Development of Scientific Applications with the Mobile Robot Programming Toolkit

The MRPT reference book

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Note:

This book is uncompleted. The most up-to-date version will always be available online at:

http://www.mrpt.org/The_MRPT_book

Recent updates:

- Oct 25, 2010: Written chapters §5 and §11.
- Aug 10, 2009: Added description of resampling schemes (§23.3).
- Apr 21, 2009: Updated to MRPT 0.7.0. Added sections on: fixed-size matrixes (§7.1.2), metric maps (§19), file formats (§4).

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Chapter 1

Introduction

1.1 Why a new library?

Many good scientific programs and programming libraries exist out there. When working with matrices, vectors, and graphical representations, applications like MATLAB or Octave excel. If one's needs are efficient image algorithms under C and C++, OpenCV or VXL are good bets. Other libraries provide Bayesian inference or random number generators for a variety of probability distributions. When interfacing a variety of sensors, a low-level language as C is probably one of the best ways to develop a robust and efficient implementation. A problem raises only when a project requires performing many or all of these tasks under a single and sensible development framework, since each library declares its own data structures. For example, an image grabbed by an OpenCV program cannot be *directly* sent to a MATLAB program which detects features.

The development of mobile robotics software is one of those complex projects that require having at hand a variety of heterogeneous tools: a robot may capture an image from an IEEE1394 camera, extract features from it, read odometry information from wheel encoders through a serial port, and then fuse all these data using a Kalman filter in matrix form. This contains tasks which range from low-level code (close to hardware), up to linear algebra.

1.2 What is MRPT?

To face the development of such software, we have created the *Mobile Robot Programming Toolkit*, or MRPT. This framework acts as the *glue* that makes

possible to interconnect several third-party libraries, but it also implements several features on its own.

Despite the name, MRPT currently comprises several generic libraries in C++ which can be perfectly employed for developing any kind of scientific application that requires 2D plots, linear algebra, 3D geometry, Bayesian inference, 3D scene animations, or any combination of them.

In the specific field of *mobile robotics*, MRPT is aimed to help researchers to design and implement algorithms in the areas of Simultaneous Localization and Mapping (SLAM), computer vision and motion planning (obstacle avoidance). The libraries include classes for easily managing 3D(6D) geometry, probability density functions (pdfs) over many predefined variables (points and poses, landmarks, maps), Bayesian inference (Kalman filters, particle filters), image processing, path planning and obstacle avoidance, 3D visualization of all kind of maps (points, occupancy grids, landmarks,...), and "drivers" for a variety of robotic sensors.

1.3 What is this book about?

This document tries to address the needs of two different kinds of readers:

- Firstable, **users of MRPT programs**. The toolkit is not only a collection of libraries, but also contains some ready-to-use programs. With those applications, a user can record data from a mobile robot, manipulate the logs if needed, and create point or occupancy grid-maps using state-of-the-art algorithms *without typing a single line of source code*.

- **Developers**. Users who pretend to integrate their own algorithms into MRPT or to use it as a layer on which to develop more powerful applications or libraries.

Obviously, many readers may fit within both kinds of readers, but for reasons of clarity, this book is structured into two well-differentiated parts. Part II addresses *using* existing programs, while Part III discusses more in-deep details required for MRPT programmers.

1.4 What is this book *not* about?

The intention is that this book does not become one of those boring, and nearly useless hard copies of a library reference. This book pretends to

let a programmer know what is inside MRPT, as a birth-eye-view. Once he or she needs to handle any specific class, the reference documentation (created with Doxygen) will be an invaluable tool, and indeed one of our main concerns during the development of MRPT has been an extensive and good reference documentation, which is available online at the MRPT web site[1].

But before reading that documentation, the programmer should have a gross idea of how things are managed within MRPT, and that is precisely the aim of this book.

1.5 How much does it cost?

MRPT is released under GNU GPL 3.

MRPT is **free software**. Free in both senses: you can use it without any cost, and it is an Open Source project. We have released the sources under GNU General Public License 3. Feel free to modify the sources for your needs, to the extent allowed by the aforementioned license. If you want to contribute with patches or bug reports (or even better, bug fixes!), please contact the authors through the forums in `http://www.mrpt.org/`.

Despite its beginnings at the MAPIR Laboratory in the University of Málaga, several people world-wide have contributed in different ways to its development since its release as an Open Source project. We kindly thank everyone who has helped in any way, and hope more people continue getting involved in the future[2].

1.6 OS restrictions

MRPT is designed to be cross-platform. It works under 32bit and 64bit systems. Thus, the good news is that any user application developed with MRPT and no other OS-dependant API will also become cross-platform without any extra effort.

The libraries are daily tested under Windows 32bit and Linux. In theory they should also work under any POSIX-compatible system equipped with a decent C++ compiler, like Mac OS X, Solaris, BSDs, etc, but all these platforms have not been tested yet[3].

[1] http://www.mrpt.org/

[2] The complete list of authors can be checked out online at http://www.mrpt.org/Authors

[3] An up-to-date list of systems where MRPT has been completely tested can be found in http://www.mrpt.org/Supported_Platforms

1.7 Robotic software architectures

MRPT provides several ready-to-use data structures and algorithms which can be directly used to build software aimed to be run on a vehicle or robot. In fact, some MRPT applications (e.g. `rawlog-grabber`) are designed for this purpose.

However, intelligent robots usually require a much more complex software than a single application. Robotic software architectures play the role of splitting the code into independent programs (or "modules") which, as a whole, comprise the robot *software*. In such a framework MRPT might be just a "low-level" library.

A number of publicly available frameworks exist. In our group, we developed the *BABEL* system [7], available online for download at [8]. Other development environments are the Player project [2], MOOS [10] and CARMEN [9].

Chapter 2

Compiling

This chapter explains how to compile the MRPT libraries and applications, and also whether a user may instead prefer a pre-compiled version.

If you are sure you prefer (or have to) compile MRPT from sources, skip the next section and continue with section 2.2.

2.1 Binary distributions

For Windows users, may want to only *use* existing MRPT applications, so they do not pretend to develop custom programs based on MRPT. For such users, precompiled binary distributions of MRPT exist and perhaps are a better choice than compiling it from sources. These binary packages also allow compiling custom MRPT-based programs, but if the user needs a compiler different that Visual Studio C++, MRPT had to be compiled from sources. For Linux users, precompiled packages from the repositories are recomendable not only for *using* MRPT applications, but also for development.

In the case of 32bit Windows XP/Vista/7, binary packages are available for download at the main MRPT download page[1]. There are packages for GNU/Linux for the following distributions:

- Debian (*unstable* and *testing* repository).
- Ubuntu (*from version 9.04*).
- Fedora Core (*from version 9*).

[1] http://www.mrpt.org/downloads/

All the packages can be installed by executing:

```
$ sudo apt-get install mrpt-apps mrpt-dev mrpt-doc
```

or manually from `synaptic` or the appropriate package manager.

2.2 Prerequisites

As with any mid or large-size software collection, MRPT requires some programs and libraries to be installed in your system *before* you can compile it. Next sections explain the required steps for each system, but in general the main requisites are:

- **CMake:** A powerful cross-platform build system.
- **wxWidgets:** An extensive GUI toolkit.
- **OpenCV:** A widely-used computer vision library.

2.2.1 GNU/Linux

Debian, Ubuntu

Invoke:

```
sudo apt-get install build-essential cmake libwxgtk2.8-dev libwxbase2.8-dbg
libwxgtk2.8-dbg libftdi-dev libglut3-dev libhighgui-dev lib3ds-dev
libboost-program-options-dev
```

Note that if version 2.8 of wxWidgets is not available in your distribution, it would have to be installed manually.

Fedora

Invoke as root:

```
yum install gcc gcc-c++ make cmake wxGTK-devel opencv-devel freeglut-devel
lib3ds-devel boost-dev
```

OpenSUSE

Invoke:

```
sudo zypper install make gcc gcc-c++ cmake cmake-gui pkg-config
zlib-devel wxGTK-devel wxGTK-gl libusb-devel freeglut-devel lib3ds-devel
libboost-program-options
```

Installing OpenCV on OpenSUSE

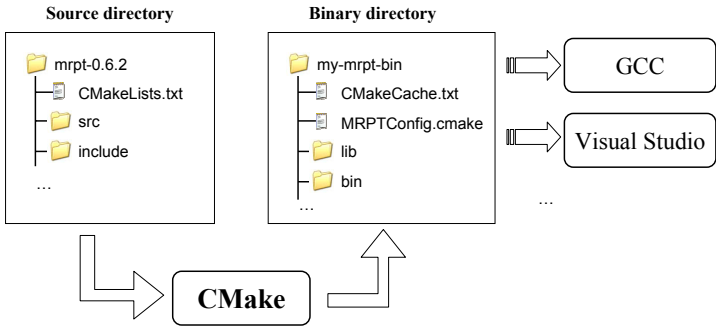


Figure 2.1: *The concepts of source and binary (or* build*) directories with the CMake toolchain.*

OpenCV must be downloaded and compiled from sources manually in OpenSUSE. Download the opencv-1.0.0.tar.gz Linux sources and follow these steps:

1. Install the dependencies. This will assure some packages required by OpenCV GUI and video grabbing. Invoke:

   ```
   sudo zypper install make gcc gcc-c++ wxGTK-devel libdc1394-devel
   libraw1394-devel libpng-devel libjpeg-devel
   ```

   Optionally, if you enable the "Packman repository", the package ffmpeg should be also installed.

2. Decompress the tarball:

   ```
   tar -xf opencv-1.0.0.tar.gz
   ```

3. Then go to the newly created directory and invoke the configure tool:

   ```
   ./configure
   ```

   If everything goes fine, no error will be reported as all the dependencies are satisfied. Now compile and install OpenCV with:

   ```
   make && sudo make install && sudo /sbin/ldconfig
   ```

2.2.2 Windows

2.3 Compiling

2.4 Building options

The table summarizes the most important options which can be set through the CMake gui (ccmake, cmakesetup, or cmake-gui):

For all platforms/compilers

BUILD_SHARED_LIBS	Build static libraries if set to OFF, or dynamic librar
BUILD_EXAMPLES	Whether you want to compile all the examples in the
MRPT_HAS_BUMBLEBEE	To enable integration of the Bumblebee stereo camer
MRPT_ALWAYS_CHECKS_DEBUG	If set to ON, additional security checks will be perfor
MRPT_ALWAYS_CHECKS_DEBUG_MATRICES	If set to ON, additional security checks will be perfor
MRPT_OCCUPANCY_GRID_CELLSIZE	Can be either 8 or 16 (bits). The size of each cell in t
USER_EXTRA_CPP_FLAGS	You can add here whatever additional flags to be pas
MRPT_HAS_ASIAN_FONTS	Enables Asian fonts in CCanvas, but increases library
BUILD_xSENS	Whether to use the CMT library for interfacing xSen

Microsoft Visual Studio

CMAKE_MRPT_HAS_VLD	Whether to include the Visual Leak Detector (VLK). Default is OFF. I

GNU GCC compiler only

MRPT_ENABLE_LIBSTD_PARALLEL_MODE	Enables the experimental GNU libstdc++ parallel mo
MRPT_ENABLE_PROFILING	Enables generation of information required for profilin
MRPT_OPTIMIZE_NATIVE	Enables optimization for the current architecture (-mt

Part II

User guide

Chapter 3

Applications

3.1 pf-localization

3.1.1 Description

3.1.2 Usage

3.1.3 Example configuration file

3.2 RawLogViewer

3.2.1 Description

3.2.2 Usage

3.3 rbpf-slam

3.3.1 Description

3.3.2 Usage

3.3.3 Example configuration file

3.4 rawlog-grabber

3.4.1 Description

`rawlog-grabber` is a command-line application which uses a generic sensor architecture to allow collecting data from a variety of robotic sensors in real-time taking into account the different rates at each sensor may work. This program creates a thread for each sensor declared in the config file and then saves the timestamp-ordered observations to a rawlog file - the format of those files is explained in Chapter 13.

The valuable utility of this application is to collect datasets from mobile robots for off-line processing.

3.4.2 Usage

This program is invoked from the command line with:

```
rawlog-grabber <config_file.ini>
```

3.4.3 Configuration files

The format of the configuration file is explained in the comments of the following prototype file. Refer also to the directory

`MRPT/shared/mrpt/config_files/rawlog-grabber`

for more sample files and to the next sections for each specific sensor[1].

```
// ------------------------------------------------------------
//  Example config file for rawlog-grabber
//
//               ~ The MRPT project ~
//           Jose Luis Blanco Claraco (C) 2005-2008
// ------------------------------------------------------------

//  Each section [XXXXX] (except [global]) sets up a thread in
//  the rawlog-grabber standalone application. Each thread collects
//  data from one sensor or device, then the main thread groups
//  and orders them before streaming everything to a rawlog file.

//  The name of the sections can be arbitrary and independent
//   of the sensor label. The driver for each sensor is actually
//   determined by the field "driver", which must match the name
//   of some class in mrpt::hwdrivers implementing CGenericSensor.


// ======================================================
//  Section: Global settings to the application
```

[1]However, notice that the most up-to-date documentation will be always available in the reference of CGenericSensor and their derived classes.

```
// ======================================================
[global]
// The prefix can contain a relative or absolute path.
// The final name will be <PREFIX>_date_time.rawlog
rawlog_prefix           = dataset

// Milliseconds between thread launches
time_between_launches   = 800

// SF=1: Enabled  -> Observations will be grouped by time periods.
// SF=0: Disabled -> All the observations are saved independently
//                   and ordered solely by their timestamps.
use_sensoryframes       = 1

// Only if "use_sensoryframes=1": The maximum time difference between
//  observations within a single sensory-frame.
SF_max_time_span        = 0.25      // seconds

// Observations will be processed at the main thread with this period
GRABBER_PERIOD_MS       = 1000      // ms


// Here follow sections for each sensor.
// This is one example for a Hokuyo laser scanner:

// ======================================================
//  SENSOR: LASER_2D
// ======================================================
[LASER_2D]
driver                  = CHokuyoURG
process_rate            = 90            ; Hz

sensorLabel             = HOKUYO_UTM
pose_x                  = 0     ; Laser range scaner 3D position
pose_y                  = 0     ;   on the robot (meters)
pose_z                  = 0.31
pose_yaw                = 0     ; Angles in degrees
pose_pitch              = 0
pose_roll               = 0

COM_port_WIN            = COM3
COM_port_LIN            = ttyACM0
```

Specification for: Hokuyo Laser

Specification for: GPS

Specification for: Camera

Chapter 4

File formats

In this chapter we summarize the format of MRPT data files which are managed by the library itself and some of the applications, sorted by their most common file extensions.

- `.gridmap` (or compressed version `.gridmap.gz`). A 2D occupancy grid map. These files consist on one `COccupancyGridMap2D` object serialized into a binary file. See Chapter 10 for more details on how to serialize and de-serialize objects.

- `.ini`. Configuration files. The format is plain text, with the file structured in sections (denoted as `[NAME]`) and variables within each section (denoted by `var=value`). These files can contain comments, which may start with `;` or `//`.

- `.simplemap` (or compressed version `.simplemap.gz`). A collection of pairs location-observations, from which metric maps can be built easily. The file actually contains a binary serialization of an object of the class `CSensFrameProbSequence`. See Chapter 10 for more details on how to serialize and de-serialize objects. The application `observations2map` can convert a simplemap file into a set of different metric maps (grid maps, point maps,...) and save them to different files. Refer to the documentation of that program for details.

- `.rawlog`. Robotic datasets. The format of these files is explained in detail in the Chapter 13. These files can be managed and visualized with the application `RawlogViewer`, or captured from sensors by `rawlog-grabber`.

Part III

Programming guide

Chapter 5

The libraries

5.1 Introduction

MRPT consists of a set of C++ libraries and a number of ready-to-use applications. This chapter briefly describes the most interesting part of MRPT for mobile robotics developers: the libraries.

The large number of C++ templates and classes in MRPT makes it a good idea to split them into a set of libraries or "modules", so users can choose to depend on a part of MRPT only, reducing compile time and future dependence problems.

The dependence graph in Figure 5.1 shows the currently existing libraries in MRPT. An arrow $A \rightarrow B$ means "A depends on B". The starred libraries are in an experimental stage and their sources may not be released yet or, if they are, changes in the API can be expected in the future without assuring backward compatibility.

5.2 Libraries summary

5.2.1 mrpt-base

This is the most fundamental library in MRPT, since it provides a vast amount of utilities and OS-abstraction classes upon which the rest of MRPT is built. Here resides critical functionality such as mathematics, linear algebra §7.1, serialization §10, smart pointers §11 and multi-threading.

All MRPT classes and functions live within the global namespace `mrpt` or one of a series of nested namespaces. This particular library comprises classes in a number of *different namespaces*, briefly described next.

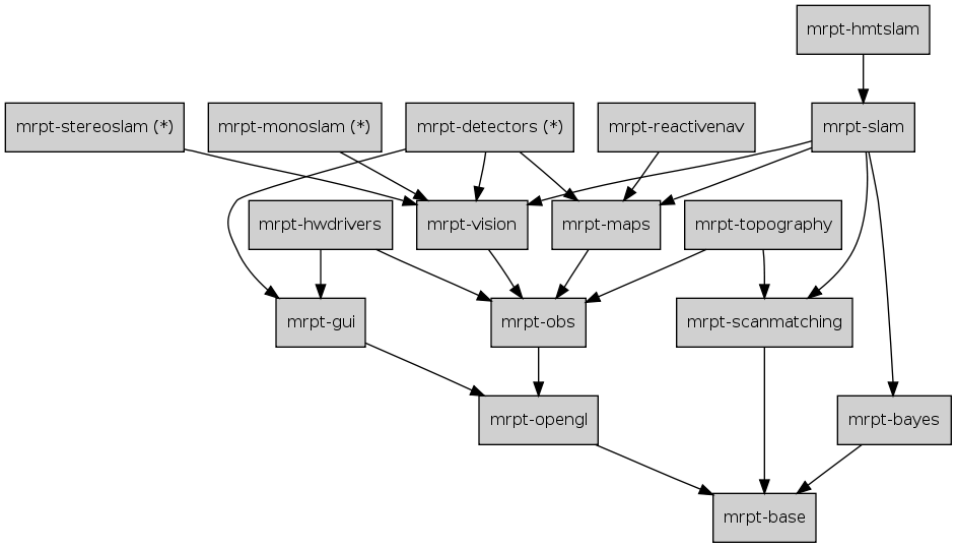


Figure 5.1: *An overview of the individual libraries within MRPT and their dependencies, as of version 0.9.2.*

mrpt::poses

This namespace contains a comprehensive collection of geometry-related classes to represent all kind of 2D and 3D geometry transformations in different formats (Euler angles, rotation matrices, quaternions), as well as networks of pose constrains (as used in GraphSLAM problems).

There are also representations for probability distributions over all of these transformations, in a generic way that allow mono and multi-modal Gaussians and particle-based representations.

mrpt::utils

The functionality of this namespace includes:

- RTTI (RunTime Type Information): A cross-platform, compiler-independent RTTI system is built around the base class `mrpt::utils::CObject`.

- Smart pointers: Based on the STLplus library, any class `CFoo` inheriting from `CObject`, automatically has an associated smart pointer class `CFooPtr`. MRPT implements advanced smart pointers capable

of multi-thread safe usage and smart pointer typecasting with runtime check for correct castings (see §11).

- Image handling: The class `CImage` represents a wrapper around OpenCV's `IplImage` data structure, plus extra functionality such as on-the-fly loading of images stored in disk upon first usage (see §12). The internal `IplImage` is always available so OpenCV functions can be still used to operate on MRPT images.
- Serialization/Persistence: Object serialization in a simple but powerful (including versioning) format is supported by dozens of MRPT classes, all based on `CSerializable`.
- Streams: Stream classes (see the base `CStream`) allow serialization of MRPT objects. There are classes for transparent GZ-compressed files, sockets, serial ports, etc.
- XML-based databases: Simple databases can be maintained, loaded and saved to files with `CSimpleDatabase`.
- Name-based argument passing: The structure `TParameters` can be used to pass a variable number of arguments to functions by name.
- Configuration files: There is one base virtual class (`CConfigFileBase`) which can be used to read/write configuration files (including basic types, vectors, matrices,...) transparently from any "configuration source" (a physical file, a text block created on the fly as a string, etc.).

mrpt::math

MRPT defines a number of generic math containers (described in §7.1), namely:

- Matrices: Dynamic-size and compile-time fixed-size matrices.
- Matrix views: Proxy classes that allow operating on the transpose, a part of, or the diagonal of another matrix as if it was a plain matrix object.
- Vectors: Dynamic-size vectors, built upon standard STL `std::vector`.
- Arrays: Fixed-size vectors, just like plain C arrays but with support for STL-like iterators and many mathematical operations.

These containers have a number of characteristics in common (e.g. STL-like iterators and typedefs) and can be mixed altogether in operations. For example, matrices of any kind can be operated together, a vector can be added to an array, or the results of a matrix operation stored in a matrix view. Fixed-size containers should be preferred where possible, since they allow more compile-time optimizations.

Apart from the containers, this namespace contains much more functionality:

- A templatized RANSAC algorithm.
- Probability distribution functions.
- Statistics: mean, covariance, covariance of weighted samples, etc... from sets of data.
- A huge amount of geometry-related functions: Lines (`TLine3D`), planes (`TPlane3D`), segments, polygons, intersections between them, etc.
- Graph-related stuff: generic directed graphs (`CDirectedGraph`) and trees (`CDirectedTree`).
- PDF transformations (uncertainty propagation): Linearized, unscented or MonteCarlo-based propagation of Gaussian distributions of any dimensionality via arbitrary transformation functions.

mrpt::synch

Threading tools can be found here such as critical sections or semaphores.

mrpt::system

Here can be found functions for filesystem managing, watching directories, creating and handling threads in an OS-independent way, etc.

mrpt::compress

This namespace contains the methods needed to compress and decompress with the GZip algorithm, independently of whether the *zlib* library exists in the system or not.

5.2.2 mrpt-opengl

This library defines 3D rendering primitive objects that can be combined into scene objects. These scenes can be saved to files or visualized in real-time.

Note that all the C++ classes in this library will be always defined, even if MRPT is built without OpenGL support, thus scene data structures can be always built and saved to disk or streamed for rendering on other system.

5.2.3 mrpt-bayes

This library provides a templatized Kalman filter (KF) implementation that includes the Extended KF (EKF) and the Iterated EKF. It only requires from the user to provide the system models and, optionally, the Jacobians.

5.2.4 mrpt-gui

This library provides three classes for creating and managing GUI windows, each having a specific specialized purpose:

- `CDisplayWindow`: Displays 2D bitmap images, and optionally sets of points over them, etc.
- `CDisplayWindow3D`: A powerful 3D rendering window capable of displaying an `COpenGLScene`. It features mouse navigation, Alt+Enter fullscreen switching, multiple viewports, etc.
- `CDisplayWindowPlots`: Displays one or more 2D vectorial graphs, with an interface resembling MATLAB's `plot` commands.

5.2.5 mrpt-obs

In this library there are five key elements or groups of elements:

- Sensor observations: All sensor observations share a common virtual base class (`mrpt::slam::CObservation`). There are classes to store laser scanners, 3D range images, monocular and stereo images, GPS data, odometry, etc. A concept very related to observations is a `mrpt::slam::CSensoryFrame`, a set of observations which were collected approximately at the same instant. Chapter 18 explores these classes.

- Rawlogs or datasets: A robotics dataset can be loaded, edited and explored by means of the class `mrpt::slam::CRawlog`, as explained in Chapter 13.

- Actions: For convenience in many Bayesian filtering algorithms, robot actions (like 2D displacement characterized by an odometry increment) can be represented by means of "actions".

- *Simple maps*: A "simple map" in MRPT is a set of pairs (position,sensory frame). The advantage of maintaining such a simple map format instead a metric map is that the metric maps can be rebuilt when needed with different parameters from the raw observations, which are never lost.

- CARMEN logs tools: Utilities to read from CARMEN log files and load their observations as MRPT observations[1].

5.2.6 mrpt-scanmatching

Within this library (which defines the namespace `mrpt::scanmatching`) we find functions in charge of solving the optimization problem of aligning a set of correspondences, both in 2D and in 3D. Note that this does not includes the *iterative* ICP algorithm, included instead into the library `mrpt-slam`.

5.2.7 mrpt-topography

This library provides, in the namespace `mrpt::topography`, conversion functions and useful data structures to handle topographic data, perform geoid transformations, geocentric coordinates, etc.

5.2.8 mrpt-hwdrivers

This namespace includes several hardware-related classes, from serial port interfaces, USB FTDI chip interfaces, to more complex ones including handling specific proprietary protocols (i.e. SICK and Hokuyo scanners), cameras, etc. All classes of this library live in the namespace `mrpt::hwdrivers`.

[1] Refer to `mrpt::slam::carmen_log_parse_line` and the applications `carmen2rawlog` and `carmen2simplemap`

5.2.9 mrpt-maps

This library includes (almost) all the maps usable for localization or mapping in the rest of MRPT classes. All the classes are defined in the namespace `mrpt::slam`. Refer to Chapter 19 for a discussion on these metric maps.

This library also adds new classes (`CAngularObservationMesh` and `CPlanarLaserScan`) to the namespace `mrpt::opengl`, which couldn't be included in the library `mrpt-opengl` due to its heavy dependence on map classes declared here.

It is worth mentioning that one of the most useful map classes, namely `mrpt::slam::CMultiMetricMap`, is *not* in this library, but within `mrpt-slam`.

5.2.10 mrpt-vision

This library includes some wrappers to OpenCV methods and other original functionality:

- The namespace `mrpt::vision::pinhole` contains several projection and Jacobian auxiliary functions for projective cameras.
- Sparse Bundle Adjustment algorithms.
- A versatile feature tracker (refer to `mrpt::vision::CFeatureTracker_KL`).
- A generic representation of visual features, with or without patches, with or without a set of descriptors (see `mrpt::vision::CFeature`).
- A hub for a number of detection algorithms and different descriptors, in the class `mrpt::vision::CFeatureExtraction`.

5.2.11 mrpt-slam

Interesting algorithms provided by this library, whose classes live in the namespace `mrpt::slam`, include:

- `mrpt::slam::CMetricMapBuilder`: A virtual base for both ICP and RBPF-based SLAM.
- `mrpt::slam::CMonteCarloLocalization2D`: Particle filter-based (Monte Carlo) localization for a robot in a planar scenario.
- `mrpt::slam::CMultiMetricMap`: The most versatile kind of metric map, which contains an arbitrary number of any other maps.

- Kalman Filter-based Range-Bearing SLAM, both in 2D and 3D. These algorithms are demonstrated in the applications `2d-slam-demo` and `kf-slam`, respectively.
- Data association: The nearest neighbor (NN) and the Joint-Compatibility Branch and Bound (JCBB) algorithms are implemented here as generic templates.
- Graph-SLAM: Methods to optimize graphs of pose constraints.

5.2.12 mrpt-reactivenav

This library implements the following algorithms in the namespace `mrpt::reactivenav`:

- Holonomic navigation algorithms: Virtual Force Fields (VFF) and Nearness Diagram (ND).
- A complex reactive navigator, using space transformations (PTGs) to drive a robot using an internal simpler holonomic algorithm (refer to class `CReactiveNavigationSystem`).
- A number of different PTGs

All these methods are demonstrated in the application ReactiveNavigationDemo.

5.2.13 mrpt-hmtslam

This library includes an implementation of the Hybrid Metric-Topological (HMT) SLAM framework.

5.2.14 mrpt-detectors

A set of generic computer-vision-based detectors are implemented here. Detectors exist that can fuse observations from different sensors to improve the detection of, for example, faces.

Chapter 6

Your first MRPT program

At this point, it is assumed that MRPT has been *already compiled* in any arbitrary user directory (or, optionally, installed in the system, e.g. using `synaptic`). If this is not the case, refer to Chapter 2 for instalation instructions.

In this chapter you will learn the basics of the CMake building system and how to use it to create and compile a very simple MRPT program. The complete files of this example can be found within the MRPT packages at `MRPT/doc/mrpt_example1.tar.gz`[1].

[1] Or downloaded from this link: mrpt_example1.tar.gz

6.1 Source files

As explained in Chapter 5, MRPT comprises different libraries (base, opengl, slam, etc.), thus the first step is determine which ones your program will need. As an example, let's assume only `mrpt-base` and `mrpt-gui` are needed. Then, the first step is to include the corresponding headers in your program:

```
#include <mrpt/base.h>
#include <mrpt/gui.h>

using namespace mrpt;
using namespace mrpt::utils;
using namespace mrpt::poses;
using namespace mrpt::gui;
using namespace std;
```

Obviously, the `using namespace` statements are not mandatory, but recommended for code clarity. Note that each library (remember they are listed in §5) has a main header, named `<mrpt/name.h>` for the libray *mrpt-name*.

Now we will see a complete program. This very basic example that only uses the library `mrpt-base` and just creates a pair of 2D (x, y, ϕ) and 3D $(x, y, z, yaw, pitch, roll)$ poses and computes the composed pose $R \oplus C$ and the distances between them:

Listing 6.1: *A very simple MPRT program*

```
#include <mrpt/base.h>

using namespace mrpt::utils;
using namespace mrpt::poses;
using namespace std;

int main()
{
 // Robot pose: 2D (x,y,phi)
 CPose2D  R(2,1, DEG2RAD(45.0) );

 // Camera pose relative to the robot: 6D (x,y,z,yaw,pitch,roll).
 CPose3D  C( 0.5,0.5,1.5,
             DEG2RAD(-90.0),DEG2RAD(0),DEG2RAD(-90.0) );

 cout << "R: " << R << endl;
 cout << "C: " << C << endl;
 cout << "R+C:" << (R+C) << endl;
 cout << "|R-C|= " << R.distanceTo(C) << endl;
 return 0;
}
```

Save this program as `test.cpp` and half the work is done!

6.2 The CMake project file

The simplest CMake project must contain just one file `CMakeLists.txt`. Create a file with that name and with the following contents in the same directory than the file `test.cpp`:

```
PROJECT(mrpt_example1)

CMAKE_MINIMUM_REQUIRED(VERSION 2.4)
# ---------------------------------------------------------------
# Indicate CMake 2.7 and above that we don't want to mix relative
#  and absolute paths in linker lib lists.
# Run "cmake --help-policy CMP0003" for more information.
# ---------------------------------------------------------------
if(COMMAND cmake_policy)
      cmake_policy(SET CMP0003 NEW)
endif(COMMAND cmake_policy)

# ------------------------------------------------------------------------------
#   The list of "libs" which can be included can be found in:
#     http://www.mrpt.org/Libraries
#
#   The dependencies of a library are automatically added, so you only
#    need to specify the top-most libraries your code depend on.
# ------------------------------------------------------------------------------
FIND_PACKAGE( MRPT REQUIRED base)

# Declare the target (an executable)
ADD_EXECUTABLE(mrpt_example1
        test.cpp
        )

# Tell the compiler to link against MRPT libraries.
TARGET_LINK_LIBRARIES(mrpt_example1 ${MRPT_LIBS})
```

There are two important steps in this CMake script: looking for the MRPT libraries and defining a target (which eventually will become a Visual Studio Project, or a Makefile) named `mrpt_example1` which contains only one source file `test.cpp`.

Let's review briefly how CMake look for the MRPT libraries. Recall Figure 2.1 and the discussion in that chapter on source vs. binary (or build) directories in CMake. With the command `FIND_PACKAGE(...)`, CMake will look for a file named `MRPTConfig.cmake`, which contains information such as where are the library header directories, or which libraries should a program link against. If you have compiled MRPT manually, this directory will be your MRPT binary directory. If MRPT has been installed in a Unix system, it should be located at `/usr/share/mrpt/`.

6.3 Generating the native projects

Now, a native project must be created to compile your program, where *native* means a project for your preferred compiler or IDE which is supported by CMake. Some examples are: Unix makefiles, Visual Studio solutions, Code Blocks projects, Eclipse projects, etc. In any case, create a new directory to make an off-tree build, for example `first_mrpt_bin`. We will refer to the directory with the sources (`test.cpp` and `CMakeLists.txt`), as `path_first_mrpt_src`.

Under Unix or GNU/Linux, go to the new empty directory and invoke:

```
first_mrpt_bin$ cmake {path_first_mrpt_src}
```

or, to invoke the NCurses GUI version:

```
first_mrpt_bin$ ccmake {path_first_mrpt_src}
```

On Windows, execute `cmake-gui` or `cmakesetup` and select the source (`{path_first_mrpt_src}`) and binary (`first_mrpt_bin`) directories. Note that in some Linux distributions `cmake-gui` is also available.

At this point, press the button "configure" in CMake, then "generate" to build your project. If CMake complains about not finding MRPT, set manually the variable `MRPT_DIR` to the directory where you compiled MRPT (or `/usr/share/mrpt/` if it was installed through synaptic or apt).

6.4 Compile

Once generated the project for your favorite compiler, just manage it as usual. For example, for Unix Makefiles, go to the binary directory and invoke `make`. For Visual Studio, open the solution file `mrpt-example1.sln` and compile as usual.

6.5 Summary

Creating user applications with MRPT requires adding the corresponding MRPT headers to the sources and creating a CMake project which includes `MRPTConfig.cmake` using the command `FIND_PACKAGE(MRPT REQUIRED {LIBS})`. The simple project presented in this chapter could be hopefuly used as a base for the user to create more complex applications.

Chapter 7

Linear algebra

In this chapter you will learn one of the most basic features of MRPT: vector and matrix manipulation. The basic syntax in many cases will remain very close to that used in MATLAB, although the syntax must change a little for using the most optimized functions if the application performance is a priority.

In the following, all the required classes can be included in a program with:

```
#include <mrpt/core.h>

using namespace mrpt;
using namespace mrpt::math;
using namespace mrpt::utils;
using namespace mrpt::system;
```

Currently there is no support for reading/writing binary MATLAB files, but this limitation is not severe since files saved from MATLAB in plain text (with the format `--ascii`) are fully supported.

Notice that, like in C/C++ languages in general, the first element in any sequence has the index 0. This convention also applies to all matrices and vectors in MRPT. As usual, for matrices the first index corresponds to rows.

7.1 Matrices

7.1.1 Declaration

MRPT defines two kind of matrices: variable-sized and fixed-sized. Most of this chapter will focus on the dynamic-size kind, but most of the operators

and methods are applicable to both types of objects.

Matrices are implemented as class templates in MRPT, but the following two types are provided for making programs more readable:

```
typedef CMatrixTemplateNumeric<float> CMatrixFloat;
typedef CMatrixTemplateNumeric<double> CMatrixDouble;
```

A matrix with any given size can be created by passing it at construction time, or otherwise it can be resized later as shown in this example:

```
CMatrixDouble   M(2,3); // Create a 2x3 matrix
cout << M(0,0) << endl; // Print out the left-top element

CMatrixDouble   A; // Another way of creating
A.setSize(3,4);    //  a 2x3 matrix
A(2,3) = 1.0;      // Change the bottom-right element
```

A matrix can be resized at any time, and the contents are preserved if possible. Notice also in the example how the element at the r'th row and c'th column can be accessed through $M(r, c)$.

Sometimes, predefined values must be loaded into a matrix, and writing all the assignments element by element can be tedious and error prone. In those cases, better use this constructor:

```
const double numbers[] = {
 1,2,3,
 4,5,6 };
CMatrixDouble  N(2,3,numbers);
cout << "Initialized␣matrix:␣" << endl << N << endl;
```

If the size of the vector does not fit exactly the matrix, an exception will raise at run-time. This example above also illustrates how to dump a matrix to the console, which is useful for debugging in case of small matrices.

7.1.2 Fixed-size matrices

When the size of matrices is known a priori, it is advisable to use the alternative implementation based on fixed-size matrices[1]. These objects are managed very similarly to dynamic matrices, including most operators and methods. Naturally, the only difference comes into their declaration:

```
const double numbers[] = {
 1,2,3,
 4,5,6 };
CMatrixFixedNumeric<double,2,3>  N ( numbers );
cout << "Initialized␣matrix:␣" << endl << N << endl;
```

Predefined type names exist for `double` matrices of many common sizes:

```
CMatrixFixedNumeric<double,10,3>  M;
CMatrixDouble33    A = (~M) * M;      // Predefined type for 3x3
```

Whenever possible, employ fixed-sized matrices, especially for small matrices, since the speed gain can be in the order of ten or more for most operations.

7.1.3 Storage in files

When managing large matrices, it is useful to load or save them in files. In particular, it would be even more handful to make those files compatible with MATLAB. This format exists and is as simple as plain text files. For example, the following small program loads a matrix from a file, then compute its eigenvectors and save them to a different file:

```
CMatrixDouble H,Z,D;
H.loadFromTextFile("H.txt");  // H <- 'H.txt'
H.eigenVectors(Z,D);          // Z: eigenvectors, D: eigenvalues
Z.saveToTextFile("Z.txt");    // Save Z in 'Z.txt'
```

7.2 Vectors

7.2.1 Declaration

The base class for vectors is the standard STL container `std::vector`, such as a user will normally declare and manipulate objects of the types

[1] This feature is available in MRPT 0.7.0 or newer.

`vector_float` or `vector_double` [2], for element types being `float` or `double`, respectively:

```
typedef std::vector<float> vector_float;
typedef std::vector<double> vector_double;
```

7.2.2 Resizing

To resize a vector we must use the standard `std::vector` methods, that is:

```
vector_double  V(5,1); // Create a vector with 5 ones.
V.resize(10);
cout << V << endl;     // Print out the vector to console
```

7.2.3 Storage in files

There is less support yet to vector I/O than in the case of matrices, so it is normally advisable to use matrices when loading text files, especially when the format of the file is unknown (e.g. column vs. row vector).

Reading a vector from a text file

This works for row vectors only:

```
vector_double v;
loadVector( CFileInputStream("in.txt"), v);
```

Saving to a text file

The function `vectorToTextFile` allows saving as a row, as a column, and optionally, to append at the end of the existing file:

```
vector_double v(4,0); // [0 0 0 0]
vectorToTextFile(v, "o1.txt");  // Save as row
vectorToTextFile(v, "o2.txt", true); // Append a new row
vectorToTextFile(v, "o3.txt", false, true ); // Save as a column
```

[2] One can also use `CVectorFloat` and `CVectorDouble`, which have some useful operations implemented as methods, but most MRPT interfaces expect the simpler STL containers.

Serializing

If you prefer to serialize the vectors in binary form (see chapter 10), that can be done as simply as:

```
vector_double v = linspace(0,1,100); // [0 ... 1]
CFileOutputStream("dump.bin") << v;
```

7.3 Basic operations

In this section we will go through a quick summary of unary and binary operations for matrices, vectors, or a mix of them. Table 7.3 lists some of the most simple of these operations in common mathematical notation, in C++ using MRPT operators and alternative functional forms. Most operations apply indistinctly to dynamic and fixed-size matrices.

Description	Operation	MRPT C++	2nd alternative
Read element	$a \leftarrow M(i,j)$	a = M(i,j)	a=M.get_unsafe(i,j)
Write element	$M(i,j) \leftarrow a$	M(i,j) = a	M.get_unsafe(i,j)=a
Matrix inverse	M^{-1}	!M	M.inv()
Matrix transpose	$M^\top$	~M	
Matrix assignment	$Q \leftarrow M$	Q = M	
Matrix comparison	$Q = M?$	Q == M, Q!=M	
Matrix sum/substract	$M+Q$, $M-Q$	M+Q, M-Q	
In place sum	$M \leftarrow M+Q$	M+=Q	
Vector sum/substract	$v+w$, $v-w$	v+w, v-w	
Scalar multiplication	$M \leftarrow Ma$	M*=a	
Matrix multiplication	MQ	M*Q	
Matrix multiplication	$M \leftarrow MQ$	M = M*Q	M.multiply(Q)
Matrix/vector mult.	Mv	M*v	
Multiply by inverse	MQ^{-1}	M/Q	
Determinant	$\|M\|$	M.det()	

Naturally, some operations carry restrictions on the sizes of the operants (e.g. matrix multiplication). An exception will be thrown if invalid operations are found in run-time for dynamic-size matrix, while the compiler will complain about the invalid operation for fixed-size ones.

This table does not contain all the implemented operators, for all the details please refer to:

- `mrpt::math`
- `mrpt::math::CMatrixTemplateNumeric<T>`

Other methods which may be easy to remember to those programmers familiarized with MATLAB are:

- `M.ones(A,B)` : Generates a $A \times B$ matrix of ones.
- `M.zeros(A,B)` : Generates a $A \times B$ matrix of zeroes.
- `M.unit(A)` : The $A \times A$ unity matrix.
- `size(M,1)` : Number of rows in M, equivalent to `M.getRowCount()`.
- `size(M,2)` : Number of columns in M, equivalent to `M.getColCount()`.
- `v=linspace(a,b,N)` : Generates a vector v with N elements in the range $[a, b]$.
- `mean(v)`, `stddev(v)` : Mean and standard deviation of the vector v. There is also a combined `meanAndStd(...)`.
- `cumsum(v)` : Cumulative sum of vector v.
- `histogram(v,...)` : Histogram of a vector. See reference documentation.

As an example of the operators described so far, the equation

$$R = H \cdot C \cdot H^\top$$

can be implemented with the next code fragment:

```
CMatrixDouble  C(3,3);
CMatrixDouble  H(5,3);

// C=diag([1 2 3])
C(0,0) = 1;
C(1,1) = 2;
C(2,2) = 3;

// randomize matrix
mrpt::random::matrixRandomUni(H,-1.0,1.0);

CMatrixDouble  R = H * C * (~H);
```

However, this operation, like many others have specialized methods which much better performance. These common expressions should be known to take advantage of them, hence they are summarized in the next section.

7.4 Optimized matrix operations

Many common operations with matrices have efficient implementations, as summarized in Table **??**. In the table M, A, B, C represent matrices while v, w are vectors and x is a scalar. All these elements must be of the appropriate sizes for the corresponding operations to make sense. For clarity, some terms in the "operation" column are represented in MATLAB notation.

Operation	Efficient implementation	Remarks
$M = M + A^\top$	`M.add_At(A)`	
$M = M + A + A^\top$	`M.add_AAt(A)`	A square
$M = AB^\top$	`M.multiply_ABt(A,B)`	
$M = AA^\top$	`M.multiply_AAt(A)`	
$M = A^\top A$	`M.multiply_AtA(A)`	
$w = Ab$	`A.multiply_Ab(b,w)`	
$w = A^\top b$	`A.multiply_Atb(b,w)`	
$M = AB$	`M.multiply_result_is_symmetric(A,B)`	AB symmetric
$M = ABA^\top$	`A.multiply_HCHt(B,M)`	B symmetric
$M = M + ABA^\top$	`A.multiply_HCHt(B,M,false,0,true)`	B symmetric
$x = ABA^\top$	`A.multiply_HCHt_scalar(B)`	B sym., result 1x1
$M = ABC$	`M.multiply_ABC(A,B,C)`	
$M = ABC^\top$	`M.multiply_ABCt(A,B,C)`	
$M = AB(r_0 : end, c_0 : (c_0 + c))$	`A.multiply_SubMatrix(B,M,c0,r0,c)`	
$M = A^{-1}$	`A.inv_fast(M)`	Contents of A are lost
$sum(A(:))$	`M.sumAll()`	

7.5 Text output

7.6 matrices manipulation

7.6.1 Extracting a submatrix

For example, the following MATLAB statement:

$$A = C(6 : 8, 7 : 8);$$

becomes:

```
CMatrixDouble  C(10,10);
CMatrixDouble  A(3,2);  // Set to the size of the patch to extract
C.extractMatrix(5,6,A)
```

Notice again how in MATLAB the first elements are referenced as 1 while in MRPT they have 0 as index.

7.6.2 Extracting a vector from a matrix

Extracting a column, for example $v = C(:, 3)$, can be implemented with:

```
CMatrixDouble  C(10,10);
vector_double  v;
C.extractCol(2,v);
```

And equivalently for rows, for example $v = C(4, :)$:

```
CMatrixDouble  C(10,10);
vector_double  v;
C.extractRow(5,v);
```

7.6.3 Building a matrix from parts

A matrix can be also built from its 4 parts, such as:

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

with:

```
CMatrixDouble  M;
M.joinMatrix(A,B,C,D);
```

Many other methods exist (please, see the reference for further details) with self-explaining names: `insertRow`, `appendRow`, `insertCol`, `insertMatrix` (for inserting a submatrix in a larger matrix), etc.

7.7 Matrix decomposition

Chapter 8

Mathematical algorithms

8.1 Fourier Transform (FFT)

8.2 Statistics

Mean, std, meanAndStd.

8.3 Spline interpolation

8.4 Spectral graph partitioning

8.5 Quaternions

8.6 Geometry functions

8.7 Numeric Jacobian estimation

Chapter 9

3D geometry

9.1 Introduction

9.2 Homogeneous coordinates geometry

9.3 Geometry elements in MRPT

9.3.1 2D points

9.3.2 3D points

9.3.3 2D poses

9.3.4 3D poses

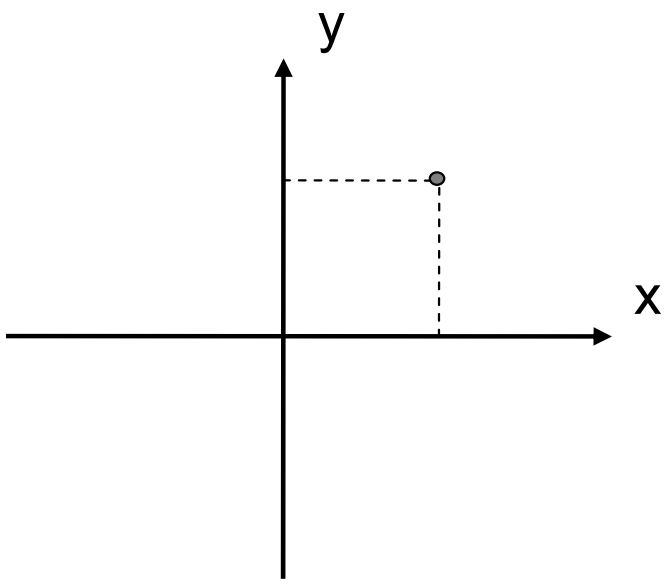


Figure 9.1: *A point in 2D.*

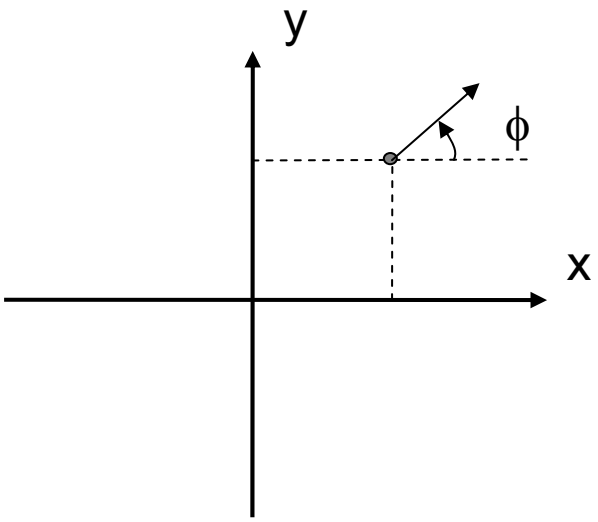


Figure 9.2: *A pose in 2D.*

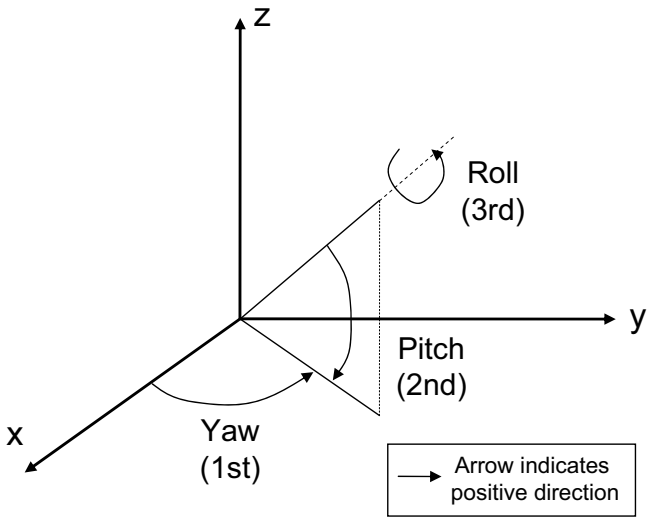


Figure 9.3: *A pose in 3D.*

Chapter 10

Serialization

10.1 The problem of persistence

Serializing consists of taking an existing object and converting it into a sequence of bytes, in any given format, such as the contents and state of the object can be afterward reconstructed, or deserialized.

10.2 Approach used in MRPT

There are many C++ libraries for serializing out there (e.g. boost), although MRPT uses a simple, custom implementation with the following aims:

1. **Simplicity:** A few and small core functions only.
2. **Versioning:** If a class changes along time (something really common), a new version number will be assigned to its serialization, but old stored data can be still imported.
3. **C++ compiler independence:** Use only standardized data-lengths. For example, a data of type "int" has different lengths depending on the machine, thus it is not allowed to serialize an "int" variable without forcing it to a known length.

Currently, the only supported format for serialization is binary, i.e. there is no support for XML. The reason is that, for robotic applications, it is typically more important to save data size (and transmission times) between a running, real-time system. The actual binary frame for each serialized object is sketched in Figure 10.1[1].

[1] In versions before MRPT 0.5.5 the end flag was not present and the first and third fields were 4 bytes wide (instead of just 1). However, data saved in the old format can be still loaded without problems.

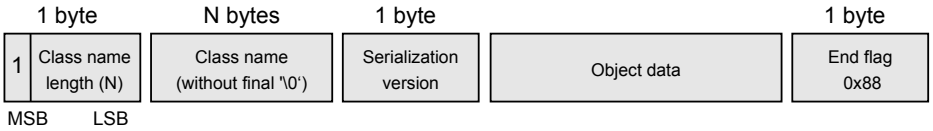


Figure 10.1: *The binary format of serialized objects in MRPT.*

When an object is serialized, its contents are written to a generic destination via a `CStream` class. The list of currently implemented streams are (see the reference of `utils::CStream` for more information).

The typical usage of serialization for storing an existing object into, for example, a file, is to use the `<<` operator of the `CStream` class:

```
#include <mrpt/core.h>

using namespace mrpt;
using namespace mrpt::slam;
using namespace mrpt::math;
using namespace mrpt::utils;

int main()
{
 // Declare serializable objects:
 COccupancyGridMap2D  grid;
 CMatrix              M(6,6);

 // Do whatever...

 // Serialize it to a file:
 CFileOutputStream("saved.gridmap") << grid << M;

 return 0;
}
```

To restore a saved object, you can use two methods, depending of whether you are sure about the class of the object which will be read from the stream, or not. If you know the class of the object to be read, you can simply use the ¿¿ operator towards an existing object, which will be passed by reference and its contents overwritten with those read from the stream. An example:

```
// Declare serializable objects:
COccupancyGridMap2D  grid;
CMatrix              M;

// Load from the file:
CFileInputStream("saved.gridmap") >> grid >> M;
```

The other situation if when you don't know the class of the object which will be read. In this case it must be declared a smart pointer to a generic `utils::CSerializable`

object (initialized as NULL to indicate that it is empty), and after using the >> operator it will point to a newly created object with the deserialized object:

```
// Declare serializable objects:
CSerializablePtr obj;  // NULL pointer

// Load from the file:
CFileInputStream("saved.gridmap") >> obj;

std::cout << "Object class:" << obj->GetRuntimeClass()->className;
```

The next section explains the most important methods of `utils::CSerializable` and runtime class information. In the case of loading objects of unknown class, it is important to read the MRPT registration mechanism and when you should call it manually.

Note that these code examples do not catch potential exceptions.

Apart from using the operators << and >> over a `utils::CStream`, there are two independent functions, `utils::ObjectToString` and `utils::StringToObject`, which serialize and deserialize, respectively, an object into a standard STL string (`std::string`). The difference of these functions with serialization over normal `CStream`'s is that the binary data stream is encoded to avoid null characters (`'\0'`), such as the resulting string can be passed as a `char *`. Avoid using these functions but when strictly necessary, since they introduce an additional processing delay.

10.3 Run-time class identification

All serializable classes must inherit from the virtual class utils::CSerializable, which provides standard methods to manage any serializable object without knowing its real class. The most common operation is probably to check whether an object is of a given type, which can be performed by:

```
CSerializablePtr obj;
stream >> obj;

// Test if "obj" points to an object of class "CMatrix".
if ( IS_CLASS(obj,CMatrix) )
// Or (old format):
if ( obj->GetRuntimeClass() == CLASS_ID( CMatrix ) )
```

If the class to test is not in the current namespace (and there is not a `using namespace NAMESPACE;`), you can alternatively use `CLASS_ID_NAMESPACE`, for example:

```
if ( obj->GetRuntimeClass() == CLASS_ID_NAMESPACE( CMatrix, UTILS) ) ...
```

The method CSerializable::GetRuntimeClass() actually returns a pointer to a UTILS::TRuntimeClassId data structure, which contains other useful members:

1. The class name as a string:

   ```
   obj->GetRuntimeClass()->className;
   ```

2. Checking whether a class is a descendent of a given virtual class. An example:

```
void func( CMetricMap * aMap )
{
 if (IS_DERIVED(aMapCPointsMap))
 {
  CPointsMap *pMap = (CPointsMap*) aMap;
 }
}
```

Other useful method of any serializable object is CSerializable::duplicate, which makes a copy of the object. The internal data, pointers, etc... will be really duplicated and the original object can be safely deleted.

10.4 Writing new serializable classes

10.5 Serializing STL containers

MRPT supports serializing arbitrarily complex data structures mixing STL containers, plain data types and MRPT classes. For example:

```
std::multimap<double,std::pair<CPose3D, COccupancyGridMap2D> > myVar;
file << myVar;
```

The code above will compile and work without the need of the user to write any extra code for the `multimap<>` type.

In the case of STL containers, the binary format consists on:

- The dump of a std::string with the STL container name (dumped using the serialization format explained above).
- The dump of the strings representing each of the types kept by the container (the key and value for a map, the values for a list, etc...).
- The number of elements in the container (for all containers but std::pair).
- The recursive dump of each of the elements. Here the same may apply if the elements are STL containers. For normal MRPT classes, the format explained above is used here.

Chapter 11

Smart Pointers

11.1 Overview of memory management

Variables, objects (that is, instantiations of classes) and arrays are the typical kinds of data managed by any program. Dynamic data on virtually all computer architectures, but some embedded systems, can be allocated into memory in two very different places: in the *stack* or in the *heap*.

Stack memory

Stack allocation is always preferred unless there are specific reasons not to use it. This technique implies a very efficient memory reservation method, typically just subtracting a fixed number to the stack pointer register when calling a function. Correspondingly, freeing memory becomes an addition to the same register. It is hard to imagine a more efficient way to handle the reservation of local memory needed in any function or class method. Below follow some examples of stack allocation:

```
void bar()
{
    int     counter;
    MyClass obj1, obj2;
    double  numbers[100];
    ...
}
```

Heap memory

On the other hand, we have *heap allocation*, also known as *dynamic memory*, where the program must make a request to the operative system to allocate a certain amount of memory on the heap space (the program's reservoir of memory space). These requests may take some time since a gap large enough must be found and problems such as memory fragmentation must be avoided by the allocation algorithm, which must also handle explicit requests from the program to free the non-needed allocated blocks. The equivalent to the example above with heap allocation would be:

```
void bar()
{
    int     *counter = new int[1];
    MyClass *obj1 = new MyClass(), *obj2 = new MyClass();
    double  *numbers = new numbers[100];
    ...
    delete[] counter;
    delete obj1;
    delete obj2;
    delete[] numbers;
}
```

Although the efficiency of heap allocation is far poorer than reserving on the stack, there are three main reasons to employ the former under some circumstances: (i) memory allocation on the stack is typically limited to a few Megabytes, thus large memory blocks should be heap allocated, (ii) when the amount of memory is unknown at compile time and (iii) when the variables are intended to still exist when the program goes out of the creation scope.

As an illustrative example, refer to the following three functions which are intended to return a newly created object:

```
// Returning by value
MyClass function1()
{
    MyClass obj; // Stack alloc
    ...
    return obj;
}

// Returning a pointer (WRONG! DON'T DO THIS)
MyClass* function2()
{
    MyClass obj; // Stack alloc
    ...
    return &obj;
}

// Returning a pointer (Correct)
MyClass* function3()
{
    MyClass *obj = new MyClass(); // Heap alloc
    ...
    return obj;
}
```

If we analyze the three alternatives, we found that the first and third versions are perfectly valid but quite different in their inner workings: while the caller to the first function must make a *copy* of the returned object, the third one will have to copy just a pointer value – obviously, the fastest solution. Regarding the second alternative `function2`, note that the pointer will be invalid out of the scope of the function (it points to the stack space of the function), thus accessing the returned pointer would lead to undefined behavior, most likely a segmentation fault. To

sum up, returning pointers is the fastest way to return objects, but in that case the memory *must* be dynamic, that is, reserved on the heap.

At this point we have established that, in some cases, pointers to objects allocated in the heap are the most efficient mechanism to transfer objects between different functions (or even threads) within one program. Now it must be highlighted the fundamental risk of this idea: memory allocated dynamically must be freed by means of explicit requests by the program. As the complexity of an application grows, it becomes increasingly difficult to keep track of how many pointers, possibly distributed throughout different threads, refer to the same object, with the idea of requesting its deletion only after the destruction of the *last* reference to the object.

Smart pointers

Here is where the concept of *smart pointers* gets into the scene. A smart pointer is actually an object itself, but behaves *as if it were* a plain pointer but has the nice property of automatically and transparently maintaining a counter with the number of active references, or *aliases*, to the object. Only when the counter reaches zero, the dynamically-allocated object is freed.

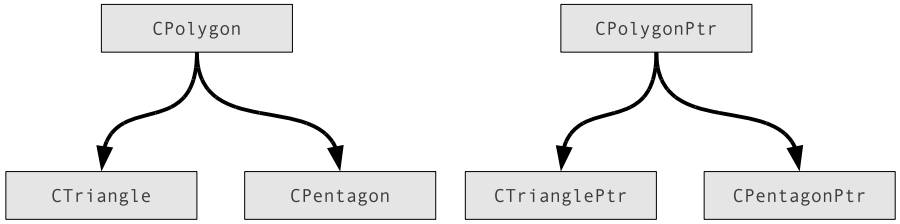
Smart pointers in MRPT are based on the wonderful implementation provided by the STLplus C++ Library Collection [11] due to its versatility, clean interface and proven robustness[1]. Next sections describe how to use these smart pointer classes correctly.

[1]The only modification to the original STLplus in MRPT is the replacement of the reference counter by a thread-safe atomic counter.

11.2 Class hierarchy

Smart pointers are introduced in MRPT mainly by means of the smart pointer class `CObjectPtr`, which represents a pointer to objects of type `CObject` (both defined in namespace `mrpt::utils` in the library `mrpt-base`).

Most MRPT classes subject to be frequently allocated as dynamic memory inherit from `CObject`. In parallel to that hierarchy of classes, a set of MRPT macros automatically define another hierarchy of smart pointer classes, one for each "normal" class. As a naming convention, names of smart pointer classes are built by adding the postfix `Ptr` to the original class name, as illustrated in Figure 11.1.



(a) Hierarchy of classes (b) Hierarchy of smart-pointer classes

Figure 11.1: *For each class in the hierarchy of classes (left) there is an associated smart pointer class (right).*

A useful built-in functionality of MRPT smart pointers is that copy constructors exist to convert between any two different smart pointer classes. Those constructors check, at runtime, the validity of the intended transformation. An incorrect assignment will raise an exception upon execution. The following example illustrates this feature, assuming the hierarchy of class defined in the previous figure (the `Create()` method is explained in the next section):

```
CTrianglePtr  ptrTri  = CTriangle::Create();   // Create new object
CPolygonPtr   ptrPoly = CPolygonPtr(ptrTri);   // Correct
CPentagonPtr  ptrPent = CPentagonPtr(ptrPoly); // Incorrect
CTrianglePtr  ptrTri2 = CTrianglePtr(ptrPoly); // Correct
```

Finally, it is very important to remark once again that smart pointers act like pointers but actually are objects themselves. Therefore, both the dot and arrow operators can be used on them but with quite different intentions:

```
CTrianglePtr  ptrTri  = CTriangle::Create();   // Create new object
ptrTri->method();  // Invoke method() of the CTriangle class
ptrTri.method();   // Invoke method() of the smart pointer class
```

11.3 Handling smart pointers

11.3.1 The `Create()` class factory

For each MRPT class `CFoo` with associated smart pointer `CFooPtr`, a static method exists implementing a smart pointer factory. These methods are something equivalent to:

```
class CFoo
{
 public:
    static CFooPtr Create() { return CFooPtr(new CFoo()); }
};
```

Put in words, this method creates a new (dynamically allocated) instance of the type `CFoo` and immediately assigns its memory management to a smart pointer of type `CFooPtr`, which from that moment on is the interface for the programmer to access the actual object. The process is sketched in Figure 11.2.

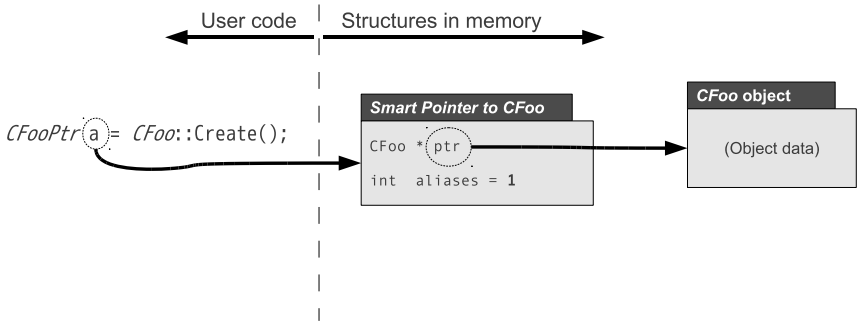


Figure 11.2: *The construction of a new object and an associated smart pointer by means of the* `Create()` *static method.*

11.3.2 Testing for empty smart pointers

Unlike standard pointers, there is no need to initially set smart pointers to a `NULL` value to mark them as *invalid*: the default internal state of the smart pointer already is "NULL valued"-like and behaves accordingly by means of the `!` operator:

```
CFooPtr a;
if (!a)
{
   // This code WILL be executed, since "a" is empty.
}
CFooPtr b = CFoo::Create();
if (!b)
{
   // This code WILL NOT be executed, "b" points to an object.
}
```

Alternatively, the method `present()` returns `true` if the smart pointer actually points to an object:

```
CFooPtr a;
if (a.present())
{
   // This code WILL NOT be executed, since "a" is empty.
}
CFooPtr b = CFoo::Create();
if (b.present())
{
   // This code WILL be executed, "b" points to an object.
}
```

11.3.3 Making multiple aliases

After creating a smart pointer, an arbitrary number of copies can be made from it, and all of them will be aliases of one single object in memory. For instance, after these instructions:

```
CFooPtr a = CFoo::Create(); // Create object
CFooPtr b = a; // Make a new alias
```

the actual memory layout would be like:

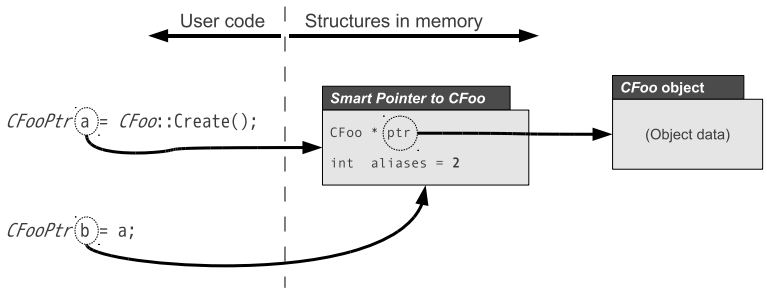


Figure 11.3: *Copying smart pointers become increasing the number of aliases to the same object.*

The copy is very efficient, and totally independent of the complexity of `CFoo`. Notice how, after the copy, the aliases counter is now increased to two. Therefore, just like when using plain pointers, both `a->` and `b->` actually dereference to exactly the same memory address.

If we consider now what happens after the program gets out of the scope where the first smart pointer `a` was created, we arrive to the situation of Figure 11.4, where the aliases counter is back again to one.

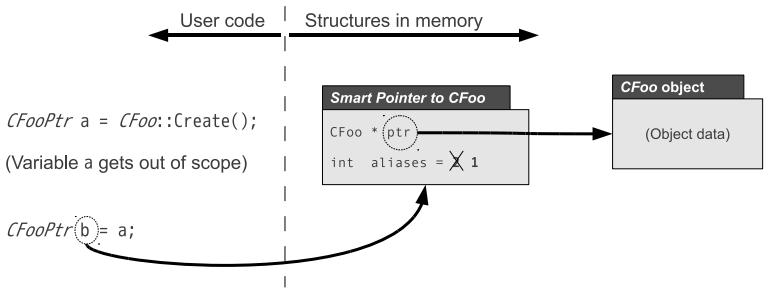


Figure 11.4: *The number of aliases automatically decreases with each smart pointer variable that is no longer used.*

11.3.4 The `clear()` method

There exists a method in all smart pointers named `clear()` which deletes the physical object the smart pointer refers to, replacing it by a `NULL` pointer. As illustrated in Figure 11.5, this operation affects all other aliases:

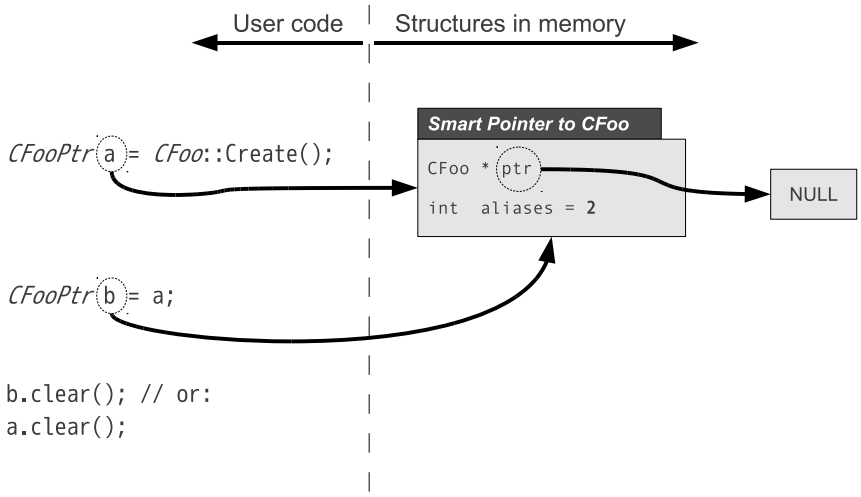


Figure 11.5: *Deleting an object affects all existing aliases.*

As an illustrative example, consider the following code fragment:

```
CFooPtr a = CFoo::Create(); // Create object
CFooPtr b = a; // Make a new alias
b.clear();
if (!b)
{
   // This code WILL be executed since "b==NULL"
}
if (!a)
{
   // This code WILL be executed since "a==NULL"
}
```

11.3.5 The `clear_unique()` method

In contrast to the previous method, one may want in some situations to free just one alias, without affecting the others. This is done with the `clear_unique()` method:

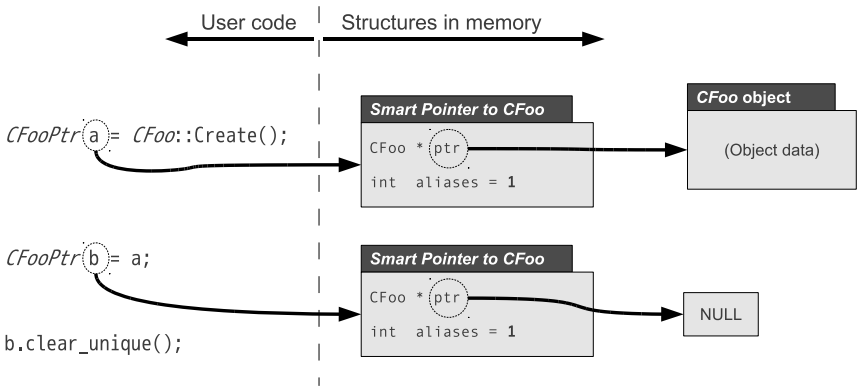


Figure 11.6: *The `clear_unique()` method clears just the referred alias.*

11.3.6 The `make_unique()` method

In this case, the affected aliases become independent of the others and a copy is made of the pointed object, as shown in the following figure:

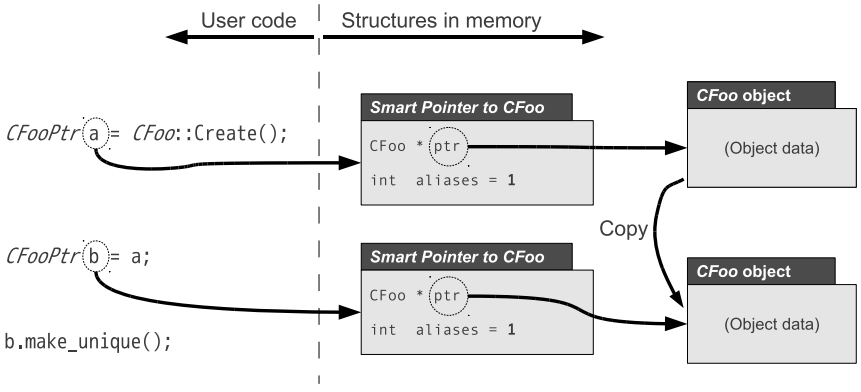


Figure 11.7: *Effects of the `make_unique()` method.*

11.3.7 Creating from dynamic memory

Apart from the `Create()` class factory mentioned above, a smart pointer can be associated to a plain pointer at any given instant by means of the smart pointer class constructor. For instance, in

```
CFoo   *obj = new CFoo(...);
CFooPtr a(obj);
```

the smart pointer `a` now holds the pointer to the object `obj`, and the programmer should *not* issue an `delete obj;` since the smart pointer is the one now in charge of freeing that memory.

11.3.8 Never create from stack-allocated memory

Unlike in the previous case, which was perfectly valid, *don't ever* try to associate a smart pointer to a local variable allocated in the stack, such as in:

```
CFoo   obj;
CFooPtr a(&obj);  // Don't ever try this.
```

It is clear that the smart pointer will eventually try to issue a `delete` on the object which was not actually dynamically allocated, which will for sure lead to an "invalid free" memory error.

Chapter 12

Images

12.1 The central class for images

The main class for image storage is `CImage`, which internally fully relies on the IPL format and OpenCV functions for memory management, format conversions, file I/O, etc. Basically, it is a wrapper for OpenCV C library functionality with the more attractive appearance of a C++ class and extended with many MRPT-specific algorithms.

12.2 Basic image operations

12.3 Feature extraction

12.4 SIFT descriptors

Chapter 13

Rawlog files (datasets)

This chapter describes the two formats for datasets in MRPT's binary format, called "rawlogs". Many existing formats can be imported as rawlogs due to its versatility to cope with a wide range of robotic sensors (see the chapter on Observations for more details).

Rawlog files are the input of many MRPT applications for off-line processing. The application `RawlogViewer` incorporates several tools to visualize and manipulate these files.

13.1 Format #1: A Bayesian filter-friendly file format

13.1.1 Description

The purpose of a rawlog file is to reflect as accurately as possible all the data gathered by a robot as it moves through an environment, autonomously or manually guided.

Under the perspective of Bayesian SLAM methods, these data are divided in two clearly differentiated groups: actions, and observations, denoted typically as u_k and z_k in the literature, respectively.

Hence, to ease the implementation of Bayesian methods in MRPT, a rawlog file is divided in a **sequence of actions, observations, actions, observations, ...** "Actions" typically include robot motor actuations (odometry), but any kind of user-defined actions can be defined as well (e.g. robot arm actuations). "Observations" include readings from the rest of robotic sensors: laser scanners, images from cameras, sonar ranges, etc.

Note that the intention of grouping several observations between two consecutive actions is to assure they are gathered approximately at the same time, although each individual observation has its own timestamp.

13.1.2 Actual contents of a ".rawlog" file in this format

A rawlog file is a binary serialization of alternating objects of the classes:

- CActionCollection, one or more actions (e.g. odometry), and
- CSensoryFrame, which stores the observations.

The serialization mechanism of MRPT is explained in Chapter 10.

13.2 Format #2: An timestamp-ordered sequence of observations

13.2.1 Description

While the previous format is really well-suited for Bayesian approaches with clearly separate steps of process action-process observation, in the case of complex datasets with many different sensors, working at different rates, and possibly without odometry (the typical 'action' in SLAM algorithms), it is more clear to just store datasets as an ordered list of observations.

13.2.2 Actual contents of a ".rawlog" file in this format

In this case, the rawlog file is a binary serialization of objects derived from the class slam::CObservation. In this case, odometry (if present) is also stored as an observation. The serialization mechanism of MRPT is explained in Chapter 10.

The applications RawLogViewer, rawlog-grabber, and the class slam::CRawlog all support both rawlog formats.

13.3 Compression of rawlog files

Since MRPT 0.6.0 all rawlog files are **transparently compressed using the gzip algorithm**. The compression level is set to 'minimum' to reduce as much as possible the computational load, while still deflating file sizes to approximately 33%.

If compatibility with old versions is required, the files can be renamed to `.rawlog.gz`, then decompressed using standard tools. To enable compressed input/output in your code, replace the stream classes by their gzip equivalents:

- `CFileInputStream` → `CFileGZInputStream`
- `CFileOutputStream` → `CFileGZOutputStream`

13.4 Generating Rawlog files

This section describes the generic method to generate rawlog files from your own source code, which is useful to transform existing datasets into the MRPT format, or to capture online data from robotics sensors. The procedure to capture rawlogs using BABEL modules [8, 7] is explained in the MRPT website. A standalone application that grabs rawlogs from a set of robotic sensors is now also included with MRPT, the program `rawlog-grabber` (see Section 3.4).

```
#include <mrpt/core.h>

using namespace mrpt;
using namespace mrpt::utils;
using namespace mrpt::slam;
using namespace mrpt::poses;

int main()
{
  CFileOutputStream  f("my_dataset.rawlog");

  while (there_is_more_data)
  {
    CActionCollection   actions;
    CSensoryFrame               SF;

    // Fill out the actions:
    // ---------------------------------
    CActionRobotMovement2D myAction;  // For example, 2D odometry
    myAction.computeFromOdometry( ... );

    actions.insert( myAction );

    // Fill out the observations:
    // ---------------------------------
    // Create a smart pointer with an empty observation
    CObservation2DRangeScanPtr myObs = CObservation2DRangeScanPtr::Create();
    myObs->...  // Fill out the data

    SF.insert( myObs );  // "myObs" will be automatically freed.

    // Save to the rawlog file:
    // --------------------------------
    f << actions << SF;
  };
  return 0;
}
```

13.5 Reading Rawlog files

13.5.1 Option A: Streaming from the file

This is the preferred mode of operation in general: actions and observations are read sequentially from the file, processed, freed, and so on. In this way only the required objects are loaded in memory at any time, which is mandatory when managing large datasets (e.g. containing thousands of embedded images). However, notice that if images are stored externally the rawlog could be loaded at once without problems.

A typical loop for loading a rawlog in this way is shown next:

```
CFileGZInputStream   rawlogFile(filename);   // "file.rawlog"
CActionCollectionPtr action;  // Smrt. pointer to actions
CSensoryFramePtr     observations;  // Smrt. pointer to observations
size_t               rawlogEntry=0;
bool                 end = false;

// Load action from rawlog:
while ( readActionObservationPair(
          rawlogFile,
          action,
          observations,
          rawlogEntry) )
{
   // Process action & observations
   ...
};
// Smart pointers will be deleted automatically.
```

13.5.2 Option B: Read at once

A rawlog file can be read as a whole using the class slam::CRawlog. Notice that this may be impractical for *very* large datasets (several millions of entries) due to memory requirements, but for mid-sized datasets it definitively is the easiest way of loading rawlogs.

```
CRawlog dataset;
dataset.loadFromRawLogFile(filename);
```

Chapter 14

GUI classes

14.1 Windows from console programs

14.2 Bitmapped graphics

See `mrpt::gui::CDisplayWindow`.

14.3 3D rendered graphics

See `mrpt::gui::CDisplayWindow3D`.

14.4 2D vectorial plots

See `mrpt::gui::CDisplayWindowPlots`.

Chapter 15

OS Abstraction Layer

15.1 Cross platform Support

To write cross-platform and cross-compiler code, we need a layer of functions that act like a minimum set of services found on any OS and compiler. In MRPT, these methods are concentrated in the namespace `mrpt::system::os`, and comprise a range of different areas as enumerated next.

15.2 Function Areas

15.2.1 Threading

15.2.2 Sockets

15.2.3 Time and date

15.2.4 String parsing

15.2.5 Files

Chapter 16

Probability density functions (pdfs)

16.1 Efficient pose sample generator

Chapter 17

Random number generators

17.1 Generators

17.2 Multiple samples

Chapter 18

Observations

18.1 The generic interface

18.2 Implemented observations

18.2.1 Monocular images

18.2.2 Stereo images

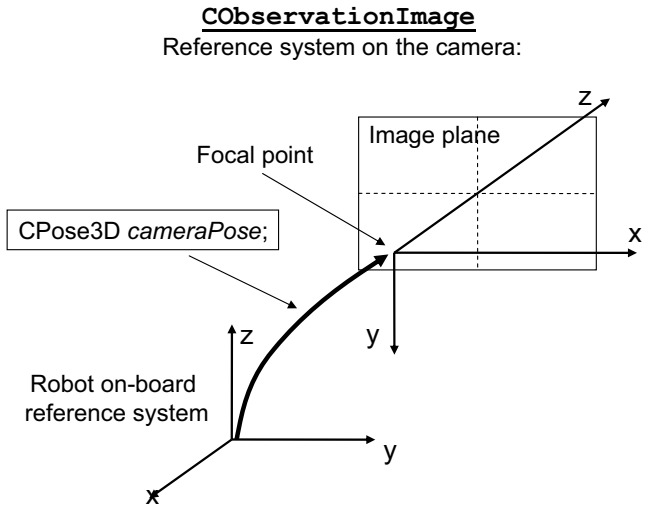


Figure 18.1: *Representation of single camera observations.*

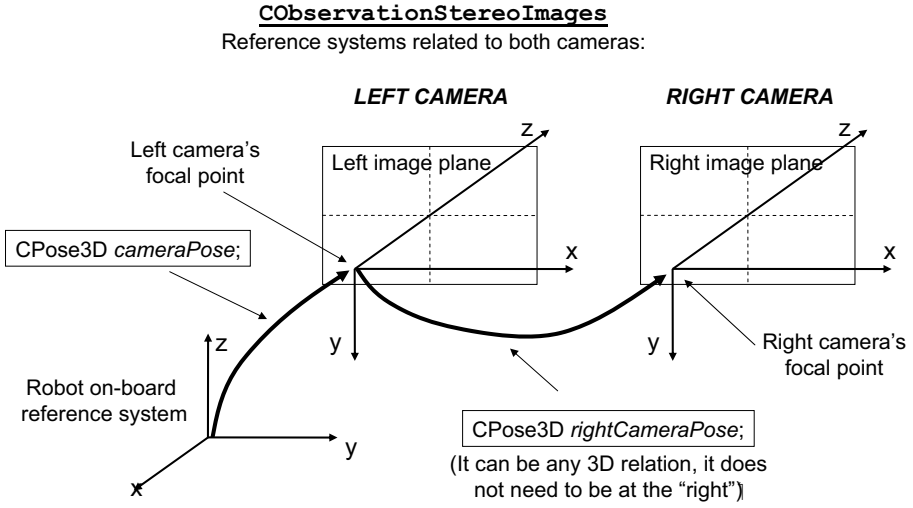


Figure 18.2: *Representation of stereo image observations.*

Chapter 19

Metric map classes

19.1 The generic interface of maps

All metric maps in MRPT have a *common interface* to ease polymorphism and generic programming. The base class is mrpt::slam::CMetricMap. All the map classes are within the namespace `mrpt::slam`, which is omitted in the rest of the chapter for readability.

We review next only the most important methods of this interface:

```
bool    insertObservation (
  const CObservation *obs,
  const CPose3D *robotPose=NULL)
```

By invoking this method, the map will be updated from the new information provided by the passed observation. It is important to remark that not all the maps can process all the kinds of observations. The returned boolean value actually indicates whether the map was affected by the observation. For example, inserting a 2D laser scan in an occupancy grid map will update it, while an observation of gas concentrations will not.

For most kinds of maps, it is crucial to provide a second argument with the location of the robot when the observation was taken from. Notice that the relative position of the sensor with respect to the robot is already taken into account during the process of updating the map, that is, the same `robotPose` must be used for a robot carrying three different laser scanners, as long as the location of each sensor is correctly annotated within the corresponding observation objects.

```
double  computeObservationLikelihood (
  const CObservation *obs,
  const CPose3D &takenFrom)
```

This important method evaluates the log-likelihood of a given observation, conditional to the robot being at the given location in map coordinates. If a given map have no way to infer any sensible value for the likelihood (e.g. a visual landmark

map queried for the likelihood of a laser scanner), an arbitrary constant value will be returned. This method is at the core of most Bayesian approaches to particle filtering-based localization and mapping.

```
void    saveMetricMapRepresentationToFile (
  const std::string &filNamePrefix) const
```

Useful for debugging, this method dumps one or several files with different representations of the map.

19.2 The "multi-metric map" container

The most powerful tool when dealing with metric maps is an especial kind of map: the "multi-metric map". This class offers the interface of a normal metric map, but it holds internally an arbitrary number of other metric maps.

To realize of the potential and simplicity of this approach, imagine programming a method which inserts scans from 3 laser range finders into a 3D point map (so, a point cloud is built incrementally). By just replacing the point map by a multi-metric map, we can now build the point cloud and, at our choice, three occupancy grid maps, once for each height. The original code would need no changes at all.

This is the reason of calling the MRPT map model *hierarchical*, in the sense that one map (the multi-metric map) propagates all the calls to the *child maps*.

19.3 Implemented maps

1. The generic map container: Multi-metric map. Implemented in the class CMultiMetricMap.

2. Beacon maps. A map of 3D beacons with an ID, used for range-only localization and SLAM. Implemented in CBeaconMap.

3. 2D gas concentration maps. A planar lattice of gas concentrations, used for gas concentration mapping. See the class CGasConcentrationGridMap2D.

4. 2D height (or elevation) maps. A lattice where each cell keeps the average elevation ("z" coordinate) of the points sensed within its square area. See the class CHeightGridMap2D.

5. Landmark maps. A set of 3D landmarks with IDs and a 3D Gaussian distribution for its position. Used mainly for visual SLAM. Implemented in CLandmarksMap.

6. Occupancy grid maps. A planar occupancy grid map. Occupancy probabilities are kept as log-odds for a better dynamic range in the possible values of each cell. It is used in many SLAM and particle filter-based localization programs. See the class COccupancyGridMap2D.

KD-tree look-up is built-in in all point maps.

7. Point maps. A virtual class for maps of 2D or 3D points. It implements efficient look-up methods based on KD-trees. The derived classes are:
   (a) Simple point maps. A type of point map where each point only have (x,y,z) coordinates. See CSimplePointsMap.
   (b) Colored point maps. A type of point map where each point have (x,y,z) coordinates, plus RGB color data. Implemented in CColouredPointsMap.

19.4 Configuration block for a multi-metric map

Typically, all the parameters to configure a multi-metric map can be loaded from a INI-like configuration file (or any other textual input, such as an input box in a GUI). Of course, they can be also hard-coded.

The key structure to use here is TSetOfMetricMapInitializers. The format of the configuration files is explained in the reference documentation of:

- TSetOfMetricMapInitializers::loadFromConfigFile.

For practical examples of use, refer also to the INI files locate in the MRPT packages at `MRPT/share/mrpt/config_files/*`.

Chapter 20

Probabilistic Motion Models

20.1 Introduction

Within a particle filter, the samples are propagated at each time step using some given proposal distribution. A common approach for mobile robots is taking the probabilistic motion model directly as this proposal.

In MRPT there are two models for probabilistic 2D motion, implemented in `mrpt::slam::CActionRobotMovement2D`.

To use them just fill out the option structure `motionModelConfiguration` and select the method in:
`CActionRobotMovement2D::TMotionModelOptions ::modelSelection`.

An example of usage would be like:

```
using namespace mrpt::slam;
using namespace mrpt::poses;

CPose2D actualOdometryReading(0.20, 0.05, DEG2RAD(1.2) );

// Prepare the "options" structure:
CActionRobotMovement2D                      actMov;
CActionRobotMovement2D::TMotionModelOptions opts;

opts.modelSelection = CActionRobotMovement2D::mmThrun;
opts.thrunModel.alfa3_trans_trans = 0.10f;

// Create the probability density
// distribution (PDF) from a 2D odometry reading:
actMov.computeFromOdometry( actualOdometryReading, opts );

// For example, draw one sample from the PDF:
CPose2D sample;
actMov.drawSingleSample( sample );
```

This chapter provides a description of the internal models used by these methods.

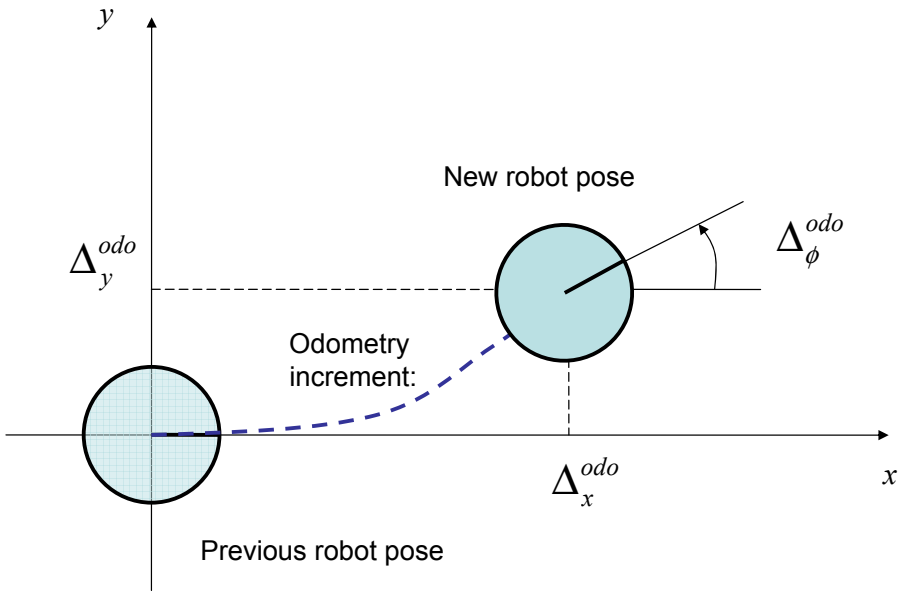


Figure 20.1: *Variables in the Gaussian motion model.*

20.2 Gaussian probabilistic motion model

Assume the odometry is read as incremental changes in the 2D robot pose. The odometry readings are denoted as $\left(\Delta_x^{odo}\ \Delta_y^{odo}\ \Delta_\phi^{odo}\right)$. The model for these variables is depicted in Figure 20.1.

The equations that relate the prior robot pose $(x\ y\ \phi)$ and the new pose $(x'\ y'\ \phi')$ after the incremental change are: (based on the proposal in [6])

$$\begin{pmatrix} x' \\ y' \\ \phi' \end{pmatrix} = \begin{pmatrix} x \\ y \\ \phi \end{pmatrix} + \begin{pmatrix} \cos(\phi + \frac{\Delta_\phi^{odo}}{2}) & -\sin(\phi + \frac{\Delta_\phi^{odo}}{2}) & 0 \\ \sin(\phi + \frac{\Delta_\phi^{odo}}{2}) & \cos(\phi + \frac{\Delta_\phi^{odo}}{2}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \Delta_x^{odo} \\ \Delta_y^{odo} \\ \Delta_\phi^{odo} \end{pmatrix}$$

Our aim here is to obtain a multivariate Gaussian distribution of the new pose, given that the prior pose has a known value (it is the particle being propragated). In this case we can just model how to draw samples from a prior pose of (0 0 0), and then the samples can be composed using the actual prior pose.

Using this simplification:

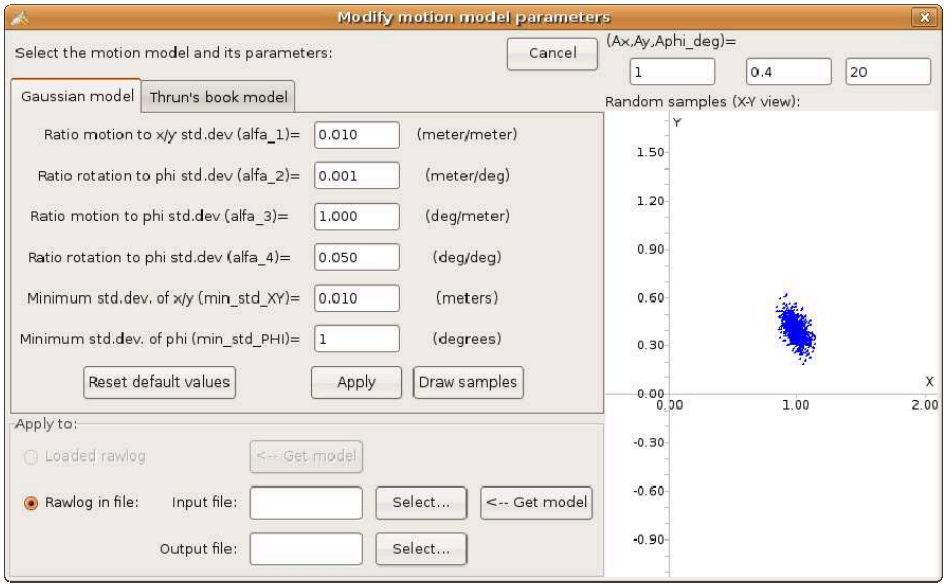


Figure 20.2: *Simulation of a Gaussian motion model in RawlogViewer.*

$$\begin{pmatrix} x' \\ y' \\ \phi' \end{pmatrix} = \begin{pmatrix} \cos\frac{\Delta_\phi^{odo}}{2} & -\sin\frac{\Delta_\phi^{odo}}{2} & 0 \\ \sin\frac{\Delta_\phi^{odo}}{2} & \cos\frac{\Delta_\phi^{odo}}{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \Delta_x^{odo} \\ \Delta_y^{odo} \\ \Delta_\phi^{odo} \end{pmatrix} = H \begin{pmatrix} \Delta_x^{odo} \\ \Delta_y^{odo} \\ \Delta_\phi^{odo} \end{pmatrix}$$

The mean of the Gaussian can be simply computed from the composition of the prior and the odometry increment. For the covariance, we need to estimate the variances of the three variables of the odometry increment. We model them as having independent, zero-mean Gaussian errors. The errors will be composed of terms that capture imperfect odometry and potential drift effects.

We denote as Σ the diagonal matrix having the three variances of the odometry variables, modeled as:

$$\sigma_{\Delta_x^{odo}} = \sigma_{\Delta_y^{odo}} = \sigma_{xy}^{min} + \alpha_1\sqrt{(\Delta_x^{odo})^2 + (\Delta_y^{odo})^2} + \alpha_2|\Delta_\phi^{odo}|$$
$$\sigma_{\Delta_\phi^{odo}} = \sigma_\phi^{min} + \alpha_3\sqrt{(\Delta_x^{odo})^2 + (\Delta_y^{odo})^2} + \alpha_4|\Delta_\phi^{odo}|$$

The default parameters (loaded in the constructor and available in RawLogViewer) are:

$$\begin{aligned}
\alpha_1 &= 0.05\ meters/meter \\
\alpha_2 &= 0.001\ meters/degree \\
\alpha_3 &= 5\ degrees/meter \\
\alpha_4 &= 0.05\ degrees/degree \\
\sigma_{xy}^{min} &= 0.01\ meters \\
\sigma_{\phi}^{min} &= 0.20\ degrees
\end{aligned}$$

And finally, the covariance of the new pose after the odometry increment (C) is computed by means of:

$C = J\ \Sigma\ J^t$

where J stands for the Jacobian of H.

An example of samples obtained using this model with the RawLogViewer application is represented by Figure 20.2.

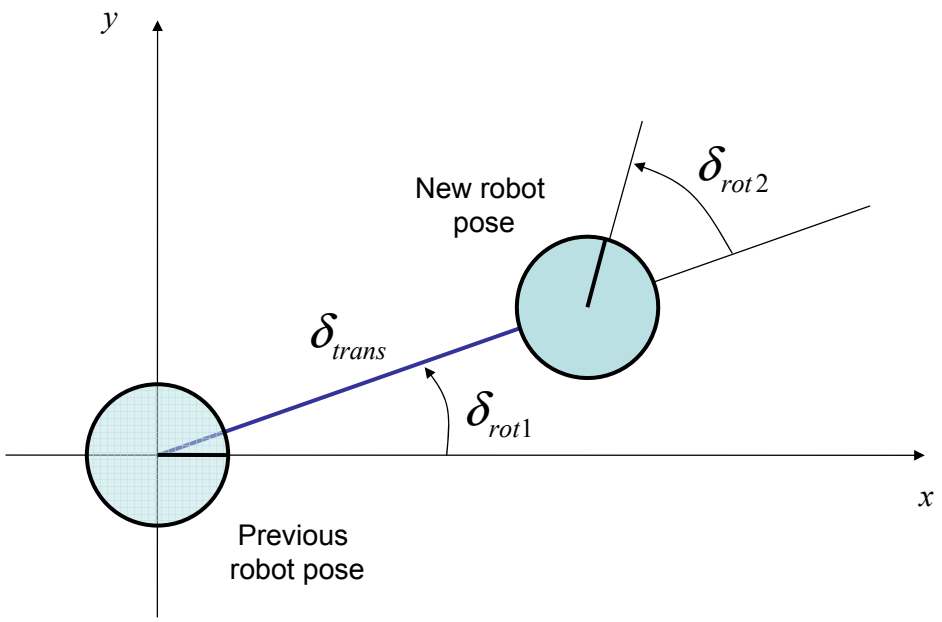


Figure 20.3: *Variables in the particle-based motion model.*

20.3 Thrun et al.'s book particle motion model

Like above, denote the odometry readings as $\left(\Delta_x^{odo}\ \Delta_y^{odo}\ \Delta_\phi^{odo}\right)$, and let's assume that the prior robot pose is (0 0 0), which means that we want to draw samples of the robot increment, not the final robot pose (to simplify the equations without loss of generality). Then, the new robot pose, which we want to draw samples from is:

$$\begin{pmatrix} x' \\ y' \\ \phi' \end{pmatrix} = \begin{pmatrix} \cos\hat{\delta}_{rot1} & 0 & 0 \\ \sin\hat{\delta}_{rot1} & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} \hat{\delta}_{trans} \\ \hat{\delta}_{rot1} \\ \hat{\delta}_{rot2} \end{pmatrix}$$

Where the variables correspond to the robot pose increment as is shown in Figure 20.3.

Here, the variables $\hat{\delta}_{trans}$, $\hat{\delta}_{rot1}$ and $\hat{\delta}_{rot2}$ are the result of adding a Gaussian, zero-mean random noise to the actual odometry readings:

$$\begin{array}{rcll} \hat{\delta}_{trans} = & \delta_{trans} + \epsilon_{trans} & \epsilon_{trans} \sim \mathcal{N}(0, \sigma^2_{trans}) \\ \hat{\delta}_{rot1} = & \delta_{rot1} + \epsilon_{rot1} & \epsilon_{rot1} \sim \mathcal{N}(0, \sigma^2_{rot1}) \\ \hat{\delta}_{rot2} = & \delta_{rot2} + \epsilon_{rot2} & \epsilon_{rot2} \sim \mathcal{N}(0, \sigma^2_{rot2}) \end{array}$$

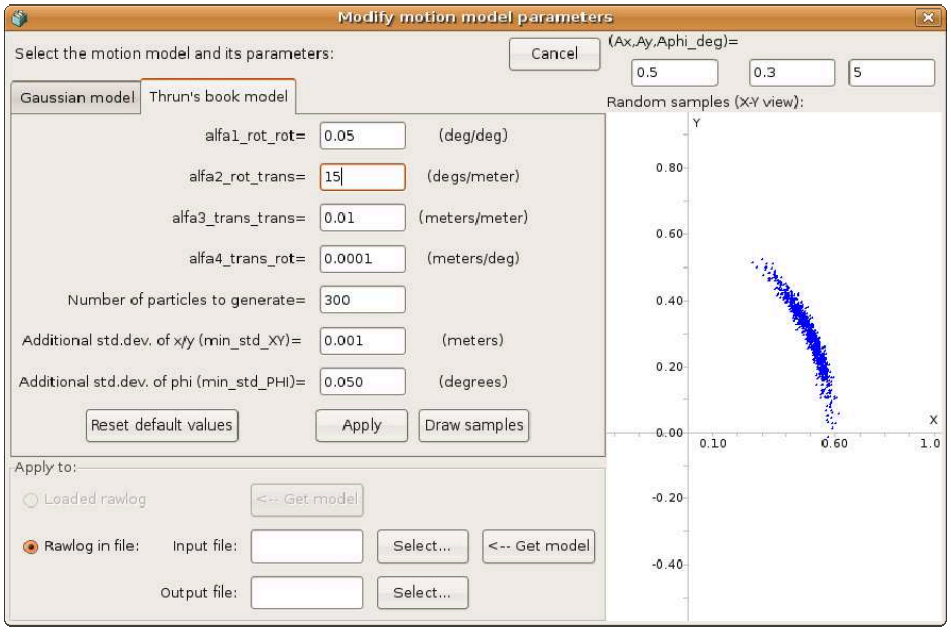


Figure 20.4: *Simulation of a particles motion model in RawlogViewer.*

The model described in [12] employs the following approximations for the values of the standard deviations required for the equations above:

$$\begin{aligned} \sigma_{rot1} &= \alpha_1|\delta_{rot1}| + \alpha_2\delta_{trans} \\ \sigma_{trans} &= \alpha_3\delta_{trans} + \alpha_4(|\delta_{rot1}| + |\delta_{rot2}|) \\ \sigma_{rot2} &= \alpha_1|\delta_{rot2}| + \alpha_2\delta_{trans} \end{aligned}$$

This is the model implemented in CActionRobotMovement2D when setting "CActionRobotMovement2D::TMotionModelOptions::modelSelection" to "mmThrun". Actually, a small additional error is summed to each pose component (x, y, ϕ) to avoid that for a null odometry increment the movement for all the particles become exactly zero, which may lead a particle filter to degenerate.

Figure 20.4 shows an example of samples generated using this model, for an excessively large value of α_2 (a very large "slippage"), generated by the application RawLogViewer.

Chapter 21

Sensor Interfaces

This chapter describes the two parts in which classes of the library `mrpt-hwdrivers` are divided: those providing the basis of communications (USB, serial), and the sensors themselves.

21.1 Communications

21.1.1 Serial ports

Even nowadays, lots of devices offer serial ports (or embedded USB-to-serial converters) as interfaces due to their simplicity of use. In MRPT, a serial port can be managed with the class `hwdrivers::CSerialPort`. An example of usage would be as follows:

```
#include <mrpt/hwdrivers.h>
...
CSerialPort  ser;
ser.setSerialPortName("ttyS0"); // or "COM3", ...
ser.setConfig(9600 /*baud*/, 0 /*no parity*/, 8 /*8 bit words*/ );
ser.open();
if (!ser.isOpen())  { // Report error }
ser.Read( ... );
ser.Write( ... );
ser.close();  // optional: it closes on destruction anyway
```

In addition, a serial port implements the generic `CStream` interface, thus it is perfectly legal to transfer arbitrarily complex objects through a serial connection as in:

```
COccupancyGridMap2D   map;
ser << map;
```

However, the most likely use of a serial ports is to send and receive short textual messages, thus the most useful methods are `Read` and `Write`.

Names of serial ports

In Windows, serial ports appear with names `COM1`, `COM2`, `COM3`, `COM4` and `\\.\COMXX` for the rest. However, if you pass a name without the prefix `\\.\` it will be added automatically.

In Linux, a variety of names can be found such as `ttyUSB0`, `ttyS0` or `ttyACM0`. It is not required to provide the full path to the device (eg. `/dev/ttyS0`), as in Windows, it will be added transparently.

As follows from above, always keep serial port names as **strings**, not only as **a number** since it will be not enough in a cross-platform application.

Timeouts

Slight changes in the timeouts of your connection can be lead to random and hard to debug errors with no apparent reason. The proper way of setting these delays is through the method:

```
void CSerialPort::setTimeouts(
  int  ReadIntervalTimeout,
  int  ReadTotalTimeoutMultiplier,
  int  ReadTotalTimeoutConstant,
  int  WriteTotalTimeoutMultiplier,
  int  WriteTotalTimeoutConstant  )
```

where all the fields have the same meaning than in the Windows API[1].

21.1.2 USB FIFO with FTDI chipset

21.2 Summary of sensors

[1] Search for the COMMTIMEOUTS structure for details.

21.3 The unified sensor interface

When implementing a new sensor class, the following execution flow must be kept in mind:

1. Object constructor: Do here basic initialization only. Parameters are still not set (see next step), thus communications must not be set up at this point.
2. `CGenericSensor::loadConfig`: Load here the parameters specific to your sensor. Notice that the application `rawlog-grabber` automatically loads the following parameters (common to all the sensors), thus they must be not loaded at this point:
   (a) "process_rate": The rate in Hertz (Hz) at which the sensor thread should invoke "doProcess". Mandatory parameter.
   (b) "max_queue_len": The maximum number of objects in the observations queue (default is 100). If overflow occurs, an error message will be issued at run-time.
3. `CGenericSensor::initialize`: Initialize here your connections, send initial commands to the device, etc.
4. `CGenericSensor::doProcess`: This method is called over and over again while the application is running. Your code must not delay too much and must always return, i.e. do not insert infinite loops. If a new piece of information from the sensor is gathered (which may not always occur), use the helper method `CGenericSensor::appendObservation` to add it to the "output queue". That is all `rawlog-grabber` expects from each sensor's class. Observations must be inserted in the list in the form of smart pointers (refer to Chapter 11).

21.4 How `rawlog-grabber` works

Chapter 22

Kalman filters

22.1 Introduction

22.2 Algorithms

22.3 How to implement a problem as a KF

The example bayesianTracking.

A more complicated model, the problem of 6D SLAM, is discussed in detail in [3] and implemented as the application `kf-slam` within MRPT.

Chapter 23

Particle filters

23.1 Introduction

A good tutorial can be found in [1].

23.2 Algorithms

23.2.1 SIR

23.2.2 Auxiliary PF

23.2.3 Optimal PF

23.2.4 Optimal-rejection sampling PF

The method presented in the paper [4].

23.3 Resampling schemes

A common problem of all particle filters is the *degeneracy of weights*, which consists in the unbounded increase of the variance of the weights $\omega^{[i]}$ with time. In order to prevent this growth of variance, which entails a loss of particle diversity, one of a set of *resampling* methods must be employed. The aim of resampling is replacing an old set of N particles by a new one with the same population but where particles have been duplicated or removed according to their weights. More specifically, the expected duplication count of the i'th particle, denoted by N_i, must tend to $N\omega^{[i]}$. After resampling, all the weights become equal to preserve the importance sampling of the target pdf.

In this section we briefly review four different strategies for resampling a set of particles whose normalized weights are given by $\omega^{[i]}$ for $i = 1, ..., N$. The methods are explained using a visual analogy with a "wheel" whose perimeter is assigned to

the different particles in such a way that the length associated to the i'th particle is proportional to its weight $\omega^{[i]}$. Therefore, picking a random direction in this "wheel" implies choosing a particle with a probability proportional to its weight. For a more formal description of the methods, please refer to the excellent paper by Douc, Cappé and Moulines [5].

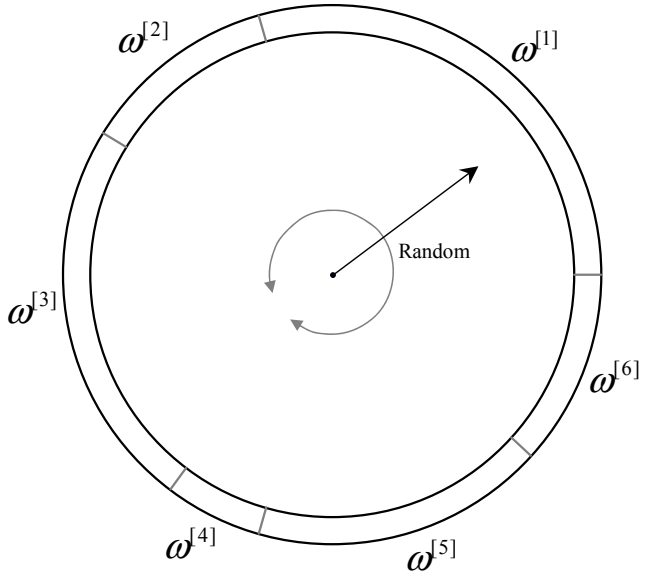


Figure 23.1: *The multinomial resampling algorithm.*

- **Multinomial resampling:** The most straighforward method, where N independent random numbers are generated to pick a particle from the old set. In the "wheel" analogy, illustrated in Figure 23.1, this method consists of picking N independent random directions.

  The name of this method comes from the fact that the probability mass function for the duplication counts N_i is the multinomial distribution with the weights as parameters.

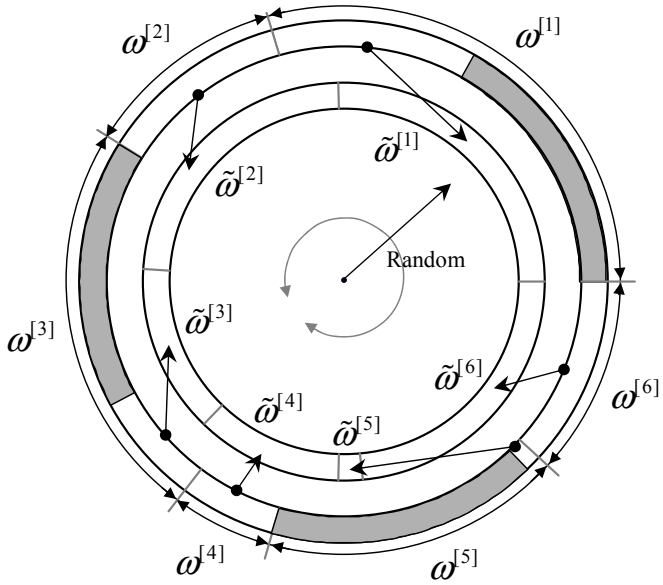


Figure 23.2: *The residual resampling algorithm. The shaded areas represent the integer parts of* $\omega^{[i]}/(1/N)$*. The residual parts of the weights, substracting these areas, are taken as the modified weights* $\tilde{\omega}^{[i]}$*.*

- **Residual resampling:** This method comprises of two stages. Firstly, particles are sampled deterministically by picking $N_i = \lfloor N\omega^{[i]} \rfloor$ copies of the i'th particle. Then, multinomial sampling is performed with the residual weights

$$\tilde{\omega}^{[i]} = \omega^{[i]} - N_i/N.$$

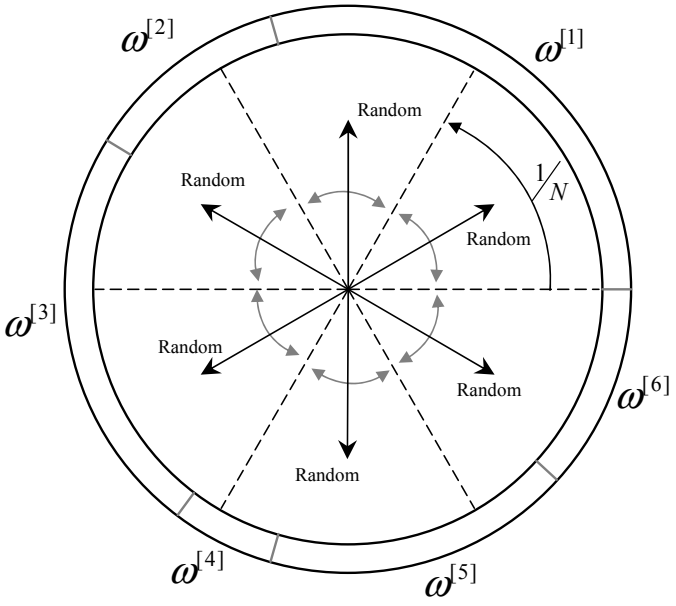


Figure 23.3: *The stratified resampling algorithm. The entire circunference is associated to the range* $[0, 1]$ *in the space of the particle weights, hence dividing it into* N *equal parts is represented as* N *circular sectors of* $1/N$ *each.*

- **Stratified resampling:** In this method, the "wheel" representing the old set of particles is divided into N equally-sized segments, as represented in Figure 23.3. Then, N uniform numbers are independently generated like in multinomial sampling, but instead of mapping each draw to the entire circunference, they are mapped to its corresponding partition.

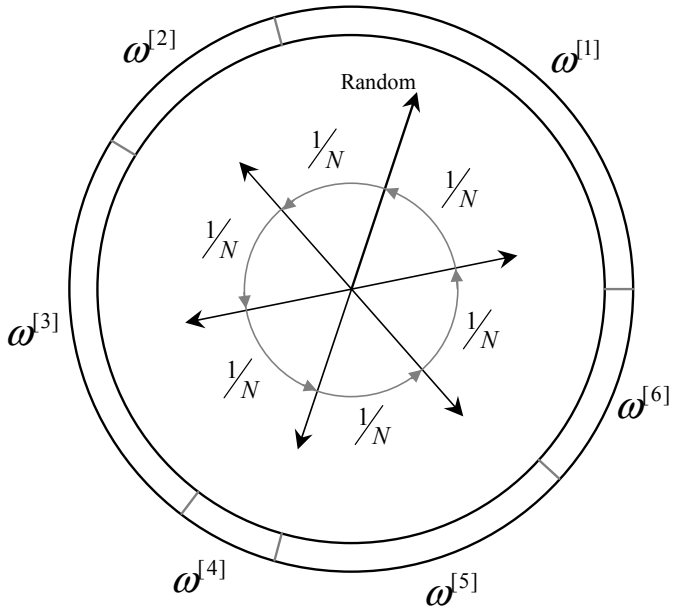


Figure 23.4: *The systematic resampling algorithm.*

- **Systematic resampling:** Also called *universal sampling*, this popular technique draws only one random number, i.e. one direction in the "wheel", with the others $N-1$ directions being fixed at $1/N$ increments from the random pick.

23.4 Implementation examples

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