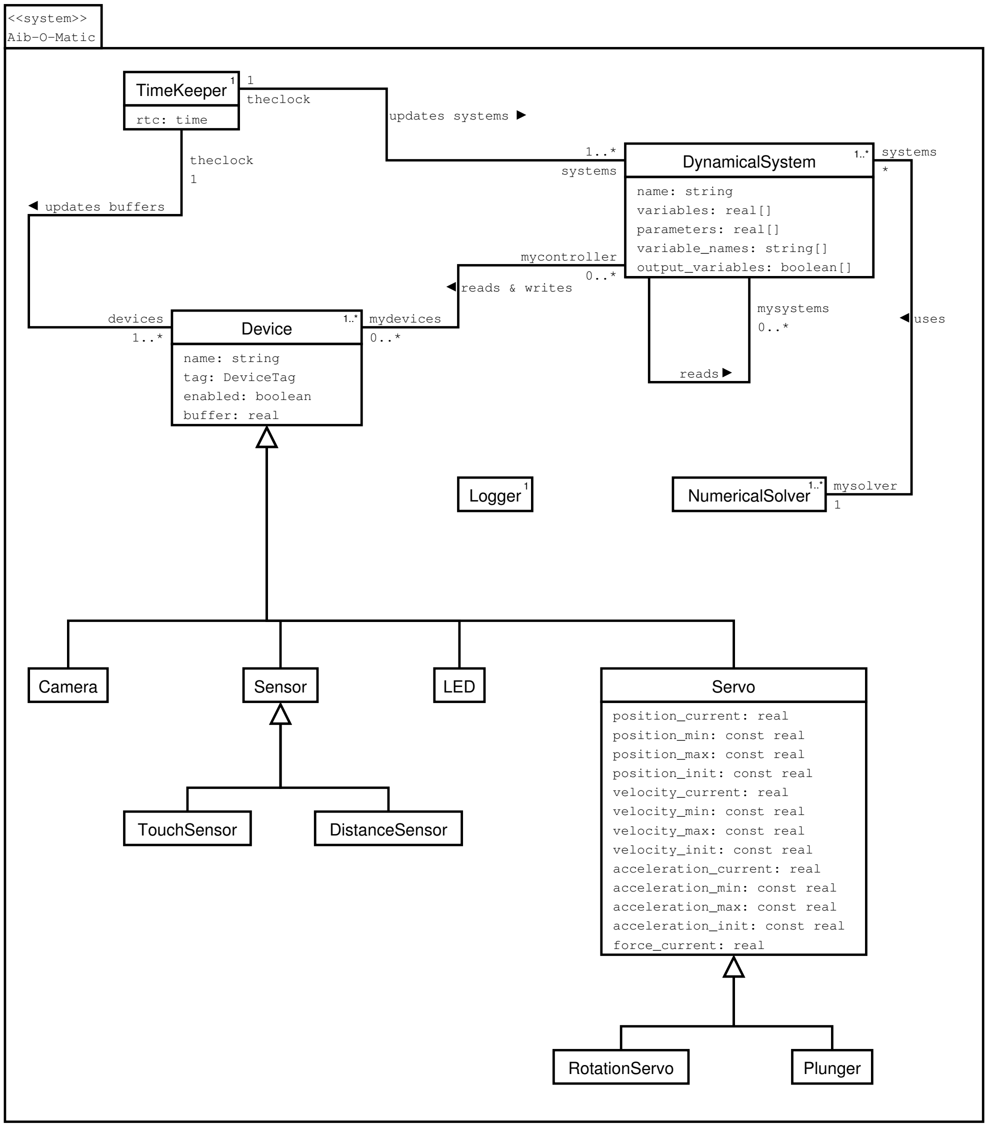

Figure 2.3: Concept diagram Complete concept model including inheritance relationships. The upper half of this figure is the same as Figure 2.2. The lower half shows the subclass "tree" of *Device* as it is planned at this stage of the process. These classes (*Camera*, *TouchSensor*, *DistanceSensor*, *LED*, *Servo*, *RotationServo*) are all inspired by Webots' controller API. *Servo* and *RotationServo* are essentially the same save their treatment of numbers: the former's base unit is meters and the latter's is radians. *Sensor* is a generic representation of a sensor device. It has little interest in itself except that it forbids writing to sensors. A *Plunger* is a limited servo which has only two positions: on and off. This class stems from AIBO's ears which are restricted to two positions. $\sum$

2.4 Behavior model

Last model of the analysis phase, the behavior model is the addition of the protocol model and the operation model. It expresses the behavior of the system regarding input messages. The operation model states what the effect of messages are. It serves as a base to write program code later. The protocol model defines the authorized sequence of messages.

2.4.1 Operation model

The OCL is not easy to read if you don't know it. That's why pre- and post-conditions are expressed in plain English rather than in OCL.

Operation schema of "tick"

Operation: Aib-O-Matic::{tick()};

Description: Advance the simulation by one time step.

Scope: TimeKeeper, Device, DynamicalSystem, NumericalSolver;

Pre: true;

Post: Read the input of all devices.
Solve the dynamical system.
Write the output of the dynamical system to the devices.

2.4.2 Protocol model

Due to the low number of messages, the protocol model is very simple (Figure 2.4, page 13). The *run* operation starts the system and brings it in the "running" state. Once it is running, it keeps on running with *tick* and it is the only thing it can do. There is no provision for stopping the system because the controller program will simply be unloaded from memory by Webots (in simulation) or by Aibo's operating system (on the real robot) at shutdown.

2.5 Interaction model

Here begins the design phase. The interaction model details what operations and methods do: how objects interact to realize what has been specified in the previous phase. Message order is specified via Dewey numbers on the collaboration diagrams.

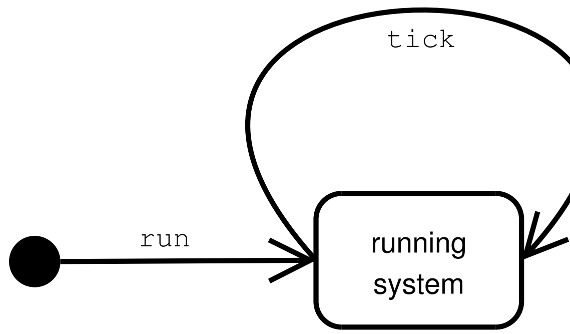

Figure 2.4: Protocol diagram The *run* operation starts the system. Once it is running, it keeps on running with *tick*. There is no provision for stopping the system because the controller program will simply be unloaded from memory by Webots or by Aibo's operating system at shutdown.

2.5.1 System operations

Aib-O-Matic::tick Figure 2.5 on page 15 shows the collaboration diagram describing the operation *tick*. It is triggered by the controller loop `robot_run` of Webots at each simulation step (function `robot_run` is documented in [11]). The *TimeKeeper* is the controller of this operation. It first instructs all *Device*s to read their values from the real robot's devices. This is done via a special object: a "collection manager" which is represented as a particular instance of the class it manages, here *deviceController: Device*. Collection managers are a new type of class introduced in the design phase. They are very useful to send messages to all instances of the same class, to insert and remove instances, and to browse or search them. Likewise, all *DynamicalSystem*s are told to update themselves, that is solve their equations. Finally, the *TimeKeeper* tells all *Device*s to write their — possibly new — values to the robot's devices.

2.5.2 Methods

Collaboration diagram for methods show what certain important or complicated methods shall do.

DeviceController::read_devices This method (Figure 2.6 on page 16) triggers the reading of every robot device in the system by the corresponding *Device* object. Each *Device* instance holds the latest value read in a buffer. The buffer speeds up access to device values because no call to the Webots

API is needed. It also prevents different values of the same device to be read in one time step. This ensures consistency of the values during a simulation step. Hence the robot's status is made available to the controller program.

DynamicalSystemController::**update_systems** This is one of the most important methods of the whole program. This method is responsible for telling every *DynamicalSystem* to read from it's input *Device*s (if any), launching the *NumericalSolver* to solve the system, and writing the new values of state variables to the *DynamicalSystem*s and their output *Device*s (if any). The collaboration diagram of *update_systems* is depicted on Figure 2.7, page 17.

The *dynamicalSystemController* first tells all *DynamicalSystem*s to read from their associated *Device*s. That is what they immediately do by calling *read()* on the *Device*s they are configured to read. They store the returned values in their state variables. The *dynamicalSystemController* then consults the *TimeKeeper* in order to know the current time. This time is used (among other parameters detailed later in section 2.9.7) to ask the *NumericalSolver* to solve the differential system. The solver calls back *derivate()* of the *dynamicalSystemController* to obtain the values of the derivatives at the given time. The latter propagates this call to each *DynamicalSystem*. Note that *solve()* is called multiple times during a single simulation step because the solver advances with smaller steps than the simulation. Finally the *dynamicalSystemController* tells each *DynamicalSystem* to write to their associated *Device*s. They call *write()* on the *Device*s they are configured to write to with the new values of their variables.

DeviceController::**write_devices** Similarly to *read_devices* seen earlier, this method (Figure 2.8 on page 18) triggers the writing of every *Device*'s buffer into the corresponding robot device, thus making the robot move, act and generally react to its environment.

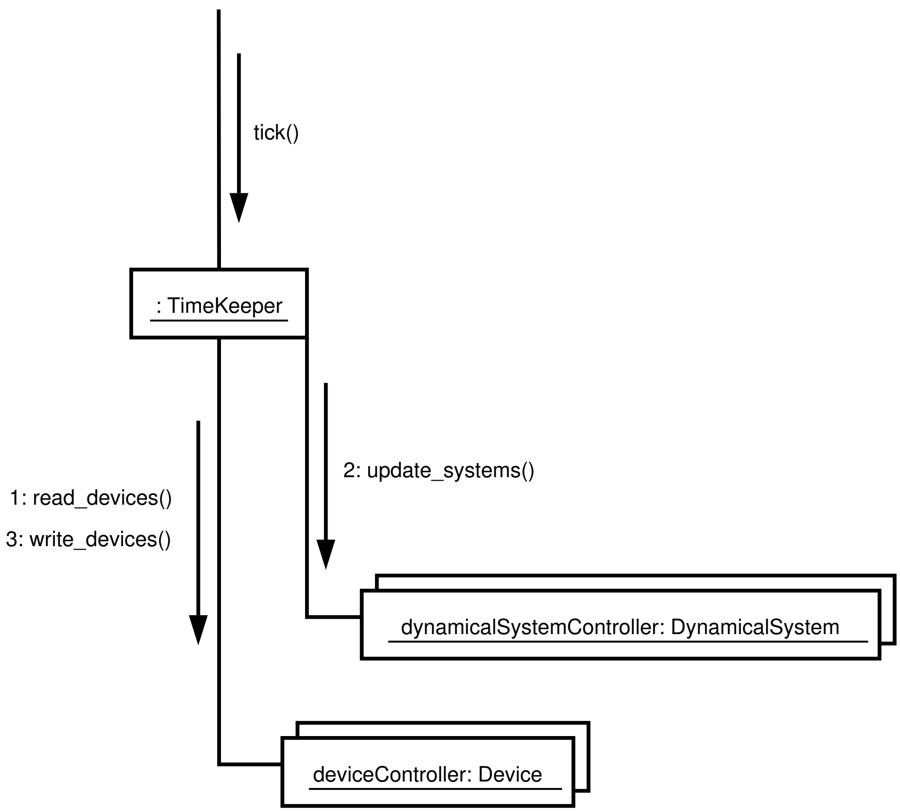

Figure 2.5: Collaboration diagram for *tick* Operation *tick* is triggered by the controller loop `robot_run` of Webots at each simulation step. The *TimeKeeper* is the controller of this operation. **(1)** It first instructs all *Device*s to read their values from the real robot's devices. This is done via a special object: a "collection manager" which is represented as a particular instance of the class it manages, here *deviceController: Device*. **(2)** Likewise, all *DynamicalSystem*s are told to update themselves, that is solve their equations. **(3)** Finally, the *TimeKeeper* tells all *Device*s to write their — possibly new — values to the robot's devices.

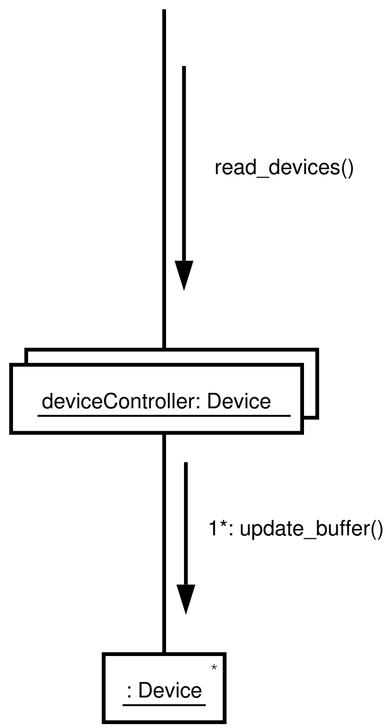

Figure 2.6: Collaboration diagram for *read_devices* (1) The object *deviceController: Device* tells every *Device* instance to update its buffer by reading the robot device they correspond to. All *Device*s hold the latest value they've read in a buffer. The star next to the message number denotes the fact that the message is sent to multiple objects.

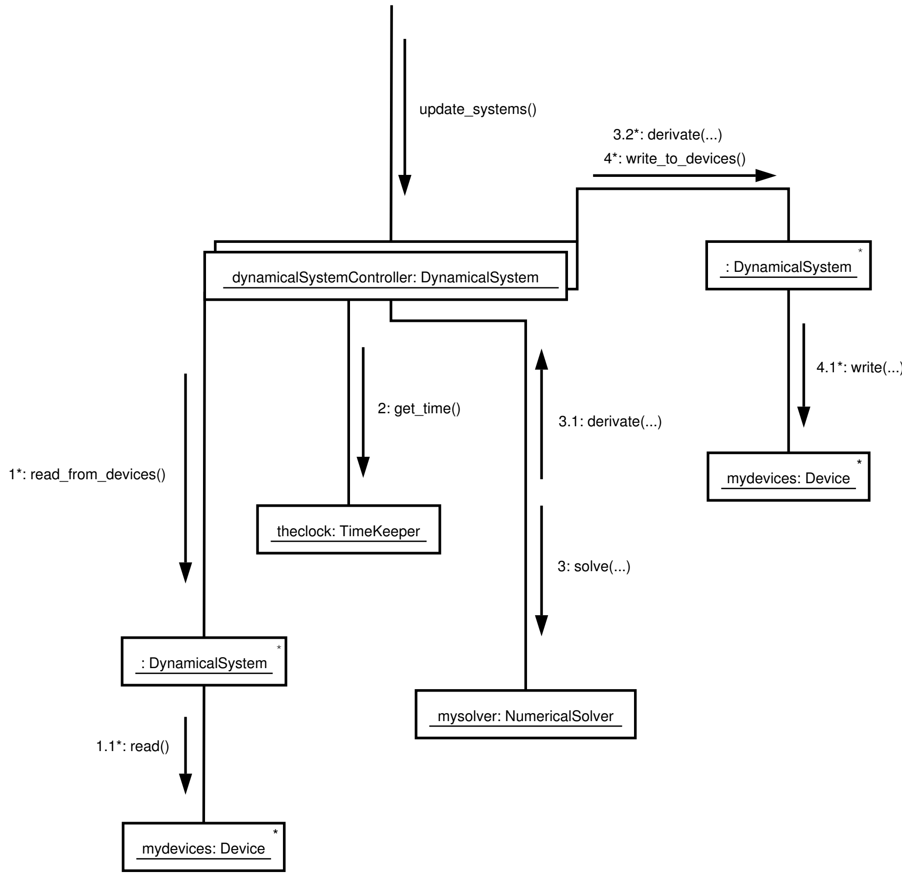

Figure 2.7: Collaboration diagram for *update_systems* **(1)** The *dynamicalSystemController* first tells all *DynamicalSystems* to read from their associated *Devices*. **(1.1)** *DynamicalSystems* call *read()* on the *Devices* they are configured to read and store the returned values in their state variables. **(2)** The *dynamicalSystemController* then consults the *TimeKeeper* in order to know the current time. **(3)** This time is used (among other parameters detailed later in section 2.9.7) to ask the *NumericalSolver* to solve the differential system. **(3.1)** The solver calls back *derivate()* of the *dynamicalSystemController* to obtain the values of the derivatives at the given time. **(3.2)** The *dynamicalSystemController* propagates this call to each *DynamicalSystem*. **(4)** Finally the *dynamicalSystemController* tells each *DynamicalSystem* to write to their associated *Devices*. **(4.1)** *DynamicalSystems* call *write()* on the *Devices* they are configured to write to with the new values of their variables.

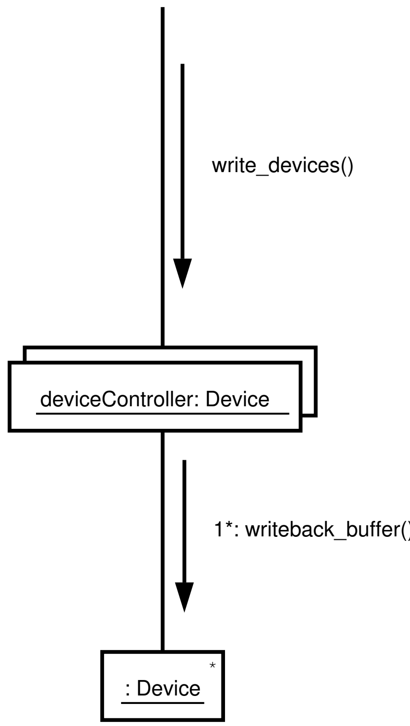

Figure 2.8: Collaboration diagram for *write_devices* Similarly to *read_devices* seen earlier, this method makes all *Device*s write to the corresponding robot device, thus making the robot move (among other actions). **(1)** The *deviceController* tells each *Device* to write the value of its buffer to the associated robot device.

2.6 Dependency model

The diagram of Figure 2.9 shows dependency relationships and navigable associations between system objects as deduced from the interaction model. They will be integrated into the design class model. The collection controllers are now separate classes.

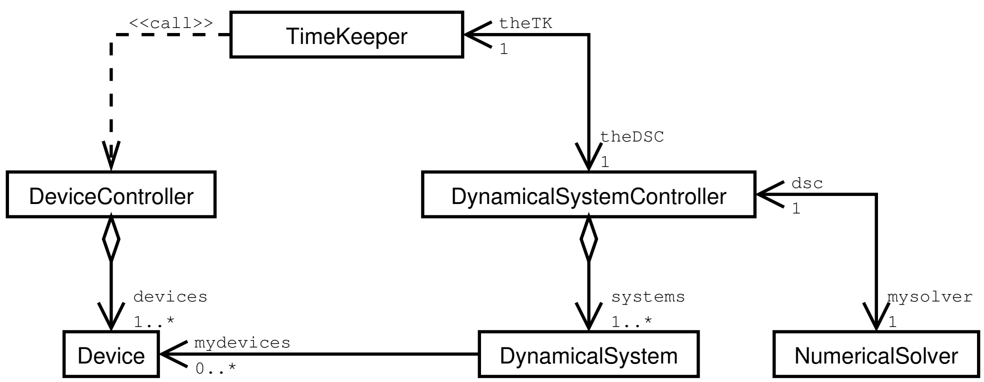

Figure 2.9: Dependency diagram This diagram shows the various dependencies between system classes. Dashed lines represent usage dependencies, plain lines represent navigable associations. Arrows show the direction of the relationships. Association ends are marked with role names and cardinalities. Here we can see the collection controllers appearing clearly as separate classes.

2.7 Inheritance model

The inheritance structure of class *Device* is shown on Figure 2.10, page 20. These subclasses have not changed since they were presented in the concept model (section 2.3). This "tree" will be integrated into the design class model as well.

Figure 2.11 is not part of the design process but hints at how a user should implement his own dynamical systems. I recommend making a subclass of *DynamicalSystem* and overriding the *derivate* method. As an example, you can refer to the ACPO implementation described in files `ACPO.hh` and `ACPO.cc`.

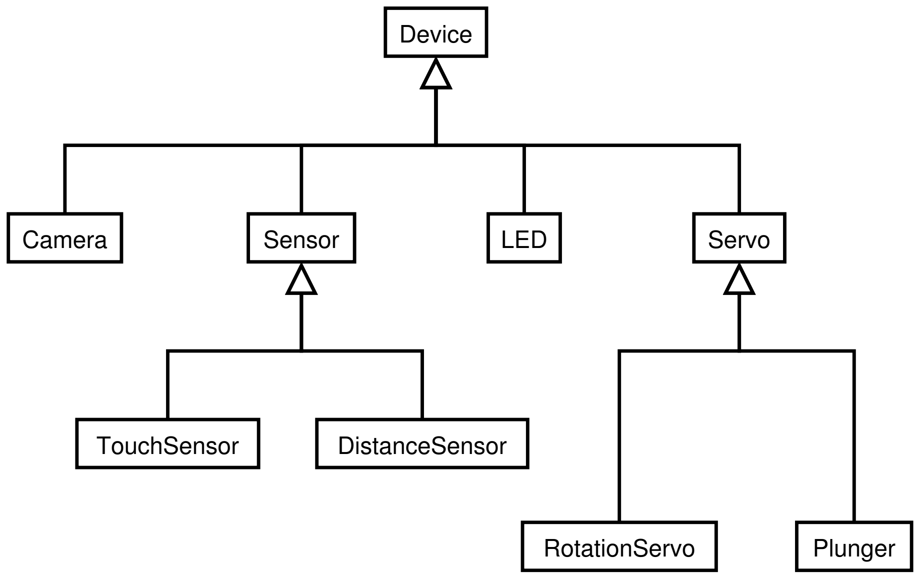

Figure 2.10: Inheritance diagram for *Device* It is the same inheritance structure as the one shown in the concept model on Figure 2.3.

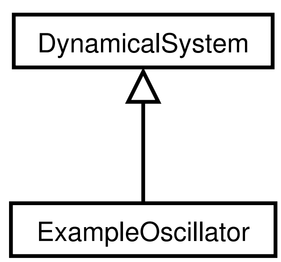

Figure 2.11: Inheritance diagram for *DynamicalSystem* This is the recommended way of implementing your own differential systems. Make a subclass of *DynamicalSystem* and override the *derivate* method. As an example, you can refer to the ACPO implementation described in files `ACPO.hh` and `ACPO.cc`.

2.8 Design class model

Last model of the design phase, the design class model regroups all information from previous models. All classes, inheritances and relationships are shown. Classes appear with their methods but without their attributes. Trivial navigation methods (i.e. *getters* and *setters*) and constructors are not shown.

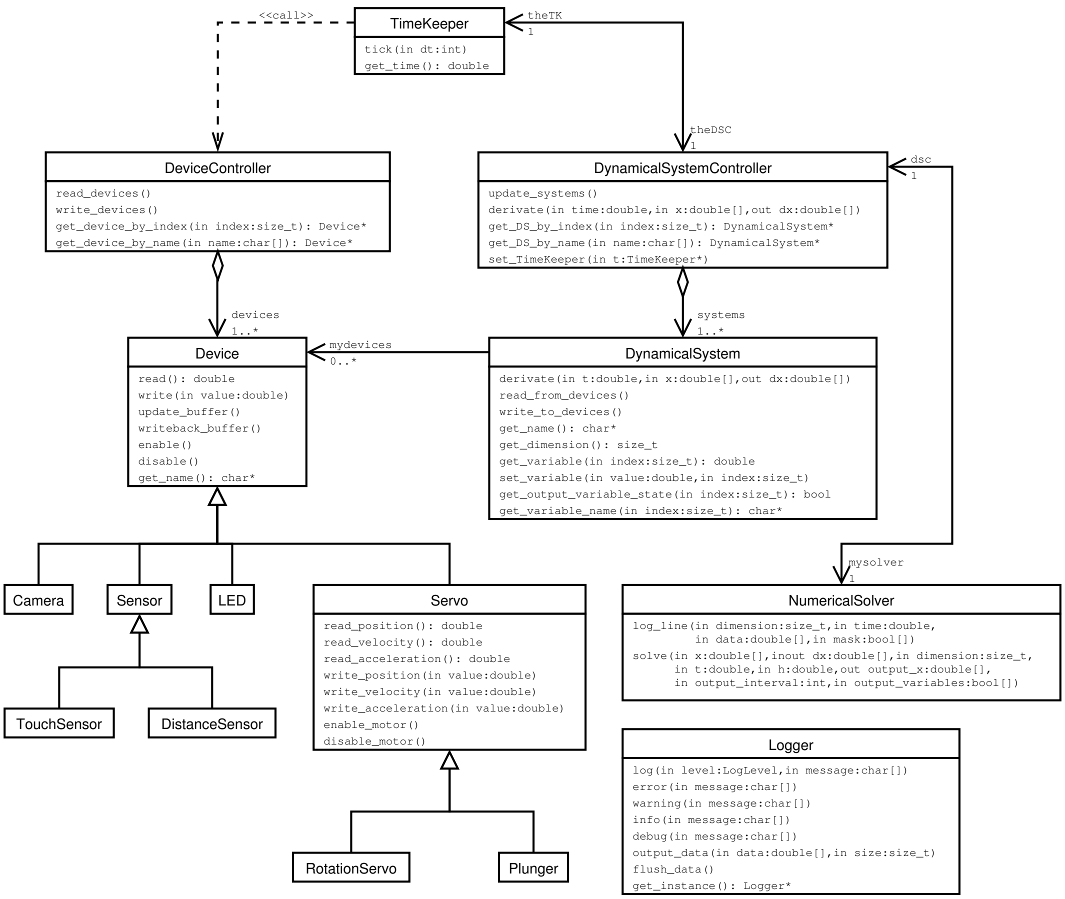

Figure 2.12: Design class diagram

2.9 Implementation class model

The implementation classes are described in this section. Their attributes and methods are shown along with their visibility. According to the UML notation, a - in front of a name means the method or attribute is *private*, a # means it is *protected*, and a + means it is *public*.

Constructors and destructors are not shown in this model. Private attributes and methods are generally not described unless they have a certain importance to the user. For more details, please refer to the source code and it's comments.

2.9.1 Class *TimeKeeper*

Since it is not possible, as of now, to read AIBO's Real Time Clock (RTC) through the Webots API this class has been designed to maintain a clock reference. At each simulation step, it counts how many milliseconds have elapsed since the beginning of the computation and accumulates this number in a counter.

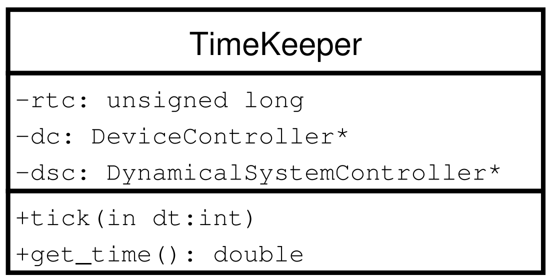

Figure 2.13: Class *TimeKeeper*

Method interface

void tick(int dt) Triggers operation *tick*. This method should be called at each simulation step for the program to work correctly. It's collaboration diagram (depicted on Figure 2.5, page 15) shows what operation *tick* does.

double get_time() Returns the elapsed time in seconds.

2.9.2 Class *DeviceController*

This class is responsible for managing the collection of *Device*s. It allows looking them up by their name or index. References to *Device*s are simply implemented with an array of fixed size. Thus lookup by index is fast (complexity is $O(1)$) but lookup by name can be inefficient (worst case complexity is $O(n)$ where n is the size of the array). A hash table could be more efficient here. Since the number of devices is rather small (32), the burden of implementing a hash table to manage them is not worth the (small) performance gain. Therefore, hash tables were left out during development.

The constructor of this class creates all *Device* objects. If one wants to add, remove or modify robot devices it is the right place to do it. Numerical data such as maximum and minimum positions of servos come from [5, 12].

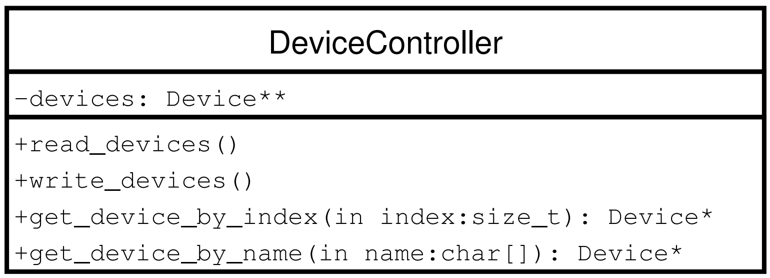

Figure 2.14: Class *DeviceController*

Method interface

void read_devices() Tell all *Device*s to read the value of their associated robot device and to put it into their buffer.

void write_devices() Tell all *Device*s to write the value stored in their buffer into the corresponding robot device.

Device* get_device_by_index(size_t index) Returns a pointer to the *Device* designated by *index*. Returns a null pointer if *index* is out of bounds (i.e. greater than the number of *Device*s minus one).

Device* get_device_by_name(const char* n) Returns a pointer to the *Device* designated by name *n*. Returns a null pointer if no *Device* with this name is found.

2.9.3 Class *Device*

This class represents a device of the AIBO robot inside the Aib-O-Matic system. Devices can be any input or output mechanism from servos to cameras. This class provides basic I/O functionalities and is meant to be sub-classed to represent more specific devices with more capabilities.

All input and output through the method interface should occur with normalized values in the $[-1; 1]$ interval. Calls to the Webots API use the *float* data type and *Device* uses *double*, a loss of precision is thus possible here.

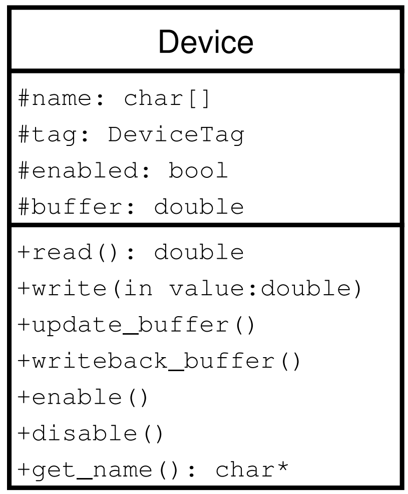

Figure 2.15: Class *Device*

Method interface All methods are declared *virtual* to allow them to be inherited.

double read() Returns the value of the device stored in its buffer. This method should return a value in $[-1; 1]$. The device must have been previously enabled, otherwise behavior is undefined.

void write(double new_value) Write a new value to the device's buffer. The new value should be in $[-1; 1]$. The device must have been previously enabled, otherwise behavior is undefined. The change in the buffer is *not* propagated to the real device. This has to be explicitly done with the *writeback_buffer* method.

void update_buffer() Read from the robot's device and update the device's buffer if the device is enabled.

void writeback_buffer() Write the device's buffer to the robot's device (if the device is enabled).

void enable() Enable device feedback, movement, etc.

void disable() Disable the device.

char* get_name() Returns the human readable name of the device.

2.9.4 Class *DynamicalSystemController*

This class is responsible for managing the collection of *DynamicalSystem*s. It allows looking up a *DynamicalSystem* by its name or index. References to the *DynamicalSystem*s are simply implemented with an array of fixed size. Thus lookup by index is fast (complexity is $O(1)$) but lookup by name can be inefficient (worst case complexity is $O(n)$ where n is the size of the array). A hash table could be more efficient here. Again, if the number of dynamical systems is small, implementing a hash table might not be worth the effort. If your system does have a lot of differential systems, you might look into it though

The constructor of this class creates all *DynamicalSystem* objects. All dynamical systems have to be specified in this constructor. This is the part of the program that the user has to edit to run his own systems.

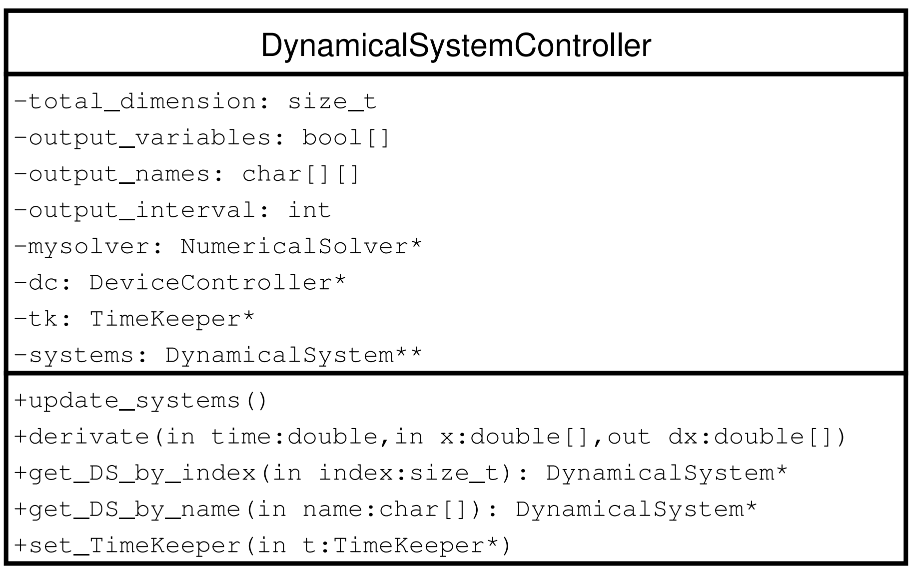

Figure 2.16: Class *DynamicalSystemController*

Method interface

void update_systems() Update all *DynamicalSystem*s. This method is the workhorse of Aib-O-Matic. You might want to have a look at it's collaboration diagram (Figure 2.7, page 17) for a visual representation of what it does.

1. Tell all *DynamicalSystem*s to read values from their devices (if they need to) and gather all state variables into one big array that will be passed to the solver.
2. Launch the solver.
3. Write back state variables into their respective systems and tell all *DynamicalSystem*s to write to their devices (if they need to).

void derivate(const double t, const double x[], double dx[]) Derivate all *DynamicalSystem*s. Should only be called by the *NumericalSolver*.

DynamicalSystem* get_DS_by_index(size_t index) Returns a pointer to the *DynamicalSystem* designated by index. Returns a null pointer if *index* is out of bounds (i.e. greater than the number of *DynamicalSystem*s minus one).

DynamicalSystem* get_DS_by_name(const char* n) Returns a pointer to the *DynamicalSystem* designated by name *n*. Returns a null pointer if no system with this name is found.

void set_TimeKeeper(TimeKeeper* t) Sets the reference to the *TimeKeeper*. Should only be called once at system startup.

This is a workaround to the "chicken and egg" problem: the *TimeKeeper* needs a reference to the *DynamicalSystemController* and vice-versa. So the *DynamicalSystemController* is created first then the *TimeKeeper* (with a reference to the *DynamicalSystemController*) and finally a reference to the *TimeKeeper* is given to the *DynamicalSystemController*. This is more of a hack than a satisfactory solution. One should have a look at design patterns [13] to find a better answer to this problem.

It might seem that this problem is solvable by using the *Singleton* design pattern. Since this requires private constructors it is incompatible with constructors that accept parameters. So that rules the *Singleton* out. Moreover doing without constructors is not the good way to initialize object references in my opinion. But some hope may reside in *Factories*...

2.9.5 Class *DynamicalSystem*

This class represents a non-linear dynamical system. It is not abstract but is expandable nonetheless — remember Figure 2.11.

DynamicalSystem
#name: char[]
#dimension: size_t
#variables_init: double[]
#variables_current[]: double[]
#variables_names: char[][]
#output_variables: bool[]
#parameters: double[]
#nb_parameters: size_t
#mydevices: Device**
#nb_devices: size_t
#variable_to_device_mapping: bool[][]
#device_to_variable_mapping: bool[][]
+derivate(in t:double,in x:double[],out dx:double[])
+read_from_devices()
+write_to_devices()
+get_name(): char*
+get_dimension(): size_t
+get_variable(in index:size_t): double
+set_variable(in value:double,in index:size_t)
+get_output_variable_state(in index:size_t): bool
+get_variable_name(in index:size_t): char*

Figure 2.17: Class *DynamicalSystem*

Method interface

void derivate(const double t, const double x[], double dx[]) Calculates the derivative of the system.

void read_from_devices() Reads the values of the devices associated with this *DynamicalSystem* and writes them into his variables according to the *device_to_variable* mapping.

void write_to_devices() Write the variables to the corresponding devices according to the *variable_to_device* mapping.

char* get_name() Returns the name of the system.

size_t get_dimension() Returns the system's dimension (i.e. the number of state variables).

double get_variable(size_t index) Returns the value of the variable designated by *index*. If *index* is out of bounds (i.e. greater than the number of variables minus one), returns 0.

int set_variable(double value, size_t index) Sets the variable designated by *index* to the given *value*. Returns 1 if *index* is out of bounds (i.e. greater than the number of variables minus one), 0 otherwise.

bool get_output_variable_state(size_t index) Tells whether a variable is selected for data output. Returns *true* if the variable designated by *index* is to be logged. Returns *false* otherwise or if *index* is out of bounds (i.e. greater than the number of variables minus one).

char* get_variable_name(size_t index) Gives the name of the variable designated by *index*. Returns a string if the name exists or a null pointer otherwise.

How to make your own dynamical systems First create a subclass of *DynamicalSystem* which overrides method *derivate*. Inside this method, you can implement your own equations. You have *get_DS_by_index* and *get_DS_by_name* from the *DynamicalSystemController* at your disposal to find other systems and *get_variable* to read their variables. Please refrain from doing anything else than reading to other *DynamicalSystem*s, otherwise they will certainly start to behave in an unexpected manner.

Likewise, you can connect your systems with I/O devices by setting the two boolean arrays *variable_to_device_mapping* and *device_to_variable_mapping* at instantiation. *variable_to_device_mapping* is first indexed by variable number and then by device number. Meaning that if the element `variable_to_device_mapping[x][y]` is *true*, variable number x will get written to device number y after the system has been solved. *device_to_variable_mapping* is the reverse: it is indexed first by device number and then by variable number. Meaning that if the element `device_to_variable_mapping[x][y]` is *true*, the value of device number x will get written to variable number y before the system is solved. You can set those two arrays to *null* if you don't use them.

Right after writing the above paragraphs, I realized that the coupling between dynamical systems had been badly designed. The coupling is frozen in the *derivate* method with no way to specify it elsewhere (for instance at object creation). Because of that, the user has to create one class for each *DynamicalSystem* even if they only differ in their coupling. If one has a lot of systems, this will be cumbersome. That design flaw makes Aib-O-Matic unsuitable for evolutionary experiments because the coupling between systems cannot be changed without recompiling the whole program. Desirable improvements for Aib-O-Matic now include refactoring it to fit the needs of GAs and to ease the task of creating lots of identical dynamical systems.

2.9.6 Class *Logger*

Utility class for logging messages and data. Messages are logged to stdout when run in Webots and to the console when run on the AIBO robot. Data is logged to a text file named `ode_out.dat`. The data file is overwritten at each new instantiation of Logger (hopefully only once at program launch).

This class is a *Singleton*: only one instance of it may exist at any time. Thus it's constructors and destructor have to be private[2].

Underlined attributes and methods on Figure 2.18 means they are *static*.

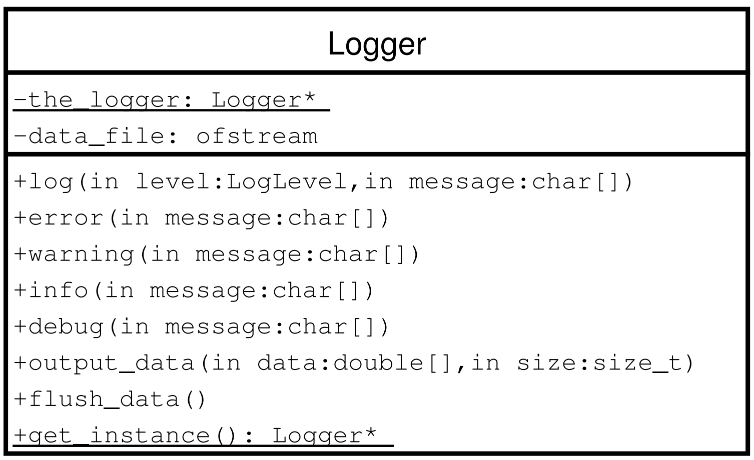

Figure 2.18: Class *Logger*

Method interface

static Logger* get_instance() Returns a pointer to the unique instance of the *Logger* class. If the instance does not exist when this method is called, it is created.

void log(LogLevel level, const char* message) Logs a *message* to the console at the given *level*.

[2]A detailed explanation of the *Singleton* design pattern is kindly waiting for you to read in [13].

void debug(const char* message) Shortcut for logging a message at the debug level.

void info(const char* message) Shortcut for logging a message at the info level.

void warning(const char* message) Shortcut for logging a message at the warning level.

void error(const char* message) Shortcut for logging a message at the error level.

void output_data(double data[], size_t size) Outputs one row of raw data into a text file. The numbers are arranged in whitespace-separated columns.

Flushing the write buffer is not done after each line for performance reasons. The decision to flush is either taken by the operating system or explicitly by the user. A separate method *flush_data* is provided for this purpose.

void flush_data() Flushes the current data file buffer to disk.

2.9.7 Class *NumericalSolver*

This class is responsible for solving ODE systems. It implements a simple solver using the fourth order Runge-Kutta method with a fixed step.

Initially, I wanted to use the GNU Scientific Library[3] (GSL) to solve the differential equations. But the inability to correctly cross-compile any library for Aibo's processor prevented me to use such precious tools. I had to turn to other implementations requiring no libraries.

The Runge-Kutta method was first implemented using the code in [14] but comparison testing with Matlab's `ode45` solver showed that this algorithm suffered some precision loss. The shape of the function was right but it was shifted along the time axis and that gap grew with time. So the "Recipes"' code was dismissed.

Wandering on the World Wide Web revealed many more implementations of the Runge-Kutta method. I eventually came up with my own which is somewhat influenced by [15]. I improved this algorithm by reducing the number of times the derivative function is called. A fixed step method was preferred over an adaptive step one for simplicity's sake and because of its quick implementation.

[3] See `http://www.gnu.org/software/gsl/`

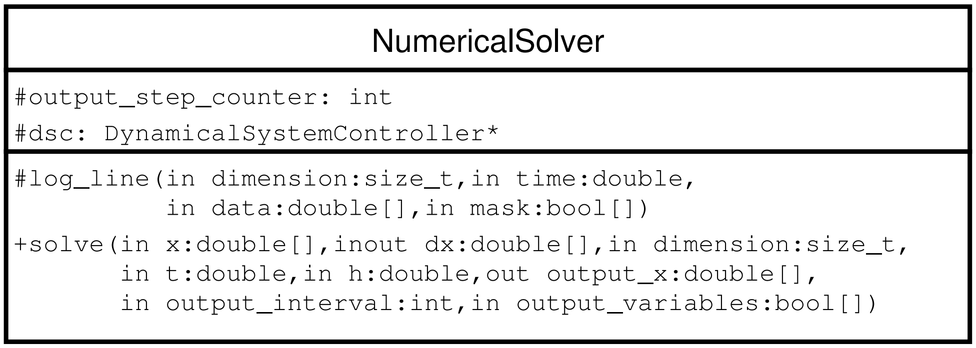

Figure 2.19: Class *NumericalSolver*

Method interface

void solve(. . .) Arguments are:

- **double *&x** Reference to $\vec{x}$.
- **double *&dx** Reference to $\dot{\vec{x}}$.
- **size_t &dimension** Dimension of the system.
- **const double t** Value of t (i.e. time).
- **const double h** Runge-Kutta interval.
- **double *&output_x** Output of $\vec{x}$ after computation.
- **int &output_interval** Log data each *output_interval* calls to solve. The time between two output lines is $h \cdot output\_interval$.
- **bool *&output_variables** Selects which variables to log.

Solves an ODE system with the fourth order Runge-Kutta method. This is a straightforward implementation, quite simple but precise enough.

2.9.8 Class *Servo*

This class represents the servo motors of the Aibo. *Servo* instances are created disabled but their motor is enabled. This prevents the Aibo from falling right after the program is loaded. Indeed the legs would not be able to bear the robot's weight without active servos. Units are supposed to be meters, $m \cdot s^{-1}$ and $m \cdot s^{-2}$, that is standard SI units.

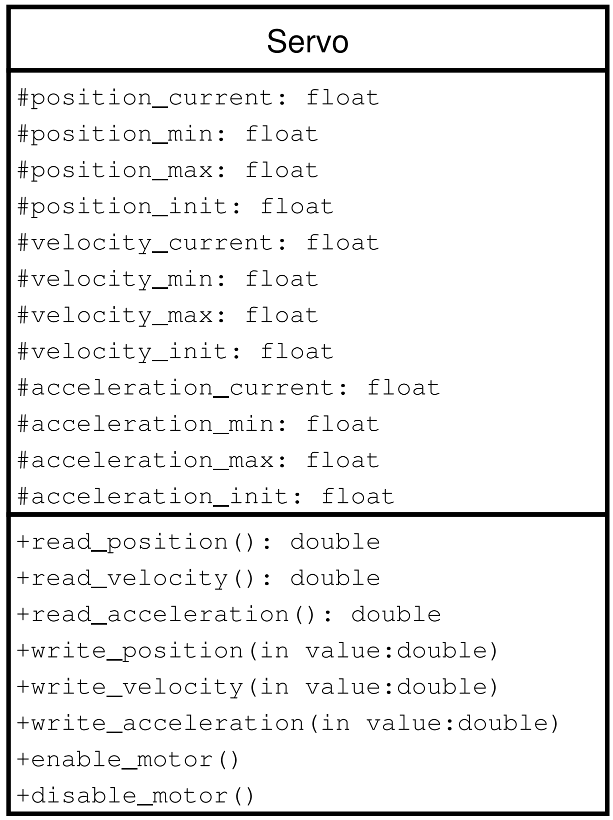

Figure 2.20: Class *Servo*

Method interface *Servo* implements all methods of the *Device* class. Generic methods like *read* and *write* affect the position of the servo (and not other parameters such as velocity or acceleration).

double read_position() Read the value of the device's position. Returns a double in $[-1;1]$.

double read_velocity() Read the value of the device's velocity. Returns a double in $[-1;1]$.

double read_acceleration() Read the value of the device's acceleration. Returns a double in $[-1;1]$.

void write_position(double new_value) Sets the position of the device. Values out of $[-1;1]$ are truncated to -1 or 1.

void write_velocity(double new_value) Sets the velocity of the device. Values out of $[-1;1]$ are truncated to -1 or 1.

void write_acceleration(double new_value) Sets the acceleration of the device. Values out of $[-1; 1]$ are truncated to -1 or 1.

void enable_motor() Enables the servo's motor.

void disable_motor() Disables the servo's motor.

2.9.9 Class *RotationServo*

RotationServo inherits from *Servo* and has the same method interface. It assumes all numbers are in radians, $rad \cdot s^{-1}$ and $rad \cdot s^{-2}$.

Figure 2.21: Class *RotationServo*

2.9.10 Class *Plunger*

A *plunger* is a joint which has only two positions: *on* and *off*. The *Plunger* class inherits from *Servo* but velocity and acceleration controls have no effect. Position values above and equal to zero mean the plunger is on, values below zero mean it is off.

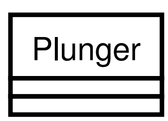

Figure 2.22: Class *Plunger*

2.9.11 Class *Sensor*

Class *Sensor* inherits from *Device* and has the same method interface.

2.9.12 Class *TouchSensor*

Class *TouchSensor* inherits from *Sensor*. *TouchSensor* instances are used to model the four paw touch sensors of the Aibo. These are binary sensors returning either 0 (off) or 1 (on).

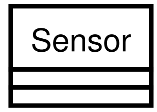

Figure 2.23: Class *Sensor*

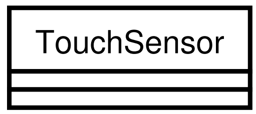

Figure 2.24: Class *TouchSensor*

2.9.13 Class *DistanceSensor*

Class *DistanceSensor* inherits from *Sensor*. A *DistanceSensor* instance is used to model the Position Sensing Device (PSD) of the AIBO. It returns only positive values as measured distances cannot be negative.

Figure 2.25: Class *DistanceSensor*

2.9.14 Class *Camera*

Class *Camera* inherits from *Device*. This class has not been implemented because AIBO's camera is not controllable via the Remote Control System[4], although it is in the Webots model of the AIBO. One could devote some time to look into this issue and offer camera support in Aib-O-Matic.

2.9.15 Class *LED*

Class *LED* inherits from *Device* and has the same method interface.

[4]See [5], section 3.5, page 30.

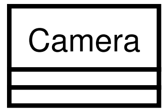

Figure 2.26: Class *Camera*

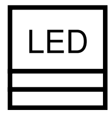

Figure 2.27: Class *LED*

2.10 Implementation quirks

This section, while not being part of the Fondue process, is nonetheless useful. It makes an inventory of the peculiarities of the current implementation of Aib-O-Matic. This information might be of some value to future developers as well as users.

Source files Every class has been put into two separate source files. A header file `Class.hh` which contains the class definition and a source file `Class.cc` which contains its implementation.

Of the various time steps The various time steps (simulation step, logger step and solver step) can be adjusted in the file `common.hh`. Care must be taken to respect the following condition:

$$SOLVER\_STEP < LOGGER\_STEP < SIMULATION\_STEP$$

Otherwise the triple loop invoking *solve* in *DynamicalSystemController* :: *update_systems* will behave incorrectly. This results from the change of the way the logging limitation is implemented. Before that, the *NumericalSolver* used to count the number of calls to *solve* and sent a line of data every N calls.

Derivate I had to choose between function pointers and methods to implement *derivate* in the *DynamicalSystem* class. I chose the latter because I thought it would ease the task of creating lots of similar dynamical systems. Instead this makes the equations impossible to change without creating another class. Thus the coupling, which is part of the equations, is frozen in the *derivate* method. It would be nice to have a dynamic way of specifying the coupling between systems so that it could be changed at run time.

2.10.1 Known bugs

Alas bug-free software almost doesn't exist! Aib-O-Matic is no exception. I discovered a few bugs too late to fix them...

Empty data file on Aibo The data file on the Memory Stick where state variables are output is empty when running on the Aibo. For some yet unknown reason, nothing is written to it.

OPEN-R logging calls System calls to log messages described in [16] are used when compiling for the Aibo. Sadly the documentation is not precise enough so as to where these messages go. The *Logger* class uses these calls but it turns out the messages end up nowhere.

Chapter 3

Testing and results

This chapter shows the results obtained by implementing an ACPO to test and demonstrate Aib-O-Matic. A single oscillator is used to exhibit synchronization of AIBO's left front leg movement on the movement of its right front leg.

3.1 Experiment setup

In order to test the software and demonstrate that it is possible to have an online dynamical systems-based controller on the AIBO, my supervisors and I have devised a simple experiment. One leg of the robot is controlled by an ACPO. Another leg driven by a human user gives this oscillator a perturbation input. If the frequency of the movement given by the user is close enough to the intrinsic frequency of the ACPO, synchronization of the two legs' movement will occur. Thus demonstrating that the robot is indeed controlled by a differential system.

The ACPO's first state variable x will be the position of the left front leg. The right front leg's position will be added to $\dot{x}$ multiplied by a coupling constant k. The oscillator is specified below.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} g\left(\frac{r_0}{\sqrt{x^2+y^2}} - 1\right) x - yw \\ g\left(\frac{r_0}{\sqrt{x^2+y^2}} - 1\right) y + xw \end{bmatrix} + k \begin{bmatrix} p \\ 0 \end{bmatrix}$$

Where:

- p is the right fore leg's position input;
- x drives the left fore leg's position;

- k is the coupling constant;
- parameters:
  - $g = 10$ is the oscillator's gain;
  - $r_0 = 1$ is the oscillator's radius;
  - $w = 2\pi$ is the oscillator's intrinsic frequency.

Trials will be run with different values of k. According to the "Arnold tongues" graphs (see [17]) the higher the value of k, the stronger the coupling between the two legs will be (until a certain value of k above which it gets chaotic).

Since this experiment consists of moving the robots legs without making it walk, we cannot allow them to touch the ground. Otherwise their movement will get hampered. Figures 3.1 and 3.2 show how this was accomplished in simulation and in the real world. The Aibo lies on a box high enough to allow its legs to move freely without touching the ground or other objects.

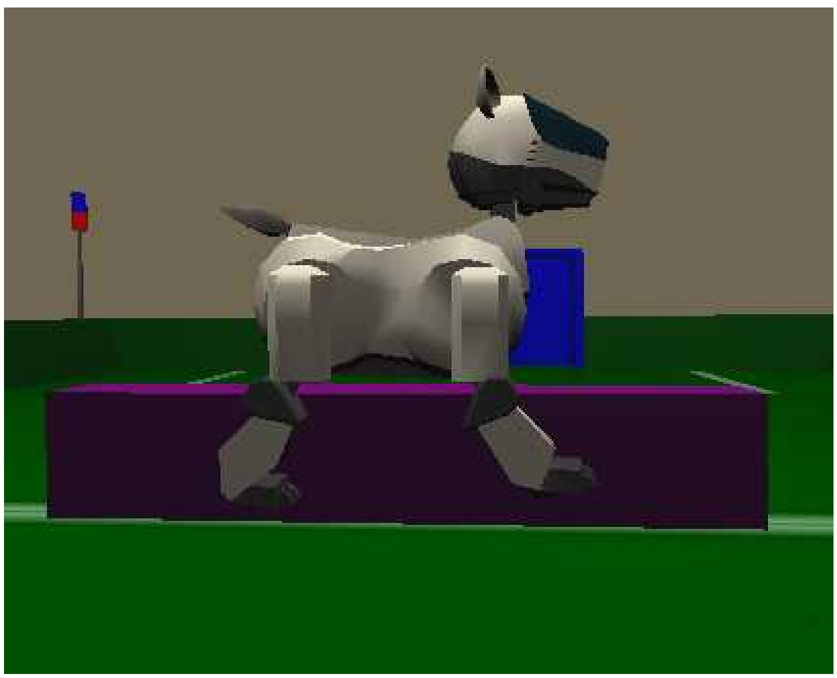

Figure 3.1: Experiment setup in simulation This screen shot from Webots shows the Aibo laid on a purple rectangular box. Such a setup allows its legs to move freely without touching the ground or other objects.

Figure 3.2: Experiment setup in reality This photos shows the Aibo laid on a white cardboard box. Such a setup allows its legs to move freely without touching the ground or other objects.

3.2 Results

Here are the results I obtained while running Aib-O-Matic on a simulated Aibo and on a real one. Movies on the project web page [18] allow you to visualize these experiments.

3.2.1 Simulation

Webots does not yet allow the user to move parts of a robot (as opposed to the robot as a whole). Therefore one cannot move Aibo's right leg "by hand". To work around this limitation, I made the leg move with a sinusoidal oscillation of frequency close to 2π. This movement was implement in the `robot_run` controller loop in order to be outside of Aib-O-Matic.

Simulation in Webots worked pretty well apart from the robot sliding on its supporting box after around thirty seconds causing its legs to rub against the side of the box and disturbing measurements. Below are two graphs of the data output by Aib-O-Matic. They show the positions of both front legs plotted against time during the first twenty seconds of simulation.

The first graph (Figure 3.3) corresponds to a run with $k = 0$ leading to no synchronization. The second one (Figure 3.4) represents a run with $k = 2$ leading to synchronization after a few seconds. The best synchronization has been observed with $k = 2$.

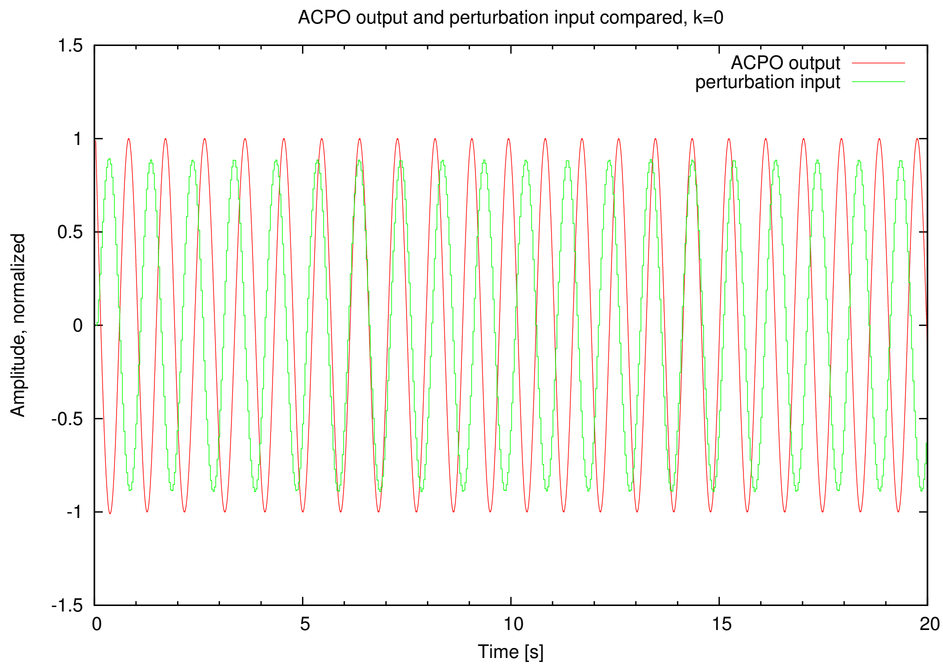

Figure 3.3: ACPO and perturbation without coupling This graph plots the ACPO output (left leg's position) and the perturbation input (right leg's position) against time. Albeit the frequencies of the two movement are close, no synchronization occurs because the coupling constant equals zero. At some points in time (between 6–7 seconds and also between 14–15 seconds), the two movements seem to be synchronized. Actually they aren't because this coincidence does not persist.

3.2.2 Reality

As in simulation, the robot has been raised on a cardboard box to allow its legs to move freely. But this time things went bad. The legs' movement was erratic and jerky at best. No synchronization could be really observed. Moreover no data could be salvaged from Aibo's Memory Stick to explain

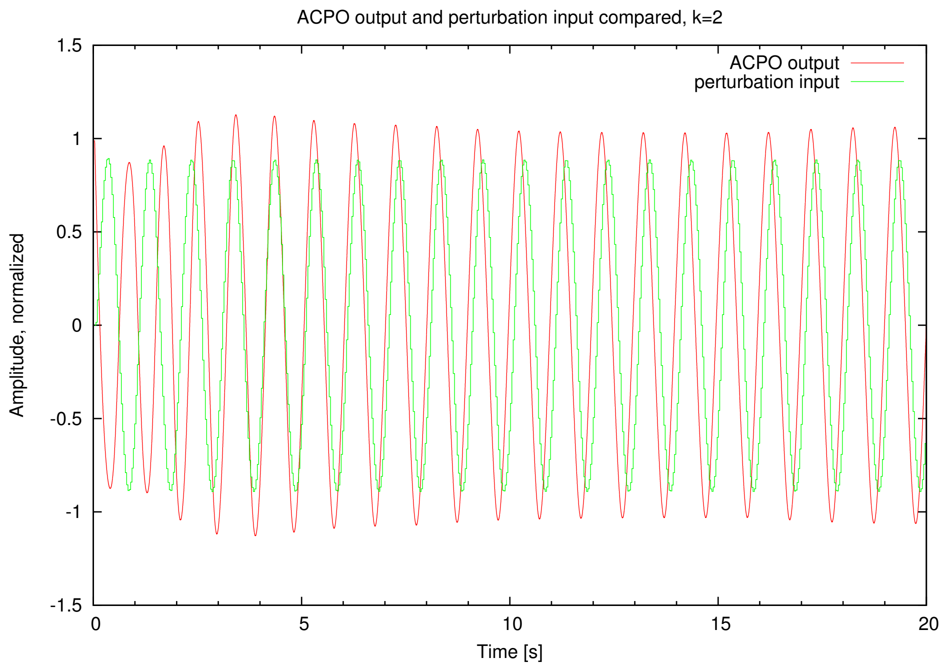

Figure 3.4: ACPO and perturbation with coupling This graph plots the ACPO output (left leg's position) and the perturbation input (right leg's position) against time. Here one can observe a short transition period (between 0–3 seconds) before the oscillator synchronizes on the perturbation. This synchronization is persistent. The best synchronization has been observed with $k = 2$.

this phenomenon because the data file remained mysteriously empty[1]. Please refer to the movies on the project web page [18] to see what happened.

3.3 Discussion

It turns out that simulation and real world results are radically different. This difference is difficult to explain because no experimental data is available for the real Aibo. Possible causes might be the differences between the simulated Aibo model and the real one, or that the robot's processor isn't fast enough to compute all derivatives in the given time step.

[1] Yes, this is a bug. It is listed in section 2.10.1.

Chapter 4

Conclusions

4.1 Conclusion

This project's goal have almost been fulfilled: Webots is well integrated with OPEN-R thanks to [4, 5], the ODE framework has been completely designed, implemented and demonstrated. The two weaknesses remaining are that this system really works in simulation only and needs more testing. On the other hand, its strong points are the completeness of the software with respect to the specification and the intrinsic documentation. We now have the tool to test new CPGs on the AIBO.

As a whole, I enjoyed working on this project. Facing last minute hardware troubles with the AIBO and having to cope with C++'s intricacies was compensated by the excitement of working at the boundary between strict mathematics and animal locomotion. Using a software development method was a bit of a masochistic initiative but it helped writing the software documentation which is of immense value to users. Speaking of users, let's turn to the future...

4.2 Future work

In decreasing order of priority here are the things to improve in Aib-O-Matic:

- Eliminate the two bugs mentioned in 2.10.1 and other yet-to-be-discovered bugs.

- Test the software. Aib-O-Matic has only had one user yet: its author. Real users which have no previous knowledge of the software make much better testers.

- Do some serious code refactoring to use more design patterns and to fit the program to use with optimization methods like genetic algorithms.
- Add the feature of being able to receive data and logs via AIBO's wireless LAN interface.
- Speed up the numerical solver or use an adaptive step method.
- Look into the library cross-compilation issue. Interesting libraries to use include the GSL (already mentionned in section 2.9.7) for numerical solving and GNU Nana[1] for assertions checking and logging.
- Improve the Webots world file to prevent the robot from sliding on the box.
- Add the "ultimate feature" to read differential systems' specifications from a file.

[1] See http://www.gnu.org/software/nana/

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Appendix A

Webots & OPEN-R Quickstart

This guide details the installation procedure on a Linux system to obtain a running Webots with OPEN-R and RCS integration plus Aib-O-Matic software.

A.1 OPEN-R installation

Install the OPEN-R SDK according to the instructions in [19]. These instructions are summarized below.

1. Fetch the following files from `http://openr.aibo.com/` (free but registration required):

   - `OPEN_R_SDK-1.1.5-r3.tar.gz` (OPEN-R SDK),
   - `OPEN_R_SDK-sample-1.1.5-r2.tar.gz` (sample programs),
   - `OPEN_R_SDK-docE-1.1.5-r1.tar.gz` (manuals),
   - `gcc-3.3.2.tar.gz` (gcc source),
   - `binutils-2.14.tar.gz` (binutils source),
   - `newlib-1.10.0.tar.gz` (newlib source),
   - `build-devtools-3.3.2-r1.sh` (installation script)

   in your home directory.

2. Unpack the OPEN-R SDK:

   - `cd`
   - `tar -xzf OPEN_R_SDK-1.1.5-r3.tar.gz`

This will create a new directory `OPEN_R_SDK` in your home directory.

3. Unpack the sample programs and documentation:
   - `cd OPEN_R_SDK/`
   - `tar -xzf ../OPEN_R_SDK-sample-1.1.5-r2.tar.gz`
   - `tar -xzf ../OPEN_R_SDK-docE-1.1.5-r1.tar.gz`
   - `cd`
4. Edit the script `build-devtools-3.3.2-r1.sh` to suit the installation directory to your needs. The default is `PREFIX = /usr/local/OPEN_R_SDK`. Since this guide is intended for normal (i.e. non-administrative) users the following value will be used: `PREFIX = /home/username/OPEN_R_SDK`. Replace "username" with your actual username.
5. Execute the `build-devtools-3.3.2-r1.sh` script. It will unpack and compile binutils, gcc and newlib for the AIBO platform. This will take some time. Depending on the speed of your machine, you might want to have a drink while it is compiling...

A.2 Webots installation

It is assumed that Webots is already installed on your system in `/usr/local/webots`. If that is not the case, head to `http://www.cyberbotics.com/products/webots/download.html` and download the latest version of Webots suitable for your system or kindly ask your system administrator[1] to install it for you. Don't forget to replace `/usr/local/webots` with the actual location of your Webots installation in the rest of this guide.

A.3 Remote Control System installation

A.3.1 Create your own Webots directory

- `cd`
- `mkdir ~/my_webots`
- `mkdir ~/my_webots/worlds`

[1] *Always* be kind to system administrators otherwise you might dearly regret it. See `http://www.theregister.co.uk/odds/bofh/` for examples of what happens when one isn't.

- `mkdir ~/my_webots/controllers`
- `cp /usr/local/webots/controllers/Makefile.include ~/my_webots/controllers/`

A.3.2 Extract the world file

- `cd ~/my_webots/worlds/`
- `gunzip ~/aibo_ers210.wbt.gz`

You'll get the `aibo_ers210.wbt` world file in your Webots directory.

A.3.3 Install the Remote Control System

- `mkdir ~/my_webots/transfer`
- `cd ~/my_webots/transfer/`
- `tar -xzf ~/openr.tgz`
- `mkdir ~/my_webots/src`
- `mkdir ~/my_webots/src/lib`
- `mkdir ~/my_webots/src/lib/openr`
- `cd ~/my_webots/src/lib/openr`
- `tar -xzf ~/remotecontrol.tgz`
- Clean up CVS files (optional):
  `find . -depth -name CVS -exec rm -rv {}\;`
- Delete the line `#include <prototype.h>` in the file `~/my_webots/src/lib/openr/remotecontrol/Controller/Controller/Controller.cc` because `prototype.h` doesn't exist anymore.
- Prepare for building:
  `cd ~/my_webots/src/lib/openr/remotecontrol/RCServer/`
- `make clean`

- Edit the file `~/my_webots/src/lib/openr/remotecontrol/Controller/Controller/Makefile`. Correct the values of `WEBOTS_HOME` and `OPENRSDK_ROOT` to suit your installation. That is `WEBOTS_HOME` should be set to `/home/username/my_webots` and `OPENRSDK_ROOT` should be set to `/home/username/OPEN_R_SDK`. Be sure to replace "username" with your actual username.

- Run `make install` to build the Remote Control System.

- `cd ~/my_webots/transfer/openr/remotecontrol/Controller/Controller/`

- `cp -v ~/my_webots/src/lib/openr/remotecontrol/Controller/Controller/controller.* .`

- `cp -v ~/my_webots/src/lib/openr/remotecontrol/Controller/Controller/Controller*.o .`

- `cp -v ~/my_webots/src/lib/openr/remotecontrol/Controller/Controller/MTN*.o .`

- Modify the value of `WEBOTS_HOME` in `~/my_webots/transfer/openr/remotecontrol/Controller/Controller/Makefile` to `/home/username/my_webots` (always replacing "username" with your actual username).

- Extract files for ERS-210:
  `cd ~/my_webots/controllers/`

- `tar -xzf ~/ers210.tgz`

- `cd ~/my_webots/controllers/ers210/`

- Modify the value of `WEBOTS_HOME` in `~/my_webots/controllers/ers210/Makefile.openr` to `/home/username/my_webots` (always replacing "username" with your actual username).

- Link to Webots installation:
  `cd ~/my_webots/`

- `ln -s /usr/local/webots/include`

- `ln -s /usr/local/webots/lib`

A.4 Aib-O-Matic installation

- `cd ~/my_webots/controllers/ers210/`
- Extract Aib-O-Matic sources, be aware that this will overwrite the `Makefile.sources` and `Makefile` files.
  `tar -xvzf ~/aibomatic-src.tar.gz`
- Build the controller program for Webots with:
  `make`
- Build the controller program for AIBO with:
  `make -f Makefile.openr`

Appendix B

Aib-O-Matic user manual

B.1 Installation

Follow this procedure to install Aib-O-Matic into your Webots directory. It is assumed that this directory is `~/my_webots`.

- `cd ~/my_webots/controllers/ers210/`
- Extract Aib-O-Matic sources, be aware that this will overwrite the `Makefile.sources` and `Makefile` files.
  `tar -xvzf ~/aibomatic-src.tar.gz`

B.2 How to change system parameters

Edit the file `common.hh`. Interesting parameters to tune include: *MAX_LOG_LEVEL*, *SIMULATION_STEP*, *LOGGER_STEP* and *SOLVER_STEP*. Care must be taken to respect the following condition:

$$SOLVER\_STEP < LOGGER\_STEP < SIMULATION\_STEP$$

Otherwise the program will behave incorrectly.

B.3 How to build your own *DynamicalSystems*

First create a subclass of *DynamicalSystem* which overrides method *derivate*. Inside this method, you can implement your own equations. You have *get_DS_by_index* and *get_DS_by_name* from the *DynamicalSystemController* at your disposal to find other systems and *get_variable* to read their variables. Please refrain from doing anything else than reading to other *DynamicalSystems*, otherwise they will certainly start to behave in an unexpected manner.

Likewise, you can connect your systems with I/O devices by setting the two boolean arrays *variable_to_device_mapping* and *device_to_variable_mapping* at instantiation. Use *get_device_by_index* and *get_device_by_name* from the *DeviceController* to obtain references to devices. *variable_to_device_-mapping* is first indexed by variable number and then by device number. Meaning that if the element `variable_to_device_mapping[x][y]` is *true*, variable number x will get written to device number y after the system has been solved. *device_to_variable_mapping* is the reverse: it is indexed first by device number and then by variable number. Meaning that if the element `device_to_variable_mapping[x][y]` is *true*, the value of device number x will get written to variable number y before the system is solved. You can set those two arrays to *null* if you don't use them.

Load your new systems in *DynamicalSystemController*'s constructor (in file `DynamicalSystemController.cc`. Add or modify array elements of array *systems*. Remember to adjust the size of the array: *NB_DYNAMICAL_SYSTEMS* in `common.hh`. You'll have to create all parameters before instantiating a new system. Refer to the ACPO implementation as an example (files `ACPO.hh` and `ACPO.cc`).

B.4 How to add new *Device*s

You can add new devices by creating a new subclass of *Device*. To load your new classes, modify the constructor in `DeviceController.cc` and add new array elements to the *devices* array. Remember to adjust the size of the array: *NB_DEVICES* in `common.hh`.

B.5 How to compile the controller

- Build the controller program for Webots with:
  `make`
- Build the controller program for Aibo with:
  `make -f Makefile.openr`

Appendix C

CD-ROM table of contents

This appendix lists the contents of the CD-ROM associated with this project.

aibomatic/ Aib-O-Matic source distribution.

fondue_models/ Fondue diagrams made with Dia.

images/ Screen shots and photos.

movies/ Movies of experiments.

ode_out/ Sample output data files with processing scripts for GNUplot and Matlab.

openr_sdk_install/ Archives files needed to install the OPEN-R SDK on Linux.

rcs_install/ Remote Control System installation files.

report/ Report LaTeX source files.

slides/ Presentation slides LaTeX source files.

Appendix D

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