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LAUREA MAGISTRALE IN INGEGNERIA DELL'AUTOMAZIONE

ODIN: A DYNAMIC SIMULATION TOOL FOR ROBOTIC PATH PLANNING

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Abstract

There are several programs that allow to plan, choose, study and analyze the different paths for a robot. These software packages provide tools to calculate a path, make collision detection and several other tasks. But many of them lack a 3D physics engine.

The purpose of this work is to present *Odin*: a modular, multi-platform, open source coded additional software tool for those motion planning software packages. This project provides a rigid body dynamics simulator that works in parallel with a collision detection engine.

The 3D physics core was developed making extensive use of the *Open Dynamics Engine* library, an open source and free software physics engine developed in *C/C++*. *Odin* provides the user with a way to build a virtual instance of a robot in a scene, move it around, apply forces, gravity, and see it interact with the obstacles. It is structured in three individually designed independent parts, loosely coupled at runtime: the virtual world, the user interface and the viewer.
Communication between them is achieved through messages and service calls in a *Robot Operating System* environment. This has been done to allow future users to easily dispose of any part of this project and replace it with their own solutions (for the user interface or the viewer), just by adding some communication features to their code.

A few simulation examples will be shown in the conclusions.

Contents

Glossary

- **API** - *Application Programming Interface*
  A specification containing a set of routines, protocols, and tools for building software applications [1].

- **BSD Licenses** - *Berkeley Software Distribution Licenses*
  A family of permissive free software licenses.

- **CFM** - *Constraint Force Mixing*
  An *ODE* parameter that allows to soften constraints in a simulation.

- **DOF** - *Degree of Freedom*
  Is the number of independent parameters that define a configuration of a system.

- **DOM** - *Document Object Model*
  A cross-platform and language-independent convention for representing and interacting with objects in HTML, XHTML and XML documents [2] in a tree structure.

- **ERP** - *Error Reduction Parameter*
  An *ODE* parameter that defines which portion of joint errors will be fixed in a time step [3].

- **FPS** - *Frames Per Second*
  A Hertz equivalent frequency unit: $1fps = 1Hz$.

- **GUI** - *Graphical User Interface*
  A type of user interface that allows users to interact with electronic devices

using images rather than text commands.

- **LGPL** - *Lesser General Public License*
  A free software license published by the Free Software Foundation (FSF), compromising between the strong-copyleft GNU GPL and permissive licenses such as the BSD licenses.

- **ODE** - *Open Dynamics Engine*
  An open source, high performance library for simulating rigid body dynamics written in C/C++ [4].

- **OpenGL** - *Open Graphics Library*
  A cross-language, multi-platform API for rendering 2D and 3D computer graphics [5].

- **PQP** - *Proximity Query Package*
  A library for performing proximity queries on a pair of geometric models composed of triangles [6].

- **ROS** - *Robot Operating System*
  An open-source, meta-operating system that provides the message-passing between processes, and package management [7].

- **RPC** - *Remote Procedure Call*
  An inter-process communication that allows a computer program to cause a subroutine or procedure to execute in another address space, also called Remote Method Invocation [8].

Preface

This project was born within the scope of the *Kautham Project*, a robot simulation toolkit for motion planning and teleoperation guiding software package developed in the Institute of Industrial and Control Engineering (IOC), at the Universitat Politècnica de Catalunya (UPC).
As defined in [9], the *Kautham Project* is "a simulation tool conceived both as an aid for the development of robot motion planners and as aid for the teleoperation of robots using haptic devices. It provides the user with an easy way to model and visualize the problem, with collision-detection and sampling capabilities, basic planners and communication modules, among others".

The *Odin* project was indeed born as a feature to be integrated in the next *Kautham Project*'s release. This has influenced the choice of some of the tools used to create this project, *C++* as the programming language to begin with, *CMake* as the make system, *Coin3D* as the graphic library, etc.
One of the most evident influences can be seen in the user interface: since *Kautham* already has a working *Graphical User Interface*, *Odin*'s one is going to be the first thing to be dismantled and incorporated. That explains why it can open *Kautham*'s structured problem files, and why it may not be as sophisticated as the other parts.

There is another influence in the collision detection system. In fact, *Kautham* already provided a *PQP*-based collision detection engine. Thus, in order to make the package lighter and simpler, *Odin* has been developed to provide also the same kind of collision detection provided by *PQP*.

But the main interest of *Odin* is the other type of collision handling: the one that's integrated with the rigid body dynamics simulator and a 3D physics engine.

Introduction

The purpose of this document is to describe the *Odin* project, by showing its structure and its main features.

The first chapter will describe the motivations behind this project, the ideas that inspired it and the requirements to be met.
The second chapter will give an overview of the software involved, with enough detail to explain why it is important and which limitations it brings.
Odin is a modular, standalone software package composed by three independent modules communicating over a peer-to-peer network. These modules are the graphical user interface, the viewer and the virtual world. Each module consists of two major classes: a core and a *ROS* layer. The core includes the module's specific activities, performs calculations and processes data. The *ROS* layer works as a portal to access the core, and deals with communication, externalization of results and performs a first level incoming data processing.
The third chapter will describe *Odin*'s *ROS* network and will give an idea of the software general macro structure. But from the third chapter on, the software structure will be explained in detail.
The first module analyzed is the most important and irreplaceable: the *Virtual World* module. A chapter will be dedicated to the *ROS* layer, and the subsequent will cover the core. One chapter will be dedicated to the *Viewer*, simpler but nonetheless tricky. Two chapters will cover the *GUI* module, the last also chronologically speaking.
The final chapters will cover cost and environmental analysis, an analysis on obtained results, and a section on future work.
Since this is a software project, an extensive *Doxygen HTML* documentation is provided in the attached compact disk.

Chapter 1

Purpose

Most of motion planning software packages are based on probabilistic path planning, random tree exploration, collision detection and other techniques.
The aim of this work is to create an additional tool for these packages: a rigid body dynamics simulator that works in parallel with a collision detection engine. But in order to be attached and integrated to any software kit, the project has to be modular, multi-platform and open source coded.
On the other hand it has to be a stand-alone program to be distributed. Yet its parts have to be detachable, so that users can just dispose of what is not needed and replace it with their own solutions.
Therefore the project is structured in three individually designed independent parts, loosely coupled at runtime: the virtual world, the user interface and the viewer. This distributed framework of processes communicates through messages and service calls in a *Robot Operating System* environment, so that future users can easily replace any part at any time by just integrating their code with communication features, that is just by adding a few lines of code.
The project has been thought to be used as a testing tool to validate a movement path in a virtual environment, but as well to help calculating new paths, by integrating its capabilities with a random tree exploration algorithm that studies the evolution of an element colliding with the environment.

1.1 Structure

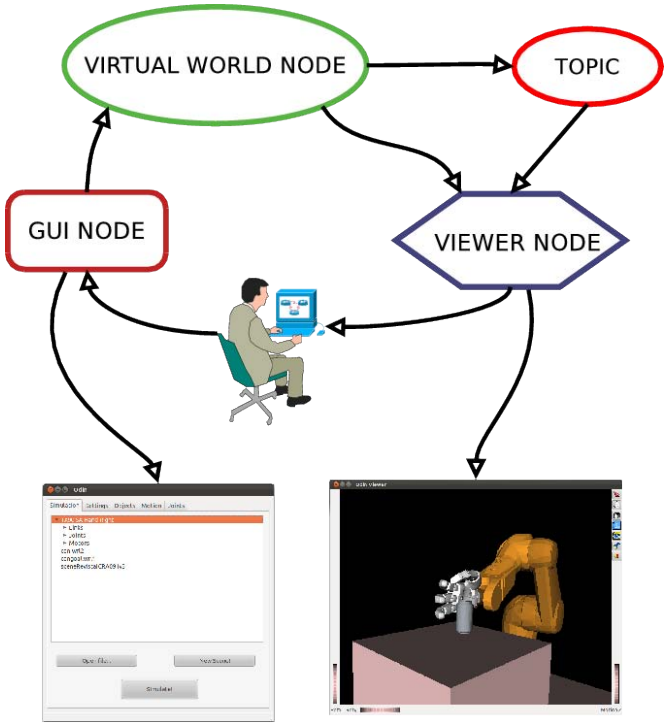


Figure 1.1: The flow of information in *Odin*.

At runtime, the program works in a peer-to-peer network, comprising three nodes: the *GUI*, the *Virtual World* and the *Viewer*. The user interacts with the *GUI*, defining every detail of the situation to be simulated, like objects, constraints, kind of collision handling and other parameters. The *GUI* converts this information into messages and service calls and sends it to the *Virtual World* node. This node creates the scene and actually runs the simulation. It attends any call from the *GUI* and periodically publishes the simulation results into topic nodes. At the same time, whenever an object is created or removed, the *Virtual World* node calls the *Viewer* for the creation or removal of the object in the viewer's scene.

The *Viewer* will pop up a window containing a 3D visualizer and build a scene according to the information coming from the *Virtual World*. This node subscribes to the simulation results topics to get information about the situation of the world. This information is used to maintain the viewer's scene up to date by

updating object transformation data and collision data when required.
A conceptual diagram is shown in figure 1.1.

1.2 Requirements

The requirements to be met were defined thinking about what would be useful for the *Kautham Project*, but at the same time having a standalone, independent, modular project. Hence the program must be capable of:

- Simulating physics in scenes and problems built by the *Kautham Project*, with the possibility of moving the robots around and see how they interact with the rest of the world.
- Detecting collisions among objects, identify them and, optionally, quantify the inter-penetration.
- Integrating collision detection in the physics engine and dealing with collisions in a realistic way.
- Externalizing all information about the simulation at a user defined variable rate.
- Simulating at different speeds and precisions.
- Communicating with other modules through a *ROS* network.
- Reproducing the scene in a viewer, updating the image at $25fps$.
- Allowing high level user interaction, letting the user the possibility of:
  - Building objects, joints and motors.
  - Applying forces and torques to objects and joints.
  - Setting and controlling motors.
  - Setting object position, orientation and velocity.
  - Loading a scene from a *XML* file.

- Loading and executing a path for the robots, defined either in position or in velocity.

Modularity is a very strong requirement. It means complete independence, flexibility, separability and replaceability of the three parts (user interaction, calculation and visualization).

Chapter 2

Background Software

This is an introduction to the software packages used in this project. Only an overview will be given on each tool, and more in-depth elucidations will be given later on.

2.1 Robot Operating System

Robot Operating System (*ROS*, logo in figure 2.1) is a software framework for robot software development, providing operating system-like services, including message-passing between processes and package management. It is based on a graph architecture where processing takes place in nodes that may receive, post and multiplex messages. The library is geared toward a *Unix*-like system (*Ubuntu Linux* is listed as supported while other variants such as *Fedora* and *Mac OS X* are considered experimental) [10]. This has prompted the author to immediately start developing under an *Ubuntu* distribution. The *ROS* runtime "graph" is a peer-to-peer network of processes, called *nodes*, loosely coupled at runtime through a communication infrastructure.

Figure 2.1: The *Robot Operating System* logo [10].

ROS communication between *Nodes* is based on the *Message*: a data structure comprising typed fields. The *Message* can be used in two different styles of communication: synchronous *RPC*-style communication and asynchronous streaming of data.
The first one is a request/reply interaction, and is done via a *Service*, which is defined by a pair of *Messages*: one for the request and one for the reply.
The second one is a publish/subscribe communication style, which decouples the production of information from its usage. The data streams from the publisher *Node* to a *Topic*, a bus that buffers up the *Messages*. Other *Nodes* can then subscribe to that *Topic* and read the *Messages*.
ROS package management features were utilized to organize the project in five packages:

- *Messages*, containing all message templates.
- *Services*, containing all the services' message templates.
- *VirtualWorld*, containing the 3D physics simulator.
- *Viewer*, containing the viewer.
- *GUI*, containing the graphical user interface.

Each package includes a file named *Manifest*, that contains information about compilation specifications. These packages are organized into a *Stack*, called *Odin* (which also contains its *Manifest*), to improve code sharing of *Messages* and *Services*, and to simplify code distribution [7]. *ROS* is released under the terms of the *BSD* license, and is an open source software. Although the last distribution *Fuerte Turtle* was released in April 2012, the one used is the previous one, released in August 2011: *Electric Emys*[11].

2.2 Open Dynamics Engine

The *Open Dynamics Engine* (*ODE*) is an open source, high performance physics engine. It is composed of a rigid body dynamics simulation engine integrated with

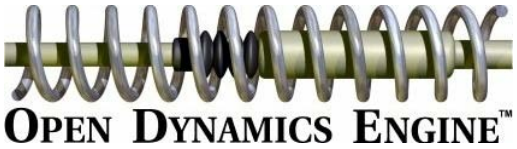


Figure 2.2: The *Open Dynamics Engine* logo [3].

a collision detection engine, and it is also a popular choice for many computer games and 3D simulation tools [4].
Another option could have been *Bullet*, a more recent open source 3D physics engine, and despite that it looks more powerful and feature-rich than *ODE*, it was discarded because its fast growing and recent age meant a rawer and less extensive documentation. A poorly documented but powerful software might be a reasonable choice for a skilled professional, but would make a poor choice for research purposes. An important fact that helped decide among the libraries is that Open Dynamics Engine is the library of choice for other existing robotics simulation software packages like *OpenRave* of *OMPL* (in *OMPL* it is only supported, not integrated).
ODE is free software, licensed under the *LGPL*.

2.3 The Kautham Project

The *Kautham Project* is a simulation tool developed at the Institute of Industrial and Control Engineering (IOC), Universitat Politècnica de Catalunya (UPC). It is conceived both as an aid for the development of robot motion planners and as an aid for the teleoperation of robots using haptic devices [9]. It provides the user with an easy way to model and visualize the problem, with collision-detection and sampling capabilities, basic planners and communication modules, among others. It has been implemented as an open-source project following the directives given in [12]. Its aim is to be a research and teaching tool, conceived as a compromise between the need to program everything from scratch and the use of abstract middleware available in the Internet.
Since the beginning of *Kautham Project*, much importance has been given to

modularity. A next step will be a complete modularization of its components, integrating *ROS* as a communication device.
Besides, many software choices are due to the packages used in the *Kautham Project*, like *CMake*, *Coin3D*, *Qt*, *PugiXML*, *PQP*.

2.4 CMake

Figure 2.3: CMake logo [13]

CMake is an open-source system that manages the build process in an operating system and in a compiler-independent manner. Nevertheless it is designed to be used in conjunction with the native build environment: being it *Make*, *Apple*'s *Xcode*, *Microsoft Visual Studio* or others [13].
The build process is controlled by creating one or more configuration files placed in each directory, called *CMakeLists.txt*. They contain simple commands that are used to generate standard build files (e.g. *Makefiles* on *Unix*) which are used in the usual way.
This way *CMake* generates a native build environment that compiles source code, creates libraries, generates wrappers and builds executables in arbitrary combinations. It is designed to support complex directory hierarchies and applications dependent on several libraries, that is why it integrates perfectly with *ROS* packages and stacks file organization [10].
CMake is integrated by default in the *ROS* build system, but was already *Kautham Project*'s build system of choice because of its cross-platform features.

2.5 Coin3D

Coin3D is a *C++* object oriented 3D graphics *API* used to provide a higher layer of programming for *OpenGL*. It is developed by the Norwegian company

Figure 2.4: Kongsberg's Coin3D logo [14]

Kongsberg Oil & Gas Technologies as clone of the 3D *API Open Inventor* [15]. It works by retaining a complete model of the object to be rendered in a tree structure called "scene graph" [14]. The scene can be built at runtime but it is usually built from a file. The file contains data in a tree structure in the *VRML* format, that will be introduced later.
Coin3D is distributed with both proprietary and *GPL* license.

2.6 XML and PugiXML

Extensible Markup Language (*XML*) is a markup language that defines a set of rules for encoding documents in a format that is both human-readable and machine-readable [16]. It has been used since the beginning of the *Kautham Project* to create the problem description files. This files describe a scene with a robot and some obstacles, addressing to *VRML* files for shape and appearance descriptions of the single parts and objects.

PugiXML is a library for fast, convenient and memory-efficient processing of *XML* files. It consists of a non-validating *XML* parser which constructs a *Document Object Model* (*DOM*) tree and enables traversing and modification [17]. It is used for parsing and processing problem files.
PugiXML is distributed under the *MIT* license.

2.7 VRML and Qooliv

VRML (*Virtual Reality Modeling Language*) is a standard text file format (with the **.wrl* extension) for representing 3-dimensional interactive vector graphics. In these files it is possible to specify vertices and edges for a 3D polygon along

with the surface color, shininess and so on [18]. They are used in this project to describe shape and color of some objects.
Both languages are open standards.

Qooliv, whose name is a portmanteau of "cool" and "inventor", is a VRML-file reader and viewer based on *Coin3D*'s *SoQtExaminerViewer*. It has been developed in the IOC and has been inspiration and a starting point for *Odin*'s viewer.

2.8 Qt

Figure 2.5: Qt logo [19]

Qt is a cross-platform application framework that is widely used for developing application software with a graphical user interface (*GUI*). It uses standard *C++* but makes extensive use of a special code generator (called the *Meta Object Compiler* or simply *moc*) together with several macros to enrich the language [20].
Qt has its own integrated development environment that helps with macros and and makes the developer work as if the "special code" had already been generated (although it is not generated until compile time), but it needs to be compiled in a certain way. *CMake* comes in aid this time too, because it all comes to a few lines in the *CMakeLists.txt* to manage the *moc* and compilation correctly. *Qt* is free and open source software, and is distributed under the terms of the *GNU Lesser General Public License* (among others)[19].

2.9 PQP

Proximity Query Package was not actually a software used in this project, but it deserves to be mentioned because it is the current collision detection library in the *Kautham Project*. This library performs three types of proximity queries:

- Detects whether two geometric models (triangle meshes) overlap.
- Computes the minimum distance between two models.
- Determines whether two models are closer or farther than a tolerance distance.

This library does not make any kind of physics simulation, it just performs collision culling and detection. Therefore, *Odin* and *PQP* can either be put side-by-side or integrated, substituting the less efficient library with the more efficient one when it comes to tasks they both perform well, like collision detection.

Chapter 3

The General Structure

3.1 The ROS Network and the Master node

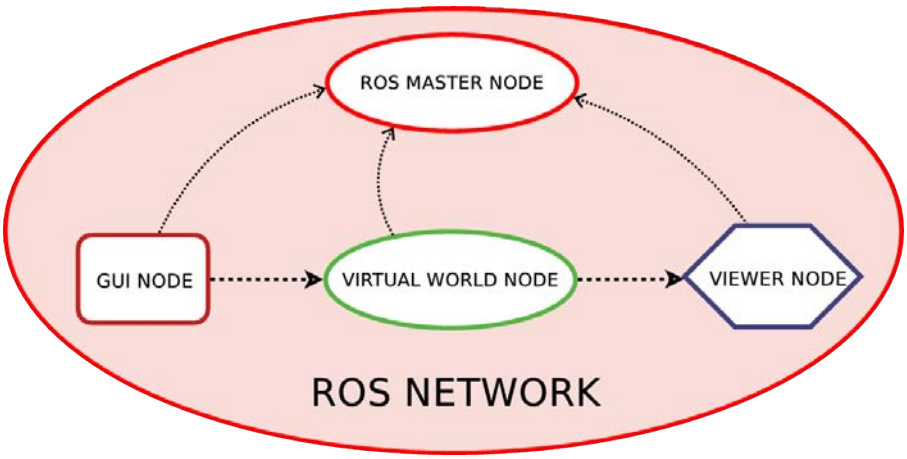


Figure 3.1: *Odin*'s *ROS* network.

At runtime, the program consists of three modules communicating over a peer-to-peer *ROS* network. The *ROS* network can be seen as a graph of nodes[10], where each node is a different process that performs computation and can communicate with other nodes, as in figure 3.1. The *Master* node provides naming and registration services to the rest of the nodes in the *ROS* system, letting them locate each other before starting a peer-to-peer connection. Besides the *Master* node, there are three major nodes: *GUI_ node* (the graphical user interface),

Viewer_ node (the viewer) and *VirtualWorld_ node* (the virtual world). Each one registers to the *Master* on initialization.
Besides the *Master*, there is another node that is set up by default. It is the *RosOut*, which is the console log reporting mechanism in *ROS*[10].

3.2 Communication paradigms

The communication unit is the message. A message is a simple data structure comprising typed fields, which can contain standard primitives, arrays of standard primitives, other messages and even arrays of messages. Nodes can communicate in two ways: through a Publisher/Subscriber semantics (figure 3.2) or through a Request/Reply paradigm.

3.2.1 Publisher/Subscriber

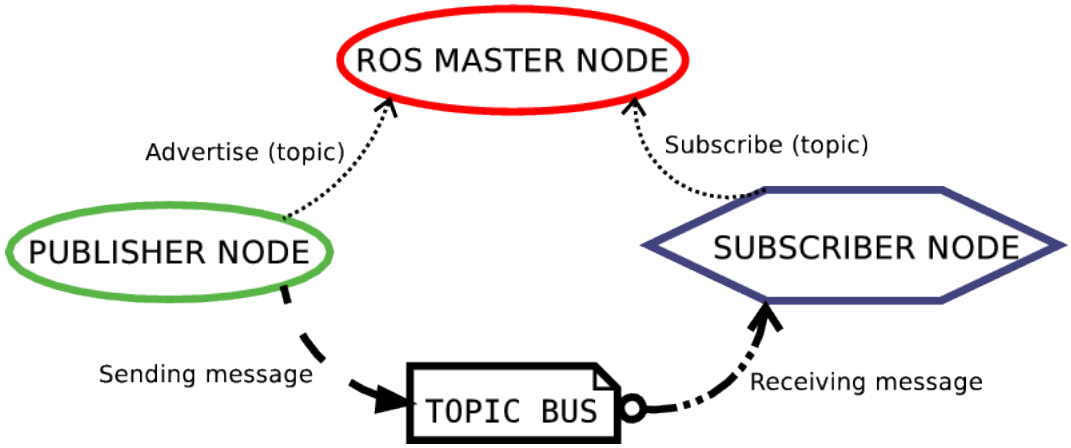


Figure 3.2: Model of the Publisher/Subscriber paradigm in *ROS*.

A node sends out a message by publishing it to a given topic. A topic is a named bus which decouples the production of information from its usage, and is intended for unidirectional, streaming communication. The topic name is used to identify the content of the message published in it. A node that wants to have access to the message locates the topic through the *Master*, and subscribes to it.

Multiple nodes can publish on and subscribe to a same topic, but they do not have to be aware of each other's existence.
Every node is connected by default to the *RosOut* topic, where it publishes logging messages.

3.2.2 Request/Reply

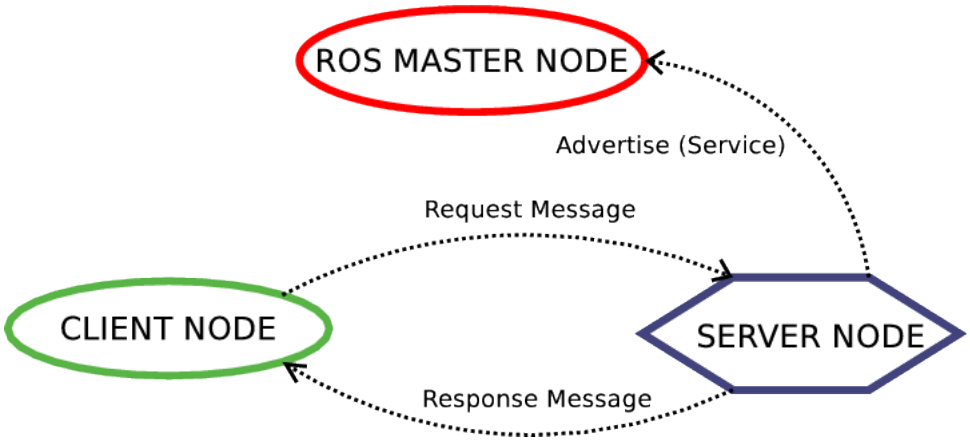


Figure 3.3: Model of the Server/Client paradigm in *ROS*.

Request/Reply interaction is made through services. A service is defined by a pair of messages: a request message and a response message. This interaction can take place only after both nodes have registered to the *Master*: the node that sends the request registers as a client, the one that serves and replies is called server. While the server must register, the client registration is optional. In fact, in the Remote Procedure Call mechanism, the calling node does not register as a client, but simply sends the request and receives the response. This mechanism is convenient for one time only calls, while for repetitive calls a client is more appropriate.

3.3 Communications in Odin

As it can be seen in figure 1.1, the flow of information within *Odin* goes from the *GUI* node to the *VirtualWorld*, and from the *VirtualWorld* node to the *Viewer*

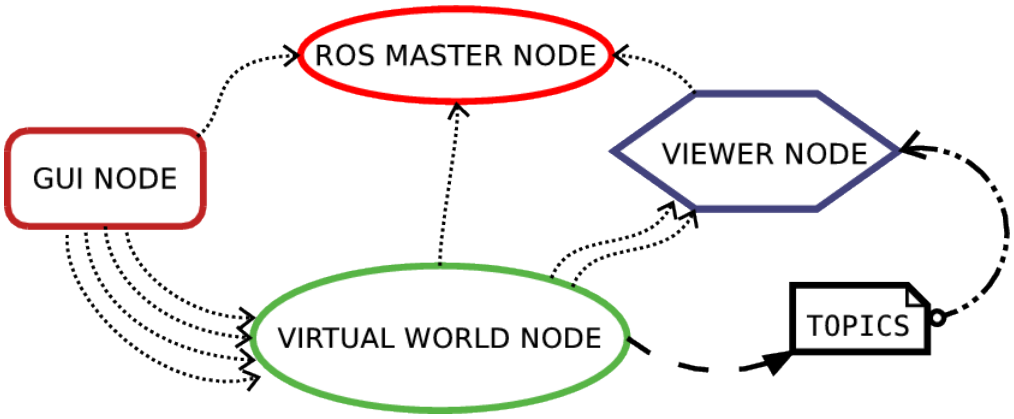


Figure 3.4: A more accurate computation graph showing the nodes, the topics and the service calls in *Odin*.

node. In fact, the *GUI* node does not set up any publisher nor server, but just clients. The *Viewer*, on the other hand, sets up servers and subscribers. In the middle there is the *VirtualWorld* node, that sets up clients, servers and publishers. A more accurate representation is shown in figure 3.4.
Another way to see the computation graph is given by a *ROS* tool called *RxGraph*, that allows to visualize the graph at runtime as shown in figure 3.5. Because of their ephemeral nature, services are not shown: *RxGraph* detects the servers indeed, which are permanent, but since they are inside the nodes, they do not appear in the graph representation.

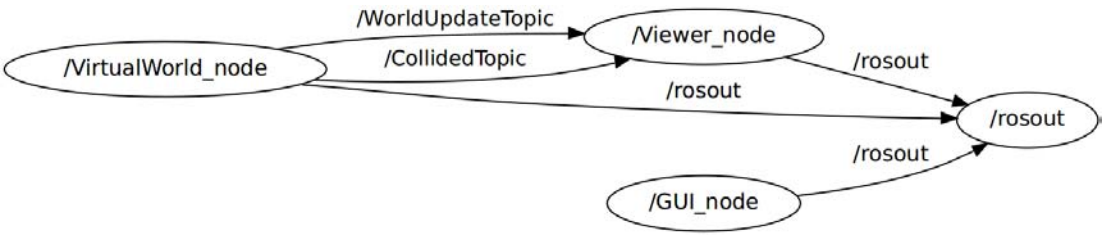


Figure 3.5: Computation graph caught with *RxGraph*, showing the nodes and the topics, including *RosOut*.

3.3.1 GUI and VirtualWorld interaction

The communication between the *GUI* node and the *VirtualWorld*'s is Server/-Client based. As shown in figure 3.6, a conspicuous number of services is needed to grant the user full action on the simulation. The services are:

Figure 3.6: Services called from the *GUI* and replied by *VirtualWorld*.

- New Scene: destroy the current scene and create a new one.
- Set World: set general simulation parameters.
- Set Step: set step sizes.
- Step Once: run one simulation step.
- Start: start/stop the simulation.
- Build Object: create a single object.

- Build Composite: create a composite object, that is an object made of simple primitive geometries.
- Build Entity: build a set of objects with some common features.
- Remove Object: destroy a single object.
- Set Joint: create a joint between two objects.
- Set Motor: add a motor to a joint or an object.
- Set Position: set object position.
- Set Velocity: set object or motor velocity.
- Set External Force: apply a force or a torque on an object.
- Set Joint Force: apply a force or a torque on a joint.

A deeper insight on the true meaning of these services will be given when addressing the nodes themselves in the next chapters.

3.3.2 VirtualWorld and Viewer interaction

The *VirtualWorld* node has to externalize all the information it produces, and does it using both paradigms: Client/Server for the initialization of the scene and the creation of new objects, and Publisher/Subscriber to update the scene information and the system spatial layout (figure 3.7). Services are used to create the scene and put objects in it, as well as to remove them. The ones called by the *VirtualWorld* node and serviced by the *Viewer*'s are:

- Viewer Remove Object: remove an object from the scene.
- View Object: add a new object to the scene.
- New Scene: reset the scene.

Subscriptions to the topics allow the *Viewer* to have updated information about the state of the world, needed to render the scene properly.

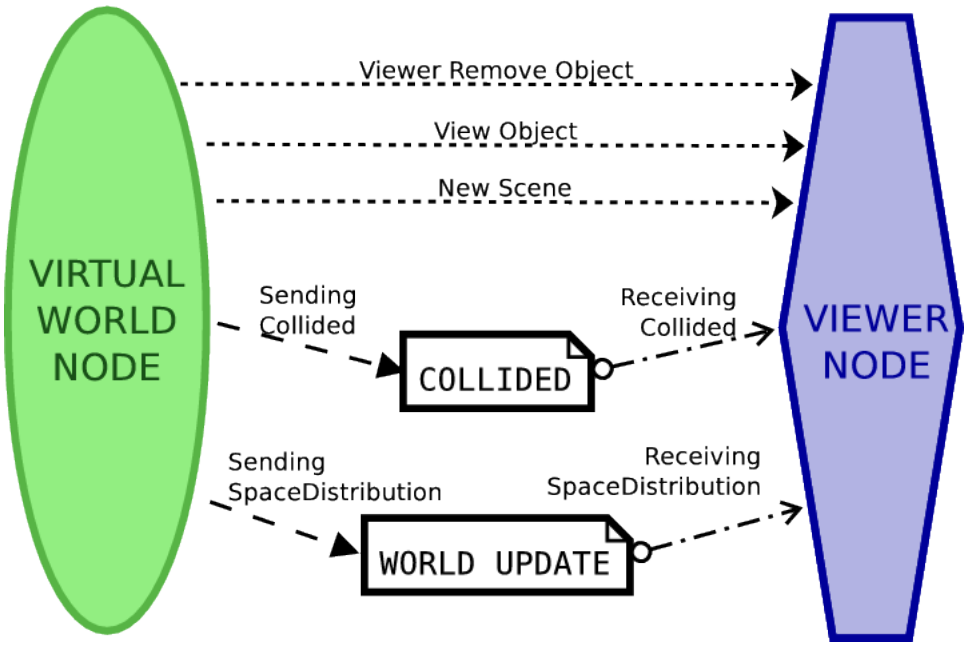


Figure 3.7: Information exchange between *VirtualWorld* and *Viewer* nodes.

- Collided (message: Collided): contains a list of all objects that collided since the last message was sent.

- World Update (message: SpaceDistribution): contains position and orientation of every object in the scene. A Space Distribution message is an example of an array of messages, in this case Situation messages, describing a single object position and orientation.

3.4 Node Structure and Class Architecture

Every module in *Odin* is a different process, a node, that both communicates and computes. To improve modularity, code reuseability and portability, every module has been divided in two main parts: a *Portal* class dealing with communications and a *Core* class dealing with specific node processing computations (figure 3.8). The *Core* class is instantiated as a member of the *Portal* class. So, the *Portal* grants access and communication to the core. The *Portal* is in fact the *ROS* layer, contains all servers, publishers and subscribers and sets up the node on start up.

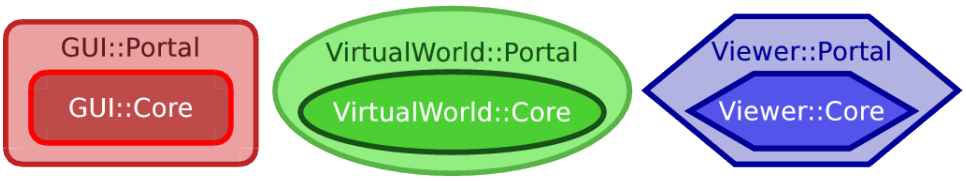


Figure 3.8: Each node is composed by a *Portal* (communication layer) and a *Core* (computation layer).

The *Core* is the computation layer that deals with actual specific calculation for the node, such as dealing with files (gui), simulating (*VirtualWorld*) or rendering (*Viewer*). It does not link to any *ROS* library, but rather links to other classes that help with its process issues.

In the following chapters, every module will be analyzed extensively. For every module, the first part to be analyzed will be the *Portal*, then the *Core* and finally the other supplementary classes. The next chapter starts with the most complicated and irreplaceable module: *VirtualWorld*.

Chapter 4

The Virtual World Portal

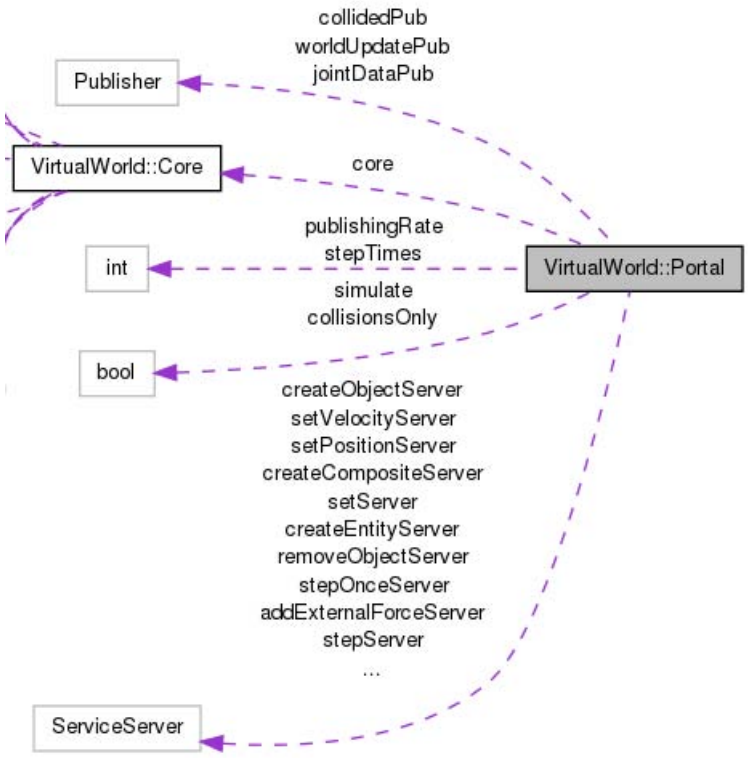


Figure 4.1: First level of collaboration diagram for *VirtualWorld::Portal*.

From the *GUI* point of view, the *VirtualWorld* node is a set of servers that grant control over the simulation. To the *Viewer* it is a client that asks for the creation of scenes and objects, as well as a publisher to the simulation related topics. It is the key module, and its three most important classes are: *Main*, *Portal* and *Core*.

The first class produces the executable that initializes, runs and closes a *VirtualWorld::Portal* instance.
The *Portal* is the *ROS* layer that covers the *Core* class, which actually runs the simulation. It instantiates the *Core* and sets up the *VirtualWorld ROS* node (figure 4.1). But most of all, it manages and controls the simulating core, by telling it when, how, what and how much it has to simulate.
As a matter of fact, the *Portal* class has only three public member functions: initialize, run and close. Besides these three, every other member is private.

4.1 Initialization

The *init* function first initializes *ROS*, the *Core*, sets up the servers and the publishers and finally sets a default value to all those variables that can be defined by the user, but are indispensable for the program to run, such as the message rate and the step sizes (figure 4.2). When initialization is over, the program enters the running loop.

4.2 Servers

The servers cover all those services that allow (through the *GUI*) user interaction with the simulation, like:

- Setting simulation parameters: gravity, ERP, CFM, maximum angular speed, maximum correcting velocity, contact surface layer, damping values and thresholds.
- Setting step sizes, number of *ODE*'s steps between messages and cycle rate.
- Creating/destroying objects, like spheres, cylinder, boxes, composites or triangular meshes.
- Creating joints and motors.
- Adding/removing forces, torques on objects or joints.

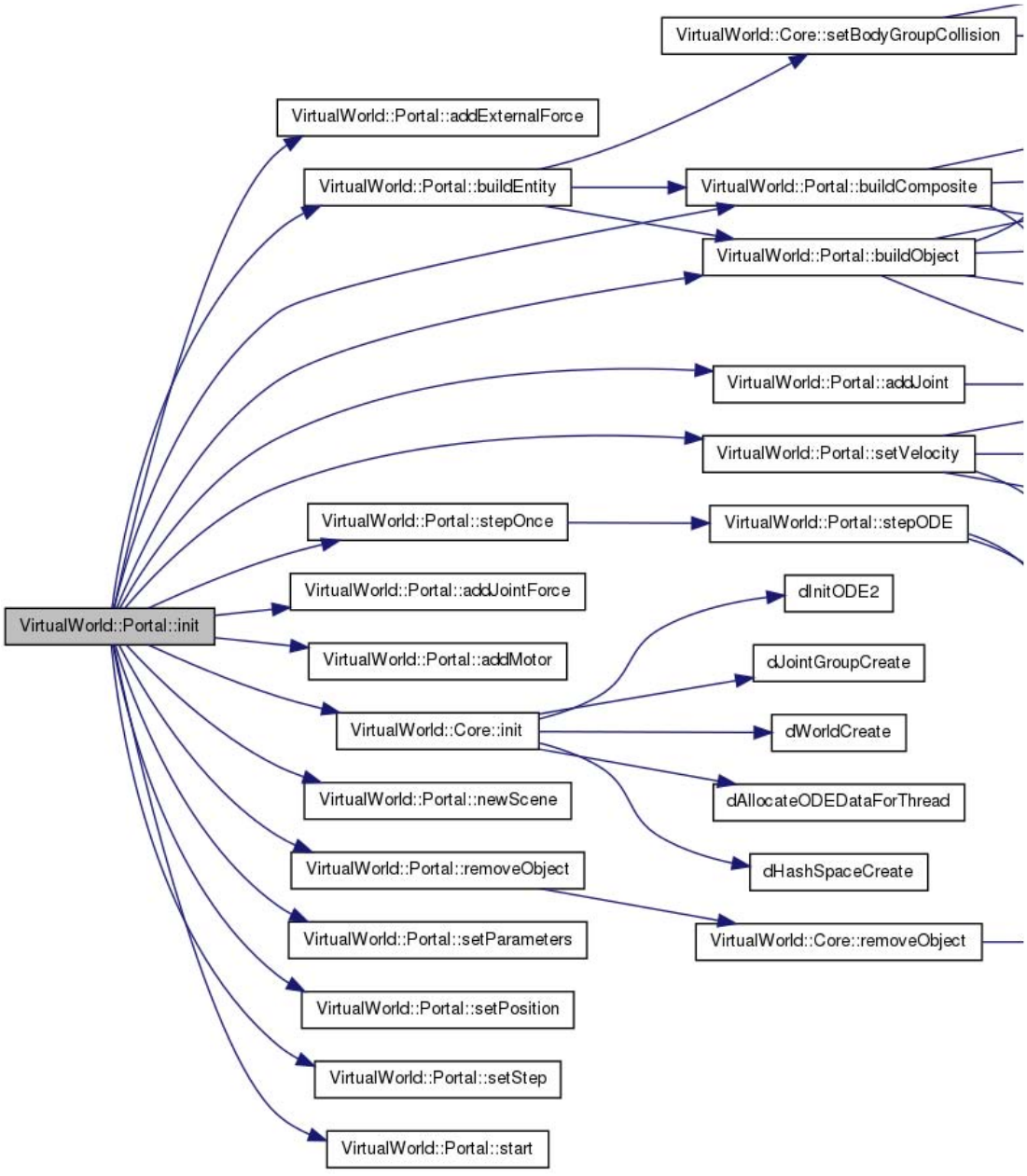


Figure 4.2: First level of call graph for *VirtualWorld::Portal::init*. All server callbacks are visible as *Portal* functions, but are private and can be used only because of *ROS*.

- Setting desired goal speeds on a list of motors.
- Setting objects position and speed values.

Most of these servers' callback function are not very interesting, since they may just set a value or wrap another *Core* function that will be analyzed later. But those described in the following sections deserve a special attention, because it is where *Portal* shows that it is not a mere access gate to the *Core*, but rather a manager and an interpreter.

4.2.1 Creating and destroying elements

Objects

Creating a new object involves a series of checks: name collision, quaternion consistency, non zero mass. If one of these checks fails, the object is not built and a message is printed on the system out.
An additional check on the number of parameters determines whether the object geometry is a simple primitive (sphere, cylinder or box as in figure 4.3a) or if it is a triangle mesh (figure 4.3b), and the corresponding *Core* function is called. Once the object is created, it has to appear in the viewer's scene.
Odin identifies its objects through user defined strings. These IDs must match those in the viewer's scene, so when an object is created (or destroyed), *Portal* takes care of calling the *Viewer*'s object creation (or destruction) service using the same ID that appears in the simulation. This separation between the *GUI* and the *Viewer* makes the communication between the virtual world and the visualizer more consistent and reliable.

The process of object destruction mirrors the one of creation: the object is first removed from the *Core*, then a call is made to the *Viewer* to prompt its removal from the rendering scene.

Composites

A composite is an object whose geometry is neither a simple primitive, nor a triangle mesh. Its geometry can otherwise be defined as a sum of primitives (figure

(a) A primitive (b) A triangle mesh (c) A composite

Figure 4.3: Simple objects

4.3c). A table, for example, can be modeled as a large, thin box with four cylinders as its legs. This way of representing the object gives several advantages over the triangle mesh representation:

- Collision detection and dynamics work faster on primitives than on triangle meshes.
- Inertia matrices are calculated internally for primitives by default, but must be user defined in the case of triangle meshes.
- Rendering is faster and the scene, in general, lighter.

But there is a little complication. While the *ODE* library wants composites to be defined as a single object with multiple geometries, the visualizer often prefers to treat geometries as single entities, since it will not perform collision detection nor it has to think about inertia matrices and other dynamics computations. Therefore, while specific *Core* composite creation functions are called, *Portal* calls standard object creation services on the *Viewer* for each primitive.

Entities

When two elements of a robot arm are linked by a joint, any collision happening among them is automatically ignored. But there are some cases in which one would like to ignore each collision happening among a group of objects. This is when Build Entity Service becomes useful: it allows to create a group of objects, and define whether they collide or not among themselves (figure 4.4).

The request message contains a vector of simple objects, a vector of composites

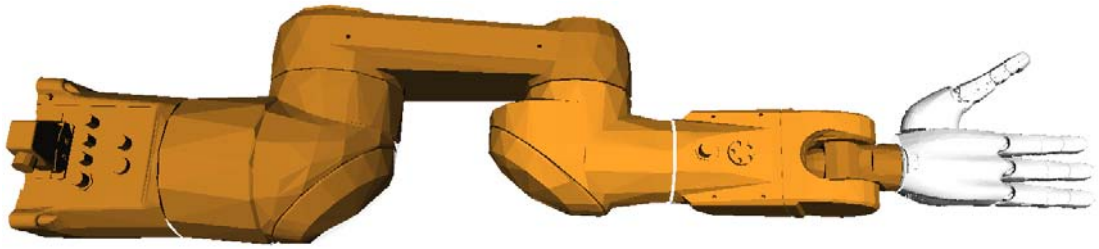


Figure 4.4: An entity.

and an internal collision flag. The callback function processes this vector by passing its elements to the competent callback functions, but in the meantime stores their IDs in a list. Once every object is built, the callback function passes this list to *Core* for it to deal with the collision flags.

4.2.2 Joints, motors, forces and torques

Adding forces and creating joints is a more interesting subject from the point of view of the *Core*, and it will be dealt with later on. But there is an aspect of it that is dealt with within the *Portal*, and that is identification.
In fact, everything in *Odin* is addressed through a string ID, from objects to forces. In all these cases the user can give a name to the element he is creating, but when he does not, *Portal* baptizes it for him.
If it is a joint, the name created is based upon the joint type and the IDs of the objects involved (e.g. if it is a ball joint between "body1" and "body2" the ID will be "0:body1& body2").
A similar thing happens when a motor is created, with the only difference that the new name will start with "motor:".
But joints and motors are unique, that is there can only be one among two objects (more than one joint is either redundant, zeros the degrees of freedom or it is just a bad joint type choice). Forces and torques on the other hand can sum up and be applied to the same joint or object. Thus, when adding a force or a torque, the algorithm has an additional twist: every force added has a number at the end of the ID. When a new force is added in the same place, the function looks for an unused number among the forces present, and uses it to baptize the new force.

4.3 Publishers

Publishers are those members that, once in a cycle, manage to collect some information about the ongoing simulation and publish it on their respective topics. Those topics can be subscribed by any node, but are particularly a feed to the *Viewer* node, that has to update the rendering scene.

4.3.1 Objects position and orientation

The main topic *VirtualWorld* publishes on is the so called *Space Distribution*. It contains all up-to-date geometries' position and orientation. This information is gathered before each publication from the *Core*, which in turns extracts it from the simulation.
The information is about geometries, not objects, which do not coincide in the case of composite objects. As it has been previously said, *ODE* and viewer models are different in the case of composites. Therefore, when publishing the position of a composite, the *VirtualWorld* node cannot give the position and orientation of the whole body, but has to tear it apart and give separate data about every single part.
The solution adopted to solve this divergence consists in letting the user define names for the composite parts, and not the whole body name. *Portal* builds the whole object name using the part names separated by the symbol ">", and uses this name as the object's identifier in the simulation: e.g. ">part1>part2". When preparing the message, however, *Portal* disassembles the object's name, and sends transformation messages for each geometry coupled with that part's name. This way, the viewer will never know whether two elements are part of the same object or not, but it will render them correctly nonetheless.

4.3.2 Colliding objects

Among the parameters, there is a flag that determines whether collisions influence the dynamics or not. In one case objects collide, bounce and slide; in the other case, they penetrate into each other constrained only by the joints that tie them

together. This kind of simulation is said to be contact-less, because no contact constraints are created during the simulation.
In case of a contact-less simulation, collision handling consists in detecting which objects are colliding and in reporting them on a list. This task is made by the *Core* and will be analyzed in the following chapter. The *Portal*, on the other hand, publishes a message containing this list of objects to the *Collided* topic. This topic will be subscribed by the *Viewer*, that will handle this information properly.

4.4 Running loop

In the running loop, the program does basically three things:

1. May or may not advance the simulation.
2. Publishes the state of the world.
3. Processes and replies all Service calls.

4.4.1 Simulation advancing from *Portal*

Usually, one would like to have many simulation steps in a *Portal* running cycle. That is because the *ODE* library becomes more exact and reliable as the simulation step becomes smaller. Hence the standard procedure is to split the cycle step time in smaller *ODE* steps. For this reason, advancing the simulation means stepping forward the *Core*'s simulation a number of times (see 4.5). For default step values see table 4.1.
Simulation automatic advancing is determined by a flag named "simulate". This flag is changed through the Start Service, which allows to start and stop the simulation at any time.

Automatic stepping

When the simulate flag is set to *true*, every *Portal* cycle runs the simulation for a certain number of steps. In this mode the user can intervene in the simulation

at any time, but will be acting on the simulation as it is running. That means that if there is gravity and a ball is created, it will start falling immediately. This mode is perfect to see a system evolve on its own, after initial conditions have been set.

Stepping at will

The simulate flag might be set to $false$ while setting the initial conditions of a system, creating some new object, moving things around or simply just stop the simulation. But the simulation can advance even if the simulate flag is always false. This is made through the Step Once Service. This service allows the user to advance the simulation at will. This is useful when the user wants to run the simulation only a certain number of times and then stop, or when he wants to give a set of service calls for every time step. For example, when driving a motor by feeding it the instantaneous velocity at each time step, one would like the simulation to stop between velocity commands, in order to give the user time to react or process information.

4.5 Step values

Step values are those variables that define how the simulation is going to handle time. There are four step values:

- The time to be simulated in one single step.
- The number of simulation steps to be taken within a *Portal* cycle.
- The time to be simulated in one *Portal* cycle, that is the time that passes in the simulation between publications.
- The publication rate.

It is easily deduced that the third value is the product of the previous two (figure 4.5). For this reason the callback function hides an interesting algorithm that allows the caller to define any number of values (from one to four), and the function

will calculate the remaining and return the final values. In case of conflicting values, precedence is given to simulation step and *Portal* step size, to the detriment of the number of steps in a Portal cycle.

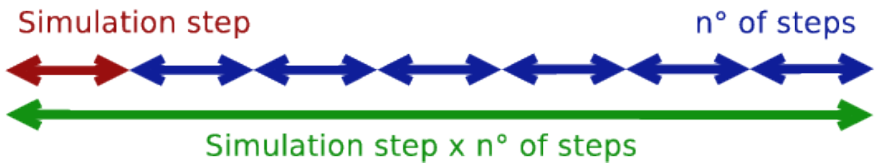


Figure 4.5: Step values diagram. In red, the time simulated in a *Core* cycle. In green, the actual time simulated in a *Portal* cycle. A *Portal* cycle includes the publication, thus the publication rate is the cycle rate.

As a matter of fact, the simulation time elapsed between *Portal* cycles is not a member variable, because the other values determine it univocally. But it is accepted by the Set Step Service: it is just a user friendly variable.
The default step values have been chosen so that one second in the virtual world equals one second in the real world, as it can be seen in table 4.1

Contact-less collision	$false$
Simulate	$false$
Number of *Core* steps in a cycle	40
Publishing rate	$25fps$
Simulation time elapsed between cycles	$0.04s$
Simulation step (Core)	0.001

Table 4.1: Default values for *VirtualWorld::Portal* and step sizes for *VirtualWorld::Core*.

4.6 Closing

When closing the process the function closes *Core* and shuts down the node. When prompted for a new simulation, it just restarts *Core* and calls the same service on the *Viewer*.

Chapter 5

The Virtual World Core

The very beating heart of this project is the dynamics simulation engine inside the *VirtualWorld* node: the *VirtualWorld::Core* class.
While *Portal* deals strictly with *ROS* features, *Core* performs the specific actions of the module: creates the virtual world, acts on it and simulates.
Core works symbiotically with four smaller classes which perform easy, specific tasks, such as body, geometry and joint creation, or force and torque management. They are *BodyManager*, *JointManager*, *BodyForce* and *JointForce* (figure 5.1). Each one will be analyzed in the following sections.

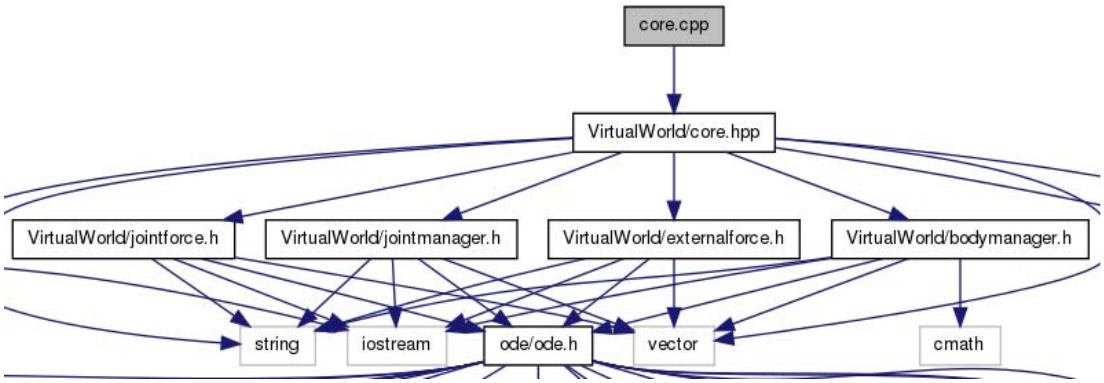


Figure 5.1: Detail of dependency graph for *VirtualWorld::Core*.

The *Core* class is initialized by *Portal* by calling *VirtualWorld::Core::init* (figure 5.2). This function involves the following tasks:

1. Initialize the *ODE* library.

2. Create a new simulation environment.
3. Instantiate body and joint creation classes.
4. Allocate the data that is required for accessing ODE from the current thread.

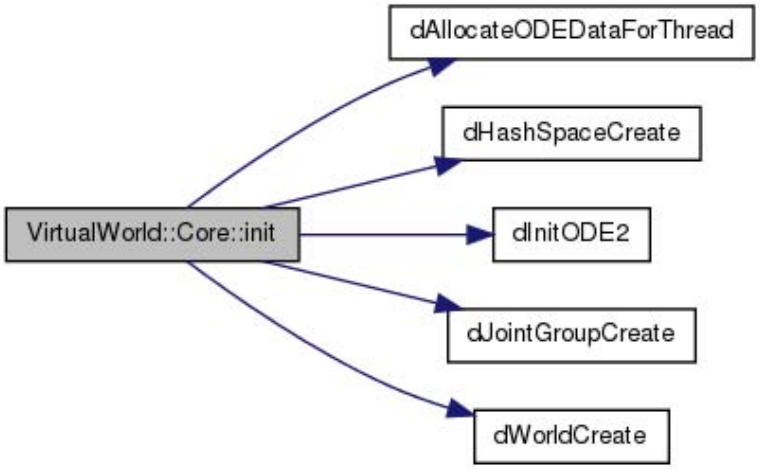


Figure 5.2: Call graph for *VirtualWorld::Core::init*. The space, the world and the joint group are parts of the new simulation environment.

After all these tasks have been performed, the thread is ready for simulation.
The simulation is an integration process through which time is advanced by a given step size, and every object state is adjusted for the new time value. It involves two separate processes: rigid body dynamics simulation and collision detection.
Rigid body dynamics deals with the object's dynamic properties. It computes the evolution of the system using the laws of motion considering joints, constraints and forces.
Collision detection deals with the object's shape and defines new constraints that are passed back to the dynamic simulator.

Anyway, no simulation makes sense unless there is actually something to simulate. The first section will cover object creation and modeling.

5.1 Object modeling

Open Dynamics Engine models an object as a combination of two concepts: body and geometry.

5.1.1 The body

A body is a set of data, some of them are variable and some others are constant. Conceptually each body has a coordinate frame embedded in it, that moves and rotates with the body, as shown in figure 5.3. The frame's origin corresponds to the body's center of mass, and body variables are always referred to this reference point.

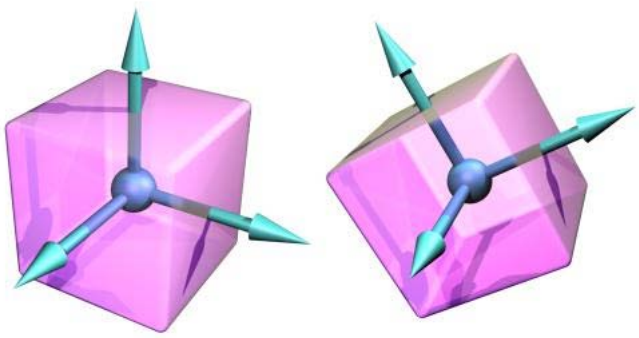


Figure 5.3: The body coordinate frame moves with the body[3].

The variables are:

- Position vector (x, y, z).
- Linear velocity vector (v_x, v_y, v_z).
- Orientation quaternion (q_w, q_x, q_y, q_z), also represented by a 3×3 rotation matrix.
- Angular velocity vector (w_x, w_y, w_z).

The remaining body properties are constant over time:

- Mass value.
- Inertia, a 3×3 matrix.

5.1.2 The geometry

A geometry is a set of data describing shape, position and orientation (Fig. 5.4). It is associated with a position and an orientation, but has no dynamic properties, such as velocity or mass.
In order to move during the simulation, a geometry must be attached to a body. This way both share position and orientation, and together describe the object.

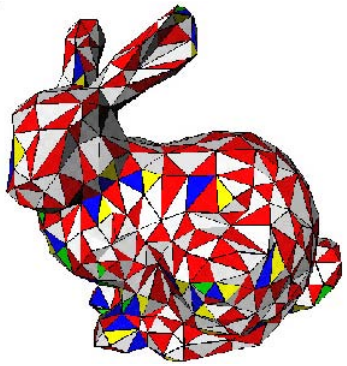


Figure 5.4: The geometry: shape.

5.1.3 Objects

Every object in *ODE* has one body, but can have multiple geometries. Therefore, in *ODE* (and in *Odin*), body and object are basically equivalent concepts.
There are five types of objects that can be created:

- Spheres;
- Cylinders;
- Boxes;
- Composites;
- Triangle meshes.

The first three are simple primitives, and are built using native *ODE* functions that automatically determine the inertia matrix from shape and total mass.

Composites

A composite is an object made of multiple primitive geometries (figure 5.5). *ODE* allows this kind of objects but they have to be built in a certain way to work well:

1. First, create the body and attach it to the first geometry, as if it was a normal object.
2. Then, for each part:
   (a) Create the geometry.
   (b) Create the mass.
   (c) Attach the geometry.
   (d) Move and rotate the geometry to its correct position respect to the body's center of mass.
   (e) Move and rotate the mass.
   (f) Add the mass to the body's mass.

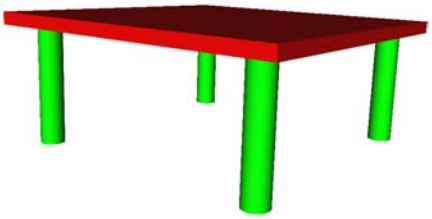


Figure 5.5: A table built as a composite made of box and cylinder primitives.

These tasks are performed automatically by the *Core*, with the help of the body builder: *BodyManager*.

Triangle meshes

A triangle mesh (figure 5.6) is defined by two vectors: a vertex vector that reports the position of the shape boundary points, and a index vector that tells how those vertices are ordered to create triangles.
While for primitives and composites the inertia matrix is automatically determined by the library, in the case of triangle meshes it is not. If the user does not define an inertia matrix, the identity matrix will be set by default.

Figure 5.6: Triangle mesh: palm of a robotic hand.

5.1.4 Objects in the simulation

The dynamics simulation engine uses body information altogether with the movement limitation given by joints and other constraints. In fact, rigid body dynamics engine does not deal with shapes or geometries, but deals only with bodies.
The collision detection engine, on the other hand, deals uniquely with geometries. At every time step it figures out which bodies touch each other and returns the resulting contact point information. A *Core* function then uses that information to define new constraints by creating contact joints between bodies.
The rigid body dynamics simulator works with a "world", an element that contains all the bodies and constraints. On the other hand, the collision detection engine works with a "space", that contains all geometries. Both these elements are created on initialization.

5.1.5 The BodyManager class

Object creation in *VirtualWorld* is managed by the *BodyManager* class. A *BodyManager* instance is present in *Core* as a private member, and creates the objects in the world and space given at the time of construction.
This class was created in an attempt to simplify the *Core* class, and to provide tools to make object and geometry creation simpler.
In fact, *BodyManager* handles the creation of bodies and geometries by requiring only essential information and figuring out the rest. For example the kind of primitive does not have to be explicit, because it is determined by the number of shape parameters: if there is one parameter it is going to be a sphere's radius; if there are two they will be a cylinder's radius and length; if there are three they will be the sides of a box, and if there are more, they are going to describe a triangle mesh.
BodyManager can also create body-less geometries, that can be used to represent objects that never move but collide with the rest of the world.

5.2 Simulation parameters

There are a few parameters that can be set to improve the quality of a simulation.

- Step size: most of dynamics calculation involve Taylor transformation's first members instead of the actual motion equations. Thus accuracy increases as the step size decreases.
- Linear and angular damping: avoid that objects drift indefinitely. After each time step, linear and angular velocities are compared to a threshold. If they are bigger than that threshold, they are reduced accordingly to the damping parameters. They can be set in a $[0, 1]$ interval for the value, and in a $[0, +\infty)$ for the threshold.
- Gravity: it is defined through a vector, thus giving the possibility to decide direction, intensity and versus.
- Contact Surface Layer: it is the depth an object can sink into another before contact is made. Even a very small value can help preventing jittering problems due to contacts being repeatedly made and broken.
- Error Reduction Parameter: when for some reason a joint happens to be out of alignment or a constraint is not met, a special force is activated to bring the bodies back into alignment. The Error Reduction Parameter is a value in the interval $[0, 1]$ that determines the fraction of error this force has to correct in a time step.
- Constraint Force Mixing: allows to soften the constraint by letting it to be violated by an amount proportional to the value times the restoring force that is needed to enforce the constraint.

The CFM and ERP can be used to simulate a spring-damping constraint with the following rule:

$$ERP = \frac{hk_p}{hk_p + k_d} \tag{5.1}$$

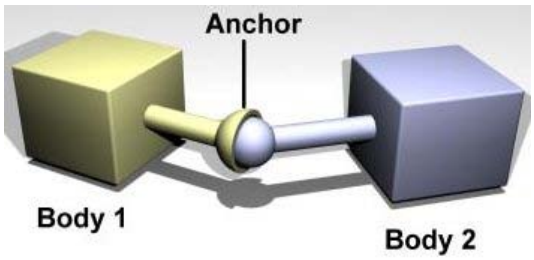
$$CFM = \frac{1}{hk_p + k_d} \tag{5.2}$$

5.3 Joints and JointManager

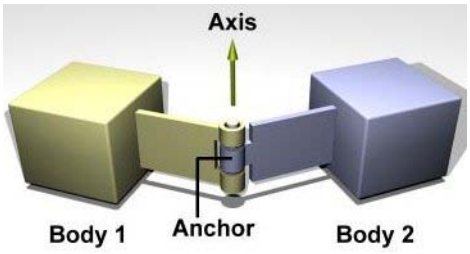
where h represent the step size, k_p the spring constant and k_d the damping constant[3].
A joint in *ODE* is represented as a constraint that imposes a relationship between two bodies. At each time step, all the joints are allowed to apply constraint forces to the bodies they affect. These forces are calculated by assuming that the bodies have to move in such a way to preserve all the joint relationships.
There are several kinds of joints, each one constraining a different set of degrees of freedom:

- Ball and socket: keeps the anchor point still in the frame of reference of each body (figure 5.7a).
- Hinge: is defined by an anchor and an axis. It is like a ball-socket but constraints an additional degree of rotation, allowing rotation only along the axis (figure 5.7b).
- Piston: a slider that does not constraint rotation along the axis (figure 5.7c).
- Slider: allows bodies to translate along an axis, but any other degree of freedom is denied (figure 5.7e).
- Universal: a cardan joint, like two perpendicular hinges with the same anchor (figure 5.7f).
- Double hinge: used to simulate vehicle suspensions, is composed of two hinges connected in series, but with orthogonal axes (figure 5.7d).
- Prismatic and Rotative: a combination of a slider and a hinge (figure 5.7g).
- Prismatic and Universal: a combination of a slider and a cardan joint (figure 5.7h).

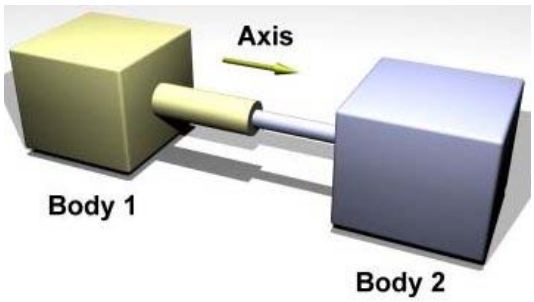
A joint usually connects two bodies, but it can also connect a body and the static environment. This case is useful, for instance, to model the moving base of a robot.



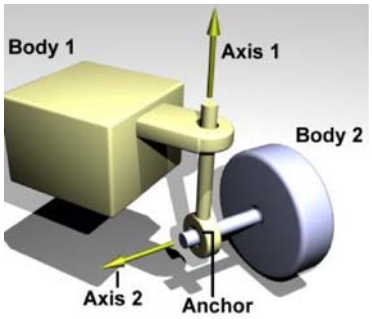
(a) *Ball and socket.*



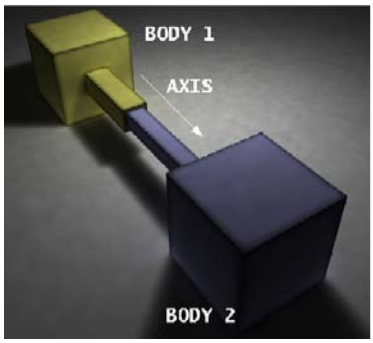
(b) *Hinge.*



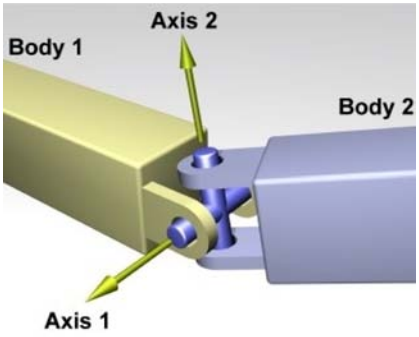
(c) *Piston.*



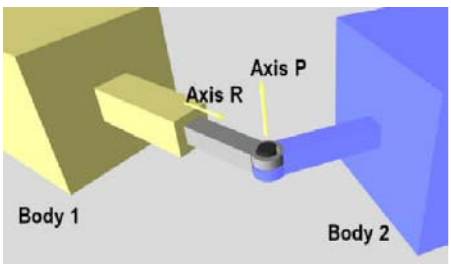
(d) *Double hinge.*



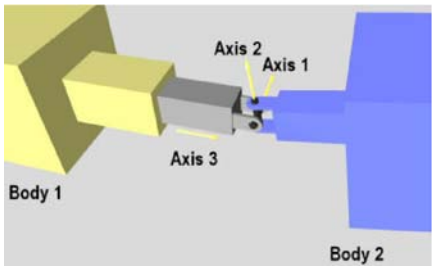
(e) *Slider.*



(f) *Universal.*



(g) *Prismatic-Rotative.*



(h) *Prismatic-Universal.*

Figure 5.7: The joints are just constraints and do not have a visual representation in the *Viewer*, hence these are just graphical aids to help understand the nature of each joint [3].

There are two additional, special joint types: the fixed joint, that constrains all DOFs among two bodies, and the contact joint, generated whenever a collision happens. The first one is not very well implemented in *ODE*, and has to be used with caution. The second one will be described in the collision section.

5.3.1 Motors

Another thing *JointManager* can do is to create motors. In *ODE*, a motor is a type of soft constraint that allows the relative velocities between two bodies to be controlled.
There are two kinds of motors: angular and linear. The user must set the velocity axes and the maximum force allowed to the motor. Once the desired speed is set, the motor will try to achieve it in one time step, limited by the maximum force allowed. The velocity axis, by default is anchored to the first body, but can otherwise be anchored to the second body or the static environment.
All motors are initialized with infinite force and null speed.

5.3.2 Additional parameters

JointManager provides functions to set some additional parameters on joints and motors. For instance, stops can be set on a joint to limit its range of motion, which can be bouncy, rigid, have customized CFM, ERP etc.

5.4 Motion

5.4.1 Setting object position and velocity

Position and velocity are body properties that are set when the body is created. They change over time, as the simulation advances, but they can also be changed through *Core* functions.

5.4.2 Forces and torques on bodies

Besides the forces generated as a result of a constraint or gravity, forces and torques can be applied to the bodies, for them to take part in the simulation. The force itself is not added when it is created, but is added at every step, as will be explained later.
A force or a torque is created by instantiating an *ExternalForce* object, which is defined by a target body pointer, a magnitude and a direction. The direction can be given either in the body's frame of reference or the world's one, while the point of application can be either the center of mass or another point, which can be given in both frames of reference.

5.4.3 Forces and torques on joints

JointForce is the *ExternalForce*'s sibling class that represents forces and torques on joints. The *JointForce* object's fields are a target joint pointer and a magnitude: it can either be a force on a sliding joint, a torque on a hinge or ball-socket joint. In the future, it will be possible to add forces and torques on other kinds of joints, but for now this feature is limited to those three. Since the target is a joint and not a generic body, no direction information is needed: it is deduced from the joint data instead.

5.4.4 Using motors

A motor is a type of soft constraint that applies all the force available to reach the goal speed, without surpassing it. Thus, another way of acting on the bodies is to create a motor and then control its speed.
On creation, *Core* creates a motor through *JointManager*, and creates a *JointForce* object that manages the motor's velocity.

5.5 Core's simulation step

Actually, *Core* does not have a running cycle because *Portal* has, and calls *Core*'s functions to step the simulation. There are two stepping functions, *contactStep* and *contactLessStep*, that share a common structure:

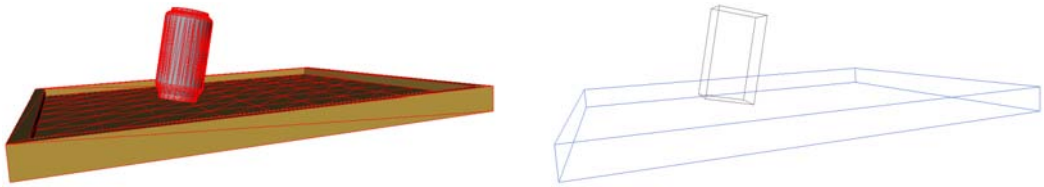
1. Detect and handle collisions.
2. Add forces and torques to bodies.
3. Add forces and torques to joints and set goal speed on motors.
4. Take a step.
5. Reset unmovable bodies, to prevent unwanted errors.

All external forces and torques are deleted automatically at the end of each step. That is the reason why they are all added before each step.
As the names suggest, the difference between the step functions resides in the way collisions are handled: one creates contacts, the other does not.

5.5.1 Collision detection

The space

Collision handling is one of the most important features of *Odin*. Its mechanism resides in the space, that is the object that contains all geometries. Among the space kinds available in the *ODE* library, the one chosen is the multi-resolution hash table space. It uses an internal data structure that records how each geometry occupies cells of three-dimensional space. This strategy speeds up collision culling if the cell sizes are accurately chosen, and if objects are not clustered together too closely. These consideration have made it easy to chose the hash space over the normal space (and the quad-tree-space, because it is still under development [3]).



(a) Wire frame overlay view. (b) Bounding box view.

Figure 5.8: Example of two objects close together but not colliding yet. Collision culling is made on bounding boxes, and their bounding boxes intersect. In this case, objects pass both collision culling and bounding box test, but are discarded when the final check is performed, that is when the collision points are searched.

Collision detection

Collision culling is the process that shortlists the pairs of geometries that are more likely to be colliding. This process is followed by a bounding box collision check, that creams off the best candidates for the final collision detection (figure 5.8).
The last process consists in finding collision points, if there are any. At this point, the program can either just record the names of colliding objects, or it can create contacts between them and handle collisions in a realistic way.

5.5.2 Contact-less collision handling

This *PQP*-like collision policy consists in pushing the colliding bodies' names in a list, without building any contacts (figure 5.9). It means that objects will simply slip through each other during simulation, inter-penetrating each other just like in a *PQP* simulation.
The list will then be accessed by another part of the program.

5.5.3 Contact collision handling

This kind of simulation is more realistic, because objects do not slip through each other but make contact and interact with each other.
This behavior is achieved through the creation of special joints that last only one

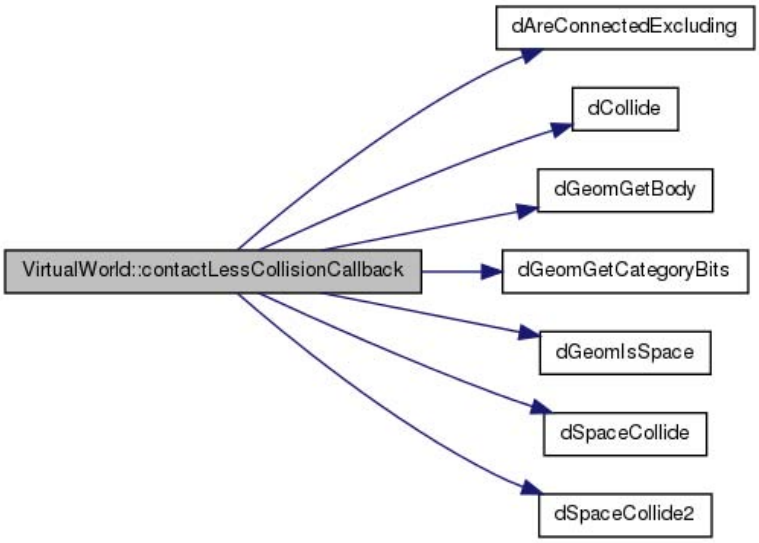


Figure 5.9: Call graph for *VirtualWorld::Core::contactLessCallback*.

step: the contact joints (figure 5.10). A contact joint constraints the bodies to have an outgoing velocity along the contact normal. Theoretically, the contact normal is the direction along which lies the shortest distance a body has to move, in order to stop colliding. Actually the one used is an approximation calculated by an *ODE* function. The *ODE* library, in fact, provides a function that besides determining if and where a pair of geometries collide, can create a contact joint. Those joints have to be attached to the colliding objects, and have to be destroyed after each step.
The maximum number of contacts allowed between a pair of geometries is a simulation parameter that influences significantly the quality of the simulation, slowing it down at the same time as the number increases. At the same time, a combination of contact joints can simulate rotation, pivoting and other contact behaviors.

An example of collision

Imagine a box falling corner-side on a table, colliding inelastically. When the parts touch, a ball joint is created in order to simulate the first contact. Within a short amount of time, the box will fall and the edge will completely touch the surface

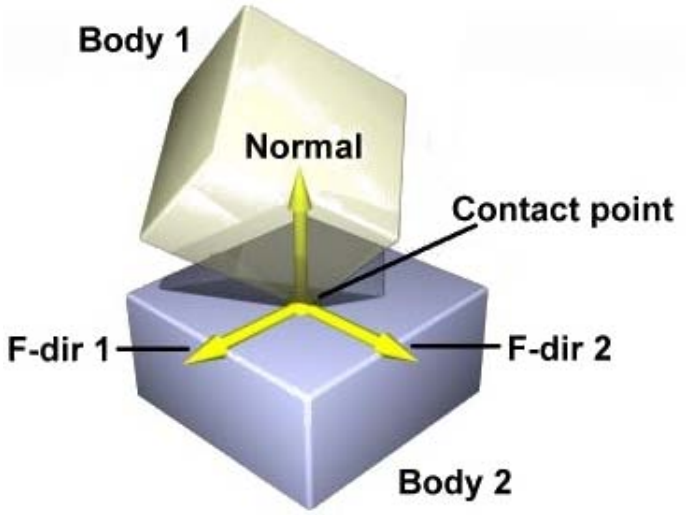


Figure 5.10: A contact joint.[3]

and then a hinge joint is created. Finally, the box will rotate along the hinge axis and will lay all a side on the surface, thus a plane joint is created: the kind of joint created depends on the type of collision. Therefore, the more the contact joints, the more realistic the simulation, on detriment of speed.

5.5.4 Optimizations and exclusions

Frequently there are situations in which collisions detection among some specific bodies has to be avoided, mostly because it slows down the simulation significantly to have bodies permanently colliding. Therefore, a few solutions have been found to make it possible to exclude some pairs of geometries from collision detection (an example is given in figure 5.11).

Since most of the data fed to the simulator consists of kinematic chains or trees, the collision has been optimized in order to ignore collisions between consecutive objects of a kinematic chain: if two objects are already connected with a joint, no contact is created.

Another possibility is to avoid collision detection within an entire group of bodies, e.g. the whole kinematic chain. This function is the one called when an Entity Service from *Portal* arrives with an internal collision flag set to $false$. In this

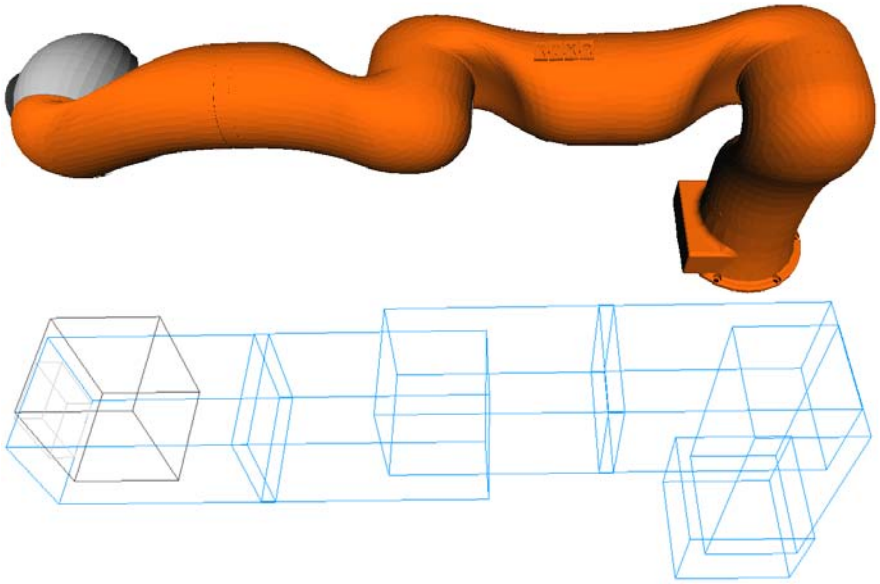


Figure 5.11: Robot geometries' bounding boxes will always collide, so it is a smart move to avoid collision detection among them.

case, a special geometry property is used to avoid collision detection among a group of geometries.

5.5.5 ODE step

ODE's function *worldStep* allows to determinate the dynamic evolution of the system over the next time step. This uses a "big matrix" method that takes time on the order of m^3 and memory on the order of m^2, where m is the total number of constraint rows.

It bases its calculations on first Taylor's transformation members for quadratic equations, therefore it is more accurate when the time step is very small. That leads to repeat its operation many times before reaching any noteworthy advance. Whenever the simulation run time is considered enough, some information can be extracted from the simulation, using the features exposed in the following section.

5.6 Information extraction

When *Portal* wants to publish on some topic the results of the simulation, it has to call a function in *Core* to retrieve it. The most important information about the simulation is the current position and orientation of each geometry. As explained in chapter 4, the information published about the state of the world involves geometries, and not bodies, since that is what is shown in the *Viewer*. In fact, the *Core::getTransformation* function iterates all the geometries, and for each one it gets its position and orientation.

Another function implemented gets position and speed of every existing joint. Although this information is published by *Portal*, no subscriber has been implemented in *Odin*.

The last information that can be retrieved from the simulation is, in case of contact-less collision detection, a list of colliding geometries. The act of reading this list automatically clears it, deleting every name on it. This makes sense because many cycles can happen before this list is read, and the calling class would like to know about all objects that have collided in the last steps, and not just in the last one.

5.7 Check functions

As it was explained before, *Core* stores all objects, joints, motors and external forces in different maps, to quickly find them by their names. Specularly, it has a complete set of functions to find the names by their pointers, find a joint by the bodies it connects, and check name validity.

5.8 Close

Closing means deleting every body, geometry, joint, forces, space and world, and clearing every list and register in the class. This function does not stop the main method, meaning that *Portal* can call *close* and then *init* just to reset the simulation.

Chapter 6

The Viewer

Figure 6.1: The *Viewer* logo: the Triple Horn of Odin[21].

6.1 Previous versions

Throughout the developing of *Odin*, several attempts have been made to make a working *Viewer* node. The main reason for that is that the viewer requirements have changed over time. At first, the idea was to put the *Kautham* in a ROS shell and use its *Coin3D* based viewer. Then, the idea changed and it was thought to separate the viewer from the *Kautham* and put them into separate *ROS* nodes. But the idea has always been that of using a *Coin3D* based viewer, because of the *Kautham* experience and previous work with that environment.

6.1.1 Drawstuff

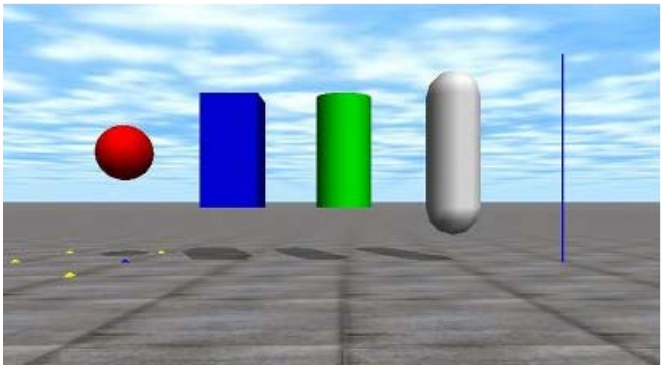


Figure 6.2: *Drawstuff*, *ODE*'s default viewer

To visualize the world, the easiest way would have been to use *ODE*'s integrated visualizer, *Drawstuff* (figure 6.2). This library is already tested, working and of simple use. But there were a few reasons not to take advantage of it:

- *Drawstuff*'s interface is terminal based, no *GUI* is provided nor any kind of user friendly features is developed.
- It has to be integrated in the *ODE* environment, which means it is neither modular nor flexible.

Kautham Project's *Coin3D* based viewer already visualizes robot and kinematics, and is developed in a *Qt* graphic framework, which makes it very flexible and prone to future changes. If one day someone wants to integrate the viewers it is going to be a simpler task if *Odin*'s viewer is already based on this one.
Hence, it was decided to take advantage of *Kautham* viewer's source code and develop it to work with *ROS*, in order to transform it in an independent stand-alone entity: a module just like *VirtualWorld*.

6.1.2 The QtRos attempt

A first attempt to build a *ROS* integration was made using *Qt_Ros* (figure 6.3. *Qt_Ros* is a package that provides tools, templates and other utilities that assist

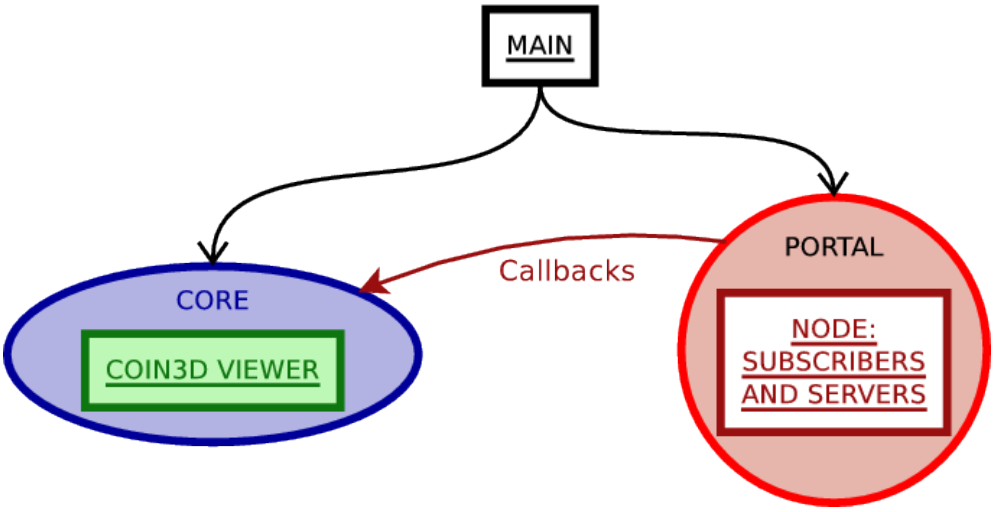


Figure 6.3: Conceptual scheme of the *QtRos* attempt. *Portal* and *Core* are two separated threads that work in parallel, communicating through a pointer given by the *main* function that instantiates both classes.

people in developing *Qt* applications in a *ROS* environment with minimum effort. It generates a template comprising a subscribing node that works in a parallel thread to a window thread, referring to each other through respective pointers exchanged in the *main* class.

The idea was to create a *Core* class by putting an instance of *Coin3D* viewer in the window, and extend the subscribing node to make an effective *Portal* for the *Viewer* node. The *Portal* worked as a communication central, handling topic subscription and the server calls from *VirtualWorld*. Each callback function then called *Core* functions to update the scene.

The *Core* class contained the viewer and kept the scene stored. It also acted on the scene tree every time the callbacks from *Portal* called the modifying functions. But it turned out that *Coin3D* is not designed to be used with multi-threading. And in this case, *Portal* was a thread calling functions in *Core*, a parallel thread. The result was a very unstable program, that crashed randomly in segmentation fault errors, sometimes after a few minutes, sometimes after a few seconds. Several attempts were made to try to ensure thread-safe operation, from applying write and read locks on the scene tree to the use of signal-slot connections from the

Boost library, but none worked.

6.2 Final solution

Giving up the idea of having two separated threads that worked in parallel, the final solution consists in unifying *Core* and *Portal* in one thread. The node is actually set up in the *main* and not in the *Portal*, which instead manages all *ROS* communications. The *Core* is a member of *Portal* and handles the viewer, as shown in figure 6.4.

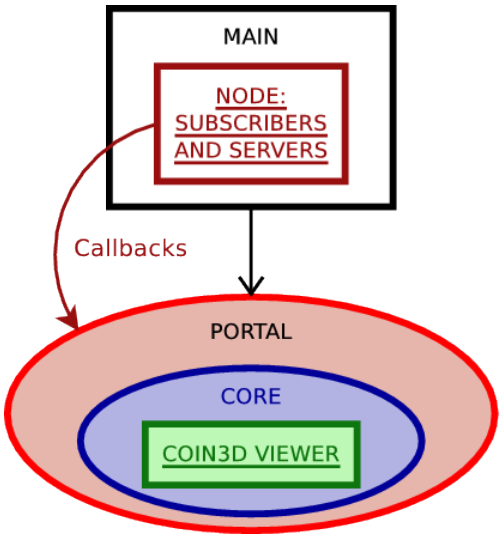


Figure 6.4: The final solution: one thread.

6.2.1 The main

The main launches the *Qt* window and sets up a ROS communications central (figure 6.5):

- Sets up servers for object creation and scene reset.
- Starts subscribers to the world situation topic and the collided objects topic.

ROS spinning through callbacks is timed by the *Core-Portal* thread, to ensure seamless connection to the scene tree modification functions. This was done substituting the *ROS* timer with a *Qt* timer, that emits a signal on time out connected to the spinning function, through the *Qt* signal-slot mechanism. Hence there is no *ROS* cycle: spinning through the available callbacks is made in *Qt*'s own cycle instead.
The timer is calibrated in order to get the scene updated at 25fps, a common value for frame refreshing rate because it is faster than the human eye.

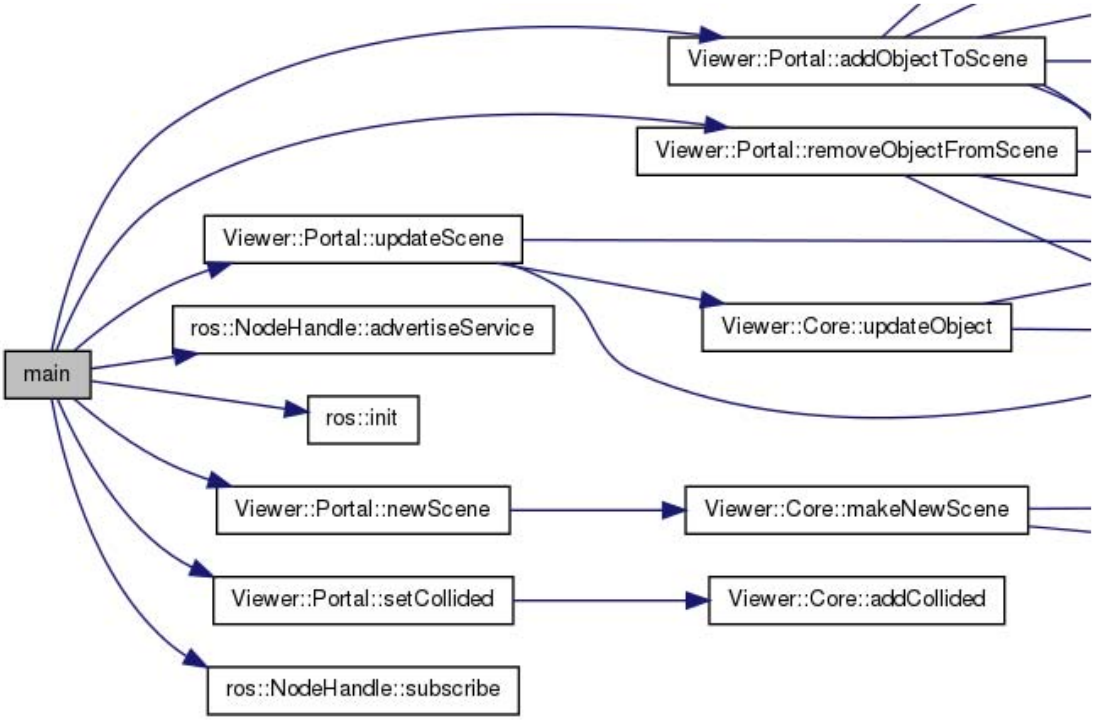


Figure 6.5: First levels of Call Graph for *Viewer*'s *main*, that sets up the node, the servers and the subscribers.

6.3 Portal

Although *Portal* in this case does not set up the node, it actually grants access to the *Core*, because here reside the callback functions that, called from the *main*, act on the *Core* (figure 6.6). In fact, *Core* is a private member that gets initialized on construction.
This class builds also the window, that works as a container for the *Core* viewer. The callback functions of this main window allow to:

- Reset the scene;
- Add and remove objects to the scene: calling the build/remove function in the *Core*;
- Update the scene, calling the *Core* updating function on every object, by passing it the latest position and orientation read from the topic;
- Add the names of colliding objects to a *Core*'s dedicated list.

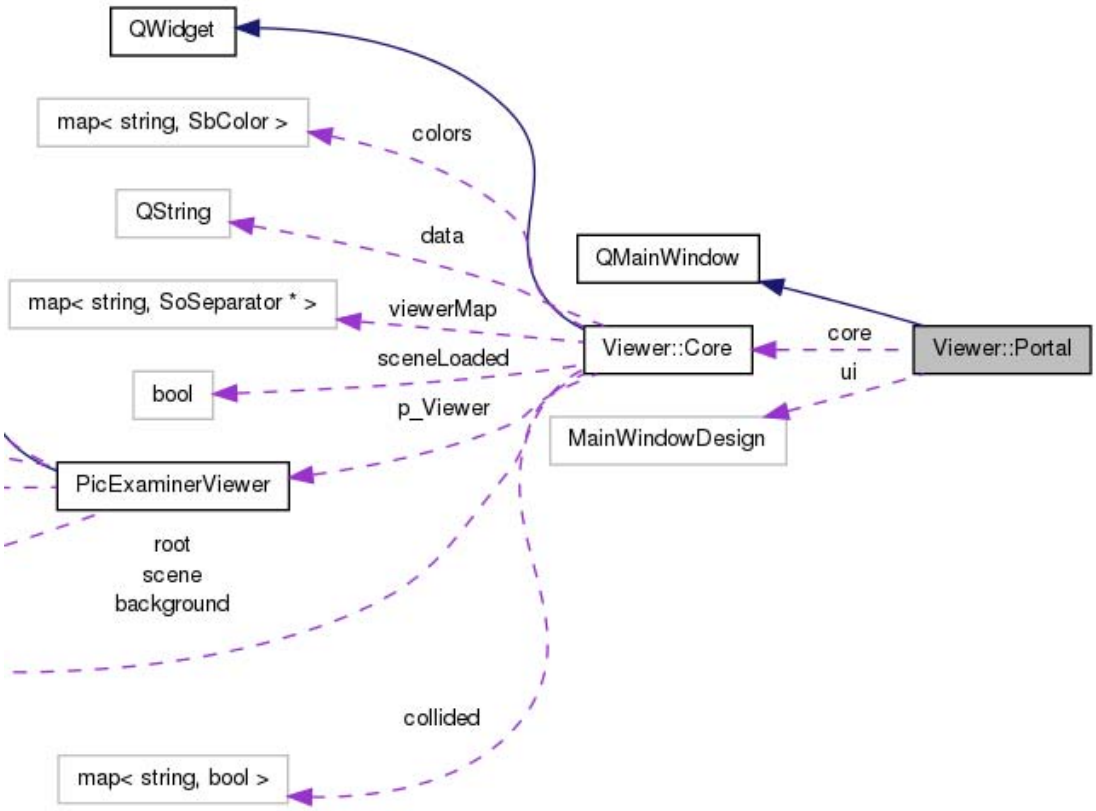


Figure 6.6: First levels of Collaboration Diagram for *Viewer::Portal*.

Whenever *Portal* acts on the scene tree, it makes sure it is locked from reading to avoid memory access errors, and unlocks it when the action is over.
As it was explained before, the *Viewer* node has a special structure due to its thread restrictions. In fact, the *ROS* spinning function that calls all available callback functions resides in this class, and not in the *main*, where the node is set up.

6.4 Core

The *Core* is the actual viewer (figure 6.8), based on *Coin3D*'s *SoQtExaminerViewer* (figure 6.7). Thus, the scene is stored in a tree structure, where all elements are children of a scene node, child of the root node.

Figure 6.7: The Coin3D's SoQtExaminerViewer.

6.4.1 Objects

An object is a Separator node with three children:

- The transformation node, that stores position and orientation;
- The color node;
- The shape node, which defines the object's geometry.

Every Separator node is stored in a map that stores key–value pairs consisting in the identification string (key) and the separator node (value). This map allows instant access to the separator node when an action on its nodes is needed.
Object creation means making a new Separator node and storing it into the object map. Then the three children nodes are created and filled with information. Once the object is created, the viewer zooms out to give a view of the whole scene.
Besides the name, the color is stored in a different map. This is needed to restore the original color in case the object has appeared as colliding, and therefore temporarily changed its color to dark gray.

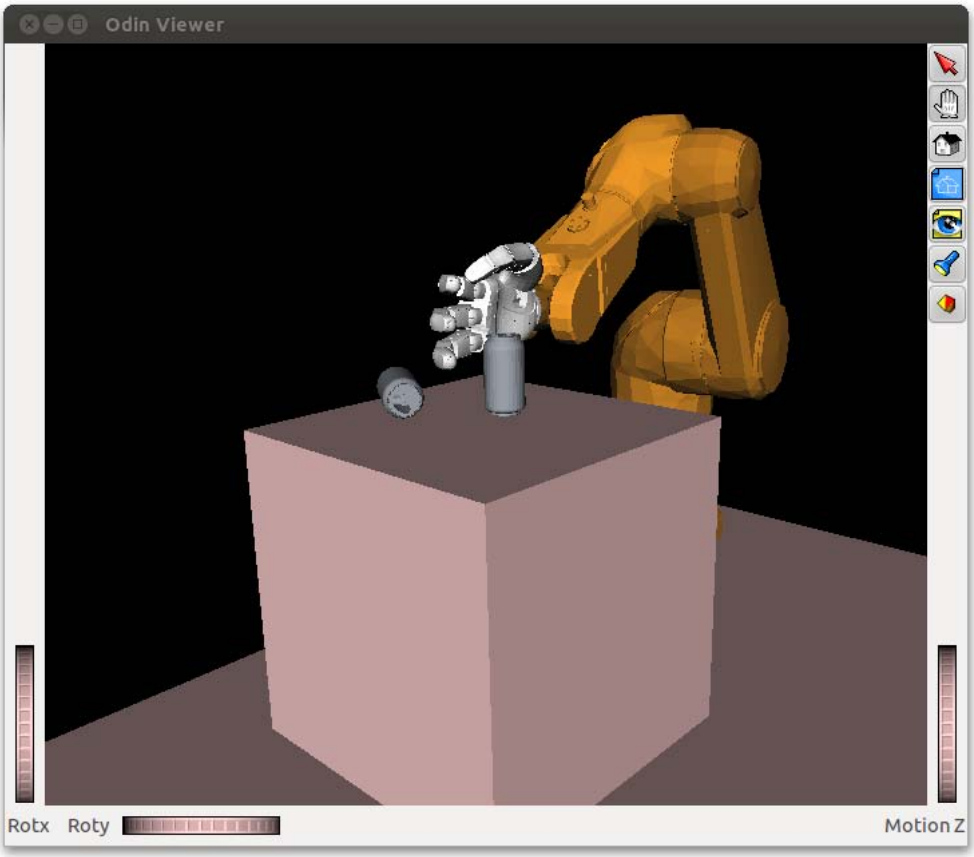


Figure 6.8: The Viewer. In this scene every object is a triangle mesh.

6.4.2 Updating the scene

Whenever *Portal* calls *Viewer::Core::updateScene*, *Core* will update position and orientation of the node, with data collected by the main's subscriber. While *ODE* has the real part of the quaternion as the first term (w, x, y, z), *Coin3D* has it as the last (x, y, z, w). Thus the topic argument has to be reordered to match the new convention.

When updating an object, *Core* also checks if the object appears as colliding. If it is, changes its color to a default gray. Then it clears the colliding status, so that in the next cycle the object will recover its original color.

Obviously in the case of contact creating collision handling policy objects will never appear as colliding, because no collision list is ever published.

6.4.3 Resetting the scene

The separator node is a child of a scene node, which in the meantime is the only child of the root node. This redundancy (the scene node could be removed because it contains no additional information) is needed to make a quick change of scene just by replacing the root's child with a new scene node.
In fact, when a new scene is queried, *Core* clears all maps and lists, closes the scene and then replaces the scene node with a new one.

Chapter 7

The GUI Portal

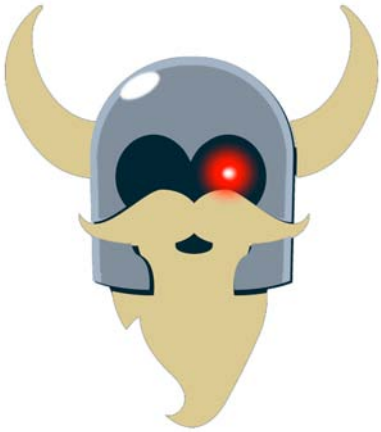


Figure 7.1: *Odin GUI* logo[22].

Odin's front-end is the Graphical User Interface, developed under a *Qt* framework. Like the other modules, it is composed of a *main*, a *Portal*, a *Core* and minor classes.
This node contains only *ROS* clients, and the *GUI* can be seen as an automatized way of calling services.
While the *main* serves only to build the executable, the *Portal* contains the graphical interface and sets up the *ROS* node and its clients. Whereas the *Core*, on the other hand, is used mainly to process input files and return the data to the *Portal*.

As a *Qt* gui, structurally it is a widget divided in five tabs:

1. Simulation: to handle the fundamentals of a simulation and open problem files;

2. Settings: to set step sizes and all other parameters;

3. Objects: to build, remove and position objects;

4. Motion: to manage forces and paths;

5. Joints: to build, remove and set joints.

7.1 First tab: Simulation

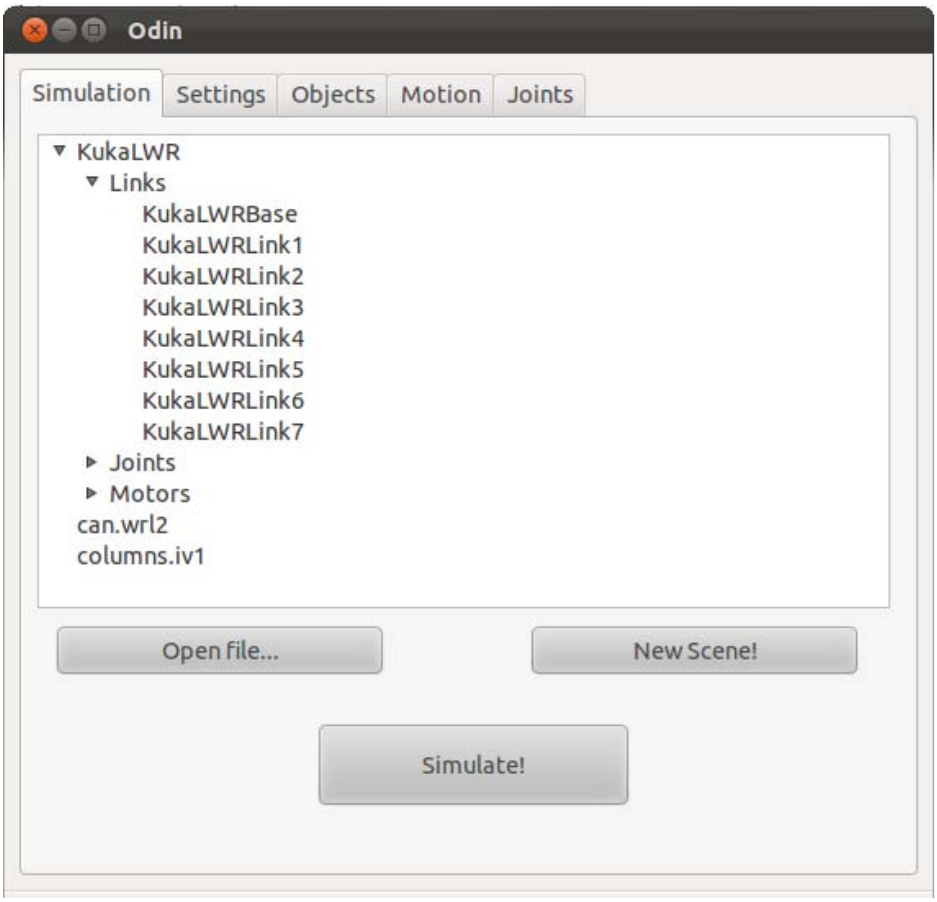


Figure 7.2: First page of *Odin GUI*. A problem file has been opened, and has appeared in the tree view: a Kuka robot, a can and columns.

The Simulation tab (figure 7.2) does basically three things:

- Requests for a new scene.
- Opens a file.
- Visualizes all scene elements IDs.
- Starts and pauses the simulation.

Asking for a new scene involves resetting all lists and memories in the widget.

Clicking the *Open file* button pops up a widget in a new window. This widget prompts the user to choose a file within its filesystem, with the *XML* extension. This file is then processed by *Core*, which returns the data and lets *Portal* build the scene based on the information in the file.
This feature is created to read and process *Kautham* style problem files, which describe a scene with some robots and becomes, through *Portal*, a series of service calls to build entities, objects, joints and motors.
Whenever a new element is built, it is stored internally in a tree structure and visualized at the top half of the page. This view lets the user know which objects, joints and motors have been sent, and to which robot they belong.
The *New scene* button resets the scene in the *VirtualWorld* (which will command the same thing to the *Viewer*), effectively resetting all lists and tree data structures in the gui.
The *Simulate* button calls the Simulate Service to start (figure 7.3b) or pause (figure 7.3a) the simulation.

(a) *Simulation paused.* (b) *Ongoing simulation.*

Figure 7.3: The button changes aspect and text on clicking.

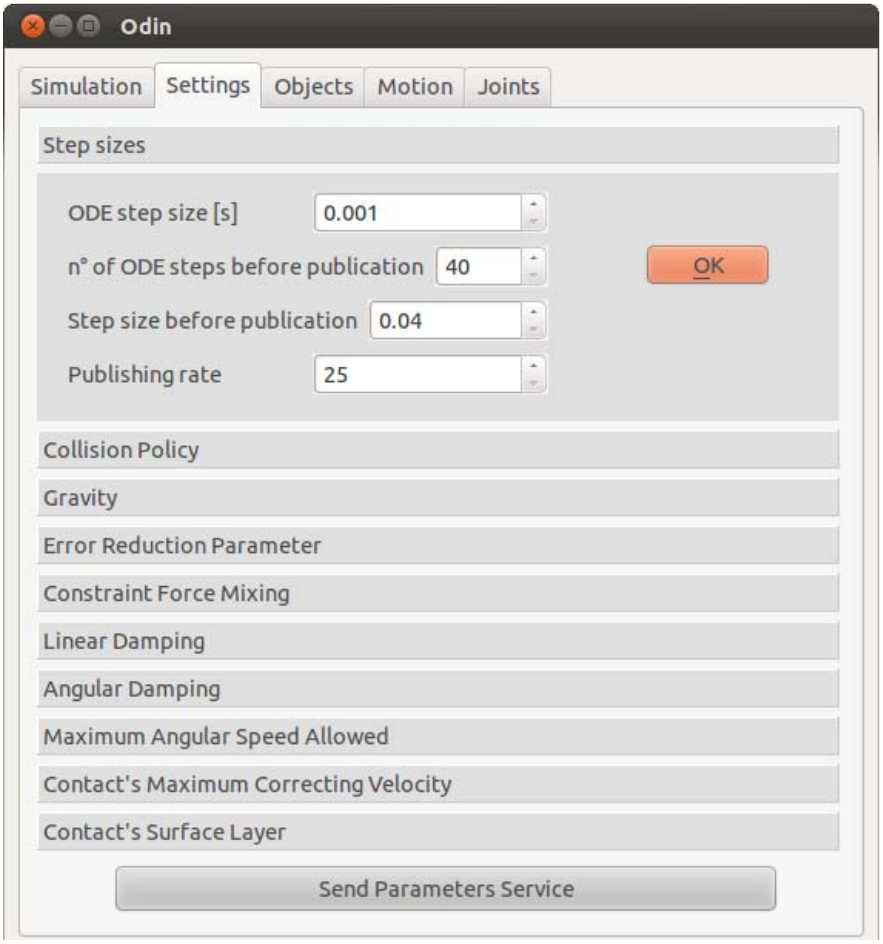


Figure 7.4: Second page of the *GUI*. Step sizes tab shows the default values.

7.2 Second tab: Settings

The second page (figure 7.4) allows setting actions on every parameter.
Actually only two services are called from this tab:

- World Set Service.
- Step Set Service.

The tab is organized as a tool box, with two buttons: one for step setting and one for the other parameters. A *Qt* toolbox is a widget that displays a column of tabs one above the other, with the current item displayed below the current tab (opened items displayed in figure 7.5). One tab is dedicated to the step services,

the others to the other parameters.
Whenever the definitions of step sizes are not consistent with each other, some of them are changed in *VirtualWorld* in order to match the others, and the actual values are returned and displayed in the step tab.

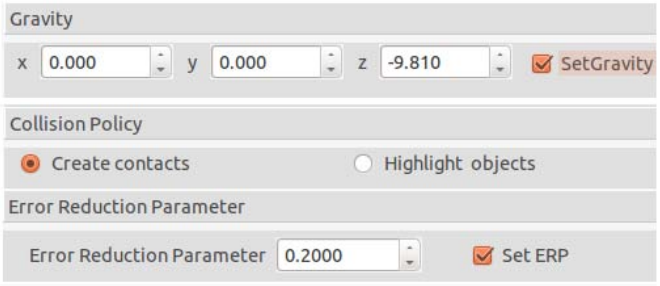


Figure 7.5: Details of Settings tool box: Gravity, Collision policy and ERP tabs open. In the parameters section, almost every parameters needs a check box, since zero is actually a valid value for each one of them.

7.3 Third tab: Objects

The third tab is for object managing (figure 7.7). It allows creation, removal and position setting on each object in the simulation.
To create an object, the user has to insert a valid name (a name that is not used already). Then a shape must be selected from a drop-down menu, choosing among sphere, cylinder, box and a trimesh (figure 7.6).

In the last case, a window will pop up to allow input from file. In the other

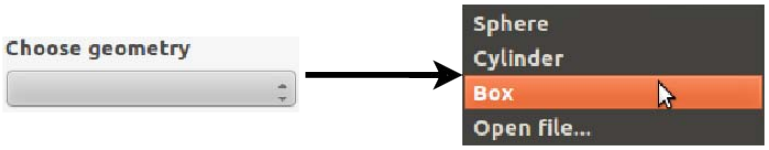


Figure 7.6: The shape selection drop down menu.

cases, the Parameters widget below the Shapes menu will change to show spin boxes for the insertion of geometric parameters.
Those parameters are in fact hidden in a stack widget. When a shape is chosen,

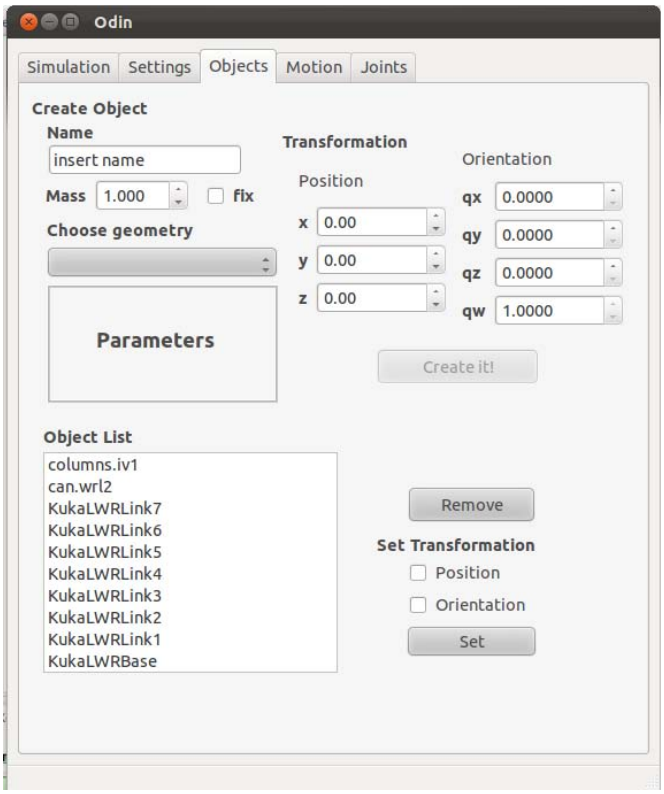
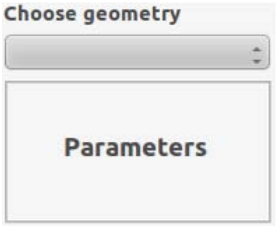
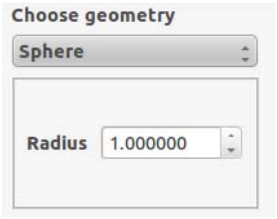


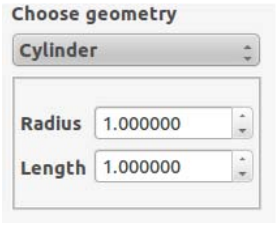
Figure 7.7: Third page of the *GUI*: object management.



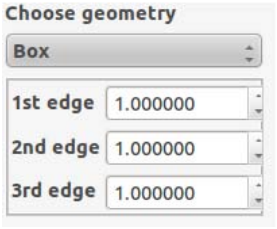
(a) *Neutral parameters.*



(b) *Sphere parameters.*



(c) *Cylinder parameters.*



(d) *Box parameters.*

Figure 7.8: Parameters are hidden in a stack widget. When a shape is chosen from the drop down menu, the correct parameters page appears on top.

the correct parameters page appears on top (figure 7.8). For each parameter, from the radius of a sphere to the four values of a quaternion, there are some preset values, that save the user the boring task of setting some random values to every parameter just to see something happen.
Each and every parameter has validity limitations, that are hard coded so that, for example, no one will ever have the chance of sending a message with a negative value for the mass.
The lower half of the widget contains a simple list of all objects in the scene. Each object can be selected for its deletion, or to change its position and/or orientation.

7.4 Fourth tab: Motion

The Motion page is organized, as well as the Settings one, in a Tool Box widget (figure 7.9). It is an interface to act on:

- Objects, by setting velocities, forces and torques.
- Joints, by setting forces and torques.
- Motors, by setting velocity controls.
- Robots, through path files.

7.4.1 Moving an object

The object motion tab allows to add forces acting on the center of mass as well as in an offset point, and the position and force vectors can be defined either relatively to the global frame or relatively to the body's own frame of reference. Besides the force, a torque can be set by just defining its intensity in a vector.
Whenever one of these actions is performed, the force ID returned from *Virtual-World* is stored and visualized in the bottom list, allowing each force or torque to be selected and deleted.
Another way of moving an object is by directly setting a velocity, either linear or angular. But these two actions only act for one step, since forces and torques

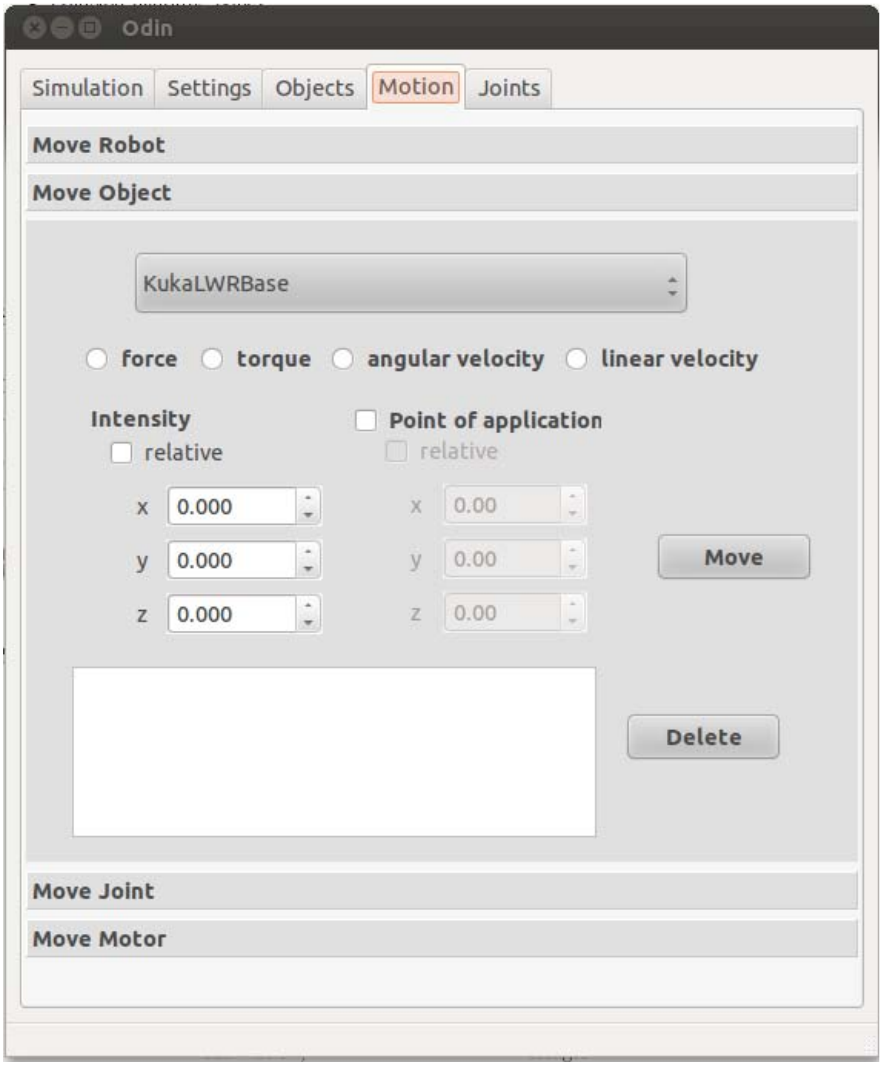


Figure 7.9: Fourth page of the *GUI*: motion.

and other constraints in the simulation will change the velocities in the following steps.

7.4.2 Moving joints and motors

Moving a joint is a much simpler task. The user chooses the joint from a drop-down menu (figure 7.10) among those present in the virtual world, and sets the action intensity: *VirtualWorld* itself will deduce, from the kind of joint, if the action is either a force or a torque, and will set the proper action to the target

bodies.

Just like in the previous tab, also this one contains a list of existing joint forces and torques, which can be selected and removed. For motors, it is even simpler.

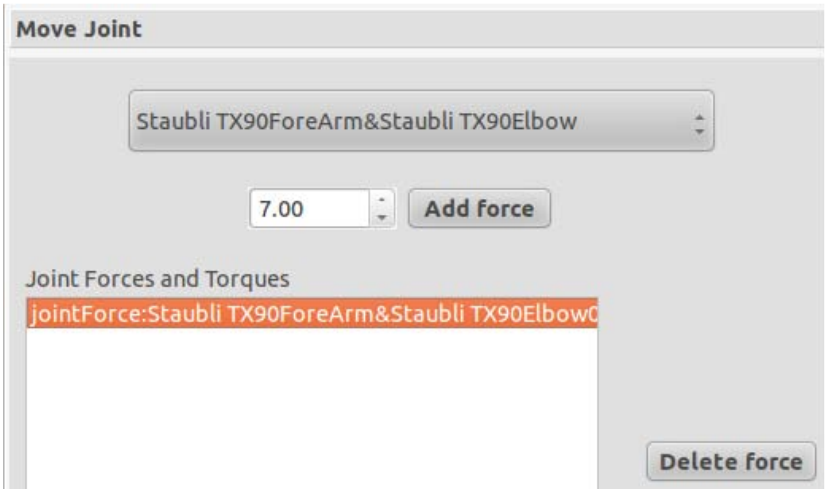


Figure 7.10: Detail of joint motion tab.

There is no list, just a menu to choose the motor (figure 7.11), a spin box to set the desired velocity and a button to send the message.

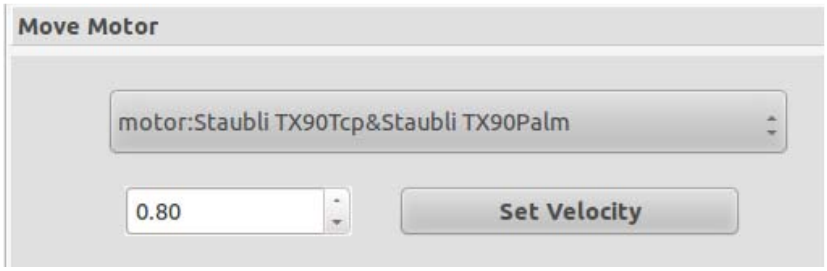


Figure 7.11: Motor motion tab.

7.4.3 Moving robots

Robots motion is done via path files, which are processed in the *Core*. Four buttons are available (figure 7.12):

- Setting the initial position. A file containing the angles of the joints is fed to the *GUI* through a pop up window, the *Core* translates it in position

Figure 7.12: Robot motion tab.

values for every object composing the robot and the Set Position Services are called.

- Velocity path: data is retrieved from a file containing velocity values for every motor. The robot starts to move from the initial position, and a service is called at the same publishing rate set in the Settings tab, every time setting the velocity values for each motor. It is a speed control motion.

- Position path: a file containing angles of joints for every time step is sent to the *VirtualWorld* in Set Position Services.

The velocity path involves a motor that applies the force to the body to achieve the goal speed. This means that the simulation can be at a fine grain scale while the file can still be at gross grain: one can just set the simulator to take many little steps between publications.
Otherwise, the position path involves setting the position of the robot at each time step, thus even if the simulator takes many steps between messages, in that lapse of time the objects will stay still, moving abruptly when the next message arrives. Thus, this kind of simulation is more "artificial", while the velocity path simulation can be seen as more "natural". In fact the position path will actually move the robot even if the simulation is paused, while the velocity path will not. The difference between position and velocity paths is appreciated in collision detection with contacts. When moving a body abruptly it will, from a step to

another, collide with another body in many points at the same time. Thus many contact joints are created in a single step and can conflict with each other: since a contact is a constraint, conflicting constraints reduce to zero the degrees of freedom of the colliding object, which stops moving at all.
This has been resolved by setting to three the maximum number of allowed contacts between objects, but it is an indicator of how a velocity path simulation will lead to more realistic collisions with respect to position paths. Another tool to improve collision precision is a button that allows to refine a position path to smaller steps. This tool interpolates between consecutive points to double the thinness of the step size.

7.5 Fifth tab: Joints

The fifth tab aids in the creation of joints(figure 7.14). It allows to choose the type of joint from a drop down menu (figure 7.13). Then there are two menus to choose the bodies among those present in the simulation.
There are spin boxes to define the geometric properties of the joint. Depending on the kind of joint, some rows will be enabled. For example, to build a hinge, only two rows are needed: therefore the third one will be disabled until another kind of joint is chosen.
Several parameters can be set for each joint. They can be defined either on a new joint, before creating it, or on an existing joint, by choosing it from the list. It is also possible to remove a joint, just like objects.

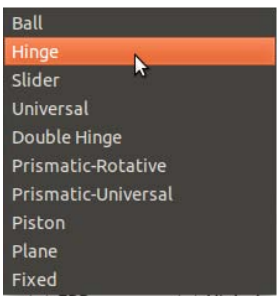


Figure 7.13: Joint type can be chosen from a drop down (combo box) menu.

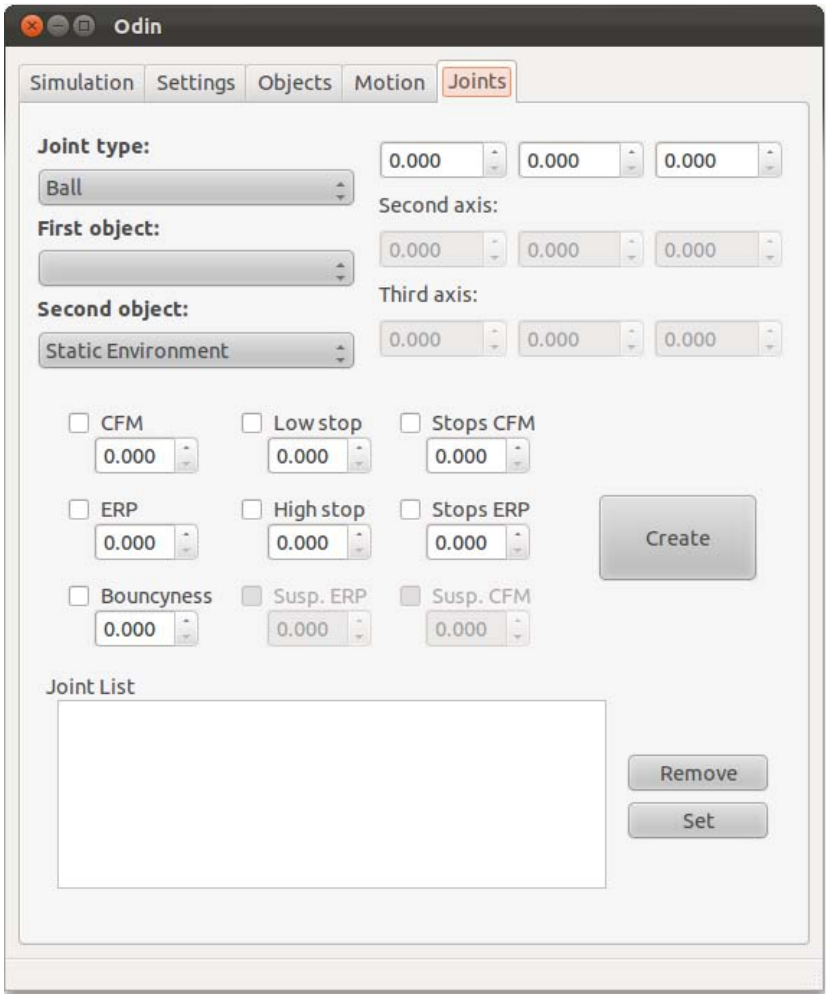


Figure 7.14: Joint creation page.

Chapter 8

The GUI Core

8.1 Reading a file

The *Core* deals mainly with processing problem, shape and path files. Problem files come in *XML* format, shape files are written in *VRML* and paths are simple text files.

8.2 Processing problem files

The *XML* problem files ideated in the *Kautham Project* are a tree structured representation of a situation of interest in robotics. The *Core* uses the *PugiXML* library to transform the file into a *Document Object Model* tree structure, which allows to navigate the tree and access the node contents (figure 8.1).

Here is an example:

```
1 <?xml version="1.0"?>
2 <Problem name="example">
3   <Robot robot="robots/KukaLWR.rob" scale="1.0">
4     <Limits name="X" min="0.0" max="1000.0" />
5     <Limits name="Y" min="0.0" max="1000.0" />
6     <Limits name="Z" min="0.0" max="1000.0" />
7     <Limits name="WX" min="0.0" max="1.0" />
```

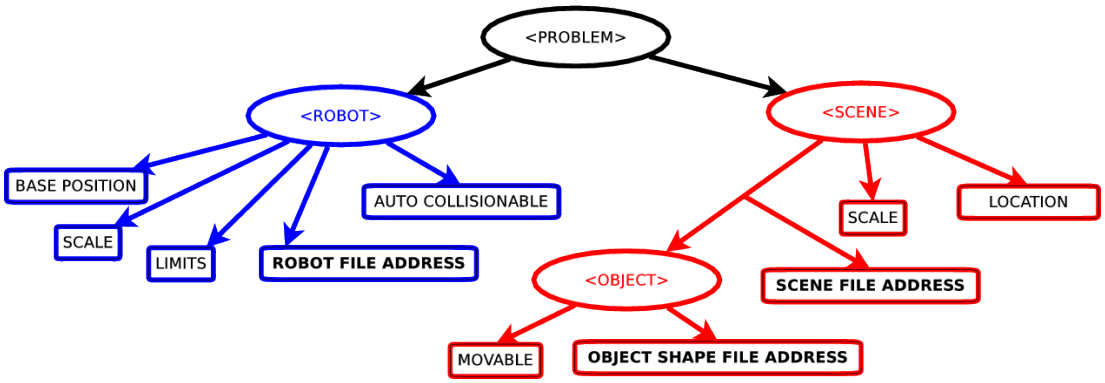


Figure 8.1: The *Document Object Model* tree structure of a problem file. Ovals: tree nodes, Boxes: values. In bold, address values.

```
8     <Limits name="WY" min="0.0" max="1.0" />
9     <Limits name="WZ" min="0.0" max="1.0" />
10    <Home TH="0.0" WZ="1.0" WY="0.0" WX="0.0" Z="0.0" Y="400.0" X="
          -300.0" />
11  </Robot>
12  <Scene scene="scenes/columns.iv" scale="18.0" movable = "false">
13    <Location TH="0.0" WZ="0.0" WY="0.0" WX="1.0" Z="0.0" Y="0.0" X=
          "250.0" />
14  </Scene>
15 </Problem>
```

Thus the first step consists in the creation of a problem node. Then an iterator is created, in order to sweep all robots and scene elements.

In case of a robot element, the program finds the *.rob extended named file (figure 8.2), searching it using data stored in the XML problem file. Those robot files have the *.rob* extension and look like this:

```
1 <?xml version="1.0" encoding="UTF-8"?>
2 <Robot  name="KukaLWR" DHType="Modified" robType="Chain">
3   <Joints size="8">
4     <Joint name="Base" ivFile="kukaLWR/base.wrl">
5       <DHPars alpha="0.0" a="0.0" theta="0.0" d="0.0"></DHPars>
6       <Description rotational="false" movable="false"></Description>
7       <Limits Hi="0" Low="0"></Limits>
8       <Weight weight="1.0"></Weight>
9       <Parent name=""></Parent>
```

```
10      </Joint>
11      <Joint name="Link1" ivFile="kukaLWR/link1.wrl">
12        <DHPars alpha="0.0" a="0.0" theta="0.0" d="310.0" ></DHPars>
13        <Description rotational="true" movable="true" ></Description
              >
14        <Limits Hi="170.0" Low="-170.0"></Limits>
15        <Weight weight="1.0"></Weight>
16        <Parent name="Base"></Parent>
17      </Joint>
18       .
19       .
20       .
21 <Joint name="Link7" ivFile="kukaLWR/link7.wrl">
22        <DHPars  alpha="-90.0" a="0.0" theta="0.0" d="78.0"></DHPars>
23        <Description rotational="true" movable="true"></Description>
24        <Limits Hi="170.0" Low="-170.0"></Limits>
25        <Weight weight="1.0"></Weight>
26        <Parent name="Link6"></Parent>
27      </Joint>
28    </Joints>
29 </Robot>
```

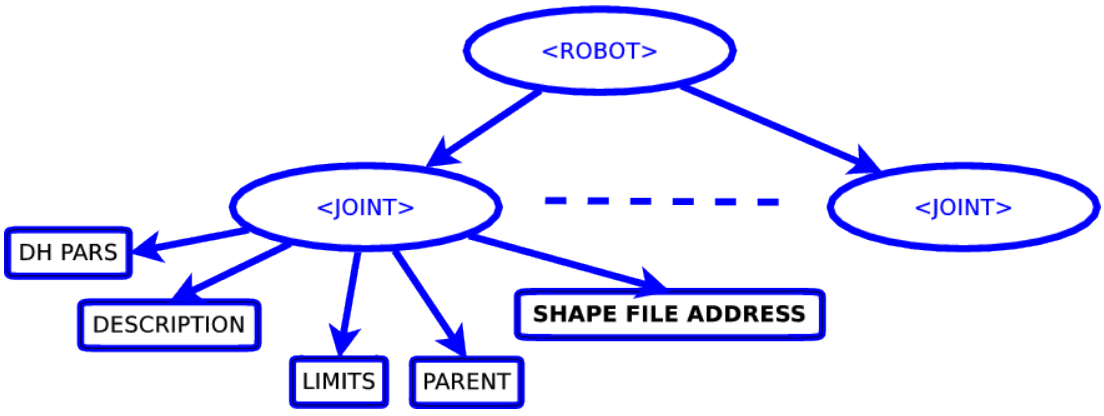


Figure 8.2: The *Document Object Model* tree structure of a robot file.

The base position was retrieved from the problem file, and the orientation is converted from axis-and-angle to quaternion. The positioning of each subsequent

element of a robot is defined with Denavit-Hartenberg coordinates, thus a conversion takes place here too.
The program then iterates through robot parts and stores them in an object vector. Since physics analysis is a new feature, most problem files don't define masses and inertias, hence default values are defined. For each object a name is defined (from file name), then the geometric data is processed.

8.2.1 Processing shapes

The shape is stored in an VRML file, which is read and processed. Any shape is turned into a triangular mesh: the mesh is defined by two vectors: vertices and indices. The vertices define the points of the triangles, the indices identify which points define a triangle.
After triangularization, if n triangles were defined, $3 \times n$ vertices and $3 \times n$ indices are produced by *Coin3D* methods. This information is redundant, thus those vectors are optimized to reduce their number and avoid double vertices.

Triangle mesh optimization

```
1  unsigned int count = 0;
2  double tolerance = 0.00001;
3
4  for (unsigned int i = 0; i < vec.size(); i+=3)
5  {
6    unsigned int j = 0;
7    for (; j<obj->vertices.size(); j+=3)
8      if (((obj->vertices[j]-tolerance)<=vec[i])&&((obj->vertices[j]+
           tolerance)>=vec[i])
9        &&((obj->vertices[j+1]-tolerance)<=vec[i+1])&&((obj->vertices[
             j+1]+tolerance)>=vec[i+1])
10       &&((obj->vertices[j+2]-tolerance)<=vec[i+2])&&((obj->vertices[
             j+2]+tolerance)>=vec[i+2]))
11       break;
12     if (j<obj->vertices.size())
13       obj->indices.push_back(j/3);
14     else
```

```
15      {
16        obj->vertices.push_back(vec[i]);
17        obj->vertices.push_back(vec[i+1]);
18        obj->vertices.push_back(vec[i+2]);
19        obj->indices.push_back(count++);
20      }
21  }
```

In the code, the input vertices vector is named *vec*, while the outputs are *vertices* and *indices*.
This optimization is a custom made process, that creates a new pair of vectors. Before inserting a new vertex, a check is performed to assure it is not already in the vector, taking into account a certain tolerance. If it is already in, it is not pushed in, but the index of the first copy is pushed in the indices vector. If it is not already in, it is a new vertex. It is inserted and a new index is pushed into the indices vector. Finally, object color is gotten if present.
The last task is analyzing the object motion to deduce the kind of joint (connected to the parent) and motor parameters. The object can be immovable, in which case no joint is stored but a flag is activated. Otherwise a joint connected to the parent is stored. Low and high stops are set on joints if existing.

In case of a scene element, like a table or a column, the program gets the object's transformation through a field in the problem file. The scenes can either be a single object or another robot, in which case the problem file addresses another robot file. In the first case, the location node is read and stored in a position vector, while the shape address is used to find the *VRML* file. The shape information is processed with the *Coin3D* library to convert it to a triangle mesh representation.

All objects built are named from their file name and their parent nodes name. In case of colliding names (which usually happens for scene objects) a number is added at the end of the name.

8.3 Increasing path resolution

The other task performed is increasing the step definition of a position path. This is achieved by making a linear interpolation between consecutive position vectors. Linear interpolation might not be a correct reproduction of the effective path wanted by the user, and indeed this process does not pretend to do that. This action serves only the purpose of feeding the *VirtualWorld* a finer grained path to avoid strange behaviors in collision handling.

Chapter 9

Costs Analysis

Since *Odin* is a free software project, it will be distributed under the *GNU General Public License*. Therefore, every software tool and library used in this project is free of charge under its license agreement and conditions.

This chapter's goal is to make a cost analysis under the assumption that it will be distributed with a commercial license.

9.1 Lines of code

A first estimation of costs involves the cost of work. Since the author is not an expert professional programmer, it is assumed that he is able to produce 150 lines of code per day. Assuming a total cost, involving taxes, of 150€per day, the cost of a line of code is $1€/line$.

9.1.1 Line count

The program *CLOC* is a tool to count lines of code that automatically excludes comments and blank lines. Its output on the project's analysis, excluding examples and documentation, counts nearly thirty thousand lines. Anyway, since *Qt* and *ROS* have their own code generating compiling tools, some of this code was auto generated. On the other hand, messages and services are not recognized by *CLOC*, thus are not counted. A more honest analysis can be made considering

only the files actually written by the author. The output of *CLOC* on *Odin* gives:

Language	files	blank	comment	code
C++	13	521	381	3350
C/C++ Header	10	377	2132	728
CMake	4	52	89	100
XML	4	21	2	65
SUM:	31	971	2604	4243

Table 9.1: Total costs.

with 1795 for the *GUI* module, 615 for the *Viewer*, 1819 for the *VirtualWorld* and 14 for the *Odin* stack.
The Messages and Services files contain 30 and 125. All those line number do not include comments or blank lines.

9.2 Commercial licenses

Of all code libraries used in this project, only two have a commercial license that has to be bought in order to produce a saleable program: *Coin3D* and *Qt*.
The first one costs 2342€. The second has more than one, but for the use made in this project, the *Qt-one platform-light edition* might be enough: 1510€.

9.3 Total cost

Programming	4398, 00€
Licenses	3852, 00€
Sum	8250, 00€

Table 9.2: Total costs.

The final cost will then be: 8250, 00€.

Chapter 10

Results

Several simulations have been made in order to test the simulator. In this chapter, three simulations will be shown and described. The first two will focus on contact and contact-less collision handling, while the third will show the simulation of a grasping problem.

10.1 Collisions without contacts

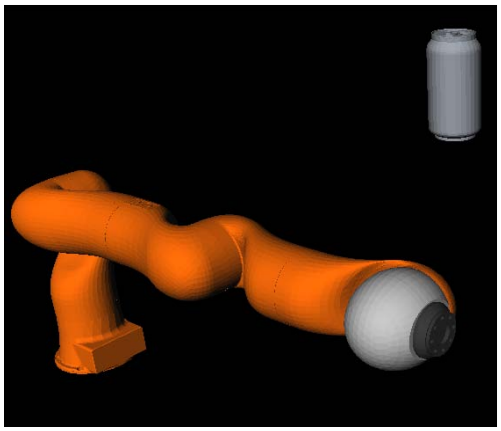


Figure 10.1: Starting position: a *Kuka* robot and a can.

To better see how contact-less simulation works, a very simple example has been chosen. A *Kuka* robot is at rest, horizontal to the ground (figure 10.1, while a can falls and slightly touches the end of the robot.

The can starts moving downwards and approaches the tip of the robot (figure 10.2a). In figure 10.2a it can be observed that even if very close, the objects are not touching and, indeed, are not highlighted. But when they do, as in figure 10.2c, they suddenly change their color to a default gray.

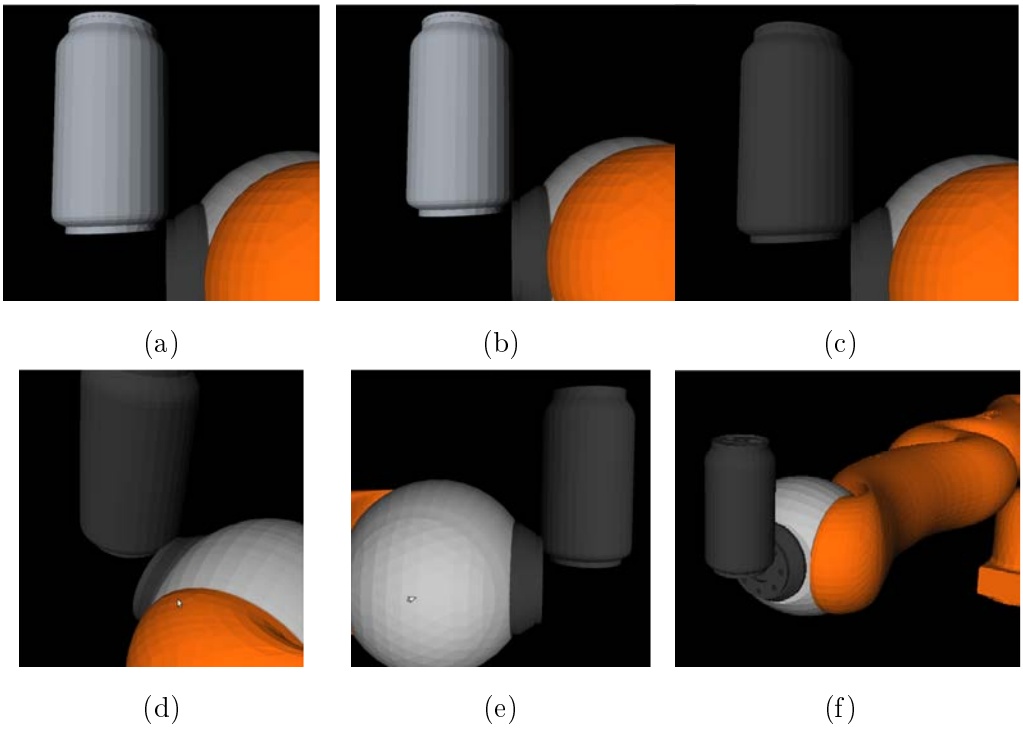


Figure 10.2: A can falls and touches the *Kuka*'s end.

10.1.1 Observations

This simulation did not slow down when the objects collided. This is due to the fact that no constraints are added to the simulation matrix when not creating contacts. Also, the simulation was successful because the can and the robot part highlighted correctly. In fact, no error could be detected even looking very closely to the contact area.

The simulation parameters are described in the following table.

Collision policy	Highlight contacts
Number of steps in a cycle	1
Publishing rate	$10 fps$
Simulation step	0.001
Gravity	$(0, 0, 0)$
Contact surface layer	0.0

Table 10.1: Parameters used during the last simulation. Those not defined had the default values.

10.2 Collisions with contacts

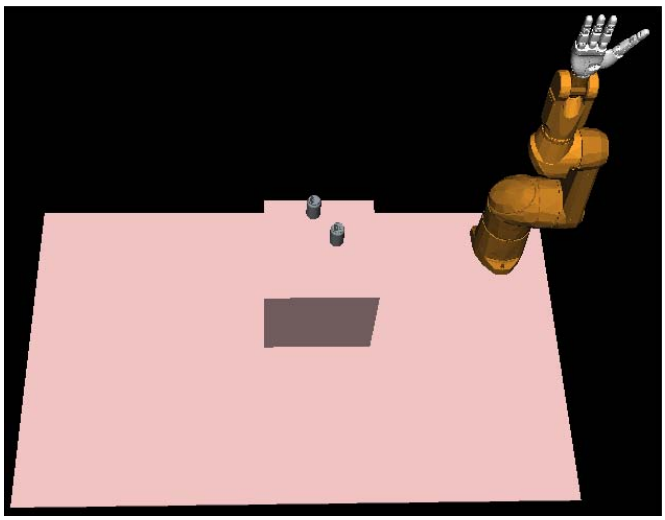


Figure 10.3: The scene is loaded from an *XML* file named "TX90_RHand_ICRA10_5PMD_TwoCanb_new".

Another interesting simulation is watching a *Staubli TX90* robot, equipped with a *Schunk SAH* anthropomorphic hand, hit a pile of cans. Like the previous simulation, it can show both collision and gravity, but this time with contacts. Through the user interface, the scene is loaded (figure 10.3) using the *Open file* button. Then the robot is set to its starting position by setting its motors velocities by hand. At last, the cans are positioned by simply changing its position. The result is figure 10.4a.

By setting the base's motor velocity to $0.1 rad/s$, the robot starts to rotate (figure

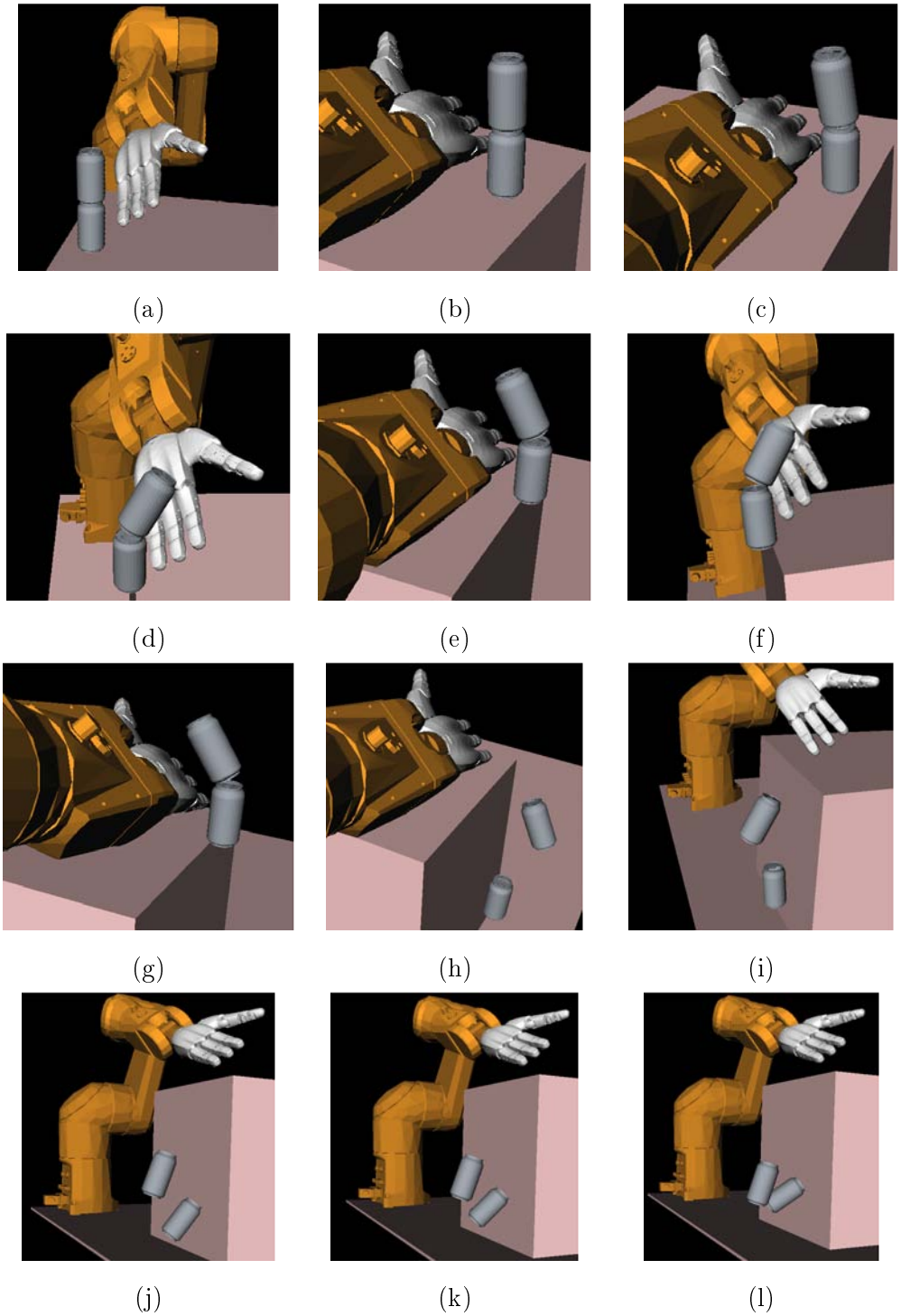


Figure 10.4: Throwing a pile of cans setting motor velocities.

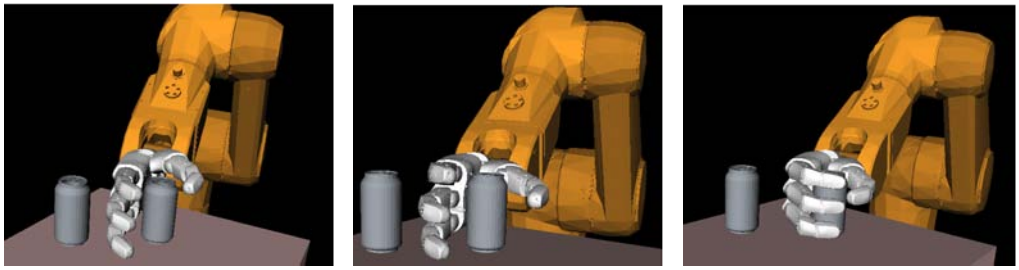
10.4b), and eventually hits the bottom can (figure 10.4c). The cans keep moving

while the robot eventually stops (figure 10.4f). In figures 10.4h and figure 10.4i, the cans drop to the ground, accelerated by gravity. In figure 10.4j, the bottom can already reached the ground and bounce, thus moving upwards.

10.3 Grasping

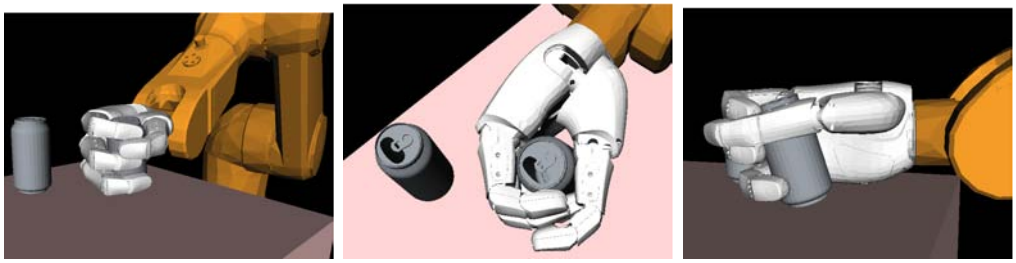
Perhaps the most significant simulation is the grasping problem. In this simulation, a *Staubli TX90* equipped with a *Schunk SAH* hand has to grasp, move and drop a can that lays on a table.

Through the user interface, the problem is loaded (figure 10.3).
A starting position is set through the appropriate gui button (figure 10.5a).



(a) Starting position. (b) Movement starts. (c) Movement continues.

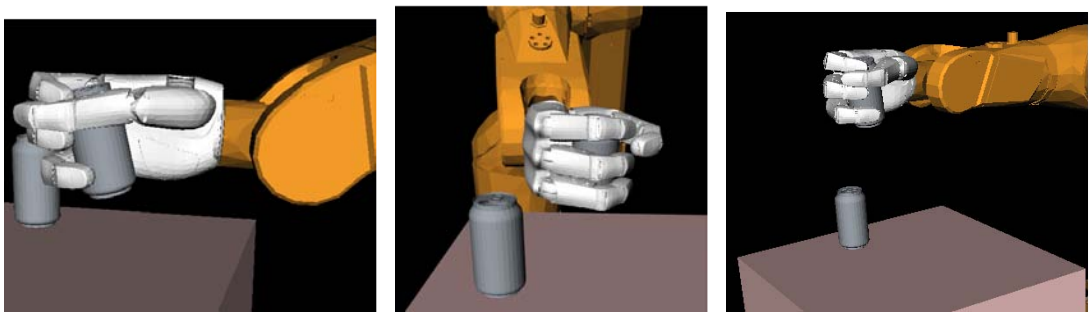
Figure 10.5: The robot grasping a can.



(d) Movement continues. (e) Top view of grasp. (f) Side view of grasp.

Figure 10.6: Different views of the grasp.

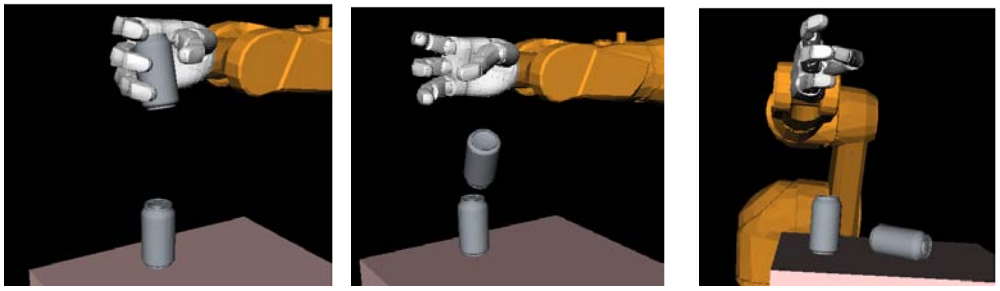
A position path is opened and its definition is increased through the "Double path precision" button.
Then the movement starts as in figure 10.5b, and continues until figure 10.5d. Once the path has been completed, the robot is moved through setting motor velocities in the *GUI* (figures 10.7a to 10.7c).



(a) (b) (c)

Figure 10.7: Moving the robot setting motor velocities.

Finally, the can is dropped by slowly opening the hand. Again, this movement is made by setting motor velocities through the *GUI*.



(a) (b) (c)

Figure 10.8: Dropping the can setting motor velocities.

10.3.1 Observations

Both simulations have distinctively slowed down when contacts were made, especially the first one. This is due to the fact that each contact represents a number of constraints. Each constraint increases the simulation matrix, and thus, the time needed to solve a step.

The parameters used to simulate are described in the following table.

Collision policy	With contacts
Number of steps in a cycle	40
Publishing rate	$25fps$
Simulation step	0.001
Gravity	$(0, 0, -9810)$
Linear damping	0.5
Linear damping threshold	0
Angular damping	0.2
Angular damping threshold	0
Contact surface layer	0.001

Table 10.2: Parameters used during the last two simulations. Those not defined had the default values.

Conclusions

The project has successfully reached the goals and the program has implemented all the features required:

- It is seamlessly submerged in a *ROS* network, thus it can interact with other modules using *ROS* communications.
- The program is modular, composed of three conceptually different parts: user interface, calculator and viewer. If someone wants to replace the gui or the viewer, he just needs to take a look at the Messages and the Services, and implement the communication features in the new module.
- It can produce information about any object position, collision situation and even about its joint. Furthermore, it can publish this information at any rate, which is set through a *ROS* service.
- The *VirtualWorld* module makes full use of the *ODE* physics library, allowing a wide spectrum of simulating tools and features, including rigid body dynamics and collision detection.
- The collision detection engine can be used in two different ways: integrated with the rigid body simulator or used in parallel with it. In the first case, it leads to a realistic simulation, whereas in the second, it leads to a *PQP*-like simulation.
- The simulation can go at any combination of simulation speed, publishing rate and step size, giving the user a wide spectrum of possibilities between slow and fast, precise and gross.

- The viewer, on the other hand, keeps updating the scene at $25fps$, no matter what.

- Through the gui, *Kautham* scenes and problems can be easily loaded with a single click. Robots can be moved through their motors or through paths stored in files, while objects and joints can be built and acted upon using forces and torques of many kinds.

Unluckily, the inter-penetration of two objects cannot be measured using the *ODE* library, thus the *PQP* library cannot be replaced in all its features. But this was not a requirement, rather an additional feature. Hence, for this kind of query, *PQP* is still a valid choice.

Finally, *Odin* is now a complete and full featured tool for physics simulation in robotics. It is ready to be integrated to the *Kautham Project*, that will then be able to extend its working scope by taking into account, from now on, the physical interactions of a robot with the environment.

Future Work

The most imminent part of future work is integrating *Odin* and *Kautham* in a big modular project. This step will be able to start once the IOC team has completed the process modularizing and putting *ROS* layers to the *Kautham Project*.
This integration will allow to develop path algorithms based on collision detection and 3D physics.

As it has been said, *Odin*'s viewer is based on *Coin3D* because of the *Kautham* experience. But *ROS* has its own very powerful and full featured viewer, that is designed specifically for robotics: *RViz*. Upgrading *Odin* to this viewer would be an interesting improvement, and could introduce a new set of features, including, for example, feedback from the user. In fact, the *RViz* has some features called "interactive markers "involving the actions of the mouse on the rendering window, which could be used to ideate many features. This way, *Odin* could become a module that allows the user to play and experiment with a physics library.
Other improvements could be made working on a more extensive *GUI*, allowing customization of contacts, creation of composites, and other features that are actually available only through the *ROS* interface.
The viewer could be improved by adding a tab that shows the output of joint data (position and speed), maybe graphically.

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Appendix A

User Manual

A.1 Installation

To successfully install *Odin*, make sure you have *ROS* installed and working.
Go to your ROS workspace. Open a terminal and create a Stack named Odin:

```
$ roscreate-stack Odin
```

The stack could be copied from file, but this way we can make sure that the stack appears in your ROS_PACKAGE_PATH.
Open the manifest.xml file with a text editor, and modify it to include the dependencies: physics_ode, qt_ros, ros_comm. Just add these three lines at the bottom:

```
1 <depend stack="physics_ode" /> <!-- opende -->
2 <depend stack="qt_ros" /> <!-- qt_build -->
3 <depend stack="ros_comm" /> <!-- std_srvs, std_msgs, roscpp -->
```

Now it should look like this:

```
1 <stack>
2 <description brief="Odin">Odin</description>
3 <author>Maintained by alfre</author>
4 <license>BSD</license>
5 <review status="unreviewed" notes=""/>
6 <url>http://ros.org/wiki/Odin</url>
7 <depend stack="ros" />
```

```
8   <depend stack="physics_ode" /> <!-- opende -->
9   <depend stack="qt_ros" /> <!-- qt_build -->
10  <depend stack="ros_comm" /> <!-- std_srvs, std_msgs, roscpp -->
11 </stack>
```

Since these packages have not been built, you have to run "rospack profile" on each:

```
1  Odin/Services$ rospack profile
2  Odin/Messages$ rospack profile
3  Odin/GUI$ rospack profile
4  Odin/Viewer$ rospack profile
5  Odin/VirtualWorld$ rospack profile
```

Now roscd to Odin, or simply cd to Odin, and run rosmake:

```
1  $ roscd Odin
2  $ rosmake
```

It should work too to simply run rosmake Odin from any directory. This command should compile and link the whole library and make it ready to use. Resuming:

- Create the Odin stack and add the dependecies to the manifest.
- Copy the packages inside it: Messages, Services, GUI, Viewer and VirtualWorld. Then "roscd" to them and run "rospack profile" to make them visible.
- Rosmake Odin.

To make sure that everything has compiled, you can cd to the build directories of each package and run:

```
1  $ cmake ..
2  $ make
```

A.2 Starting

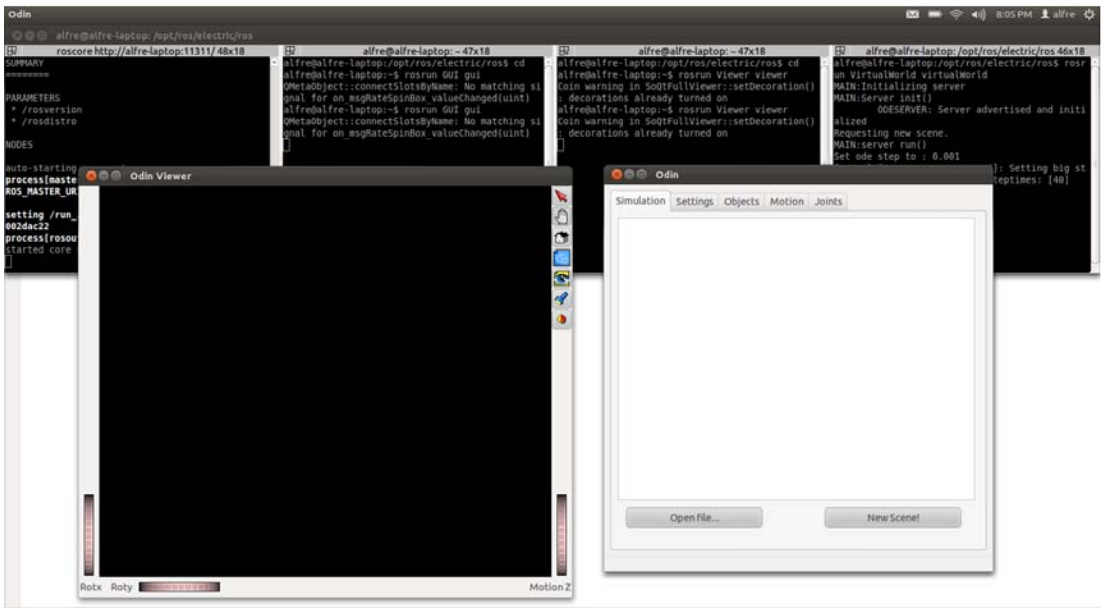

Figure A.1: Odin at start up. A terminator window is open in the background, running "roscore", "rosrun GUI gui", "rosrun Viewer viewer" and "rosrun VirtualWorld virtualWorld". On top, the gui and the viewer windows.

Open four terminals (a Terminator window should help). On the first one, launch ROS:

```
$ roscore
```

On the remaining three, launch the gui, the viewer and the simulator:

```
$ rosrun GUI gui
```

The gui window should pop up.

```
$ rosrun Viewer viewer
```

The viewer window should pop up.

```
$ rosrun VirtualWorld
```

This starts the simulator A.1. Enjoy!