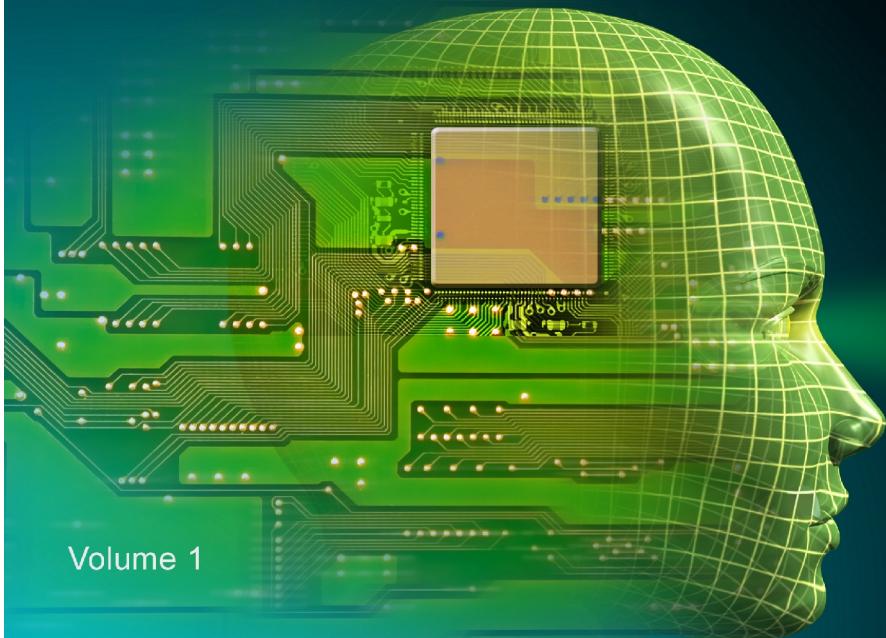


ROS

By Example

A Do-It-Yourself Guide to the
Robot Operating System



Volume 1

R. Patrick Goebel

ROS By Example

A Do-It-Yourself Guide to the
Robot Operating System

VOLUME 1

A PI ROBOT PRODUCTION

R. PATRICK GOEBEL

Version 1.02
For ROS Fuerte

ROS BY EXAMPLE. Copyright © 2012 by R. Patrick Goebel

All Rights Reserved. No part of this work may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage or retrieval system, without the prior written permission of the copyright owner and the publisher.

ISBN: 5-800085-311092

LEGO® is a trademark of the LEGO group which does not sponsor, authorize, or endorse this book.

Other products and company names mentioned herein may be the trademarks of their respective owners. Rather than use a trademark symbol with every occurrence of a trademark name, we are using the names only in an editorial fashion and to the benefit of the trademark owner, with no intention of infringement of the trademark.

Information contained in this work (Paperback or eBook) has been obtained from sources believed to be reliable. However, the author does not guarantee the accuracy or completeness of any information contained in it, and the author shall not be responsible for any errors, omissions, losses, or damages caused or alleged to be caused directly or indirectly by the information published herein. This work is published with the understanding that the author is supplying information but is not attempting to render professional services. This product almost certainly contains errors. It is your responsibility to examine, verify, test, and determine the appropriateness of use, or request the assistance of an appropriate professional to do so.

PREFACE

This book is about programming your robot to do amazing things, whether it be detecting people's faces and other visual objects, navigating autonomously around your house, or responding to spoken commands. We will be using some of the most advanced robotics software available today thanks to ROS, the Robot Operating System from California-based [Willow Garage](#).

The primary goal of ROS (pronounced "Ross") is to provide a unified and open source programming framework for controlling robots in a variety of real world and simulated environments. ROS is certainly not the first such effort; in fact, doing a Wikipedia search for "robot software" turns up over 25 such projects. But Willow Garage is no ordinary group of programmers banging out free software. Propelled by some serious funding, strong technical expertise, and a well planned series of developmental milestones, Willow Garage has ignited a kind of programming fever among roboticists with hundreds of user-contributed ROS packages already created in just a few short years. ROS now includes software for tasks ranging from navigation and localization (SLAM), 3D object recognition, action planning, motion control for multi-jointed arms, machine learning and even [playing billiards](#).

In the meantime, Willow Garage has also designed and manufactured a \$400,000 robot called the PR2 to help showcase its operating system. Using the latest in robot hardware, including two stereo cameras, a pair of laser scanners, arms with 7 degrees of freedom, and an omni-directional drive system, only a lucky few will be able to run ROS directly on the PR2, including 11 research institutions that were awarded free PR2s as part of a beta-test contest. However, you do not need a PR2 to leverage the power of ROS; packages have already been created to support lower-cost platforms and components including the iRobot Create, TurtleBot, Arduino, WowWee Rovio, LEGO® NXT, Phidgets, ArbotiX, Serializer and Robotis Dynamixels.

The guiding principle underlying ROS is "don't reinvent the wheel". Many thousands of very smart people have been programming robots for over fifty years—why not bring all that brain power together in one place? Fortunately, the Web is the perfect medium for sharing code. Many universities, companies and individuals now openly share their ROS code repositories, and with free cloud space available through services such as Google Code, anyone can share their own ROS creations easily and at no cost.

Perhaps the best part of jumping on the ROS train is the excitement that comes from working with thousands of like-minded roboticists from around the world. Not only will you save many days of frustration by not duplicating someone else's work, you can also feel the satisfaction that comes from contributing back to this rapidly developing field.

PRINTED VS PDF VERSIONS OF THE BOOK

The printed and PDF versions of this book are nearly the same with a few important differences. The page formatting is identical but most PDF readers start page numbering from the first page and ignore what is set by the document itself. Images and code syntax are in color in the PDF version but grayscale in the printed version to keep the cost reasonable. The PDF version is full of clickable links to other resources on the Web. In the printed version, these links appear as underlined text with a numbered superscript. The expanded URLs are then listed as endnotes at the end of the book.

Staying Up-To-Date: If you'd like to receive notifications of updates to both the book and the accompanying code, please join the [ros-by-example Google Group](#).

Main Chapter Headings

1. Purpose of this Book.....	1
2. Real and Simulated Robots.....	3
3. Operating Systems and ROS Versions.....	5
4. Reviewing the ROS Basics.....	7
5. Installing the ros-by-example Code.....	21
6. Installing the Arbotix Simulator.....	25
7. Controlling a Mobile Base.....	29
8. Navigation, Path Planning and SLAM.....	67
9. Speech Recognition and Synthesis.....	111
10. Robot Vision.....	127
11. Combining Vision and Base Control.....	181
12. Dynamixel Servos and ROS.....	197
13. Where to Go Next?.....	223

Contents

Preface	vii
Printed vs PDF Versions of the Book	ix
1. Purpose of this Book	1
2. Real and Simulated Robots	3
2.1 Gazebo, Stage, and the ArbotiX Simulator	3
2.2 Introducing the TurtleBot, Maxwell and Pi Robot	4
3. Operating Systems and ROS Versions	5
3.1 Installing Ubuntu Linux	5
3.2 Getting Started with Linux	6
4. Reviewing the ROS Basics	7
4.1 Installing ROS	7
4.2 Installing rosinstall	7
4.3 Creating Your Personal ROS Directory	7
4.4 Working through the Official ROS Tutorials	8
4.5 RViz: The ROS Visualization Tool	9
4.6 Using ROS Parameters in your Programs	10
4.7 Using dynamic_reconfigure to set ROS Parameters	10
4.8 Networking Between a Robot and a Desktop Computer	11
4.9 ROS Recap	13
4.10 The Official ROS Cheat Sheet	13
4.11 What is a ROS Application?	13
4.12 Installing Packages with SVN, Git, and Mercurial	15
4.12.1 SVN	15
4.12.2 Git	15

4.12.3 Mercurial	16
4.13 Removing Packages from your Personal ROS Directory	16
4.14 How to Find Third-Party ROS Packages	17
4.14.1 Searching the ROS Wiki	17
4.14.2 Using the roslocate Command	17
4.14.3 Browsing the ROS Software Index	19
4.14.4 Doing a Google Search	19
4.15 Getting Further Help with ROS	19
5. Installing the ros-by-example Code	21
5.1 Installing the Prerequisites	21
5.2 Installing the rbx_vol_1 Stack	21
5.3 Installing the Pi Robot URDF Files	23
5.4 About the Code Listings in this Book	23
6. Installing the Arbotix Simulator	25
6.1 Installing the Simulator	25
6.2 Testing the Simulator	25
6.3 Running the Simulator with Your Own Robot	27
7. Controlling a Mobile Base	29
7.1 Units and Coordinate Systems	29
7.2 Levels of Motion Control	29
7.2.1 Motors, Wheels, and Encoders	30
7.2.2 Motor Controllers and Drivers	30
7.2.3 The ROS Base Controller	30
7.2.4 Frame-Based Motion using the move_base ROS Package	31
7.2.5 SLAM using the gmapping and amcl ROS Packages	31
7.2.6 Semantic Goals	32
7.2.7 Summary	32
7.3 Twisting and Turning with ROS	33

7.3.1 Example Twist Messages	33
7.3.2 Monitoring Robot Motion using RViz	34
7.4 Calibrating Your Robot's Odometry	36
7.4.1 Linear Calibration	37
7.4.2 Angular Calibration	38
7.5 Sending Twist Messages to a Real Robot	39
7.6 Publishing Twist Messages from a ROS Node	40
7.6.1 Estimating Distance and Rotation Using Time and Speed	40
7.6.2 Timed Out-and-Back in the ArbotiX Simulator	41
7.6.3 The Timed Out-and-Back Script	42
7.6.4 Timed Out and Back using a Real Robot	46
7.7 Are We There Yet? Going the Distance with Odometry	48
7.8 Out and Back Using Odometry	50
7.8.1 Odometry-Based Out and Back in the ArbotiX Simulator	51
7.8.2 Odometry-Based Out and Back Using a Real Robot	52
7.8.3 The Odometry-Based Out-and-Back Script	53
7.8.4 The /odom Topic versus the /odom Frame	59
7.9 Navigating a Square using Odometry	59
7.9.1 Navigating a Square in the ArbotiX Simulator	60
7.9.2 Navigating a Square using a Real Robot	61
7.9.3 The nav_square.py Script	62
7.9.4 The Trouble with Dead Reckoning	62
7.10 Teleoperating your Robot	63
7.10.1 Using the Keyboard	63
7.10.2 Using a Logitech Game Pad	64
7.10.3 Using the ArbotiX Controller GUI	65
7.10.4 TurtleBot Teleoperation Using Interactive Markers	66
7.10.5 Writing your Own Teleop Node	66

8. Navigation, Path Planning and SLAM	67
8.1 Path Planning and Obstacle Avoidance using move_base	67
8.1.1 Specifying Navigation Goals Using move_base	68
8.1.2 Configuration Parameters for Path Planning	69
8.1.2.1 <i>base_local_planner_params.yaml</i>	70
8.1.2.2 <i>costmap_common_params.yaml</i>	71
8.1.2.3 <i>global_costmap_params.yaml</i>	71
8.1.2.4 <i>local_costmap_params.yaml</i>	72
8.2 Testing move_base in the ArbotiX Simulator	73
8.2.1 Point and Click Navigation in RViz	77
8.2.2 Navigation Display Types for RViz	77
8.2.3 Navigating a Square using move_base	78
8.2.4 Avoiding Simulated Obstacles	84
8.2.5 Setting Manual Goals with Obstacles Present	86
8.3 Running move_base on a Real Robot	86
8.3.1 Testing move_base without Obstacles	86
8.3.2 Avoiding Obstacles using the TurtleBot's Fake Laser Scan	88
8.4 Map Building using the gmapping Package	89
8.4.1 Laser Scanner or Depth Camera?	90
8.4.2 Collecting and Recording Scan Data	91
8.4.3 Can I Extend or Modify an Existing Map?	94
8.5 Navigation and Localization using a Map and amcl	95
8.5.1 Testing amcl with Fake Localization	95
8.5.2 Using amcl with a Real Robot	97
8.5.3 Fully Autonomous Navigation	98
8.5.4 Running the Navigation Test in Simulation	99
8.5.5 Understanding the Navigation Test Script	101
8.5.6 Running the Navigation Test on a Real Robot	106
8.5.7 What's Next?	109

9. Speech Recognition and Synthesis	111
9.1 Installing PocketSphinx for Speech Recognition	111
9.2 Testing the PocketSphinx Recognizer	112
9.3 Creating a Vocabulary	114
9.4 A Voice-Control Navigation Script	116
9.4.1 Testing Voice-Control in the ArbotiX Simulator	120
9.4.2 Using Voice-Control with a Real Robot	121
9.5 Installing and Testing Festival Text-to-Speech	122
9.5.1 Using Text-to-Speech within a ROS Node	124
9.5.2 Testing the talkback.py script	126
10. Robot Vision	127
10.1 OpenCV, OpenNI and PCL	127
10.2 A Note about Camera Resolutions	128
10.3 Installing and Testing the ROS Camera Drivers	128
10.3.1 Installing the OpenNI Drivers	128
10.3.2 Installing Webcam Drivers	128
10.3.3 Testing your Kinect or Xtion Camera	129
10.3.4 Testing your USB Webcam	130
10.4 Installing OpenCV on Ubuntu Linux	130
10.5 ROS to OpenCV: The cv_bridge Package	132
10.6 The ros2opencv2.py Utility	137
10.7 Processing Recorded Video	139
10.8 OpenCV: The Open Source Computer Vision Library	140
10.8.1 Face Detection	140
10.8.2 Keypoint Detection using GoodFeaturesToTrack	146
10.8.3 Tracking Keypoints using Optical Flow	152
10.8.4 Building a Better Face Tracker	158
10.8.5 Dynamically Adding and Dropping Keypoints	161

10.8.6 Color Blob Tracking (CamShift)	162
10.9 OpenNI and Skeleton Tracking	169
10.9.1 Viewing Skeletons in RViz	170
10.9.2 Accessing Skeleton Frames in your Programs	170
10.10 PCL Nodelets and 3D Point Clouds	175
10.10.1 The PassThrough Filter	176
10.10.2 Combining More than One PassThrough Filter	177
10.10.3 The VoxelGrid Filter	178
11. Combining Vision and Base Control	181
11.1 A Note about Camera Coordinate Axes	181
11.2 Object Tracker	181
11.2.1 Testing the Object Tracker with rxplot	181
11.2.2 Testing the Object Tracker with a Simulated Robot	182
11.2.3 Understanding the Object Tracker Code	182
11.2.4 Object Tracking on a Real Robot	187
11.3 Person Follower	188
11.3.1 Testing the Follower Application in Simulation	189
11.3.2 Understanding the Follower Script	190
11.3.3 Running the Follower Application on a TurtleBot	194
11.3.4 Running the Follower Node on a Filtered Point Cloud	194
12. Dynamixel Servos and ROS	197
12.1 A TurtleBot with a Pan-and-Tilt Head	198
12.2 Choosing a Dynamixel Hardware Controller	198
12.3 A Note Regarding Dynamixel Hardware	199
12.4 Choosing a ROS Dynamixel Package	199
12.5 Understanding the ROS JointState Message Type	199
12.6 Controlling Joint Position, Speed and Torque	200
12.6.1 Setting Servo Position	201

12.6.2 Setting Servo Speed	202
12.6.3 Controlling Servo Torque	202
12.7 Checking the USB2Dynamixel Connection	203
12.8 Setting the Servo Hardware IDs	204
12.9 Configuring and Launching <code>dynamixel_controllers</code>	205
12.9.1 The <code>dynamixel_controllers</code> Configuration File	205
12.9.2 The <code>dynamixel_controllers</code> Launch File	206
12.10 Testing the Servos	208
12.10.1 Starting the Controllers	208
12.10.2 Monitoring the Robot in RViz	209
12.10.3 Listing the Controller Topics and Monitoring Joint States	209
12.10.4 Listing the Controller Services	211
12.10.5 Setting Servo Position, Speed and Torque	211
12.10.6 Using the <code>relax_all_servos.py</code> Script	213
12.11 Tracking a Visual Target	213
12.11.1 Tracking a Face	213
12.11.2 The Head Tracker Script	214
12.11.3 Tracking Colored Objects	219
12.11.4 Tracking Manually Selected Targets	220
12.12 A Complete Head Tracking ROS Application	221
13. Where to Go Next?	223

1. PURPOSE OF THIS Book

ROS is extremely powerful and continues to expand and improve at a rapidly accelerating pace. Yet one of the challenges facing many new ROS users is knowing where to begin. There are really two phases to getting started with ROS: Phase 1 involves learning the basic concepts and programming techniques while Phase 2 is about using ROS to control your own robot.

Phase 1 is best tackled by referring to the [ROS Wiki](#) where you will find a set of [installation instructions](#) and a collection of superbly written [Beginner Tutorials](#). These tutorials have been battle-tested by hundreds if not thousands of users so there is no sense in duplicating them here. **These tutorials are considered a prerequisite for using this book.** We will therefore assume that the reader has worked through all the tutorials at least once. It is also essential to read the [tf overview](#) and do the [tf Tutorials](#) which will help you understand how ROS handles different frames of reference. If you run into trouble, check out the [ROS Answers](#) (<http://answers.ros.org>) forum where many of your questions may already have been answered. If not, you can post your new question there. (Please do not use the `ros-users` mailing list for such questions which is reserved for ROS news and announcements.)

Phase 2 is what this book is all about: using ROS to make your robot do some fairly impressive tasks. Each chapter will present tutorials and code samples related to different aspects of ROS. We will then apply the code to either a real-world robot, a pan-and-tilt head, or even just a camera (e.g. face detection). For the most part, you can do these tutorials in any order you like. At the same time, the tutorials will build on one another so that by the end of the book, your robot will be able to autonomously navigate your home or office, respond to spoken commands, and combine vision and motion control to track faces or follow a person around the house.

In this volume we will cover the following topics:

- Installing and configuring ROS (review).
- Controlling a mobile base at different levels of abstraction, beginning with motor drivers and wheel encoders, and proceeding upward to path planning and map building.
- Navigation and SLAM (Simultaneous Localization And Mapping) using either a laser scanner or a depth camera like the Microsoft Kinect or Asus Xtion.
- Speech recognition and synthesis, as well as an application for controlling your robot using verbal commands.

- Robot vision, including face detection and color tracking using OpenCV, skeleton tracking using OpenNI, and a brief introduction to PCL for 3D vision processing.
- Combining robot vision with a mobile base to create two applications, one for tracking faces and colored objects, and another for following a person as they move about the room.
- Controlling a pan-and-tilt camera using Dynamixel servos to track a moving object.

Given the breadth and depth of the ROS framework, we must necessarily leave out a few topics in this introductory volume. In particular, we will not cover the [Gazebo](#) simulator, [arm navigation](#), [tabletop object manipulation](#), [general object detection](#), creating your own [URDF robot model](#), robot [diagnostics](#), or the use of task managers such as [SMACH](#). Nonetheless, as you can see from the list above, we still have much to do!

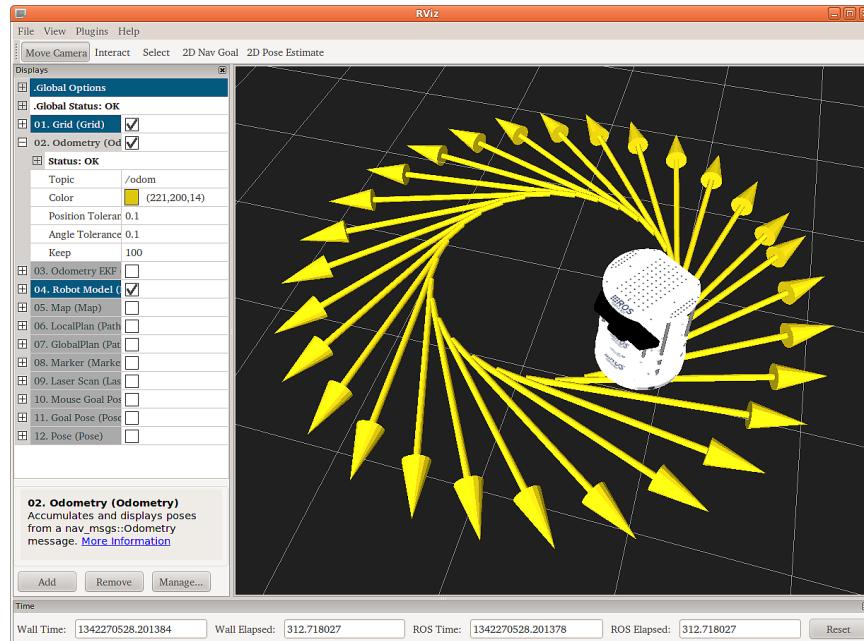
2. REAL AND SIMULATED ROBOTS

While ROS can be used with a large variety of hardware, you don't need an actual robot to get started. ROS includes packages to run a number of robots in simulation so that you can test your programs before venturing into the real world.

2.1 Gazebo, Stage, and the ArbotiX Simulator

There are a number of ways to simulate a robot in ROS. The most sophisticated uses [Gazebo](#), a full-featured 3-D physics simulator that pre-dates ROS but now integrates nicely with it. The second uses [Stage](#), a simpler 2-D simulator that can manage multiple robots and various sensors such as laser scanners. The third uses Michael Ferguson's [arbotix_python](#) package that can run a fake simulation of a differential drive robot but without sensor feedback or any physics. We will use this last method as it is the simplest to set up and we don't need physics for our purposes. Of course, feel free to explore Gazebo and Stage but be prepared to spend a little time working on the details. Also, Gazebo in particular demands a fair bit of CPU power.

Even if you do have your own robot, it is a good idea to run some of the examples in this book in the simulator first. Once you are happy with the results, you can try it on your robot.



2.2 Introducing the TurtleBot, Maxwell and Pi Robot

For the purposes of this book, we need a robot that we can at least run in simulation to test our code. The `ros-by-example` repository includes support for two test robots,

the Willow Garage [TurtleBot](#) created by [Melonee Wise](#) and [Tully Foote](#), and the author's own home-built robot called [Pi Robot](#).

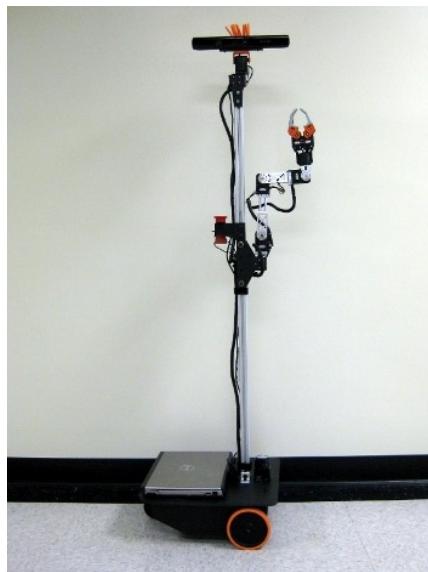


The TurtleBot

Pi was inspired by [Michael Ferguson's Maxwell](#) which in turn was modeled after Georgia Tech's [EL-E](#) robot. If you have a URDF model of your own robot, you can use it instead of one of these. In any event, most of the code we develop will run on almost any robot that supports the basic ROS message interfaces.



Pi Robot



Maxwell

3. OPERATING SYSTEMS AND ROS VERSIONS

ROS can run on various flavors of Linux, MacOS X and partially on Microsoft Windows. However, the easiest way to get started is to use Ubuntu Linux as this is the OS officially supported by Willow Garage. Furthermore, Ubuntu is free and easy to install alongside other operating systems. In case you are not already using Ubuntu, we will list a few pointers on installing it in the next section.

ROS can be run on anything from a supercomputer to a Beagleboard. But much of the code we will develop will require some CPU-intensive processing. You will therefore save yourself some time and potential frustration if you use a laptop or other full-size PC to run the sample applications in this book. The Turtlebot, Maxwell, and Pi Robot are designed so that you can easily place a laptop on the robot. This means that you can develop your code directly on the laptop, then simply slide it onto the robot for testing autonomous behavior. You can even go half-way during development and tether the robot to your laptop or PC using some long USB cables.

The latest version of Ubuntu is 12.04 (Precise) and the latest version of ROS is Fuerte. This version of the book was tested against ROS Fuerte and Ubuntu 11.10 (Oneiric) which is the latest version of Ubuntu that supports both Fuerte and Electric. The code has also been tested under Ubuntu 10.04 (Lucid) and there are reports that it runs under Ubuntu 12.04 (Precise).

Multiple versions of ROS can happily coexist on your machine but be sure that Fuerte is your active version when running the code samples.

3.1 Installing Ubuntu Linux

If you already have Ubuntu Linux up and running on your machine, great. But if you're starting from scratch, installing Ubuntu is not difficult.

The latest version of Ubuntu is 12.04 but as explained above, this book was tested against Ubuntu 11.10 (Oneiric) and 10.04 (Lucid). There are also reports that the code works under Precise. For a list of Ubuntu versions that are officially compatible with ROS Fuerte, see the [ROS Installation Guide](#).

Ubuntu can be installed on an existing Windows machine or an Intel-based Mac and you'll probably want to leave those installations intact while installing Ubuntu alongside them. You'll then have a choice of operating systems to use at boot time. On the other hand, if you have a spare laptop lying around that you can dedicate to your robot, then you can install Ubuntu over the entire disk. (It will also tend to run faster this way.) In general, it is not a good idea to install Ubuntu inside a virtual machine like VMware. While this is a great way to run through the ROS tutorials, the virtual machine will

likely get bogged down when trying to run graphics intensive programs like RViz. (In fact, they might not run at all.)

Here are a few links to get you started:

- [Installing Ubuntu 12.04 on a Windows computer](#)
- [Installing Ubuntu 11.10 on a Windows computer](#). However, be aware that the "download" links on this page will take you back to the 12.04 version so here is the link to the 11.10 download page: [direct link to the 11.10 download page](#). You will probably want to install the Desktop CD rather than the Server CD.
- Using Wubi: You can also try the `wubi.exe` installer found at the very end of the file list on the download page linked to above. This installer runs under Windows and will install Ubuntu as if it were just another Windows application. This means you can uninstall it at a later time using Add/Remove Programs (Windows XP) or Programs and Features. This is the easiest way to get Ubuntu up and running alongside Windows but there are a few caveats: (1) the Ubuntu disk size may be limited, (2) you will not be able to Hibernate the machine from within Linux, though you will still be able to put it in Standby, and (3) Linux will not run quite as fast as regular installation to a raw partition.
- Dual-booting [Ubuntu/MacOS X on an Apple/Intel machine](#)

To keep this book focused on ROS itself, please use Google or the Ubuntu support forums if you have any trouble with the installation.

3.2 Getting Started with Linux

If you are already a veteran Linux user, you are well ahead of the game. If not, you might want to run through a tutorial or two before proceeding. Since web tutorials come and go every day, you can simply Google something like "Ubuntu tutorial" to find something you like. However, bear in mind that most of your work with ROS will take place at the command line or in some form of text editor. A good place to start on command line basics is [Using the Ubuntu Terminal](#). The text editor you choose for programming is up to you. Choices include gedit, nano, pico, emacs, vim, Eclipse and many others. (See for example <https://help.ubuntu.com/community/Programming>.) Programs like Eclipse are actually full featured IDEs and can be used to organize projects, test code, manage SVN repositories and so on. For more information on using different IDEs with ROS, see <http://www.ros.org/wiki/IDEs>.

4. REVIEWING THE ROS BASICS

4.1 Installing ROS

The easiest and quickest way to install ROS on your Ubuntu Linux machine is to use the Debian packages rather than compiling from source. Well-tested instructions can be found at [Ubuntu Install of Fuerte](#). Be sure to choose the correct instructions for the version of the OS you are using (e.g. Ubuntu 11.10 versus 12.04). It is also recommended that you do the Desktop Full Install.

PLEASE NOTE: This version of the book is written for and tested against **ROS Fuerte**.

One advantage of using the Debian package install (rather than compiling from source) is that you'll get updates automatically through the Ubuntu Update Manager. You can also pick and choose additional ROS packages using the Synaptics Package Manager or the Ubuntu Software Center. If you need to compile the bleeding edge version of some package or stack from source, you can install it in your own personal ROS directory as explained below.

4.2 Installing rosinstall

Some third-party ROS packages use a ROS installation utility called `rosinstall`. This utility is not part of the standard ROS installation and so we need to get it now using the following commands:

```
$ sudo apt-get install python-setuptools  
$ sudo easy_install -U rosinstall
```

That's all there is to it!

4.3 Creating Your Personal ROS Directory

If you followed the installation instructions above, the official ROS stacks and packages will be found under `/opt/ros/release`, where `release` is the named release of ROS you are using; e.g. `/opt/ros/fuerte`. This is a read-only part of the file system and should not be changed except through the package manager, so you'll want to create a personal ROS directory in your home directory so you can (1) install third-party ROS packages that don't have Debian versions and (2) create your own ROS packages.

NOTE: For a more advanced method of creating and managing ROS workspaces, see the documentation for the [rosws](#) tool. The simpler procedure described below will suffice for the purposes of this book. (Apologies to the ROS purists!)

If you haven't already done so, create your personal ROS directory using the command:

```
$ mkdir ~/ros_workspace
```

where ~ is the Linux shorthand for your home directory and we use the \$ sign to indicate the start of the Linux command line. (It is not part of the command itself and so you do not have to type it.) You can create your personal ROS directory anywhere you like but just remember to substitute your own path whenever we refer to `~/ros_workspace` in this book.

Once you have created your personal ROS directory, add it to your `ROS_PACKAGE_PATH` environment variable by editing your `.bashrc` file (note the leading period in the filename). For example, if you use the `gedit` text editor, run the command:

```
$ gedit ~/.bashrc
```

Then add the following to the end of the file:

```
export ROS_PACKAGE_PATH=~/ros_workspace:$ROS_PACKAGE_PATH
```

(Remember, substitute your own directory for `~/ros_workspace` if you created it somewhere else.) Save your changes, exit the editor, and run the command:

```
$ source ~/.bashrc
```

You only have to do this once in any open terminal—new terminal windows will pick up the new path automatically. With your personal ROS directory appearing first in the `ROS_PACKAGE_PATH` variable as shown above, not only will ROS pick up packages you add to your personal ROS directory, it will also find them first. This means that if you have a later experimental version of one of the standard ROS packages that also lives in the `/opt/ros/release` directory, your experimental version will be used instead.

4.4 Working through the Official ROS Tutorials

Before diving into the Beginner Tutorials on the ROS Wiki, it is highly recommended that you look first at the [ROS Start Guide](#). Here you will find an overall introduction as well as an explanation of the key concepts, libraries and technical design.

The official [ROS Beginner Tutorials](#) are superbly written and have been tested by many new ROS users. It is therefore essential to begin your introduction to ROS by running through these tutorials in sequence. Be sure to actually run the code samples—don't just read through them. ROS itself is not difficult: while it might seem unfamiliar at first, the more practice you have with the code, the easier it becomes. Expect to spend at least a few days or weeks going through the tutorials.

Once you have completed the beginner tutorials, it is essential to also read the [tf overview](#) and do the [tf Tutorials](#) which will help you understand how ROS handles different frames of reference. For example, the location of an object within a camera image is usually given relative to a frame attached to the camera, but what if you need to know the location of the object relative to the base of the robot? The ROS `tf` library does most of the hard work for us and such frame transformations become relatively painless to carry out.

Finally, we will need to understand the basics of [ROS actions](#) when we get to the Navigation Stack. You can find an introduction to ROS actions in the [actionlib tutorials](#).

You will notice that most of the tutorials provide examples in both Python and C++. All of the code in this book is written in Python, but if you are a C++ programmer, feel free to do the tutorials in C++ as the concepts are the same.

Many individual ROS packages have their own tutorials on the ROS Wiki pages. We will refer to them as needed throughout the book, but for now, the [Beginner](#), [tf](#), and [actionlib](#) tutorials will suffice.

4.5 RViz: The ROS Visualization Tool

If you have already been working with ROS for awhile, you are probably familiar with [RViz](#), the all-seeing ROS visualization utility. However, since `RViz` is not covered in the standard ROS beginners tutorials, you might not have been formally introduced. Fortunately, there is already an excellent [RViz User's Guide](#) that will take you step-by-step through its features. Please be sure to run through the guide before going further as we will make heavy use of `RViz` in several parts of the book.

`RViz` can sometimes be a little finicky about running on different graphics cards. If you find that `RViz` aborts during start up, first just try launching it again. Keep trying a few times if necessary. (On one of my computers, it is usually the third attempt that works.) If that fails, check out the `RViz` [Troubleshooting Guide](#) for possible solutions. In particular, the section on [Segfaults during startup](#) tends to solve the most common problems.

4.6 Using ROS Parameters in your Programs

As you know from completing the [Beginner Tutorials](#), ROS nodes store their configuration parameters on the ROS [Parameter Server](#) where they can be read and modified by other active nodes. You will often want to use ROS parameters in your own scripts so that you can set them in your launch files, override them on the command line, or modify them through `dynamic_reconfigure` if you add dynamic support. We will assume you already know how to use ROS parameters through the `rospy.get_param()` function which is explained fully in this tutorial on [Using Parameters in rospy](#).

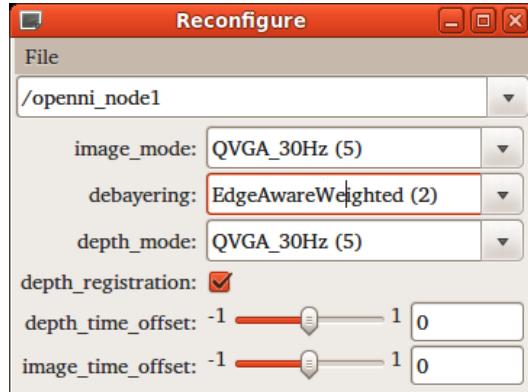
4.7 Using `dynamic_reconfigure` to set ROS Parameters

Being able to tweak ROS parameters on the fly is often useful for tuning or debugging a running application. As you will recall from the [Services and Parameters Tutorial](#), ROS provides the command line tool `rosparam` for getting and setting parameters. However, parameter changes made this way will not be read by a node until the node is restarted.

The ROS [dynamic_reconfigure](#) package provides an easy-to-use GUI interface to a subset of the parameters on the Parameter Server. It can be launched any time using the command:

```
$ rosrun dynamic_reconfigure reconfigure_gui
```

The image below shows how the GUI would look when configuring an OpenNI camera node that connects to a Kinect or Xtion Pro camera:



As its name implies, `dynamic_reconfigure` changes parameters in such a way that a node can apply the update dynamically—i.e., without restarting. However, there is one catch: only nodes that have been programmed using the `dynamic_reconfigure` API

will be visible in the `dynamic_reconfigure` GUI. This includes most nodes in the key ROS stacks and packages such as Navigation, but many third-party nodes do not use the API and therefore can only be tweaked using the `rosparam` command line tool followed by a node restart.

Adding `dynamic_reconfigure` support to your own nodes is not difficult and if you would like to learn how, refer to the step-by-step [Dynamic Reconfigure Tutorials](#) on the ROS Wiki. We will have the occasion to use the reconfigure GUI in several sections of the book. It would therefore be a good idea to familiarize yourself with its behavior by going through the [dynamic_reconfigure](#) introduction on the ROS Wiki.

4.8 Networking Between a Robot and a Desktop Computer

A fairly typical setup when using ROS is to mount a laptop or single board computer on the robot while monitoring its actions on a desktop machine. ROS makes it easy for multiple machines to view the same set of topics, services and parameters. This is particularly useful when your robot's onboard computer is not very powerful since it allows you to run the more demanding processes such as `RViz` on your desktop. (Programs like `RViz` can also run down a laptop battery very quickly.)

It is important to understand how to set up multiple ROS machines on a network, so be sure to work through the [ROS Multiple Machines](#) tutorial. If you run into trouble, take a look at the [ROS Network Setup](#) guide. For convenience, we provide a brief summary here.

One machine is designated as the ROS master and it alone runs the `roscore` process. Other machines must then set the `ROS_MASTER_URI` environment variable to point to the master host. If your robot and desktop are connected through your home network, chances are your machines will not have resolvable hostnames so you will more likely have to use numerical IP addresses. You will also have to set the `ROS_IP` environment variable on each machine with its own IP address.

To determine the IP address of a machine, run the following command:

```
$ ifconfig | grep "inet addr" | grep -v 127.0.0.1
```

The output should look something like this:

```
inet addr:192.168.1.7 Bcast:192.168.1.255 Mask:255.255.255.0
```

The address you want is displayed after "inet addr:", in this case 192.168.1.7. If a machine is connected to the network both wirelessly and using a hard line, it will have two addresses. It is probably best to turn off the wireless connection on that machine and let it use the hard line only. This will free up some bandwidth for your other wireless connection(s). When you have turned off the wireless connection, re-run the

command above to find the address for the hard line. (If you run the `ifconfig` command on its own, you can see all the details for all network interfaces.)

Here's how the setup process would go if your desktop computer has IP address 192.168.1.2 and your robot's computer has IP address 192.168.1.3. We will run the `roscore` process on the desktop computer.

Starting on your desktop machine, run the following. Remember to substitute your own IP addresses where appropriate!

```
$ export ROS_MASTER_URI=http://192.168.1.2:11311  
$ export ROS_IP=192.168.1.2  
$ roscore
```

Next, open another terminal window and log into your robot's computer using `ssh`. First synchronize the clock with the master. Then set the `ROS_MASTER_URI` and `ROS_IP` environment variables:

```
$ ssh 192.168.1.3  
$ sudo ntpdate -b 192.168.1.2  
$ export ROS_MASTER_URI=http://192.168.1.2:11311  
$ export ROS_IP=192.168.1.3
```

If all goes well, you should be able to see the `/rosout` and `/rosout_agg` topics on both machines:

```
$ rostopic list
```

```
/rosout  
/rosout_agg
```

You can now run your robot's startup launch file(s) in the same `ssh` window that you used to log in via your desktop.

To run `RViz` on the desktop, open another terminal, set the environment variables as we did for the master above, then start up `RViz`:

```
$ export ROS_MASTER_URI=http://192.168.1.2:11311  
$ export ROS_IP=192.168.1.2  
$ rosrun rviz rviz
```

If your robot and desktop always have the same IP addresses on your local network, you can add the appropriate `export` commands to the `~/.bashrc` file on each machine so that you don't have to run them every time you open a new terminal.

4.9 ROS Recap

Since it might have been awhile since you did the [Beginner](#) and [tf Tutorials](#), here is a brief recap of the primary ROS concepts. The core entity in ROS is called a node. A node is generally a small program written in Python or C++ that executes some relatively simple task or process. Nodes can be started and stopped independently of one another and they communicate by passing messages. A node can publish messages on certain topics or provide services to other nodes.

For example, a publisher node might report data from sensors attached to your robot's microcontroller. A message on the `/head_sonar` topic with a value of 0.5 would mean that the sensor is currently detecting an object 0.5 meters away. (Remember that ROS uses meters for distance and radians for angular measurements.) Any node that wants to know the reading from this sensor need only subscribe to the `/head_sonar` topic. To make use of these values, the subscriber node defines a callback function that gets executed whenever a new message arrives on the subscribed topic. How often this happens depends on the rate at which the publisher node updates its messages.

A node can also define one or more services. A ROS service produces some behavior or sends back a reply when sent a request from another node. A simple example would be a service that turns an LED on or off. A more complex example would be a service that returns a navigation plan for a mobile robot when given a goal location and the starting pose of the robot.

Higher level ROS nodes will subscribe to a number of topics and services, combine the results in a useful way, and perhaps publish messages or provide services of their own. For example, the object tracker node we will develop later in the book subscribes to camera messages on a set of video topics and publishes movement commands on another topic that are read by the robot's base controller to move the robot in the appropriate direction.

4.10 The Official ROS Cheat Sheet

For a quick reference to all the core ROS commands and their options, be sure to check out the most excellent [ROS Cheat Sheet](#). You can print it out and keep it handy instead of having to constantly look things up on the ROS Wiki.

4.11 What is a ROS Application?

If you are not already familiar with a publish/subscribe architecture like ROS, programming your robot to do something useful might seem a little mysterious at first. For instance, when programming an Arduino-based robot using C, one usually creates a

single large program that controls the robot's behavior. Moreover, the program will usually talk directly to the hardware, or at least, to a library specifically designed for the hardware you are using.

When using ROS, the first step is to divide up the desired behavior into independent functions that can be handled by separate nodes. For example, if your robot uses a webcam or a depth camera like a Kinect or Xtion Pro, one node will connect to the camera and simply publish the image and/or depth data so that other nodes can use it. If your robot uses a mobile base, a base controller node will listen for motion commands on some topic and control the robot's motors to move the robot accordingly. These nodes can be used without modification in many different applications whenever the desired behavior requires vision and/or motion control.

An example of a complete application is the "follower" application we will develop later in the book. (The original C++ version by [Tony Pratkanis](#) can be found in the `turtlebot_follower` package.) The goal of the follower app is to program a Kinect-equipped robot like the TurtleBot to follow the nearest person. In addition to the camera and base controller nodes, we need a third node that subscribes to the camera topic and publishes on the motion control topic. This "follower" node must process the image data (using OpenCV or PCL for example) to find the nearest person-like object, then command the base to steer in the appropriate direction. One might say that the follower node is our ROS application; however, to be more precise, the application really consists of all three nodes running together. To run the application, we use a [ROS launch](#) file to fire up the whole collection of nodes as a group. Remember that launch files can also [include other launch files](#) allowing for even easier reuse of existing code in new applications.

Once you get used to this style of programming, there are some significant advantages. As we have already mentioned, many nodes can be reused without modification in other applications. Indeed, some ROS applications are little more than launch files combining existing nodes in new ways or using different values for the parameters. Furthermore, many of the nodes in a ROS application can run on different robots without modification. For example, the TurtleBot follower application can run on any robot that uses a depth camera and a mobile base. This is because ROS allows us to abstract away the underlying hardware and work with more generic messages instead.

Finally, ROS is a network-centric framework. This means that you can distribute the nodes of your application across multiple machines as long as they can all see each other on the network. For example, while the camera and motor control nodes have to run on the robot's computer, the follower node and `RViz` could run on any machine on the Internet. This allows the computational load to be distributed across multiple computers if necessary.

4.12 Installing Packages with SVN, Git, and Mercurial

Once in awhile the ROS package you need won't be available as a Debian package and you will need to install it from source. There are three major source control systems popular with code developers: SVN, Git and Mercurial. The type of system used by the developer determines how you install the source. To make sure you are ready for all three systems, run the following install command on your Ubuntu machine:

```
$ sudo apt-get install git subversion mercurial
```

For all three systems, there are two operations you will use most of the time. The first operation allows you to check out the software for the first time, while the second is used for getting updates that might be available later on. Since these commands are different for all three systems, let's look at each in turn.

4.12.1 SVN

Let's assume that the SVN source you would like to check out is located at http://repository/svn/package_name. To do the initial checkout and build the package in your personal ROS directory, run the following commands. (If necessary, change the first command to reflect the actual location of your personal ROS directory.)

```
$ cd ~/ros_workspace  
$ svn checkout http://repository/svn/package_name  
$ cd package_name  
$ rosmake
```

To update the package later on, run the commands:

```
$ rosdep package_name  
$ svn update  
$ rosmake --pre-clean
```

4.12.2 Git

Let's assume that the Git source you would like to check out is located at git://repository/package_name. To do the initial checkout and build the package in your personal ROS directory, run the following commands. (If necessary, change the first command to reflect the actual location of your personal ROS directory.)

```
$ cd ~/ros_workspace  
$ git clone git://repository/package_name  
$ cd package_name  
$ rosmake
```

To update the package later on, run the commands:

```
$ rosdep package_name  
$ git pull  
$ rosmake --pre-clean
```

4.12.3 Mercurial

Let's assume that the Mercurial source you'd like to check out is located at http://repository/package_name. To do the initial checkout and build the package in your personal ROS directory, run the following commands. (If necessary, change the first command to reflect the actual location of your personal ROS directory.)

```
$ cd ~/ros_workspace  
$ hg clone http://repository/package_name  
$ cd package_name  
$ rosmake
```

(In case you are wondering why Mercurial uses `hg` for its main command name, Hg is the symbol for the element Mercury on the Periodic Table in chemistry.) To update the package later on, run the commands:

```
$ rosdep package_name  
$ hg update  
$ rosmake --pre-clean
```

4.13 Removing Packages from your Personal ROS Directory

To remove a package or stack installed in your personal ROS directory, simply remove the entire package or stack directory or move it to a different location outside of your `ROS_PACKAGE_PATH`. For example, to remove a package called `my_ros_package` from your `~/ros_workspace` directory, run the commands:

```
$ cd ~/ros_workspace  
$ \rm -rf my_ros_package
```

(The backslash escapes any aliases you might have created for the Linux `rm` command.) You can test that the package has been removed using the `rosdep` command:

```
$ rosdep my_ros_package
```

which should produce the output:

```
rosdep: No such package 'my_ros_package'
```

Alternatively, create a directory outside of your ROS package path and move the unwanted package into that directory. If you want to re-activate the package at a later time, just move it back into your personal ROS directory.

4.14 How to Find Third-Party ROS Packages

Sometimes the hardest thing to know about ROS is what's available from other developers. For example, suppose you are interested in face recognition and want to know if someone else has already created a ROS package to do the job. There are a few ways to do the search.

4.14.1 Searching the ROS Wiki

The ROS Wiki at www.ros.org includes a searchable index to many ROS packages and stacks. If a developer has created some ROS software they'd like to share with others, they can post a message to the `ros-users` mailing list together with the link to their repository (which could be anywhere on the Internet but often resides on Google Code or Github). The good folks at Willow Garage then add the link to their index which allows the developer to create a Wiki page on www.ros.org to more fully document their software (if they are so inclined).

The end result is that you can often find what you are looking for by simply doing a keyword search on the ROS Wiki. Coming back to our face recognition example, if we type "face recognition" (without the quotes) into the Search box, the very first result is a link to the ROS package [face_recognition](#) by Pouyan Ziafati. You will also find a link to the source code as well as instructions on how to use it.

4.14.2 Using the `roslocate` Command

If you know the exact package name you are looking for and you want to find the URL to the package repository, use the `roslocate` command. (This command is only available if you installed `rosinstall` as described earlier.) For example, to find the location of the `face_recognition` package, run the command:

```
$ roslocate uri face_recognition
```

At the time of this writing, the result of the above command is:

```
git://github.com/procrob/procrob_functional.git
```

This means that we can install the package into our personal ROS directory using the `git` command:

```
$ cd ~/ros_workspace  
$ git clone git://github.com/procrob/procrob_functional.git  
$ cd procrob_functional  
$ rosmake
```

An example using SVN is the `skeleton_markers` package:

```
$ roslocate uri skeleton_markers
```

which results in the output:

```
http://pi-robot-ros-pkg.googlecode.com/svn/trunk/skeleton_markers
```

In this case, we see that the repository uses SVN, so to install the package we would run:

```
$ cd ~/ros_workspace  
$ svn co http://pi-robot-ros-\  
  pkg.googlecode.com/svn/trunk/skeleton_markers  
$ rosmake skeleton_markers
```

(Note: You would not normally type the backslash character (\) on the second command line above. It is included here to "escape" the line break which will not otherwise copy-and-paste correctly if using the PDF version of this book. You will see other instances of the \ character throughout the book where a command wraps across more than one line.)

Finally, an example that use Mercurial (hg) is the rosjava stack. Running `roslocate` to find the rosjava stack yields:

```
$ roslocate uri rosjava
```

```
https://rosjava.googlecode.com/hg
```

The hg at the end of the URL makes us suspect that this is probably a Mercurial repository. To be sure, use the `roslocate vcs` command:

```
$ roslocate vcs rosjava
```

which yields the output:

```
hg
```

and we see that this is indeed a Mercurial repository. To install the source we would run:

```
$ cd ~/ros_workspace  
$ hg clone https://rosjava.googlecode.com/hg rosjava_core  
$ cd rosjava_core  
$ rosmake
```

Note how we add the directory name `rosjava_core` at the end of the `hg clone` command. Otherwise the resulting directory would be named the rather nondescript "hg" since that is the last part of the URL.

4.14.3 Browsing the ROS Software Index

To browse through the complete list of ROS packages, stacks and repositories as indexed on the ROS Wiki, click on the [Browse Software](#) link found in the banner at the top of every Wiki page.

4.14.4 Doing a Google Search

If all else fails, you can always try a regular Google search. For example, searching for "ROS face recognition package" returns a [ROS News item](#) that announces the release of the `face_recognition` package. A link to the [ROS News](#) home page is listed in the banner alongside the Browse Software link at the top of every ROS wiki page. ROS News has its own search box for finding archived news items .

4.15 Getting Further Help with ROS

There are several sources for additional help with ROS. Probably the best place to start is at the main ROS wiki at <http://www.ros.org>. As described in the previous section, be sure to use the Search box at the top right of the page.

If you can't find what you are looking for on the Wiki, try the ROS Questions and Answers forum at <http://answers.ros.org>. The answers site is a great place to get help. You can browse through the list of questions, do keyword searches, look up topics based on tags, and even get email notifications when a topic is updated. But be sure to do some kind of search before posting a new question to avoid duplication.

Next, you can search one of the ROS mailing list archives:

- [ros-users](#): for general ROS news and announcements
- [ros-kinect](#): for Kinect related issues
- [pcl-users](#): for PCL related issues

NOTE: Please do not use the `ros-users` mailing list to post questions about using ROS or debugging packages. Use <http://answers.ros.org> instead.

If you want to subscribe to one or more of these lists, use the appropriate link listed below:

- [ros-users](#): Subscription page
- [ros-kinect](#) – Subscription page
- [pcl_users](#) - Subscription page

5. INSTALLING THE ROS-BY-EXAMPLE CODE

5.1 Installing the Prerequisites

Before installing the `ros-by-example` code itself, it will save some time if we install most of the additional ROS packages we will need later. (Instructions will also be provided for installing individual packages as needed throughout the book.) Simply copy and paste the following command (without the \$ sign) into a terminal window to install the Debian packages we will need (the \ characters make the following lines look like one line to Linux when doing a copy-and-paste):

```
$ sudo apt-get install ros-fuerte-turtlebot* ros-fuerte-control \
ros-fuerte-openni-kinect ros-fuerte-laser-drivers \
ros-fuerte-audio-common ros-fuerte-joystick-drivers \
ros-fuerte-orocos-kinematics-dynamics \
ros-fuerte-dynamixel-motor gstreamer0.10-pocketsphinx \
python-setuptools ros-fuerte-opencv2 ros-fuerte-vision-opencv
```

We also need one pre-requisite not currently available as a Debian package. Run the following commands to install the `pocketsphinx` ROS package for speech recognition:

```
$ cd ~/ros_workspace
$ svn checkout http://albany-ros-pkg.googlecode.com/svn/trunk/rharmony
$ rosmake pocketsphinx
```

5.2 Installing the `rbx_vol_1` Stack

All of the code used in this book is contained in the `ros-by-example` repository on Google Code. Within that repository, the code for this volume is stored as a ROS stack called `rbx_vol_1`. To check out this stack, first move into your personal ROS directory:

```
$ cd ~/ros_workspace
```

and then run the following commands:

```
$ svn checkout http://ros-by-example.googlecode.com/svn/trunk/rbx_vol_1
$ rosmake rbx_vol_1
$ rospack profile
```

The `rospack profile` command simply ensures that the new stack and packages will be visible in your ROS package path. It is not usually necessary to run this command but it doesn't hurt either.

To update the stack at a later date, run the commands:

```
$ rosdep rbx_v1_1  
$ svn update  
$ rosmake --pre-clean
```

Staying Up-To-Date: If you'd like to receive notifications of updates to both the book and the accompanying code, please join the [ros-by-example Google Group](#).

All of the `ros-by-example` packages begin with the letters `rbx1`. To see the package names, make sure you are in the stack directory and use the Linux `ls` command:

```
$ rosdep rbx_v1_1  
$ ls -F
```

which should result in the following listing:

```
CMakeLists.txt    rbx1_apps/      rbx1_description/   rbx1_nav/      rbx1_vision/  
Makefile          rbx1_bringup/   rbx1_dynamixels/   rbx1_speech/   stack.xml
```

You can also use the `rosstack` command:

```
$ rosstack contents rbx_v1_1
```

which will yield just the package names:

```
rbx1_description  
rbx1_apps  
rbx1_nav  
rbx1_vision  
rbx1_speech  
rbx1_dynamixels  
rbx1_bringup
```

Throughout the book we will be using the `rosdep` command to move from one package to another. For example, to move into the `rbx1_speech` package, you would use the command:

```
$ rosdep rbx1_speech
```

Note that you can run this command from any directory and ROS will find the package —you do not already have to be in the stack directory.

IMPORTANT: If you are using two computers to control or monitor your robot, such as a laptop on the robot together with a second computer on your desktop, be sure to install the `rbx_v1_1` stack on both machines.

5.3 Installing the Pi Robot URDF Files

If you want to run Pi Robot in simulation, install the `pi_robot_description` package with the following commands:

```
$ cd ~/ros_workspace  
$ svn co `roslocate uri pi_robot_description`
```

Here we use the Linux "backtick" operator to combine the `svn` command ("co" is short for checkout) with the output from the `roslocate` command.

5.4 About the Code Listings in this Book

For the benefit of those who would like to work from a printed version of the book instead of or in addition to the PDF version, most of the sample programs are displayed in their entirety as well as broken down line-by-line for analysis. At the top of each sample script is a link to the online version of the file as found in the `ros-by-example` repository. If you are reading the PDF version of the book, clicking on the link will bring you to a nicely formatted and color coded version of the program. Be aware though that the line numbers in the online version will not match those in the book since the printed version leaves out some extraneous comments to save space and make things easier to read. Of course, once you have downloaded the code from the `ros-by-example` repository, you can also bring up your local copy of the same files in your favorite editor.

As with most programming code, there is usually more than one way to solve a problem. The sample programs described here are no exception and if you can think of a better way to accomplish the same goal, great. The code included in the `ros-by-example` repository is meant only as a guide and certainly does not represent the best or only way to accomplish a given task using ROS.

6. INSTALLING THE ARBOTIX SIMULATOR

To test our code on a simulated robot, we will use the `arbotix_python` simulator found in the ArbotiX stack by Michael Ferguson.

6.1 Installing the Simulator

To install the simulator in your personal ROS directory, run the following commands:

```
$ cd ~/ros_workspace  
$ sudo apt-get install ros-fuerte-control  
$ svn checkout http://vanadium-ros-pkg.googlecode.com/svn/trunk/arbotix  
$ rosmake arbotix
```

NOTE: The `arbotix` stack is also available as a Debian package. However, we need the latest version from trunk which fixes a small bug in how the odometry data is published.

6.2 Testing the Simulator

To make sure everything is working, make sure `roscore` is running, then launch the simulated TurtleBot as follows:

```
$ roslaunch rbx1_bringup fake_turtlebot.launch
```

which should result in the following startup messages:

```
process[arbotix-1]: started with pid [4896]  
process[robot_state_publisher-2]: started with pid [4897]  
process[odom_left_wheel_broadcaster-3]: started with pid [4898]  
process[odom_right_wheel_broadcaster-4]: started with pid [4899]  
[INFO] [WallTime: 1338681385.068539] ArbotiX being simulated.  
[INFO] [WallTime: 1338681385.111492] Started DiffController  
(base_controller). Geometry: 0.26m wide, 4100.0 ticks/m.
```

To use a model of Pi Robot instead, run the command:

```
$ roslaunch rbx1_bringup fake_pi_robot.launch
```

Next, bring up `RViz` so we can observe the simulated robot in action:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/sim_fuerte.vcg
```

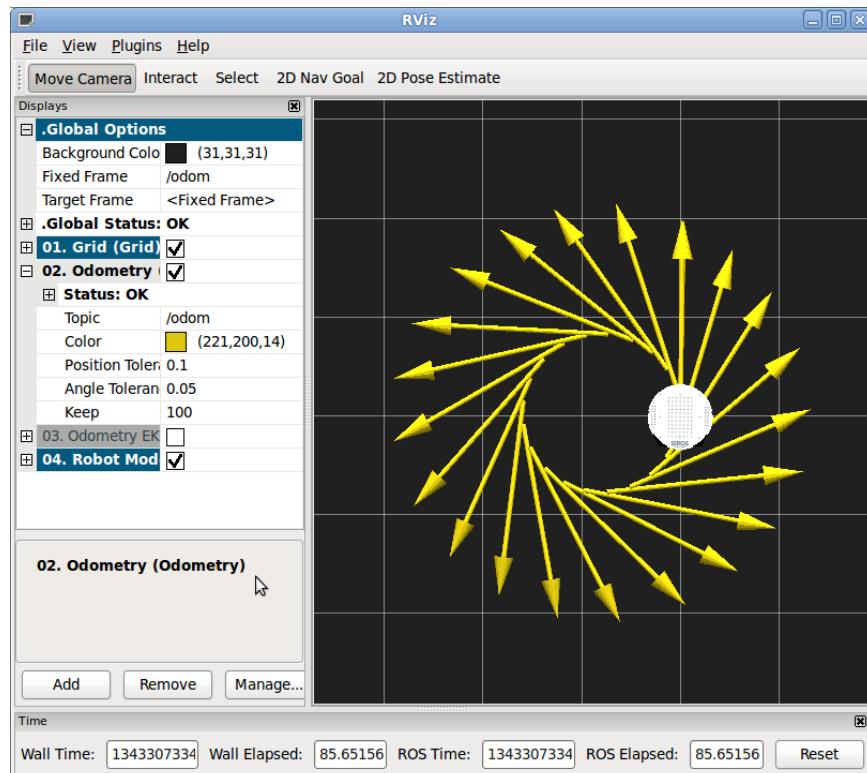
(Note how we use the Linux backtick operator together with the `rospack find` command to locate the `rbx1_nav` package without having to type the entire path.)

If everything went right, you should see the TurtleBot (or Pi Robot) in RViz. (The default view is top down. To change views, click on the **Panels** menu in RViz.)

To test the simulation, open another terminal window and run the following command which should cause the simulated robot to move in a counter-clockwise circle:

```
$ rostopic pub -r 10 /cmd_vel geometry_msgs/Twist '{linear: {x: 0.2, y: 0, z: 0}, angular: {x: 0, y: 0, z: 0.5}}'
```

The view in RViz should look something like this:



To stop the rotation, type `Ctrl-C` in the same terminal window, then publish the empty Twist message:

```
$ rostopic pub -l /cmd_vel geometry_msgs/Twist '{}'
```

6.3 Running the Simulator with Your Own Robot

If you have a [URDF](#) model of your own robot, you can run it in the ArbotiX simulator instead of the TurtleBot or Pi Robot. First, make a copy of the fake TurtleBot launch file:

```
$ roscd rbx1_bringup/launch  
$ cp fake_turtlebot.launch fake_my_robot.launch
```

Then bring up your launch file in your favorite editor. At first it will look like this:

```
<launch>  
    <!-- Load the URDF/Xacro model of our robot -->  
    <arg name="urdf_file" default="$(find xacro)/xacro.py '$(find  
turtlebot_description)/urdf/turtlebot.urdf.xacro'" />  
  
    <param name="robot_description" command="$(arg urdf_file)" />  
  
    <node name="arbotix" pkg="arbotix_python" type="driver.py" output="screen">  
        <rosparam file="$(find rbx1_bringup)/config/fake_turtlebot_arbotix.yaml"  
command="load" />  
        <param name="sim" value="true"/>  
    </node>  
  
    <node name="robot_state_publisher" pkg="robot_state_publisher"  
type="state_publisher">  
        <param name="publish_frequency" type="double" value="20.0" />  
    </node>  
  
    <!-- We need a static transforms for the wheels -->  
    <node pkg="tf" type="static_transform_publisher"  
name="odom_left_wheel_broadcaster" args="0 0 0 0 0 0 /base_link /left_wheel_link  
100" />  
    <node pkg="tf" type="static_transform_publisher"  
name="odom_right_wheel_broadcaster" args="0 0 0 0 0 0 /base_link  
/right_wheel_link 100" />  
</launch>
```

As you can see, the URDF model is loaded near the top of the file. Simply replace the package and path names to point to your own URDF/Xacro file. You can leave most of the rest of the launch file the same. However, you probably don't need the static transforms at the end of the file which are there for the TurtleBot wheels. So you can delete those lines. The result would look something like this:

```
<launch>  
    <!-- Load the URDF/Xacro model of our robot -->  
    <arg name="urdf_file" default="$(find xacro)/xacro.py '$(find  
YOUR_PACKAGE_NAME)/YOUR_URDF_PATH'" />  
  
    <param name="robot_description" command="$(arg urdf_file)" />  
  
    <node name="arbotix" pkg="arbotix_python" type="driver.py" output="screen">  
        <rosparam file="$(find rbx1_bringup)/config/fake_turtlebot_arbotix.yaml"  
command="load" />  
        <param name="sim" value="true"/>
```

```
</node>

<node name="robot_state_publisher" pkg="robot_state_publisher"
type="state_publisher">
    <param name="publish_frequency" type="double" value="20.0" />
</node>
</launch>
```

If your robot has an arm or a pan-and-tilt head, you can start with the `fake_pi_robot.launch` file as a template.

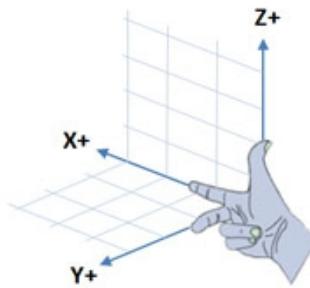
7. CONTROLLING A MOBILE BASE

In this chapter we will learn how to control a mobile base that uses a pair of differential drive wheels and a passive caster wheel for balance. ROS can also be used to control an omni-directional base as well as flying robots or underwater vehicles but a land-based differential drive robot is a good place to start.



7.1 Units and Coordinate Systems

Before we can send movement commands to our robot, we need to review the measurement units and coordinate system conventions used in ROS.



When working with reference frames, keep in mind that ROS uses a right-hand convention for orienting the coordinate axes as shown on left. The index and middle fingers point along the positive x and y axes and the thumb points in the direction of the positive z axis. The direction of a rotation about an axis is defined by the right-hand rule shown on the right: if you point your thumb in the positive direction of any axis,



your fingers curl in the direction of a positive rotation. For a mobile robot using ROS, the x-axis points forward, the y-axis points to the left and the z-axis points upward. Under the right-hand rule, a positive rotation of the robot about the z-axis is counterclockwise while a negative rotation is clockwise.

Remember also that ROS uses the metric system so that linear velocities are always specified in meters per second (m/s) and angular velocities are given in radians per second (rad/s). A linear velocity of 0.5 m/s is actually quite fast for an indoor robot (about 1.1 mph) while an angular speed of 1.0 rad/s is equivalent to about one rotation in 6 seconds or 10 RPM. When in doubt, start slowly and gradually increase speed. For an indoor robot, I tend to keep the maximum linear speed at or below 0.2 m/s.

7.2 Levels of Motion Control

Controlling a mobile robot can be done at a number of levels and ROS provides methods for most of them. These levels represent different degrees of abstraction, beginning with direct control of the motors and proceeding upward to path planning and SLAM (Simultaneous Localization and Mapping).

7.2.1 Motors, Wheels, and Encoders

Most differential drive robots running ROS use encoders on the drive motors or wheels. An encoder registers a certain number of ticks (usually hundreds or even thousands) per revolution of the corresponding wheel. Knowing the diameter of the wheels and the distance between them, encoder ticks can be converted to the distance traveled in meters or the angle rotated in radians. To compute speed, these values are simply divided by the time interval between measurements.

This internal motion data is collectively known as **odometry** and ROS makes heavy use of it as we shall see. It helps if your robot has accurate and reliable encoders but wheel data can be augmented using other sources. For example, the TurtleBot uses a single-axis gyro to provide an additional measure of the robot's rotational motion since the iRobot Create's encoders are notably inaccurate during rotations.

It is important to keep in mind that no matter how many sources of odometry data are used, the *actual* position and speed of the robot in the world can (and probably will) differ from the values reported by the odometry. The degree of discrepancy will vary depending on the environmental conditions and the reliability of the odometry sources.

7.2.2 Motor Controllers and Drivers

At the lowest level of motion control we need a driver for the robot's motor controller that can turn the drive wheels at a desired speed, usually using internal units such as encoder ticks per second or a percentage of max speed. With the exception of the Willow Garage PR2 and TurtleBot, the core ROS packages do not include drivers for specific motor controllers. However, a number of third-party ROS developers have published drivers for some of the more popular controllers and/or robots such as the [ArbotiX](#), [Serializer](#), [LEGO® NXT](#) and [Rovio](#). (For a more complete list of supported platforms, see [Robots Using ROS](#).)

7.2.3 The ROS Base Controller

At the next level of abstraction, the desired speed of the robot is specified in real-world units such as meters and radians per second. It is also common to employ some form of PID control. PID stands for "Proportional Integral Derivative" and is so-named because the control algorithm corrects the wheel velocities based not only on the difference (proportional) error between the actual and desired velocity, but also on the derivative and integral over time. You can learn more about PID control on [Wikipedia](#). For our purposes, we simply need to know that the controller will do its best to move the robot in the way we have requested.

The driver and PID controller are usually combined inside a single ROS node called the **base controller**. The base controller must always run on a computer attached directly to the motor controller and is typically one of the first nodes launched when bringing up

the robot. A number of base controllers can also be simulated in Gazebo including the [TurtleBot](#), [PR2](#) and [Erratic](#).

The base controller node typically publishes odometry data on the `/odom` topic and listens for motion commands on the `/cmd_vel` topic. At the same time, the controller node typically (but not always) publishes a transform from the `/odom` frame to the base frame—either `/base_link` or `/base_footprint`. We say "not always" because some robots like the TurtleBot, uses the [robot_pose_ekf](#) package to combine wheel odometry and gyro data to get a more accurate estimate of the robot's position and orientation. In this case, it is the `robot_pose_ekf` node that publishes the transform from `/odom` to `/base_footprint`. (The `robot_pose_ekf` package implements an Extended Kalman Filter as you can read about on the Wiki page linked to above.)

Once we have a base controller for our robot, ROS provides the tools we need to issue motion commands either from the command line or by using other ROS nodes to publish these commands based on a higher level plan. At this level, it does not matter what hardware we are using for our base controller: our programming can focus purely on the desired linear and angular velocities in real-world units and any code we write should work on any base controller with a ROS interface.

7.2.4 Frame-Based Motion using the move_base ROS Package

At the next level of abstraction, ROS provides the [move_base](#) package that allows us to specify a target position and orientation of the robot with respect to some frame of reference; `move_base` will then attempt to move the robot to the goal while avoiding obstacles. The `move_base` package is a very sophisticated path planner and combines odometry data with both local and global cost maps when selecting a path for the robot to follow. It also controls the linear and angular velocities and accelerations automatically based on the minimum and maximum values we set in the configuration files.

7.2.5 SLAM using the gmapping and amcl ROS Packages

At an even higher level, ROS enables our robot to create a map of its environment using the SLAM [gmapping](#) package. The mapping process works best using a laser scanner but can also be done using a Kinect or Asus Xtion depth camera to provide a simulated laser scan. If you own a TurtleBot, the [TurtleBot stack](#) includes all the tools you need to do SLAM.

Once a map of the environment is available, ROS provides the [amcl](#) package (adaptive Monte Carlo localization) for automatically localizing the robot based on its current scan and odometry data. This allows the operator to point and click on any location on a map and the robot will find its way there while avoiding obstacles. (For a superb

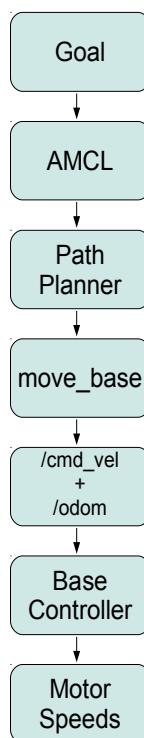
introduction to the mathematics underlying SLAM, check out Sebastian Thrun's online [Artificial Intelligence](#) course on Udacity.)

7.2.6 Semantic Goals

Finally, at the highest level of abstraction, motion goals are specified semantically such as "go to the kitchen and bring me a beer", or simply, "bring me a beer". In this case, the semantic goal must be parsed and translated into a series of actions. For actions requiring the robot to move to a particular location, each location can be passed to the localization and path planning levels for implementation. While beyond the scope of this volume, a number of ROS packages are available to help with this task including [smach](#), [executive_teer](#), [worldmodel](#), [semantic_framer](#), and [knowrob](#).

7.2.7 Summary

In summary, our motion control hierarchy looks something like this:



In this chapter and the next, we will learn how to use these levels of motion control. But before we can understand the more powerful features provided by `move_base`, `gmapping` and `amcl`, we need to start with the basics.

7.3 Twisting and Turning with ROS

ROS uses the [Twist](#) message type (see details below) for publishing motion commands to be used by the base controller. While we could use almost any name for a topic, it is usually called `/cmd_vel` which is short for "command velocities". The base controller node subscribes to the `/cmd_vel` topic and translates `Twist` messages into motor signals that actually turn the wheels.

To see the components of a `Twist` message, run the command:

```
$ rosmsg show geometry_msgs/Twist
```

which will produce the following output:

```
geometry_msgs/Vector3 linear
  float64 x
  float64 y
  float64 z
geometry_msgs/Vector3 angular
  float64 x
  float64 y
  float64 z
```

As you can see, the `Twist` message is composed of two sub-messages with type `Vector3`, one for the `x`, `y` and `z` linear velocity components and another for the `x`, `y` and `z` angular velocity components. Linear velocities are specified in meters per second and angular velocities are given in radians per second. (1 radian equals approximately 57 degrees.)

For a differential drive robot operating in a two-dimensional plane (such as the floor), we only need the linear `x` component and the angular `z` component. This is because this type of robot can only move forward/backward along its longitudinal axis and rotate only around its vertical axis. In other words, the linear `y` and `z` components are always zero (the robot cannot move sideways or vertically) and the angular `x` and `y` components are always zero since the robot cannot rotate about these axes. An omni-directional robot would also use the linear `y` component while a flying or underwater robot would use all six components.

7.3.1 Example Twist Messages

Suppose we want the robot to move straight ahead with a speed of 0.1 meters per second. This would require a `Twist` message with linear values `x=0.1`, `y=0` and `z=0`, and angular values `x=0`, `y=0` and `z=0`. If you were to specify this `Twist` message on the command line, the message part would take the form:

```
'{linear: {x: 0.1, y: 0, z: 0}, angular: {x: 0, y: 0, z: 0}}'
```

Notice how we delineate the sub-messages using braces and separate the component names from their values with a colon and a space (the space is required!) While this might seem like a lot of typing, we will rarely control the robot this way. As we shall see later on, `Twist` messages will be sent to the robot using other ROS nodes.

To rotate counterclockwise with an angular velocity of 1.0 radians per second, the required `Twist` message would be:

```
'{linear: {x: 0, y: 0, z: 0}, angular: {x: 0, y: 0, z: 1.0}}'
```

If we were to combine these two messages, the robot would move forward while turning toward the left. The resulting `Twist` message would be:

```
'{linear: {x: 0.1, y: 0, z: 0}, angular: {x: 0, y: 0, z: 1.0}}'
```

The larger the angular `z` value compared to the linear `x` value, the tighter the turn.

7.3.2 Monitoring Robot Motion using `RViz`

We will use `RViz` to visualize the robot's motion as we try out various `Twist` commands and motion control scripts. Recall from the [RViz User's Guide](#) that we can use the [Odometry Display](#) type to track the pose (position and orientation) of the robot at various points along its path. Each pose of the robot is indicated by a large arrow pointing in the direction that the robot was facing at that point. Note that these poses reflect what is reported by the robot's odometry which could differ—sometimes substantially—from how the robot is positioned in the real world. However, if the robot is well-calibrated and operating on a relatively hard surface, the odometry data is usually good enough to get a rough idea of how the robot is doing. Furthermore, when running a fake robot in the ArbotiX simulator where there is no physics, the correspondence will be exact.

Let's try a couple of examples using the ArbotiX simulator. First, fire up the fake TurtleBot using the command:

```
$ roslaunch rbx1_bringup fake_turtlebot.launch
```

In another terminal, bring up `RViz` with the included configuration file that is already set up with the Odometry display:

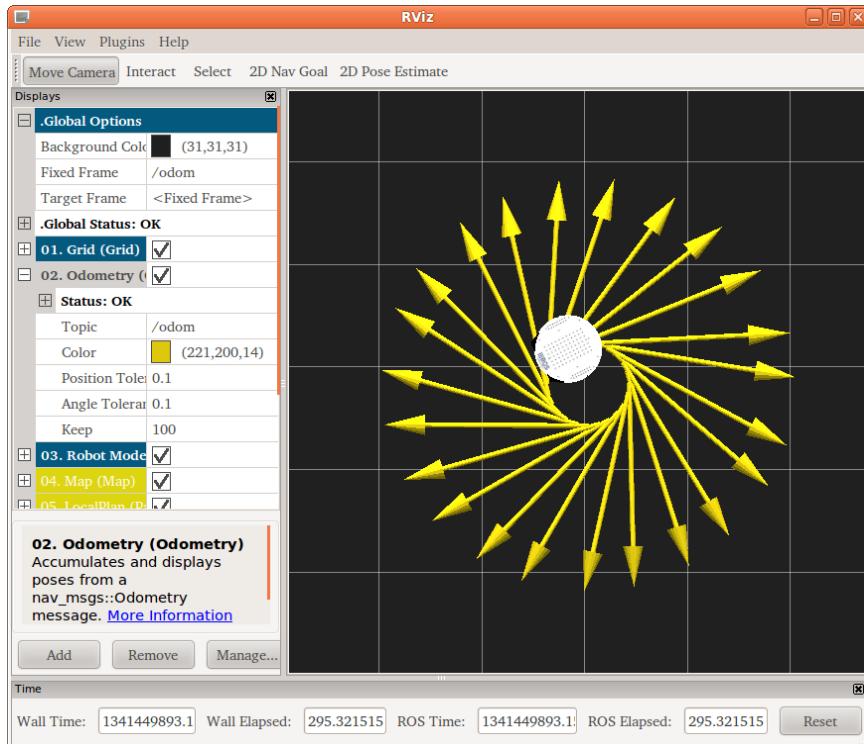
```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/sim_fuerte.vcg
```

Finally, bring up yet another terminal window and set the robot moving in a clockwise circle by publishing the following `Twist` message:

```
$ rostopic pub -r 10 /cmd_vel geometry_msgs/Twist '{linear: {x: 0.1, y: 0, z: 0}, angular: {x: 0, y: 0, z: -0.5}}'
```

We use the `-r` parameter to publish the `Twist` message continually at 10Hz. Some robots like the TurtleBot require the movement command to be continually published or the robot will stop: a nice safety feature. While this parameter is not necessary when running the ArbotiX simulator, it doesn't hurt either.

If everything is working OK, the result in `RViz` should look something like this:



Note that we have set the **Keep** field to 100 for the **Odometry** Display which indicates that we want to display up to the last 100 arrows before the oldest one drops off. The **Position Tolerance** (in meters) and **Angle Tolerance** (in radians) allow you to control how often a new arrow will be displayed.

To clear the arrows at any point, either click the **Reset** button or un-check the checkbox beside the **Odometry** display, then check it again. To turn off the arrows altogether, leave the checkbox un-checked.

To stop the robot from rotating, type `Ctrl-C` in the same terminal window, then publish the empty `Twist` message:

```
$ rostopic pub -1 /cmd_vel geometry_msgs/Twist '{}'
```

Now let's try a second example. First clear the odometry arrows by clicking the **Reset** button in **RViz**. The following pair of commands (separated by a semi-colon) will first move the robot straight for about 3 seconds (the "-1" option means "publish once"), then continue indefinitely in a counter-clockwise circle:

```
$ rostopic pub -1 /cmd_vel geometry_msgs/Twist '{linear: {x: 0.2, y: 0, z: 0}, angular: {x: 0, y: 0, z: 0}}'; rostopic pub -r 10 /cmd_vel geometry_msgs/Twist '{linear: {x: 0.2, y: 0, z: 0}, angular: {x: 0, y: 0, z: 0.5}}'
```

To stop the robot, type **Ctrl-C** in the same terminal window and publish the empty **Twist** message:

```
$ rostopic pub -1 /cmd_vel geometry_msgs/Twist '{}'
```

Before we try out some **Twist** messages on a real robot, we have to spend a few moments talking about calibration.

7.4 Calibrating Your Robot's Odometry

If you don't have a robot, you can skip this section altogether. If you have a TurtleBot, be sure use to use the automated [calibration routine](#) to set the angular correction factors for your robot. You can still use the first part of this section to set the linear correction factor. Note that in all cases you might have to use different calibration parameters for different types of floor surfaces; e.g. carpet versus hardwood. The easiest way to manage the different parameters is to use different launch files for each surface.

If you are using your own custom built robot, you might already have your own calibration method. If so, you can safely skip this section. Otherwise, read on.

Before running the calibration routines, be sure to get the Orococos kinematics packages using the command:

```
$ sudo apt-get install ros-fuerte-orocos-kinematics-dynamics
```

The **rbx1_nav** package includes two calibration scripts: `calibrate_linear.py` and `calibrate_angular.py`. The first attempts to move the robot 1.0 meters forward by monitoring the `/odom` topic and stopping when the reported distance is within 1 cm of the target. You can adjust the target distance and movement speed by editing the script or by using `dynamic_reconfigure`. The second script rotates the robot 360 degrees, again by monitoring the `/odom` topic. We'll describe how to adjust your PID parameters based on the results in the next two sections.

7.4.1 Linear Calibration

First make sure you have plenty of room in front of your robot—at least 2 meters for the default test distance of 1.0 meters. Using a tape measure, lay out at least 1 meter of tape on the floor and align the starting end of the tape with some identifiable mark on your robot. Rotate the robot so that it is aimed parallel to the tape.

Next, bring up your robot's base controller with the appropriate launch file. For a TurtleBot, you would run:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

Next, run `dynamic_reconfigure`:

```
$ rosrun dynamic_reconfigure reconfigure_gui
```

Finally, run the linear calibration node:

```
$ rosrun rbx1_nav calibrate_linear.py
```

Return to the `dynamic_reconfigure` window and select the `calibrate_linear` node. To start the test, check the checkbox beside `start_test`. Your robot should move forward approximately 1 meter. To get the correction factor, follow these steps:

- Measure the actual distance with the tape and make a note of it.
- Divide the actual distance by the target distance and make a note of the ratio.
- Return to the `dynamic_reconfigure` GUI and *multiply* the `odom_linear_scale_correction` value by the ratio you just computed. Set the parameter to the new value.
- Repeat the test by moving the robot back to the start of the tape, then checking the `start_test` checkbox in the `dynamic_reconfigure` window.
- Continue repeating the test until you are satisfied with the result. An accuracy of 1 cm in 1 meter is probably good enough.

With your final correction factor in hand, you need to apply it to the parameters of your robot's base controller using the appropriate launch file. For a TurtleBot, first take the *reciprocal* of the number you found above. Let's call the resulting number X. Add the following line to your `turtlebot.launch` file:

```
<param name="turtlebot_node/odom_linear_scale_correction" value="X"/>
```

substituting your value where indicated by the X.

If your robot uses the ArbotiX base controller, edit your YAML configuration file and change the `ticks_meter` parameter by *dividing* it by your correction factor.

As a final check, launch your robot's startup file with the new correction factor. Then run the `calibration_linear.py` script but with the `odom_linear_scale_correction` parameter set to 1.0. Your robot should now go 1 meter without further correction.

7.4.2 Angular Calibration

If you have a TurtleBot, do not use this method. Instead, run the TurtleBot's automated [calibration procedure](#).

In this test, your robot will only rotate in place so space is not so much an issue. Place a marker (e.g. a piece of tape) on the floor and align it with the front center of the robot. We will rotate the robot 360 degrees and see how close it comes back to the mark.

Bring up your robot's base controller with the appropriate launch file. For a TurtleBot, you would run:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

Next, run `dynamic_reconfigure`:

```
$ rosrun dynamic_reconfigure reconfigure_gui
```

Finally, run the angular calibration node:

```
$ rosrun rbx1_nav calibrate_angular.py
```

Return to the `dynamic_reconfigure` window and select the `calibrate_angular` node. To start the test, check the checkbox beside `start_test`. Your robot should rotate approximately 360 degrees. Don't worry if it seems to rotate significantly more or less than a full rotation. That's what we're about to fix. To get the correction factor, follow these steps:

- If the actual rotation falls short of a full 360 degrees, eyeball the fraction it did rotate and enter that estimated fraction in the `odom_angular_scale_correction` field in the `dynamic_reconfigure` window. So if it looks like the robot rotated about 85% of the way, enter something like 0.85. If it rotated about 5% too far, enter something like 1.05.
- Repeat the test by realigning the marker with the front center of the robot, then check the `start_test` checkbox in the `dynamic_reconfigure` window.

- Hopefully the rotation will be closer to 360 degrees. If it is still short, decrease the `odom_angular_scale_correction` parameter a little and try again. If it rotates too far, increase it a little and try again.
- Repeat until you are happy with the result.

What you do with your final correction factor depends on your base controller's PID parameters. For a robot controlled by the ArbotiX base controller, edit your YAML configuration file and change the `base_width` parameter by *dividing* it by your correction factor.

As a final check, launch your robot's startup file with the new correction factor. Then run the `calibration_angular.py` script but with the `odom_angular_scale_correction` parameter set to 1.0. Your robot should now rotate 360 degrees without further correction.

7.5 Sending `Twist` Messages to a Real Robot

If you have a TurtleBot or any other robot that listens on the `/cmd_vel` topic for motion commands, you can try some `Twist` messages in the real world. Always be sure to start with small values for the linear and angular speeds. Try a pure rotation first so that your robot will not suddenly fly across the room and ruin the furniture.

First power on your robot and launch the appropriate startup files. If you have a TurtleBot, you would run the following on the robot's laptop:

```
$ roslaunch turtlebot_bringup turtlebot.launch
```

Or, if you have your own launch file that includes your calibration parameters, run that file instead.

To rotate the robot counterclockwise in place at 1.0 radians per second (about 6 seconds per revolution), run the command:

```
$ rostopic pub -r 10 /cmd_vel geometry_msgs/Twist '{linear: {x: 0, y: 0, z: 0}, angular: {x: 0, y: 0, z: 1.0}}'
```

To stop the robot, type `Ctrl-C` and, if necessary, publish the empty `Twist` message:

```
$ rostopic pub -1 /cmd_vel geometry_msgs/Twist '{}'
```

(A TurtleBot should stop on its own after typing `Ctrl-C` the first time.)

Next, to move the robot forward at a speed of 0.1 meters per second (about 4 inches per second or 3 seconds per foot), make sure you have lots of space in front of the robot, then run the command:

```
$ rostopic pub -r 10 /cmd_vel geometry_msgs/Twist '{linear: {x: 0.1, y: 0, z: 0}, angular: {x: 0, y: 0, z: 0}}'
```

To stop the movement, type `Ctrl-C`, and, if necessary, publish the empty `Twist` message:

```
$ rostopic pub -l /cmd_vel geometry_msgs/Twist '{}'
```

If you feel satisfied with the result, try other combinations of linear x and angular z values. For example, the following command should send the robot turning in a clockwise circle:

```
$ rostopic pub -r 10 /cmd_vel geometry_msgs/Twist '{linear: {x: 0.15, y: 0, z: 0}, angular: {x: 0, y: 0, z: -0.4}}'
```

To stop the movement, type `Ctrl-C`, and, if necessary, publish the empty `Twist` message:

```
$ rostopic pub -l /cmd_vel geometry_msgs/Twist '{}'
```

As we mentioned earlier, we don't often publish `Twist` messages to the robot directly from the command line although it can be useful for debugging and testing purposes. More often, we will send such messages programmatically from a ROS node that controls the robot's behavior in some interesting way. Let's look at that next.

7.6 Publishing `Twist` Messages from a ROS Node

So far we have been moving our robot from the command line, but most of the time you will rely on a ROS node to publish the appropriate `Twist` messages. As a simple example, suppose you want to program your robot to move one 1.0 meters forward, turn around 180 degrees, then come back to the starting point. We will attempt to accomplish this task a number of different ways which will nicely illustrate the different levels of motion control in ROS.

7.6.1 Estimating Distance and Rotation Using Time and Speed

Our first attempt will be to use timed `Twist` commands to move the robot forward a certain distance, rotate 180 degrees, then move forward again for the same time and at the same speed where it will hopefully end up where it started. Finally, we will rotate the robot 180 degrees one more time to match the original orientation.

The script can be found in the file `timed_out_and_back.py` in the `rbx1_nav/nodes` subdirectory. Before looking at the code, let's try it in the ArbotiX simulator.

7.6.2 Timed Out-and-Back in the ArbotiX Simulator

If the simulator is not already running, start it with the command:

```
$ roslaunch rbx1_bringup fake_turtlebot.launch
```

(If desired, replace the `fake_turtlebot.launch` file with the one for Pi Robot or your own robot. It won't make a difference to the results.)

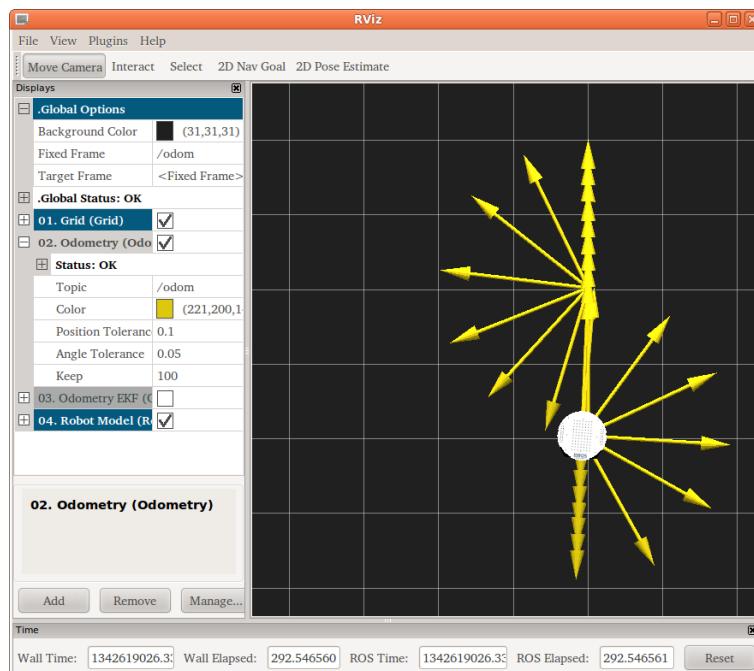
If `RViz` is not already running, fire it up now:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/sim_fuerte.vcg
```

Finally, run the `timed_out_and_back.py` node:

```
$ rosrun rbx1_nav timed_out_and_back.py
```

Hopefully `RViz` will show your robot executing an out-and-back maneuver and the end result will look something like the following:



The large arrows represent the position and orientation of the robot at various points along its trajectory as reported by the robot's (fake) internal odometry. We will learn how to make use of this odometry information in the next few sections.

So far, things look pretty good in the ideal simulator. But before trying it out on a real robot, let's look at the code.

7.6.3 The Timed Out-and-Back Script

Here is the full script for the timed out and back node. After the listing, we will break it down into smaller pieces.

Link to SVN source: [timed_out-and-back.py](#)

```
1 #!/usr/bin/env python
2 import roslib; roslib.load_manifest('rbxl_nav')
3 import rospy
4 from geometry_msgs.msg import Twist
5 from math import pi
6
7 class OutAndBack():
8     def __init__(self):
9         # Give the node a name
10        rospy.init_node('out_and_back', anonymous=False)
11
12        # Set rospy to execute a shutdown function when exiting
13        rospy.on_shutdown(self.shutdown)
14
15        # Publisher to control the robot's speed
16        self.cmd_vel = rospy.Publisher('/cmd_vel', Twist)
17
18        # How fast will we update the robot's movement?
19        rate = 50
20
21        # Set the equivalent ROS rate variable
22        r = rospy.Rate(rate)
23
24        # Set the forward linear speed to 0.2 meters per second
25        linear_speed = 0.2
26
27        # Set the travel distance to 1.0 meters
28        goal_distance = 1.0
29
30        # How long should it take us to get there?
31        linear_duration = goal_distance / linear_speed
32
33        # Set the rotation speed to 1.0 radians per second
34        angular_speed = 1.0
35
36        # Set the rotation angle to Pi radians (180 degrees)
37        goal_angle = pi
38
39        # How long should it take to rotate?
```

```

40     angular_duration = goal_angle / angular_speed
41
42     # Loop through the two legs of the trip
43     for i in range(2):
44         # Initialize the movement command
45         move_cmd = Twist()
46
47         # Set the forward speed
48         move_cmd.linear.x = linear_speed
49
50         # Move forward for a time to go 1 meter
51         ticks = int(linear_duration * rate)
52
53         for t in range(ticks):
54             self.cmd_vel.publish(move_cmd)
55             r.sleep()
56
57         # Stop the robot before the rotation
58         move_cmd = Twist()
59         self.cmd_vel.publish(move_cmd)
60         rospy.sleep(1)
61
62         # Now rotate left roughly 180 degrees
63
64         # Set the angular speed
65         move_cmd.angular.z = angular_speed
66
67         # Rotate for a time to go 180 degrees
68         ticks = int(goal_angle * rate)
69
70         for t in range(ticks):
71             self.cmd_vel.publish(move_cmd)
72             r.sleep()
73
74         # Stop the robot before the next leg
75         move_cmd = Twist()
76         self.cmd_vel.publish(move_cmd)
77         rospy.sleep(1)
78
79         # Stop the robot
80         self.cmd_vel.publish(Twist())
81
82     def shutdown(self):
83         # Always stop the robot when shutting down the node.
84         rospy.loginfo("Stopping the robot...")
85         self.cmd_vel.publish(Twist())
86         rospy.sleep(1)
87
88 if __name__ == '__main__':
89     try:
90         OutAndBack()
91     except:
92         rospy.loginfo("Out-and-Back node terminated.")

```

Since this is our first script, let's take it line-by-line starting from the top:

```
1 #!/usr/bin/env python
2 import roslib; roslib.load_manifest('rbx1_nav')
3 import rospy
```

If you did the ROS Beginner Tutorials in Python, you'll already know that all of our ROS nodes begin with these three lines, although the name of the manifest (`rbx1_nav` in this case) will reflect the package the node belongs to.

```
4 from geometry_msgs.msg import Twist
5 from math import pi
```

Here we take care of any other imports we need for the script. In this case, we will need the `Twist` message type from the ROS `geometry_msgs` package and the constant `pi` from the Python `math` module. Note that a common source of import errors is to forget to include the necessary ROS `<depend package>` line in your package's `manifest.xml` file. In this case, our `manifest.xml` file has to include the line:

```
<depend package="geometry_msgs"/>
```

so that we can import `Twist` from `geometry_msgs.msg`.

```
7 class OutAndBack():
8     def __init__(self):
```

Here we begin the main body of our ROS node by defining it as a Python class along with the standard class initialization line.

```
9         # Give the node a name
10        rospy.init_node('out_and_back', anonymous=False)
11
12        # Set rospy to execute a shutdown function when exiting
13        rospy.on_shutdown(self.shutdown)
```

Every ROS node requires a call to `rospy.init_node()` and we also set a callback for the `on_shutdown()` function so that we can perform any necessary cleanup when the script is terminated—e.g. when the user hits `Ctrl-C`. In the case of a mobile robot, the most important cleanup task is to stop the robot! We'll see how to do this later in the script.

```
15        # Publisher to control the robot's speed
16        self.cmd_vel = rospy.Publisher('/cmd_vel', Twist)
17
18        # How fast will we update the robot's movement?
19        rate = 50
20
21        # Set the equivalent ROS rate variable
22        r = rospy.Rate(rate)
```

Here we define our ROS publisher for sending `Twist` commands to the `/cmd_vel` topic. We also set the rate at which we want to update the robot's movement—50 times per second in this case.

```
24      # Set the forward linear speed to 0.2 meters per second
25      linear_speed = 0.2
26
27      # Set the travel distance to 1.0 meters
28      goal_distance = 1.0
29
30      # How long should it take us to get there?
31      linear_duration = linear_distance / linear_speed
```

We initialize the forward speed to a relatively safe 0.2 meters per second and the target distance to 1.0 meters. We then compute how long this should take.

```
33      # Set the rotation speed to 1.0 radians per second
34      angular_speed = 1.0
35
36      # Set the rotation angle to Pi radians (180 degrees)
37      goal_angle = pi
38
39      # How long should it take to rotate?
40      angular_duration = angular_distance / angular_speed
```

Similarly, we set the rotation speed to 1.0 radians per second and the target angle to 180 degrees or `Pi` radians.

```
42      # Loop through the two legs of the trip
43      for i in range(2):
44          # Initialize the movement command
45          move_cmd = Twist()
46
47          # Set the forward speed
48          move_cmd.linear.x = linear_speed
49
50          # Move forward for a time to go the desired distance
51          ticks = int(linear_duration * rate)
52
53          for t in range(ticks):
54              self.cmd_vel.publish(move_cmd)
55              r.sleep()
```

This is the loop that actually moves the robot—one cycle for each of the two legs. Recall that some robots require a `Twist` message to be continually published to keep it moving. So to move the robot forward `linear_distance` meters at a speed of `linear_speed` meters per second, we publish the `move_cmd` message every `1/rate` seconds for the appropriate duration. The expression `r.sleep()` is a shorthand for `rospy.sleep(1/rate)` since we defined the variable `r = rospy.Rate(rate)`.

```

62         # Now rotate left roughly 180 degrees
63
64         # Set the angular speed
65         move_cmd.angular.z = angular_speed
66
67         # Rotate for a time to go 180 degrees
68         ticks = int(goal_angle * rate)
69
70         for t in range(ticks):
71             self.cmd_vel.publish(move_cmd)
72             r.sleep()

```

In the second part of the loop, we rotate the robot at a rate of `angular_speed` radians per second for the appropriate duration (Pi seconds in this case) which should yield 180 degrees.

```

79         # Stop the robot.
80         self.cmd_vel.publish(Twist())

```

When the robot has completed the out-and-back journey, we stop it by publishing an empty `Twist` message (all fields are 0).

```

82     def shutdown(self):
83         # Always stop the robot when shutting down the node.
84         rospy.loginfo("Stopping the robot...")
85         self.cmd_vel.publish(Twist())
86         rospy.sleep(1)

```

This is our shutdown callback function. If the script is terminated for any reason, we stop the robot by publishing an empty `Twist` message.

```

88 if __name__ == '__main__':
89     try:
90         OutAndBack()
91     except rospy.ROSInterruptException:
92         rospy.loginfo("Out-and-Back node terminated.")

```

Finally, this is the standard Python block for running the script. We simply instantiate the `OutAndBack` class which sets the script (and robot) in motion.

7.6.4 Timed Out and Back using a Real Robot

If you have a robot like the TurtleBot, you can try the `timed_out_and_back.py` script in the real world. Remember that we are only using time and speed to estimate distance and rotation angles. So we expect that the robot's inertia will throw things off compared to the ideal ArbotiX simulation (which, as you will recall, does not model any physics.)

First, terminate any running simulations. Next, make sure your robot has plenty of room to work in—at least 1.5 meters ahead of it and a meter on either side. Then bring up your robot's startup launch file(s). If you have a TurtleBot, you would run the following on the robot's laptop:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

Or use your own launch file if you have created one to store your calibration parameters.

We will also use an auxiliary script so that we can see the TurtleBot's combined odometry frame in `RViz`. (This will become clearer in the next section.) You can skip this if you are not using a TurtleBot. This launch file should be run on the TurtleBot's laptop:

```
$ rosrun rbt_bringup odom_ekf.launch
```

Next we're going to configure `RViz` to display the combined odometry data (encoders + gyro) rather than `/odom` which only shows the encoder data. If you already have `RViz` running from the previous test, you can simply un-check the **Odometry** display and check the **Odometry EKF** display, then skip the following step.

If `RViz` is not already up, run it now with the `ekf_fuerte` config file. This file simply pre-selects the `/odom_ekf` topic for displaying the combined odometry data:

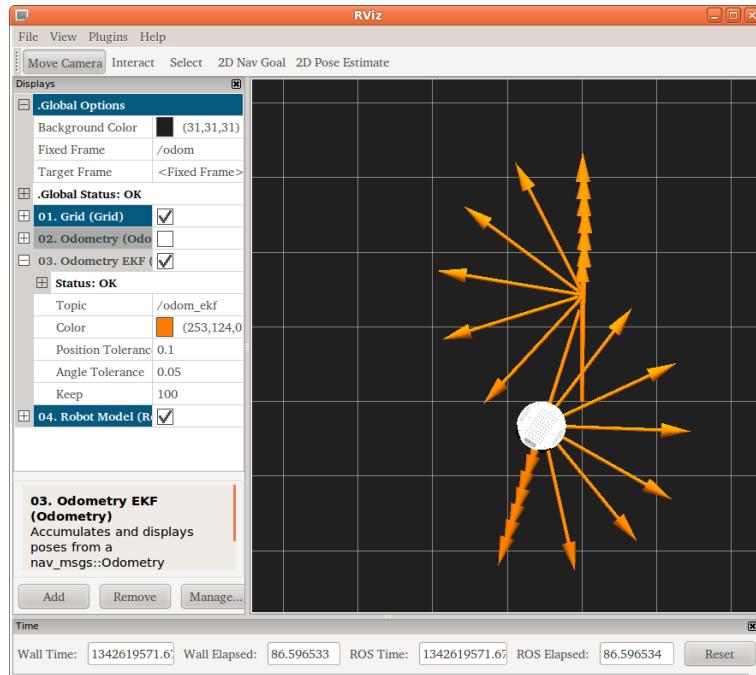
```
$ rosrun rviz rviz -d `rospack find rbt_nav`/ekf_fuerte.vcg
```

The only difference between this configuration and the previous one is that we are now displaying the combined odometry data on the `/odom_ekf` topic rather than just the wheel encoder data published on the `/odom` topic. You can check both displays if you want to compare the two.

Finally, we run the out and back script just like we did before. Note that the script itself does not care if we are running a simulation or controlling a real robot. It is simply publishing `Twist` messages on the `/cmd_vel` topic for anyone who cares to listen. This is one example of how ROS allows us to abstract away the lower levels of the motion control hierarchy.

```
$ rosrun rbt_nav timed_out_and_back.py
```

Here is the result for my own TurtleBot when operating on a low-ply carpet:



As you can tell from the picture, the robot did not end up very close to the starting position. First of all, it did not go far enough before turning around (the grid squares are 0.5 meters apart). Then it did not rotate a full 180 degrees before heading back. The result is that the robot is about 0.5m to the left and behind the starting point, and it is oriented in the wrong direction.

Fortunately, the data we need to correct the problem is staring us right in the face. The large odometry arrows in the image above indicate the robot's position and orientation as reported by its internal odometry. In other words, the robot "knows" it messed up but we have unfairly handicapped it by not using the odometry data in our script. While the odometry data will not match the real motion exactly, it should give us a better result if we use it.

7.7 Are We There Yet? Going the Distance with Odometry

When we ask our robot to move or rotate at a certain speed, how do we know that it is actually doing what we asked? For example, if we publish a `Twist` message to move the robot forward at 0.2 m/s, how do we know that the robot isn't really going 0.18 m/s? In fact, how do we know that both wheels are even traveling at the same speed?

As we explained earlier in this chapter, the robot's base controller node uses odometry and PID control to turn motion requests into real-world velocities. The accuracy and reliability of this process depends on the robot's internal sensors, the accuracy of the calibration procedure, and environmental conditions. (For example, some surfaces may allow the wheels to slip slightly which will mess up the mapping between encoder counts and distance traveled.)

The robot's internal odometry can be supplemented with external measures of the robot's position and/or orientation. For example, one can use wall-mounted visual markers such as fiducials together with the ROS packages [ar_pose](#) or [ar_kinect](#) to provide a fairly accurate localization of the robot within a room. A similar technique uses visual feature matching without the need for artificial markers ([rgbdslam](#)), and yet another package ([laser_scan_matcher](#)) uses laser scan matching. Outdoor robots often use [GPS](#) to estimate position and indoor robots can use other active localization techniques like the NorthStar system by Evolution Robotics.

For the purposes of this book, we will use the term "odometry" to mean internal position data. However, regardless of how one measures odometry, ROS provides a message type to store the information; namely [nav_msgs/Odometry](#). The abbreviated definition of the `Odometry` message type is shown below:

```
Header header
string child_frame_id
geometry_msgs/PoseWithCovariance pose
geometry_msgs/TwistWithCovariance twist
```

Here we see that the `Odometry` message is composed of a `Header`, a `string` identifying the `child_frame_id`, and two sub-messages, one for `PoseWithCovariance` and one for `TwistWithCovariance`.

To see the expanded version of the definition, run the command:

```
$ rosmsg show nav_msgs/Odometry
```

which should yield the following output:

```

Header header
  uint32 seq
  time stamp
  string frame_id
string child_frame_id
geometry_msgs/PoseWithCovariance pose
  geometry_msgs/Pose pose
    geometry_msgs/Point position
      float64 x
      float64 y
      float64 z
    geometry_msgs/Quaternion orientation
      float64 x
      float64 y
      float64 z
      float64 w
    float64[36] covariance
geometry_msgs/TwistWithCovariance twist
  geometry_msgs/Twist twist
    geometry_msgs/Vector3 linear
      float64 x
      float64 y
      float64 z
    geometry_msgs/Vector3 angular
      float64 x
      float64 y
      float64 z
    float64[36] covariance

```

The `PoseWithCovariance` sub-message records the position and orientation of the robot while the `TwistWithCovariance` component gives us the linear and angular speeds as we have already seen. Both the `pose` and `twist` can be supplemented with a `covariance` matrix which measures the uncertainty in the various measurements.

The `Header` and `child_frame_id` define the reference frames we are using to measure distances and angles. It also provides a timestamp for each message so we know not only where we are but when. By convention, odometry measurements in ROS use `/odom` as the parent frame id and `/base_link` (or `/base_footprint`) as the child frame id. While the `/base_link` frame corresponds to a real physical part of the robot, the `/odom` frame is defined by the translations and rotations encapsulated in the odometry data. These transformations move the robot relative to the `/odom` frame. If we display the robot model in `RViz` and set the fixed frame to the `/odom` frame, the robot's position will reflect where the robot "thinks" it is relative to its starting position.

7.8 Out and Back Using Odometry

Now that we understand how odometry information is represented in ROS, we can be more precise about moving our robot on an out-and-back course. Rather than guessing

distances and angles based on time and speed, our next script will monitor the robot's position and orientation as reported by the transform between the `/odom` and `/base_link` frames.

The new file is called `odom_out_and_back.py` in the `rbx1_nav/nodes` directory. Before looking at the code, let's compare the results between the simulator and a real robot.

7.8.1 Odometry-Based Out and Back in the ArbotiX Simulator

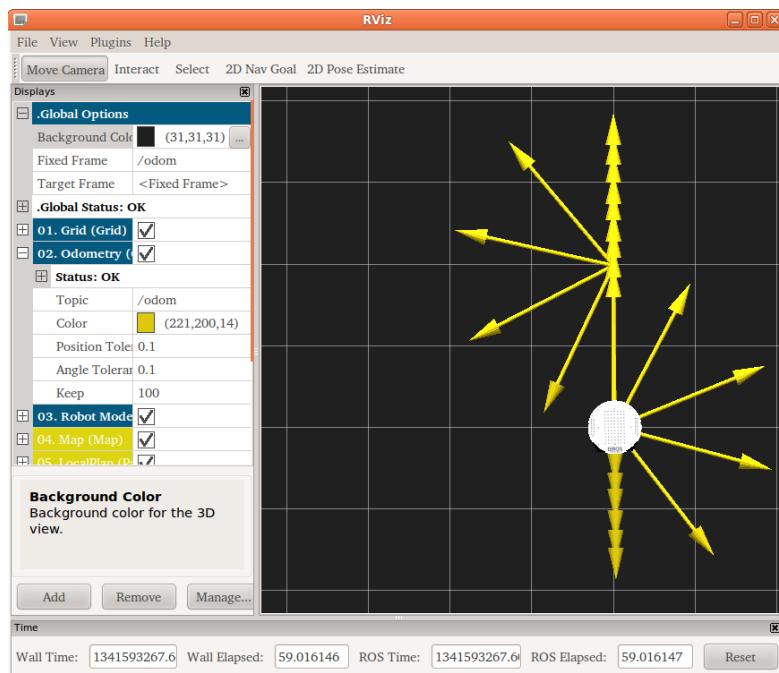
If you already have a simulated robot running, first `Ctrl-C` out of the simulation so we can start the odometry readings from scratch. Then bring up the simulated robot again, run `RViz`, then run the `odom_out_and_back.py` script as follows:

```
$ rosrun rbt1_bringup fake_turtlebot.launch
```

```
$ rosrun rviz rviz -d `rospack find rbt1_nav`/sim_fuerte.vcg
```

```
$ rosrun rbt1_nav odom_out_and_back.py
```

A typical result is shown below:



As you can see, using odometry in an ideal simulator without physics produces basically perfect results. This should not be terribly surprising. So what happens when we try it on a real robot?

7.8.2 *Odometry-Based Out and Back Using a Real Robot*

If you have a TurtleBot or other ROS-compatible robot, you can try the odometry based out-and-back script in the real world.

First make sure you terminate any running simulations. Then bring up your robot's startup launch file(s). For a TurtleBot you would run:

```
$ roslaunch turtlebot_bringup turtlebot.launch
```

(Or use your own launch file if you have created one to store your calibration parameters.)

Make sure your robot has plenty of room to work in—at least 1.5 meters ahead of it and a meter on either side.

If you are using a TurtleBot, we will also run the `odom_ekf.py` script (included in the `rbx1_bringup` package) so we can see the TurtleBot's combined odometry frame in `RViz`. You can skip this if you are not using a TurtleBot. This launch file should be run on the TurtleBot's laptop:

```
$ roslaunch rbx1_bringup odom_ekf.launch
```

If you already have `RViz` running from the previous test, you can simply un-check the **Odometry** display and check the **Odometry EKF** display, then skip the following step.

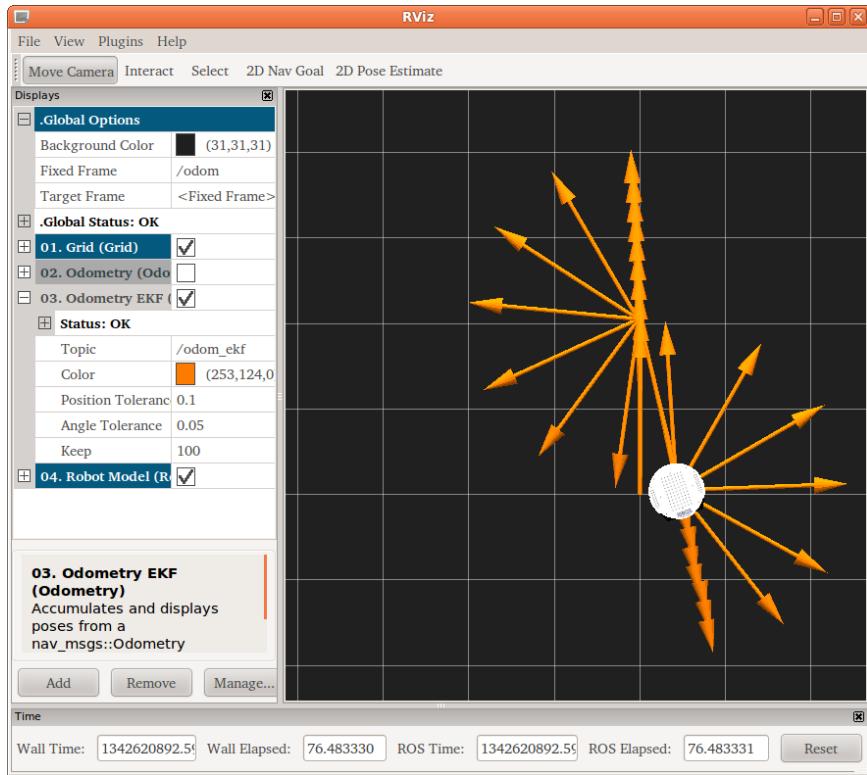
If `RViz` is not already up, run it now with the `ekf_fuerte` config file. This file simply pre-selects the `/odom_ekf` topic for displaying the combined odometry data:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/ekf_fuerte.vcg
```

Finally, launch the odometry-based out-and-back script just like we did in simulation:

```
$ rosrun rbx1_nav odom_out_and_back.py
```

Here is the result for my own TurtleBot when operating on a low-ply carpet:



As you can see from the picture, the result is much better than the timed out-and-back case. If fact, in the real world, the result was even better than shown in RViz.

(Remember that the odometry arrows in RViz won't line up exactly with the actual position and orientation of the robot in the real world.) In this particular run, the robot ended up less than 1 cm from the starting position and only a few degrees away from the correct orientation. Of course, to get results even this good, you will need to spend some time carefully calibrating your robot's odometry as described earlier.

7.8.3 The Odometry-Based Out-and-Back Script

Here now is the full odometry-based out-and-back script. The embedded comments should make the script fairly self-explanatory but we will describe the key lines in greater detail following the listing.

```

1 #!/usr/bin/env python
2 import roslib; roslib.load_manifest('rbx1_nav')
3 import rospy
4 from geometry_msgs.msg import Twist, Point, Quaternion
5 import tf
6 from transform_utils import quat_to_angle, normalize_angle
7 from math import radians, copysign, sqrt, pow, pi
8

```

```

9  class OutAndBack():
10     def __init__(self):
11         # Give the node a name
12         rospy.init_node('out_and_back', anonymous=False)
13
14         # Set rospy to execute a shutdown function when exiting
15         rospy.on_shutdown(self.shutdown)
16
17         # Publisher to control the robot's speed
18         self.cmd_vel = rospy.Publisher('/cmd_vel', Twist)
19
20         # How fast will we update the robot's movement?
21         rate = 20
22
23         # Set the equivalent ROS rate variable
24         r = rospy.Rate(rate)
25
26         # Set the forward linear speed to 0.2 meters per second
27         linear_speed = 0.2
28
29         # Set the travel distance in meters
30         goal_distance = 1.0
31
32         # Set the rotation speed in radians per second
33         angular_speed = 1.0
34
35         # Set the angular tolerance in degrees converted to radians
36         angular_tolerance = radians(2.5)
37
38         # Set the rotation angle to Pi radians (180 degrees)
39         goal_angle = pi
40
41         # Initialize the tf listener
42         self.tf_listener = tf.TransformListener()
43
44         # Set the odom frame
45         self.odom_frame = '/odom'
46
47         # Find out if the robot uses /base_link or /base_footprint
48         try:
49             self.tf_listener.waitForTransform(self.odom_frame,
50                                             '/base_footprint', rospy.Time(), rospy.Duration(1.0))
51             self.base_frame = '/base_footprint'
52         except (tf.Exception, tf.ConnectivityException, tf.LookupException):
53             try:
54                 self.tf_listener.waitForTransform(self.odom_frame,
55                                             '/base_link', rospy.Time(), rospy.Duration(1.0))
56                 self.base_frame = '/base_link'
57             except (tf.Exception, tf.ConnectivityException,
58                     tf.LookupException):
59                 rospy.loginfo("Cannot find transform between /odom and
60 /base_link or /base_footprint")
61                 rospy.signal_shutdown("tf Exception")
62
63         # Initialize the position variable as a Point type
64         position = Point()

```

```

62     # Loop once for each leg of the trip
63     for i in range(2):
64         # Initialize the movement command
65         move_cmd = Twist()
66
67         # Set the movement command to forward motion
68         move_cmd.linear.x = linear_speed
69
70         # Get the starting position values
71         (position, rotation) = self.get_odom()
72
73         x_start = position.x
74         y_start = position.y
75
76         # Keep track of the distance traveled
77         distance = 0
78
79         # Enter the loop to move along a side
80         while distance < goal_distance and not rospy.is_shutdown():
81             # Publish the Twist message and sleep 1 cycle
82             self.cmd_vel.publish(move_cmd)
83
84             r.sleep()
85
86             # Get the current position
87             (position, rotation) = self.get_odom()
88
89             # Compute the Euclidean distance from the start
90             distance = sqrt(pow((position.x - x_start), 2) +
91                             pow((position.y - y_start), 2))
92
93             # Stop the robot before the rotation
94             move_cmd = Twist()
95             self.cmd_vel.publish(move_cmd)
96             rospy.sleep(1)
97
98             # Set the movement command to a rotation
99             move_cmd.angular.z = angular_speed
100
101            # Track the last angle measured
102            last_angle = rotation
103
104            # Track how far we have turned
105            from geometry_msgs.msg import Twist, Point, Quaternion
106            import tf
107            from transform_utils import quat_to_angle, normalize_angle
108            turn_angle = 0
109            while abs(turn_angle + angular_tolerance) < abs(goal_angle) and not
rospy.is_shutdown():
110                # Publish the Twist message and sleep 1 cycle
111                self.cmd_vel.publish(move_cmd)
112                r.sleep()
113
114                # Get the current rotation
115                (position, rotation) = self.get_odom()
116
117                # Compute the amount of rotation since the last lopp

```

```

118     delta_angle = normalize_angle(rotation - last_angle)
119
120     # Add to the running total
121     turn_angle += delta_angle
122     last_angle = rotation
123
124     # Stop the robot before the next leg
125     move_cmd = Twist()
126     self.cmd_vel.publish(move_cmd)
127     rospy.sleep(1)
128
129     # Stop the robot for good
130     self.cmd_vel.publish(Twist())
131
132 def get_odom(self):
133     # Get the current transform between the odom and base frames
134     try:
135         (trans, rot) = self.tf_listener.lookupTransform(self.odom_frame,
136             self.base_frame, rospy.Time(0))
137     except (tf.Exception, tf.ConnectivityException, tf.LookupException):
138         rospy.loginfo("TF Exception")
139         return
140
141     return (Point(*trans), quat_to_angle(Quaternion(*rot)))
142
143 def shutdown(self):
144     # Always stop the robot when shutting down the node.
145     rospy.loginfo("Stopping the robot...")
146     self.cmd_vel.publish(Twist())
147     rospy.sleep(1)
148
149 if __name__ == '__main__':
150     try:
151         OutAndBack()
152     except:
153         rospy.loginfo("Out-and-Back node terminated.")

```

Let's now look at the key lines in the script.

```

4  from geometry_msgs.msg import Twist, Point, Quaternion
5  import tf
6  from transform_utils import quat_to_angle, normalize_angle

```

We will need the `Twist`, `Point` and `Quaternion` data types from the `geometry_msgs` package. We will also need the `tf` library to monitor the transformation between the `/odom` and `/base_link` (or `/base_footprint`) frames. The `transform_utils` library is a small module that you can find in the `rbx1_nav/src` directory and contains a couple of handy functions borrowed from the `TurtleBot` package. The function `quat_to_angle` converts a quaternion to an Euler angle (yaw) while the `normalize_angle` function removes the ambiguity between 180 and -180 degrees as well as 0 and 360 degrees.

```

35      # Set the angular tolerance in degrees converted to radians
36      angular_tolerance = radians(2.5)

```

Here we define an `angular_tolerance` for rotations. The reason is that it is very easy to overshoot the rotation with a real robot and even a slight angular error can send the robot far away from the next location. Empirically it was found that a tolerance of about 2.5 degrees gives acceptable results.

```

41      # Initialize the tf listener
42      self.tf_listener = tf.TransformListener()
43
44      # Set the odom frame
45      self.odom_frame = '/odom'
46
47      # Find out if the robot uses /base_link or /base_footprint
48      try:
49          self.tf_listener.waitForTransform(self.odom_frame,
50                                          '/base_footprint', rospy.Time(), rospy.Duration(1.0))
50          self.base_frame = '/base_footprint'
51      except (tf.Exception, tf.ConnectivityException, tf.LookupException):
52          try:
53              self.tf_listener.waitForTransform(self.odom_frame,
53                                          '/base_link', rospy.Time(), rospy.Duration(1.0))
54              self.base_frame = '/base_link'
55          except (tf.Exception, tf.ConnectivityException,
56                  tf.LookupException):
56              rospy.loginfo("Cannot find transform between /odom and
56              /base_link or /base_footprint")
57              rospy.signal_shutdown("tf Exception")

```

Next we create a `TransformListener` object to monitor frame transforms. To obtain the robot's position and orientation, we need the transform between the `/odom` frame and either the `/base_footprint` frame as used by the TurtleBot or the `/base_link` frame as used by Pi Robot and Maxwell. First we test for the `/base_footprint` frame and if we don't find it, we test for the `/base_link` frame. The result is stored in the `self.base_frame` variable to be used later in the script.

```

63      for i in range(2):
64          # Initialize the movement command
65          move_cmd = Twist()

```

As with the timed out-and-back script, we loop through the two legs of the trip: first moving the robot 1 meter forward, then rotating it 180 degrees.

```

71      (position, rotation) = self.get_odom()
72
73      x_start = position.x
74      y_start = position.y

```

At the start of each leg, we record the starting position and orientation using the `get_odom()` function. Let's look at that next so we understand how it works.

```
132 def get_odom(self):
133     # Get the current transform between the odom and base frames
134     try:
135         (trans, rot) = self.tf_listener.lookupTransform(self.odom_frame,
136             self.base_frame, rospy.Time(0))
137     except (tf.Exception, tf.ConnectivityException, tf.LookupException):
138         rospy.loginfo("TF Exception")
139     return
140
141     return (Point(*trans), quat_to_angleQuaternion(*rot))
```

The `get_odom()` function first uses the `tf_listener` object to look up the current transform between the odometry and base frames. If there is a problem with the lookup, we throw an exception. Otherwise, we return a `Point` representation of the translation and a `Quaternion` representation of the rotation. The `*` in front of the `trans` and `rot` variables is Python's notation for passing a list of numbers to a function and we use it here since `trans` is a list of x, y, and z coordinates while `rot` is a list of x, y, z and w quaternion components.

Now back to the main part of the script:

```
76     # Keep track of the distance traveled
77     distance = 0
78
79     # Enter the loop to move along a side
80     while distance < goal_distance and not rospy.is_shutdown():
81         # Publish the Twist message and sleep 1 cycle
82         self.cmd_vel.publish(move_cmd)
83
84         r.sleep()
85
86         # Get the current position
87         (position, rotation) = self.get_odom()
88
89         # Compute the Euclidean distance from the start
90         distance = sqrt(pow((position.x - x_start), 2) +
91                         pow((position.y - y_start), 2))
```

This is just our loop to move the robot forward until we have gone 1.0 meters.

```
104     # Track how far we have turned
105     turn_angle = 0
106
107     while abs(turn_angle + angular_tolerance) < abs(goal_angle) and not
rospy.is_shutdown():
108         # Publish the Twist message and sleep for 1 cycle
109         self.cmd_vel.publish(move_cmd)
110         r.sleep()
111
```

```

112     # Get the current rotation
113     (position, rotation) = self.get_odom()
114
115     # Compute the amount of rotation since the last loop
116     delta_angle = normalize_angle(rotation - last_angle)
117
118     # Add to the running total
119     turn_angle += delta_angle
120     last_angle = rotation

```

And this is our loop for rotating through 180 degrees within the angular tolerance we set near the beginning of the script.

7.8.4 The `/odom` Topic versus the `/odom` Frame

The reader may be wondering why we used a `TransformListener` in the previous script to access odometry information rather than just subscribing to the `/odom` topic. The reason is that the data published on the `/odom` topic is not always the full story. For example, the TurtleBot uses a single-axis gyro to provide an additional estimate of the robot's rotation. This is combined with the data from the wheel encoders by the `robot_pose_ekf` node (which is started in the TurtleBot launch file) to get a better estimate of rotation than either source alone.

However, the `robot_pose_ekf` node does not publish its data back on the `/odom` topic which is reserved for the wheel encoder data. Instead, it publishes it on the `/robot_pose_ekf/odom` topic. Furthermore, the data is published not as an Odometry message but as a `PoseWithCovarianceStamped` message. It *does* however, publish a transform from the `/odom` frame to the `/base_link` frame which provides the information we need. As a result, it is generally safer to use `tf` to monitor the transformation between the `/odom` and `/base_link` (or `/base_footprint`) frames than to rely on the `/odom` message topic.

In the `rbx1_bringup/nodes` directory you will find a node called `odom_ekf.py` that republishes the `PoseWithCovarianceStamped` message found on the `/robot_pose_ekf/odom` topic as an Odometry type message on the topic called `/odom_ekf`. This allows us to view both the `/odom` topic and the `/odom_ekf` topic in `RViz` to compare the TurtleBot's wheel-based odometry with the combined odometry that includes the gyro data.

7.9 Navigating a Square using Odometry

As we did with the odometry-based out-and-back script, we will monitor the position and orientation of the robot using the `tf` transform between the `/odom` and `/base_link` (or `/base_footprint`) frames. However, this time we will attempt to move the robot in a square by setting four waypoints, one at each corner. At the end of

the run, we can see how close the robot gets back to the starting location and orientation. Let's start with a simulation and then try it on a real robot.

7.9.1 Navigating a Square in the ArbotiX Simulator

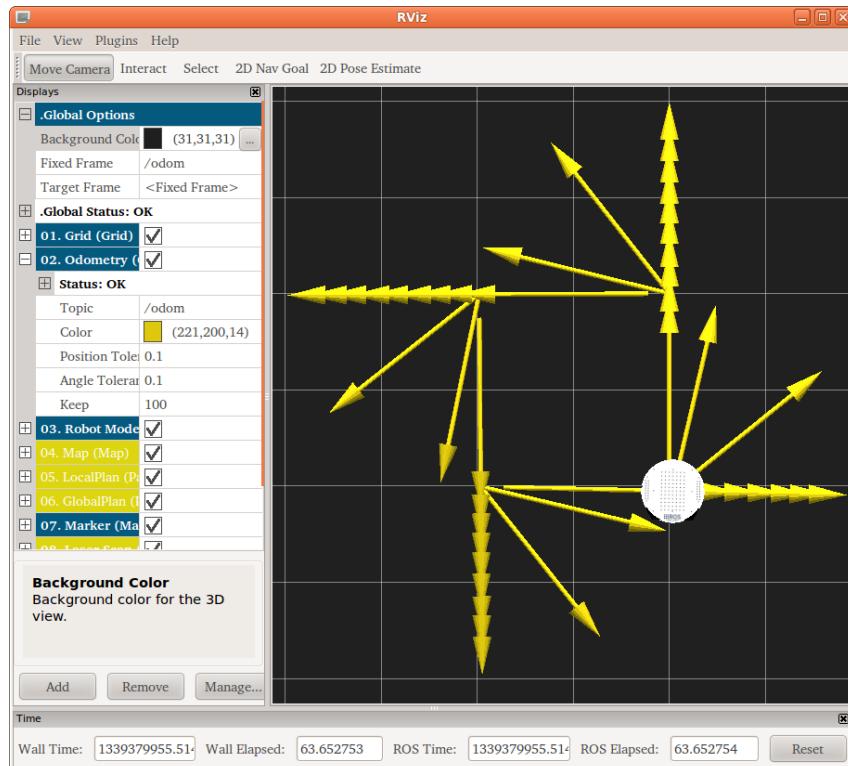
If you already have a simulated TurtleBot or Pi Robot running, first **Ctrl-C** out of the simulation so we can start the odometry readings from scratch. Then bring up the simulated robot again, run **RViz**, then run the `nav_square.py` script as follows:

```
$ rosrun rbt1_bringup fake_turtlebot.launch
```

```
$ rosrun rviz rviz -d `rospack find rbt1_nav`/sim_fuerte.vcg
```

```
$ rosrun rbt1_nav nav_square.py
```

A typical result is shown below:



As before, the odometry arrows illustrate the heading of the robot at various points along its route. As you can see, the square is not perfectly aligned with the grid lines, but it's not bad.

7.9.2 Navigating a Square using a Real Robot

If you have a robot, try out the `nav_square` script now to see how well it does with real-world odometry. First terminate any running simulated robots, then launch the startup file(s) for your robot. For a TurtleBot you would run:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

(Or use your own launch file if you have created one to store your calibration parameters.)

Make sure your robot has plenty of room to work in—at least 1.5 meters ahead of it and on either side.

If you are using a TurtleBot, we also need to run the `odom_ekf.py` script to be able to see the TurtleBot's combined odometry frame in `RViz`. You can skip this if you are not using a TurtleBot. The launch file should be run on the TurtleBot's laptop:

```
$ rosrun rbx1_bringup odom_ekf.launch
```

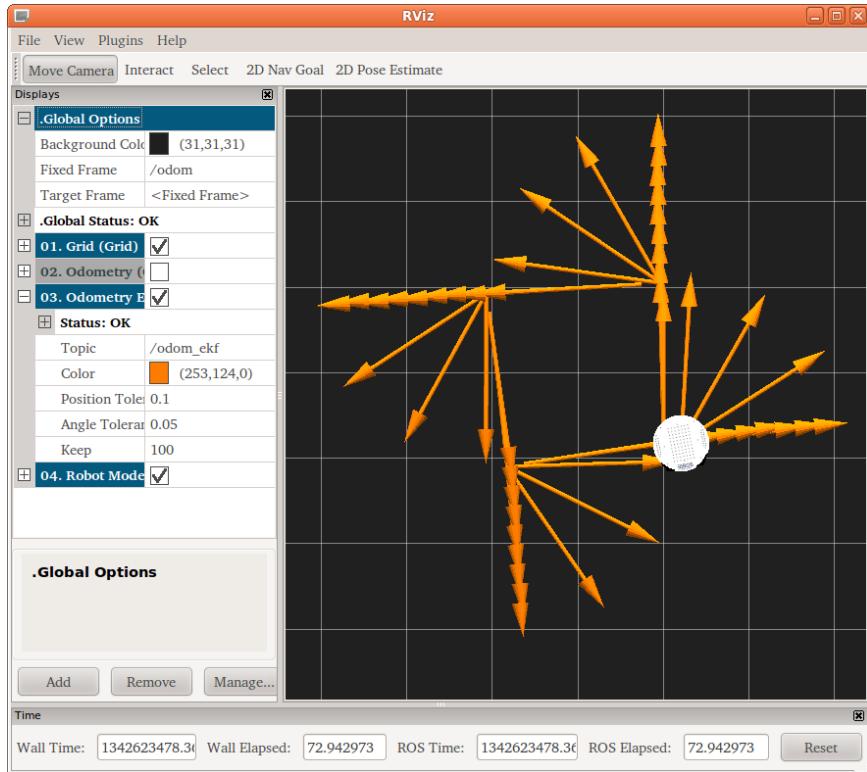
If `RViz` is still running on your workstation, shut it down and bring it back up with the `ekf` configuration file. Alternatively, simply un-check the **Odometry** display and check the **Odometry EKF** display.

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/ekf_fuerte.vcg
```

Finally, run the `nav_square` script again:

```
$ rosrun rbx1_nav nav_square.py
```

The following image shows the results when using my own TurtleBot on a low-ply carpet:



As you can see, the result is not too bad. In the real world, the robot ended up 15 cm away from the starting point and about 20 degrees off the original orientation. But of course, if we were to run the script a second time without repositioning the robot, the error in the starting orientation would throw off the entire trajectory.

7.9.3 The `nav_square.py` Script

The `nav_square.py` script is nearly identical to the odometry-based out-and-back script that we just looked at so we won't display it here. The only difference is that we now send the robot along four 1 meter legs using 90 degree rotations instead of two 1 meter legs using 180 rotations. You can look at the code at the link below or by viewing your own copy in the `rbx1_nav/nodes` directory.

Link to SVN source: [nav_square.py](#)

7.9.4 The Trouble with Dead Reckoning

The processing of navigating a course while relying only on internal motion data and without reference to external landmarks is referred to as dead reckoning. Any robot that relies entirely on dead reckoning for any length of time will eventually become

completely lost. The root of the problem is that even small errors in odometry accumulate over time. Imagine for example an error of even 1 degree in the robot's estimated heading just before it moves straight for 3 meters. At the end of the run, the robot will have accumulated an error of over 5 cm in its position. Since the robot does not know that it is 5 cm away from its intended destination, the calculation of the next movement will be off by this amount before it even gets started.

Fortunately, roboticists long ago started working on various ways to incorporate landmarks or other external references into robot navigation and we will do the same with ROS in the chapter on SLAM.

7.10 Teleoperating your Robot

It is always a good idea to maintain some kind of manual control over your robot, especially when testing new code. We have seen that the base controller for a robot subscribes to the `/cmd_vel` topic and maps any `Twist` messages published there into motor signals. If we can coax a remote control device such as a joystick or game controller to publish `Twist` messages on the `/cmd_vel` topic, we can use it to teleoperate the robot. (This is another good example of how ROS enables us to abstract away from the underlying hardware.)

Fortunately, the `turtlebot_teleop` package already includes teleoperation nodes for using the keyboard, a joystick or a PS3 controller. First make sure you have the required ROS packages:

```
$ sudo apt-get install ros-fuerte-joystick-drivers \
  ros-fuerte-turtlebot-apps
```

Before teleoperating a real robot, try it out using the ArbotiX simulator. Bring up the fake TurtleBot if it is not already running:

```
$ roslaunch rbx1_bringup fake_turtlebot.launch
```

And if `RViz` is not still running, fire it up now:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/sim_fuerte.vcg
```

Now let's take a look at teleoperating the simulated robot using either the keyboard or a joystick.

7.10.1 Using the Keyboard

The `turtlebot_teleop` package includes a `keyboard_teleop.launch` file that has been copied to the `rbx1_nav/launch` directory so that we can edit a couple of

parameters described below. Use the following command to run this copy of the launch file:

```
$ rosrun rbx1_nav keyboard_teleop.launch
```

You should then see the following instructions on your terminal screen:

```
Control Your TurtleBot!
-----
Moving around:
  u      i      o
  j      k      l
  m      ,      .

q/z : increase/decrease max speeds by 10%
w/x : increase/decrease only linear speed by 10%
e/c : increase/decrease only angular speed by 10%
anything else : stop

CTRL-C to quit
```

With your cursor over the teleop terminal window, try tapping the letter `i`. You should see the simulated TurtleBot move forward in `RViz`. Try some of the other keys to make sure everything is working.

If you look at the `keyboard_teleop.launch` file in the `rbx1_nav/launch` directory, you will see that the keyboard teleop node takes two parameters: `scale_linear` and `scale_angular` for determining the default linear and angular speed of the robot. When first testing teleoperating on a real robot, it is a good idea to set these values smaller than the defaults so that the robot will move slowly. Unfortunately, at the time of this writing, there is [a bug](#) in the `turtlebot_teleop` package that prevents the two parameters from being read by the `keyboard_teleop` node, so for the time being, we have to accept the default values.

7.10.2 Using a Logitech Game Pad

If you have a joystick or game pad you can use the `joystick_teleop.launch` file in the `turtlebot_teleop` package. We have made a local copy of this file in the `rbx1_nav/launch` directory so that various parameters can be edited to suit your needs. The following description applies specifically to a Logitech wireless game pad.

To use the joystick teleop node, run the following command:

```
$ rosrun rbx1_nav joystick_teleop.launch
```

If you get an error such as:

```
[ERROR] [1332893303.227744871]: Couldn't open joystick /dev/input/js0.  
Will retry every second.
```

then your joystick or game pad is either not plugged in to a USB port or it is not recognized by Ubuntu. If you do not receive any errors, press the "dead man" button (see Note below) and try moving the joystick or the left-hand toggle stick on the game pad.

NOTE: If you are using a Logitech game pad, you must first press and hold the right index finger button before the robot will respond to the left toggle stick. This button is called the "dead man" switch since the robot will stop moving if you release it.

You can edit the `joystick_teleop.launch` file to change the scale factors for linear and angular speed. You can also map the dead man switch to a different button. To find out the numbers corresponding to each button, try the `jstest` program:

```
$ sudo apt-get install joystick  
$ jstest /dev/input/js0
```

Then press various buttons and look at the numbers at the bottom of the screen to see which one turns from "off" to "on". Type `Ctrl-C` to exit the test screen.

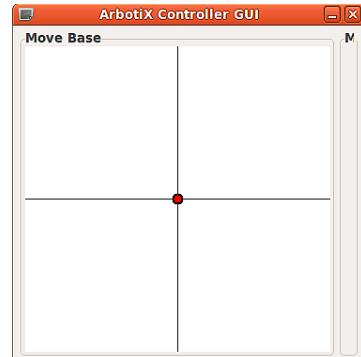
7.10.3 Using the ArbotiX Controller GUI

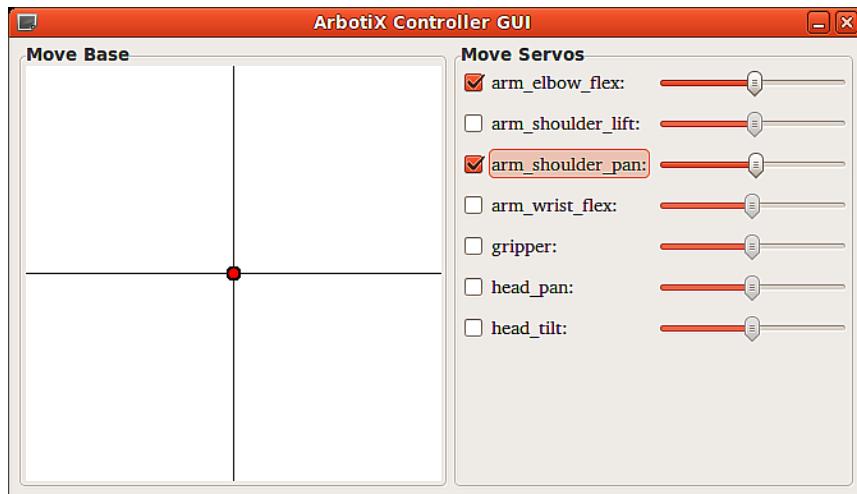
The `arbotix_python` package by Michael Ferguson includes a very nice graphical display for teleoperating a robot. You can bring up the interface with the following command:

```
$ rosrun arbotix_python controllerGUI.py
```

You should see a window appear that looks like the image on the right. To move your robot (either real or simulated), click and hold the red dot with your mouse. Then move the dot in the direction you want your robot to move. Take care not to move it too far as the robot's speed is controlled by the distance from the origin.

If you are using the Pi Robot simulator, you will also see controls for the arm joints as shown below:





To move one of the joints in the simulator, check the box beside the servo name, then use the slider.

7.10.4 TurtleBot Teleoperation Using Interactive Markers

The Turtlebot stack includes a very cool interactive markers package that allows you to move the real robot by dragging controls in RViz. Instructions on how to use it are provided on the [turtlebot_interactive_markers](#) tutorials Wiki page.

7.10.5 Writing your Own Teleop Node

For an example of how to write your own teleop node for a PS3 game controller, see the [tutorial on the ROS Wiki](#).

8. NAVIGATION, PATH PLANNING AND SLAM

Now that we have covered the basics of how to control a differential drive robot, we are ready to try one of the more powerful features in ROS; namely, Simultaneous Localization and Mapping or SLAM.

A SLAM-capable robot can build a map of an unknown environment while simultaneously locating itself in that map. Until recently, about the only way to do reliable SLAM was to use a fairly expensive laser scanner to collect the data. With the arrival of the Microsoft Kinect and Asus Xtion cameras, one can now do more affordable SLAM by using the 3D point cloud from the camera to generate a "fake" laser scan. (See the [kinect_2d_scanner](#) package for one way to do this.) The Willow Garage TurtleBot is configured to do this out of the box. If you own a TurtleBot, you might want to skip directly to the [TurtleBot SLAM tutorial](#) on the ROS Wiki.

Another affordable SLAM robot is the Neato XV-11 vacuum cleaner which includes a 360-degree laser scanner. In fact, you can run the complete Navigation Stack using the XV-11 thanks to the [neato_robot](#) ROS stack by Michael Ferguson.

In this chapter, we will cover the three essential ROS packages that make up the core of the Navigation Stack:

- [move_base](#) for moving the robot to a goal pose within a given reference frame
- [gmapping](#) for creating a map from laser scan data (or simulated laser data from a depth camera)
- [amcl](#) for localization using an existing map

When we are finished, we will be able to command the robot to go to any location or series of locations within the map, all while avoiding obstacles. Before going further, it is highly recommended that the reader check out the [Navigation Robot Setup](#) tutorial on the ROS Wiki. This tutorial provides an excellent overview of the ROS navigation stack. For an even better understanding, check out all of the [Navigation Tutorials](#). And for a superb introduction to the mathematics underlying SLAM, check out Sebastian Thrun's online [Artificial Intelligence](#) course on Udacity.

8.1 Path Planning and Obstacle Avoidance using `move_base`

In the previous chapter, we wrote a script to move the robot in a square. In that script, we monitored the `tf` transform between the `/odom` frame and the `/base_link` (or `/base_footprint`) frame to keep track of the distance traveled and the angles rotated.

ROS provides a much more elegant way to do the same thing using the [move_base](#) package. (Please see the [move_base](#) Wiki page for a full explanation including an excellent [diagram](#) of the various components of the package.)

The `move_base` package implements a [ROS action](#) for reaching a given navigation goal. You should be familiar with the basics of ROS actions from the [actionlib tutorials](#) on the ROS Wiki. Recall that actions provide feedback as progress is made toward the goal. This means we no longer have to query the odometry topic ourselves to find out if we have arrived at the desired location.

The `move_base` package incorporates the [base_local_planner](#) that combines odometry data with both global and local cost maps when selecting a path for the robot to follow. The global plan or path is computed before the robot starts moving toward the next destination and takes into account known obstacles or areas marked as "unknown". To actually move the robot, the local planner monitors incoming sensor data and chooses appropriate linear and angular velocities for the robot to traverse the current segment of the global path. How these local path segments are implemented over time is highly configurable as we shall see.

8.1.1 Specifying Navigation Goals Using move_base

To specify a navigation goal using `move_base`, we provide a target pose (position and orientation) of the robot with respect to a particular frame of reference. The `move_base` package uses the [MoveBaseActionGoal](#) message type for specifying the goal. To see the definition of this message type, run the command:

```
$ rosmsg show MoveBaseActionGoal
```

which should produce the following output:

```

Header header
  uint32 seq
  time stamp
  string frame_id
actionlib_msgs/GoalID goal_id
  time stamp
  string id
move_base_msgs/MoveBaseGoal goal
  geometry_msgs/PoseStamped target_pose
    Header header
      uint32 seq
      time stamp
      string frame_id
    geometry_msgs/Pose pose
      geometry_msgs/Point position
        float64 x
        float64 y
        float64 z
      geometry_msgs/Quaternion orientation
        float64 x
        float64 y
        float64 z
        float64 w

```

As you can see, the goal consists of a standard ROS header including a `frame_id`, a `goal_id`, and the goal itself which is given as a [PoseStamped](#) message. The `PoseStamped` message type in turn consists of a header and a `pose` which itself consists of a `position` and an `orientation`.

While the `MoveBaseActionGoal` message might seem a little complicated when written out in full, in practice we will only have to set a few of the fields when specifying `move_base` goals.

8.1.2 Configuration Parameters for Path Planning

The `move_base` node requires four configuration files before it can be run. These files define a number of parameters related to the cost of running into obstacles, the radius of the robot, how far into the future the path planner should look, how fast we want the robot to move and so on. The four configuration files can be found in the `config` subdirectory of the `rbx1_nav` package and are called:

- `base_local_planner_params.yaml`
- `costmap_common_params.yaml`
- `global_costmap_params.yaml`
- `local_costmap_params.yaml`

We will describe just a few of the parameters here; in particular, those that you will be most likely to tweak for your own robot. To learn about all of the parameters, please refer to the [Navigation Tutorial](#) on the ROS Wiki as well as the parameters section of the [costmap_2d](#) and [base_local_planner](#) Wiki pages.

8.1.2.1 `base_local_planner_params.yaml`

The values listed here are taken from `base_local_planner_params.yaml` in the `rbx1_nav/config/turtlebot` directory and have been found to work fairly well for the TurtleBot and Pi Robot. (Values that work well in the ArbotiX simulator can be found in the directory `rbx1_nav/config/fake`.)

- `controller_frequency: 3.0` – How many times per second should we update the planning process? Setting this value too high can overload a underpowered CPU. A value of 3 to 5 seems to work fairly well for a typical laptop.
- `max_vel_x: 0.2` – The maximum linear velocity of the robot in meters per second. A value of 0.5 is rather fast for an indoor robot so a value of 0.2 is chosen to be conservative.
- `min_vel_x: 0.05` – The minimum linear velocity of the robot.
- `max_vel_theta: 2.0` – The maximum rotational velocity of the robot in radians per second. Don't set this too high or the robot will overshoot its goal orientation.
- `min_vel_theta: 0.5` – The minimum rotational velocity of the robot in radians per second.
- `min_in_place_vel_theta: 0.5` – The minimum in-place rotational velocity of the robot in radians per second. Setting this value too low for a real robot can cause it to get bogged down on high friction surfaces like carpet.
- `acc_lim_x: 0.5` – The maximum linear acceleration in the x direction.
- `acc_lim_y: 0.5` – The maximum linear acceleration in the y direction.
- `acc_lim_theta: 1.0` – The maximum angular acceleration.
- `holonomic_robot: false` – Unless you have an omni-directional drive robot, this is always set to false.
- `xy_goal_tolerance: 0.1` – How close (in meters) do we have to get to the goal? If you set the tolerance too small, your robot may try endlessly to make

small adjustments around the goal location. **NOTE:** Do not set the tolerance less than the resolution of your map (described in a later section) or your robot will end up spinning in place indefinitely without reaching the goal.

- `yaw_goal_tolerance`: 0.2 – How close to the goal orientation (in radians) do we have to get? Setting this value to small may cause the robot to oscillate near the goal.
- `gdist_scale`: 0.6 – The relative importance of getting to the goal rather than sticking to the global path. Set this parameter larger than the `pdist_scale` to favor getting to the goal by whatever path necessary.
- `pdist_scale`: 0.8 – The relative importance of sticking to the global path as opposed to getting to the goal. Set this parameter larger than the `gdist_scale` to favor following the global path.
- `sim_time`: 2.5 – How many seconds into the future should the planner look? This parameter together with the next (`dwa`) can greatly affect the path taken by your robot toward a goal.
- `dwa`: `true` – Whether or not to use the Dynamic Window Approach when simulating trajectories into the future. See the [Base Local Planner Overview](#) for more details.

8.1.2.2 `costmap_common_params.yaml`

There are only two parameters in this file that you might have to tweak right away for your own robot:

- `robot_radius`: 0.15 – The radius of your robot in meters. For a non-circular robot, you can use the `footprint` parameter instead as shown next.
- `footprint`: `[[x0, y0], [x1, y1], [x2, y2], [x3, y3], etc]` – Each coordinate pair in the list represents a point on the boundary of the robot with the robot's center assumed to be at [0, 0]. The measurement units are meters.
- `inflation_radius`: 0.5 – The radius in meters that obstacles will be inflated in the map. If your robot is having trouble passing through narrow doorways or other tight spaces, trying reducing this value slightly.

8.1.2.3 `global_costmap_params.yaml`

There are two parameters in this file that you might experiment with depending on the power of the computer you are using for your robot:

- `update_frequency`: 1.0 – The frequency in Hz of how often the global map is updated with sensor information. The higher this number, the greater the load on your computer's CPU. Especially for the global map, one can generally get away with a relatively small value of between 1.0 and 5.0.
- `publish_frequency`: 0 – For a static global map, there is generally no need to continually publish it.

8.1.2.4 `local_costmap_params.yaml`

There are a few more parameters to be considered for the local cost map:

- `update_frequency`: 5.0 – How frequently (times per second) do we update the local map based on sensor data. For a really slow computer, you may have to reduce this value.
- `publish_frequency`: 1.0 – We definitely want updates to the local map published so we set a non-zero value here.
- `static_map`: `false` – This parameter and the next are always set to opposite values. The local map is dynamically updated with sensor data so we set `static_map` to `false`.
- `rolling_window`: `true` – The local map is updated within a rolling window defined by the next few parameters.
- `width`: 5.0 – The x dimension in meters of the rolling map.
- `height`: 5.0 – The y dimension in meters of the rolling map.
- `resolution`: 0.05 – The resolution in meters of the rolling map. This should match the resolution set in the YAML file for your map (explained in a later section).
- `transform_tolerance`: 1.0 – Sensor data must arrive within this tolerance (in seconds) or the mapping process will temporarily abort. On a fast computer connected directly to the robot, a value 1.0 should work OK. But on slower computers and especially over wireless connections, the tolerance may have to be increased. The tell-tale warning message you will see when the tolerance is set too low will look like the following:

```
[ WARN] [1339438850.439571557]: Costmap2DROS transform
timeout. Current time: 1339438850.4395, global_pose stamp:
1339438850.3107, tolerance: 0.0001
```

If you are running the `move_base` node on a computer other than the robot's computer, the above warning can also indicate that the clocks on the two machines are out of sync. Recall from the earlier section on Networking that you can use the `ntpdate` command to synchronize the two clocks. Refer back to that section for details or review the [Network Setup](#) pages on the ROS Wiki.

8.2 Testing `move_base` in the ArbotiX Simulator

The `move_base` node requires a map of the environment but the map can simply be blank if we just want to test the `move_base` action interface. We will learn how to create and use real maps in a later section. The `rbx1_nav` package includes a blank map called `blank_map.pgm` in the `maps` subdirectory and its corresponding description file is `blank_map.yaml`. The launch file for bringing up the `move_base` node and the blank map is called `fake_move_base_blank_map.launch` in the `launch` subdirectory. Let's take a look at it now:

```
<launch>
  <!-- Run the map server with a blank map -->
  <node name="map_server" pkg="map_server" type="map_server" args="$(find
rbx1_nav)/maps/blank_map.yaml"/>

  <!-- Launch move_base and load all navigation parameters -->
  <include file="$(find rbx1_nav)/launch/fake_move_base.launch" />

  <!-- Run a static transform between /odom and /map -->
  <node pkg="tf" type="static_transform_publisher" name="odom_map_broadcaster"
args="0 0 0 0 0 0 /odom /map 100" />
</launch>
```

The comments in the launch file help us understand what is going on. First we run the ROS `map_server` node with the blank map. Note how the map is specified in terms of its `.yaml` file which describes the size and resolution of the map itself. Then we include the `fake_move_base.launch` file (also in the `launch` subdirectory) which runs the `move_base` node and loads all the required configuration parameters that work well in the fake simulator. Let's take a look at the `fake_move_base.launch` file now:

```
<launch>

  <node pkg="move_base" type="move_base" respawn="false" name="move_base"
output="screen">
    <rosparam file="$(find rbx1_nav)/config/fake/costmap_common_params.yaml"
command="load" ns="global_costmap" />
    <rosparam file="$(find rbx1_nav)/config/fake/costmap_common_params.yaml"
command="load" ns="local_costmap" />
    <rosparam file="$(find rbx1_nav)/config/fake/local_costmap_params.yaml"
command="load" />
    <rosparam file="$(find rbx1_nav)/config/fake/global_costmap_params.yaml"
command="load" />
```

```

<rosparam file="$(find rbx1_nav)/config/fake/base_local_planner_params.yaml"
command="load" />
</node>

</launch>

```

The launch file runs the `move_base` node together with five calls to `rosparam` to load the parameter files we described earlier. The reason that we load the `costmap_common_params.yaml` file twice is to set those common parameters in both the `global_costmap` namespace and the `local_costmap` namespace. This is accomplished using the appropriate "ns" attribute in each line.

Since we are using a blank map and our simulated robot has no sensors, the robot cannot use scan data for localization. Instead, we simply set a static identity transform to tie the robot's odometry frame to the map frame which essentially assumes that the odometry is perfect.

If you're not already running the ArbotiX simulator, fire it up now:

```
$ rosrun arbotiX bringup fake_turtlebot.launch
```

(Replace with your favorite fake robot.)

To launch the `move_base` node together with the blank map, run the command:

```
$ rosrun rbx1_nav fake_move_base_blank_map.launch
```

You should see a series of messages similar to:

```

process[map_server-1]: started with pid [13264]
process[move_base-2]: started with pid [13265]
process[odom_map_broadcaster-3]: started with pid [13266]
[ INFO] [1338905635.769589879]: Subscribed to Topics: scan
[ INFO] [1338905635.787684145]: Requesting the map...
[ INFO] [1338905635.789905777]: Still waiting on map...
[ INFO] [1338905636.791806213]: Still waiting on map...
[ INFO] [1338905637.797366325]: Received a 600 X 600 map at 0.010000
m/pix
[ INFO] [1338905637.968983191]: MAP SIZE: 600, 600
[ INFO] [1338905637.975645399]: Subscribed to Topics: scan
[ INFO] [1338905638.189242664]: Sim period is set to 0.2

```

If you're not already running `RViz`, bring it up now with the included navigation config file:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/nav_fuerte.vcg
```

We are now ready to control the motion of our robot using `move_base` actions rather than simple `Twist` messages. To test it out, let's move the robot 1.0 meters directly forward. Since our robot is starting off at coordinates (0, 0, 0) in the `/map` frame, we could use either the `/map` frame or the `/base_link` frame to specify the movement. Let's try it with the `/base_link` frame. Referring to the `move_base` goal message syntax listed earlier, the command we want is:

```
$ rostopic pub /move_base_simple/goal geometry_msgs/PoseStamped \
'{ header: { frame_id: "base_link" }, pose: { position: { x: 1.0, y: 0, z: 0 }, orientation: { x: 0, y: 0, z: 0, w: 1 } } }'
```

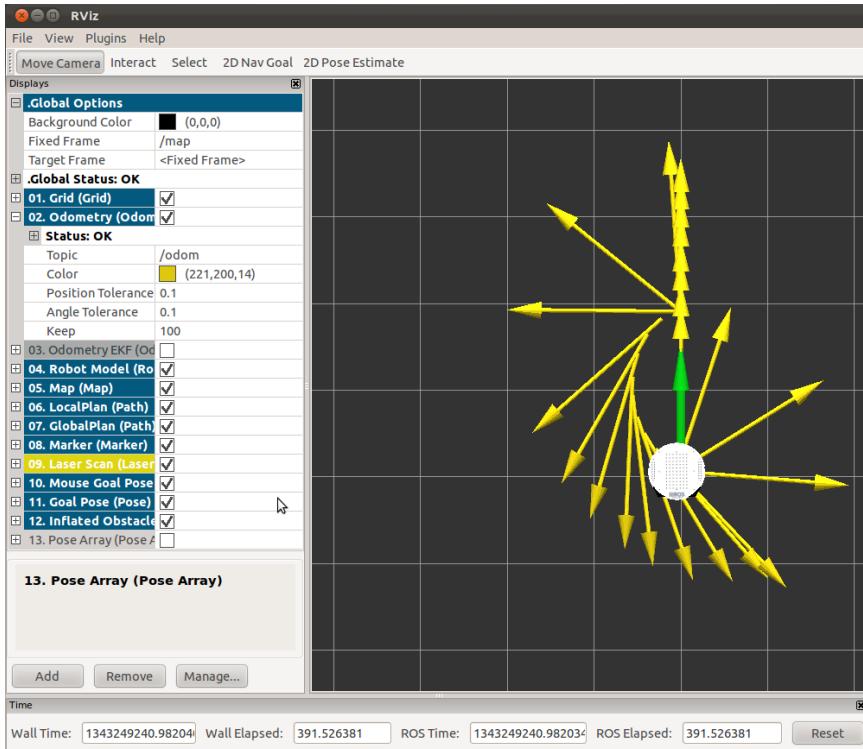
You should see the robot move about 1 meter forward in `RViz`. (The large green arrow that appears is the target pose.) Note that the orientation in the command above is specified as a quaternion and a quaternion with components (0, 0, 0, 1) specifies an identity rotation.

To move the robot back to the starting point, first type `Ctrl-C` to end the previous command. Then switch to the `/map` frame and send the coordinates (0, 0, 0):

```
$ rostopic pub /move_base_simple/goal geometry_msgs/PoseStamped \
'{ header: { frame_id: "map" }, pose: { position: { x: 0, y: 0, z: 0 }, orientation: { x: 0, y: 0, z: 0, w: 1 } } }'
```

Note that in this case we don't really want to use the `/base_link` frame. The reason is that for a real robot, the first movement would not be perfect so the robot would not be exactly at position (1, 0, 0) and it would not be facing exactly "upward" in `RViz`. So if we executed the second motion relative to the `/base_link` frame without knowing how far off we are from the ideal starting location, we will only compound the error.

The view in `RViz` after both commands should look something like the following:



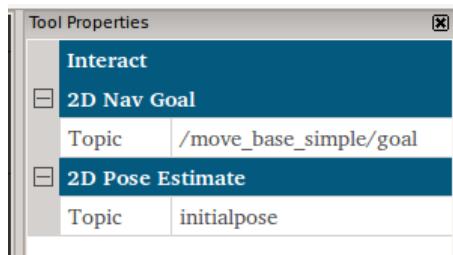
As the robot moves, the thin blue line (which might be difficult to see if it overlaps a grid line) is the global path planned for the robot from the starting position to the goal. The shorter red line is the locally planned trajectory that gets updated more often as the robot makes progress toward the destination.

You will notice that the local trajectory in this case follows an arc that is fairly far off the straight line global path. This is due partly to the fact that there are no obstacles in the map, so the planner selects a nice smooth turning trajectory. It also reflects our default choice of the two parameters `gdist_scale` (0.6) and `pdist_scale` (0.8) which puts roughly equal weight on following the path and simply getting to the goal in whatever way the local planner chooses. To make the robot follow the global path more closely, bring up `dynamic_reconfigure` and try setting the `pdist_scale` parameter to something like 2.5. Then clear the Odometry arrows by clicking the **Reset** button in `RViz` and run the two `move_base` commands again to see the effect.

The display of the global and local paths can be turned off and on using the check boxes beside the appropriate displays in the **Displays** panel on the left in `RViz`. You can also change the colors of the paths using the appropriate property value for each display. We will say a little more about these display after the next section.

8.2.1 Point and Click Navigation in RViz

We can also specify a goal pose using the mouse in `RViz`. If you launched `RViz` with the `nav_fuerte.vcg` file as described above, you should be good to go. However, just to check, if you don't see the **Tool Properties** window on the right side of the `RViz` screen, click on the **Panels** menu and select **Tool Properties**. Under the **2D Nav Goal** category, the topic should be listed as `/move_base_simple/goal`. If not, type that topic name into the field now. The end result should look like this:



If you had to make any changes, click on the **File** menu and choose **Save Config**. Select the "`nav_fuerte.vcg`" file in the `rbx1_nav` directory and overwrite it when prompted. When you are finished, you can close the **Tool Properties** window by clicking the little x in the upper right corner.

With these preliminaries out of the way, we can now use the mouse to move the robot. First, click on the **2D Nav Goal** button near the top of the `RViz` screen. Then click and hold the mouse somewhere on the grid where you'd like the robot to end up. If you move the mouse slightly while holding down the button, a green arrow will appear. Rotate the arrow to indicate the goal orientation of the robot. Now release the mouse button and `move_base` should guide the robot to the goal. Try setting a few different goals and observe the changes in the global and local paths.

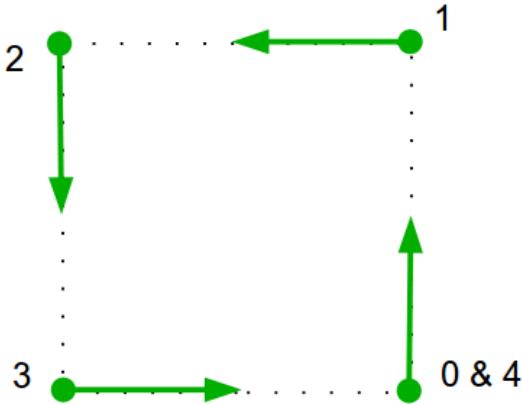
8.2.2 Navigation Display Types for RViz

As you can see from the earlier `RViz` screen shot, the `nav_fuerte.vcg` config file we used includes a number of display types typically used for navigation. In addition to the **Odometry** and **Robot Model** displays, we also have one for the **Map**, the **Local** and **Global Plan**, a **Laser Scan**, **Inflated Obstacle** cells, the **Goal Pose** (including one for goals set using the mouse) and one for **Markers**. (We will talk about the **Pose Array** later on when we discuss localization.)

For a complete list of display types used with ROS navigation see the tutorial on the ROS Wiki called [Using rviz with the Navigation Stack](#). The tutorial includes an excellent demonstration video which is a must-see if you are new to either `RViz` or ROS navigation.

8.2.3 Navigating a Square using `move_base`

We are now ready to move our robot in a square using `move_base` rather than simple `Twist` messages. The script `move_base_square.py` in the `nodes` subdirectory does the work. The script simply cycles through four target poses, one for each corner of the square. The four target poses are shown by the arrows in the figure below:



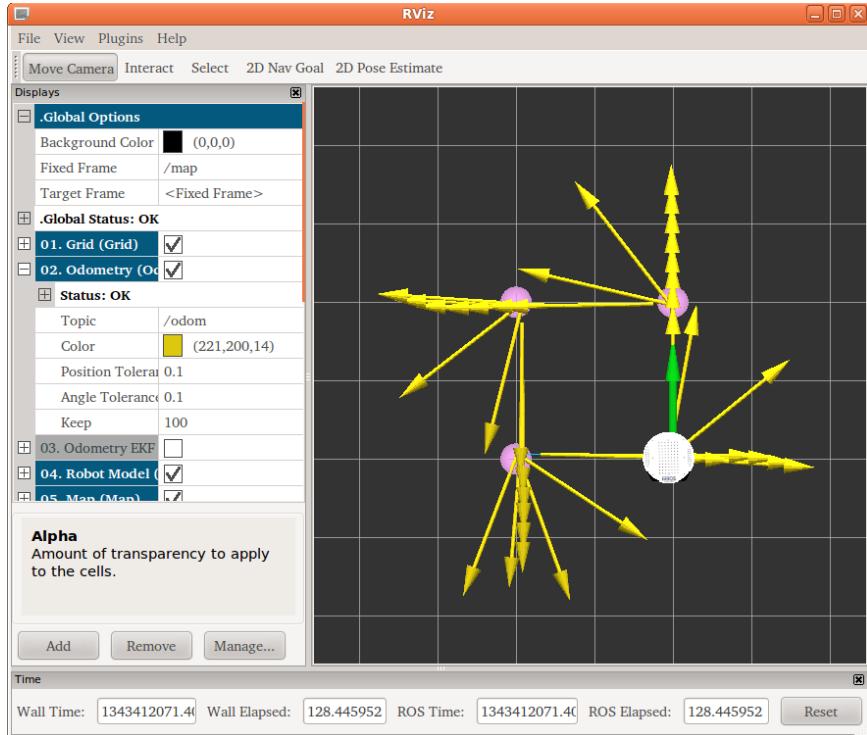
Remember that a "pose" in ROS means both a position and orientation. So the numbered arrows above indicate where we want the robot to go and the direction we want it to face when it gets there. Before trying out the script, move the robot back to the starting position with the command:

```
$ rostopic pub /move_base_simple/goal geometry_msgs/PoseStamped \
  '{ header: { frame_id: "map" }, pose: { position: { x: 0, y: 0, z: 0 }, orientation: { x: 0, y: 0, z: 0, w: 1 } } }'
```

When the robot is re-positioned, type `Ctrl-C`, clear the Odometry arrows by clicking the **Reset** button in `RViz`, then run the `move_base_square.py` script:

```
$ rosrun rbx1_nav move_base_square.py
```

When the scripts completes, the view in `RViz` should look something like the following:



The small discs indicate the locations of the four corner points we want to hit. (The first disc is hidden beneath the robot in the picture above.) As you can see, the square trajectory is not bad even though all we specified were the four corner poses. One could refine the trajectory even further by tweaking the configuration parameters for the base local planner, or setting intermediate waypoints between the corners. But the real purpose of `move_base` is not to follow a precise path, but to reach arbitrary goal locations while avoiding obstacles. Consequently, it works very well for getting a robot around the house or office without running into things as we shall see in the next section.

Let's now take a look at the code.

Link to SVN source: [move_base_square.py](#)

```

1. #!/usr/bin/env python
2. import roslib; roslib.load_manifest('rbxl_nav')
3. import rospy
4. import actionlib
5. from actionlib_msgs.msg import *
6. from geometry_msgs.msg import Pose, Point, Quaternion, Twist
7. from move_base_msgs.msg import MoveBaseAction, MoveBaseGoal
8. from tf.transformations import quaternion_from_euler
9. from visualization_msgs.msg import Marker

```

```

10.     from math import radians, pi
11.
12.     class MoveBaseSquare():
13.         def __init__(self):
14.             rospy.init_node('nav_test', anonymous=False)
15.
16.             rospy.on_shutdown(self.shutdown)
17.
18.             # How big is the square we want the robot to navigate?
19.             square_size = rospy.get_param("~square_size", 1.0) # meters
20.
21.             # Create a list to hold the target quaternions (orientations)
22.             quaternions = list()
23.
24.             # First define the corner orientations as Euler angles
25.             euler_angles = (pi/2, pi, 3*pi/2, 0)
26.
27.             # Then convert the angles to quaternions
28.             for angle in euler_angles:
29.                 q_angle = quaternion_from_euler(0, 0, angle, axes='sxyz')
30.                 q = Quaternion(*q_angle)
31.                 quaternions.append(q)
32.
33.             # Create a list to hold the waypoint poses
34.             waypoints = list()
35.
36.             # Append each of the four waypoints to the list. Each waypoint
37.             # is a pose consisting of a position and orientation in the map
38.             # frame.
39.             waypoints.append(Pose(Point(square_size, 0.0, 0.0),
40.             quaternions[0]))
41.             waypoints.append(Pose(Point(square_size, square_size, 0.0),
42.             quaternions[1]))
43.             waypoints.append(Pose(Point(0.0, square_size, 0.0),
44.             quaternions[2]))
45.             waypoints.append(Pose(Point(0.0, 0.0, 0.0), quaternions[3]))
46.
47.             # Initialize the visualization markers for RViz
48.             self.init_markers()
49.
50.             # Set a visualization marker at each waypoint
51.             for waypoint in waypoints:
52.                 p = Point()
53.                 p = waypoint.position
54.                 self.markers.points.append(p)
55.
56.             # Publisher to manually control the robot (e.g. to stop it)
57.             self.cmd_vel_pub = rospy.Publisher('cmd_vel', Twist)
58.
59.             # Subscribe to the move_base action server
60.             self.move_base = actionlib.SimpleActionClient("move_base",
61.             MoveBaseAction)
62.
63.             rospy.loginfo("Waiting for move_base action server...")
64.
65.             # Wait 60 seconds for the action server to become available
66.             self.move_base.wait_for_server(rospy.Duration(60))

```

```

62.         rospy.loginfo("Connected to move base server")
63.         rospy.loginfo("Starting navigation test")
64.
65.         # Initialize a counter to track waypoints
66.         i = 0
67.
68.         # Cycle through the four waypoints
69.         while i < 4 and not rospy.is_shutdown():
70.             # Update the marker display
71.             self.marker_pub.publish(self.markers)
72.
73.             # Intialize the waypoint goal
74.             goal = MoveBaseGoal()
75.
76.             # Use the map frame to define goal poses
77.             goal.target_pose.header.frame_id = 'map'
78.
79.             # Set the time stamp to "now"
80.             goal.target_pose.header.stamp = rospy.Time.now()
81.
82.             # Set the goal pose to the i-th waypoint
83.             goal.target_pose.pose = waypoints[i]
84.
85.             # Start the robot moving toward the goal
86.             self.move(goal)
87.
88.             i += 1
89.
90.     def move(self, goal):
91.         # Send the goal pose to the MoveBaseAction server
92.         self.move_base.send_goal(goal)
93.
94.
95.         # Allow 1 minute to get there
96.         finished_within_time =
97.         self.move_base.wait_for_result(rospy.Duration(60))
98.
99.         # If we don't get there in time, abort the goal
100.        if not finished_within_time:
101.            self.move_base.cancel_goal()
102.            rospy.loginfo("Timed out achieving goal")
103.        else:
104.            # We made it!
105.            state = self.move_base.get_state()
106.            if state == GoalStatus.SUCCEEDED:
107.                rospy.loginfo("Goal succeeded!")
108.
109.    def init_markers(self):
110.        # Set up our waypoint markers
111.        marker_scale = 0.15
112.        marker_lifetime = 0 # 0 is forever
113.        marker_ns = 'waypoints'
114.        marker_id = 0
115.        marker_color = {'r': 1.0, 'g': 0.0, 'b': 0.0, 'a': 1.0}
116.
117.        # Define a marker publisher.
118.        self.marker_pub = rospy.Publisher('waypoint_markers', Marker)

```

```

118.         # Initialize the marker points list.
119.         self.markers = Marker()
120.         self.markers.ns = marker_ns
121.         self.markers.id = marker_id
122.         self.markers.type = Marker.SPHERE_LIST
123.         self.markers.action = Marker.ADD
124.         self.markers.lifetime = rospy.Duration(marker_lifetime)
125.         self.markers.scale.x = marker_scale
126.         self.markers.scale.y = marker_scale
127.         self.markers.color.r = marker_color['r']
128.         self.markers.color.g = marker_color['g']
129.         self.markers.color.b = marker_color['b']
130.         self.markers.color.a = marker_color['a']
131.
132.         self.markers.header.frame_id = 'map'
133.         self.markers.header.stamp = rospy.Time.now()
134.         self.markers.points = list()
135.
136.
137.     def shutdown(self):
138.         rospy.loginfo("Stopping the robot...")
139.         # Cancel any active goals
140.         self.move_base.cancel_goal()
141.         rospy.sleep(2)
142.         # Stop the robot
143.         self.cmd_vel_pub.publish(Twist())
144.         rospy.sleep(1)
145.
146.     if __name__ == '__main__':
147.         try:
148.             MoveBaseSquare()
149.         except rospy.ROSInterruptException:
150.             rospy.loginfo("Navigation test finished.")

```

Let's now examine the key lines of the script.

```

24.         # First define the corner orientations as Euler angles
25.         euler_angles = (pi/2, pi, 3*pi/2, 0)
26.
27.         # Then convert the angles to quaternions
28.         for angle in euler_angles:
29.             q_angle = quaternion_from_euler(0, 0, angle, axes='sxyz')
30.             q = Quaternion(*q_angle)
31.             quaternions.append(q)

```

Here we define the target orientations at the four corners of the square, first as Euler angles which are easier to visualize on the map, and then converted to quaternions.

```

38.         waypoints.append(Pose(Point(square_size, 0.0, 0.0),
39.                               quaternions[0]))
40.         waypoints.append(Pose(Point(square_size, square_size, 0.0),
41.                               quaternions[1]))
40.         waypoints.append(Pose(Point(0.0, square_size, 0.0),
41.                               quaternions[2]))
41.         waypoints.append(Pose(Point(0.0, 0.0, 0.0), quaternions[3]))

```

Next we create the four waypoint poses by combining the rotations with the coordinates of the four corners.

```
43.      # Initialize the visualization markers for RViz
44.      self.init_markers()
45.
46.      # Set a visualization marker at each waypoint
47.      for waypoint in waypoints:
48.          p = Point()
49.          p = waypoint.position
50.          self.markers.points.append(p)
```

While not covered in this volume, setting visualization markers in `RViz` is fairly straightforward and a number of existing tutorials can be [found here](#). The script places a red disc at each target corner and the function `self.init_markers()`, defined toward the end of the script, sets up the marker shapes, sizes and colors. We then append the four markers to a list to be used later.

```
56.      self.move_base = actionlib.SimpleActionClient("move_base",
MoveBaseAction)
```

Here we define a `SimpleActionClient` which will send goals to the `move_base` action server.

```
61.      self.move_base.wait_for_server(rospy.Duration(60))
```

Before we can start sending goals, we have to wait for the `move_base` action server to become available. We give it 60 seconds before timing out.

```
69.      # Cycle through each waypoint
70.      while i < 4 and not rospy.is_shutdown():
71.          # Update the marker display
72.          self.marker_pub.publish(self.markers)
73.
74.          # Initialize the waypoint goal
75.          goal = MoveBaseGoal()
76.
77.          # Use the map frame to define goal poses
78.          goal.target_pose.header.frame_id = 'map'
79.
80.          # Set the time stamp to "now"
81.          goal.target_pose.header.stamp = rospy.Time.now()
82.
83.          # Set the goal pose to the i-th waypoint
84.          goal.target_pose.pose = waypoints[i]
85.
86.          # Start the robot moving toward the goal
87.          self.move(goal)
88.
89.          i += 1
```

We then enter our main loop, cycling through each of the four waypoints. First we publish the markers to indicate the four goal poses. (This has to be done on each cycle to keep them visible throughout the movement.) Then we initialize the `goal` variable as a `MoveBaseGoal` action type. Next we set the goal `frame_id` to the `map` frame and the time stamp to the current time. Finally, we set the goal pose to the current waypoint and send the goal to the `move_base` action server using the helper function `move()`, which we describe next.

```
91.     def move(self, goal):
92.         # Send the goal pose to the MoveBaseAction server
93.         self.move_base.send_goal(goal)
94.
95.         # Allow 1 minute to get there
96.         finished_within_time =
97.             self.move_base.wait_for_result(rospy.Duration(60))
98.
99.         if not finished_within_time:
100.             self.move_base.cancel_goal()
101.             rospy.loginfo("Timed out achieving goal")
102.         else:
103.             # We made it!
104.             state = self.move_base.get_state()
105.             if state == GoalStatus.SUCCEEDED:
106.                 rospy.loginfo("Goal succeeded!")
```

The `move()` helper function takes a goal as input, sends it to the `MoveBaseAction` server, then waits up to 60 seconds for the robot to get there. A success or failure message is then displayed on the screen. Note how much easier this approach is to code than our earlier `nav_square.py` script that used `Twist` messages directly. In particular, we no longer have to monitor the odometry data directly. Instead the `move_base` action server takes care of it for us.

8.2.4 Avoiding Simulated Obstacles

One of the more powerful features of `move_base` is the ability to avoid obstacles while still getting to the goal. Obstacles can be a static part of the current map (such as a wall) or they can appear dynamically such as when someone walks in front of the robot. The base local planner can recompute the robot's path on the fly to keep the robot from striking objects yet still allowing it to reach its destination.

To illustrate the process, the following launch file will load a blank map with a pair of obstacles in the way of the robot. We will then run the `move_base_square.py` script again to see if the base local planner can find a path around the obstacles and still guide the robot to the four goal locations.

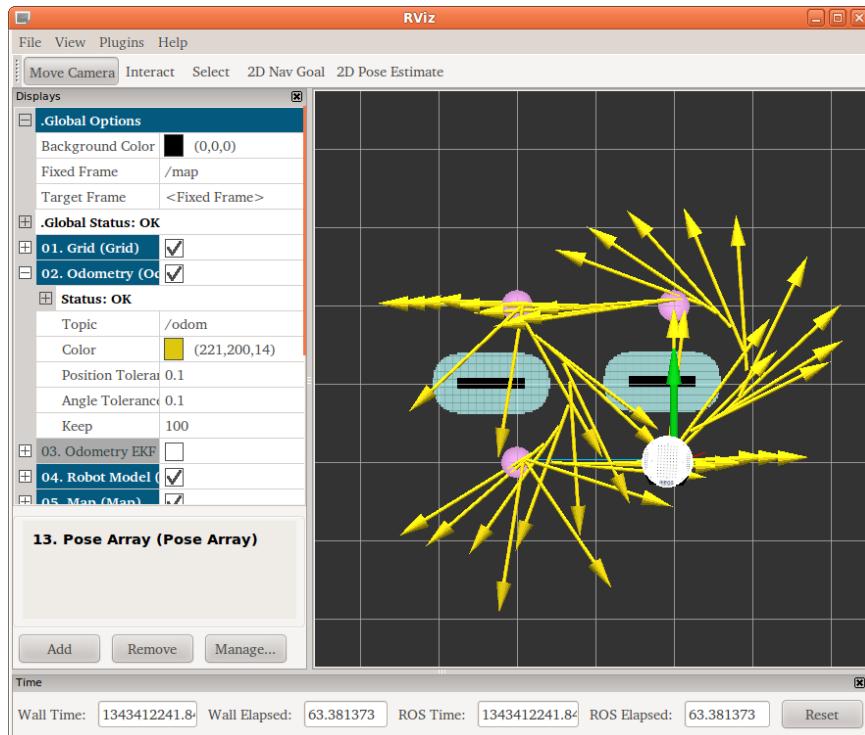
First terminate the earlier `fake_move_base_blank_map.launch` file by typing `Ctrl-C` in the appropriate terminal window. Then run the following command:

```
$ roslaunch rbx1_nav fake_move_base_obstacle.launch
```

When the `move_base` node is up and you see the obstacles in `RViz`, set the **Odometry Angle Tolerance** to 0.05. This will produce a better image for this particular test. Click the **Reset** button in `RViz` to clear the display, then run the `move_base_square.py` script:

```
$ rosrun rbx1_nav move_base_square.py
```

When the script completes, the view in `RViz` should look something like this:



The obstacles are represented by the horizontal black bars while the lighter oval-shaped regions around the obstacles reflect the inflation radius we have set to provide a safety buffer. As you can see, the simulated robot has no difficulty getting to the goal locations while avoiding the obstacles. Even better, on the way to the third corner of the square (lower left), the base local planner chose the shorter route between the two obstacles rather than going around the outside.

During the simulation you will notice a thin blue line that indicates the global path planned for the next goal location. The shorter red line that appears to shoot out in front

of the robot is the local path which can adapt more quickly to local conditions. Since we aren't simulating any sensors, the robot is actually running blind and is relying only on the static map and its (fake) odometry.

You can play with all of the path planner parameters in real time using `dynamic_reconfigure`. For example, to see how important the `dwa` parameter is (Dynamic Window Approach) bring up `dynamic_reconfigure`, choose the `/move_base/TrajectoryPlannerROS` node, then un-check the checkbox beside `dwa` (it's near the bottom of the window). Click the **Reset** button in `RViz` to clear any markers, then run the `move_base_square.py` script again. This time the robot has a much harder time getting around the obstacles.

8.2.5 Setting Manual Goals with Obstacles Present

You can also use the mouse as we have done before to set navigation goals when obstacles are present. As before, first click on the **2D Nav Goal** button near the top of the `RViz` window, then click somewhere on the map. If you try setting a goal inside one of the obstacles or even too close to one, the base local planner will abort any attempt to get there. As usual, any time you want to clear the markers on the screen, just click the **Reset** button.

8.3 Running `move_base` on a Real Robot

If you have a ROS-compatible robot with a mobile base, you can try out the `move_base_square.py` script in the real world. If you are using a TurtleBot, you can probably get away with the `move_base` configuration included in the `rbx1_nav/config/turtlebot` directory. Otherwise, you might have to change a few parameters to better match your robot. For a good introduction on tuning the navigation parameters, see the [Navigation Tuning Guide](#) on the ROS Wiki.

8.3.1 Testing `move_base` without Obstacles

To make sure we are running with a clean slate, `Ctrl-C` out of any running ROS launch files or nodes including `roscore`. Then start up `roscore` again and get your robot ready.

Make sure your robot has enough room to trace out the square (you can shorten the sides in the script if you like). When you are ready, fire up the required launch file(s) to connect to your robot. For a TurtleBot you would run:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

(Or use your own launch file if you have created one to store your calibration parameters.)

If you are using a TurtleBot, we also need to run the `odom_ekf.py` script to be able to see the TurtleBot's combined odometry frame in `RViz`. You can skip this if you are not using a TurtleBot. The launch file should be run on the TurtleBot's laptop:

```
$ roslaunch rbx1_bringup odom_ekf.launch
```

Next, launch the `move_base` node with a blank map. **NOTE:** This is a different launch file than the one we used for the simulated robot. This particular launch file loads a set of navigation parameters that should work fairly well with the TurtleBot.

```
$ roslaunch rbx1_nav tb_move_base_blank_map.launch
```

Now bring up `RViz` on your workstation with the `nav_ekf` config file. You'll probably want to run this on your desktop machine rather than the TurtleBot's laptop:

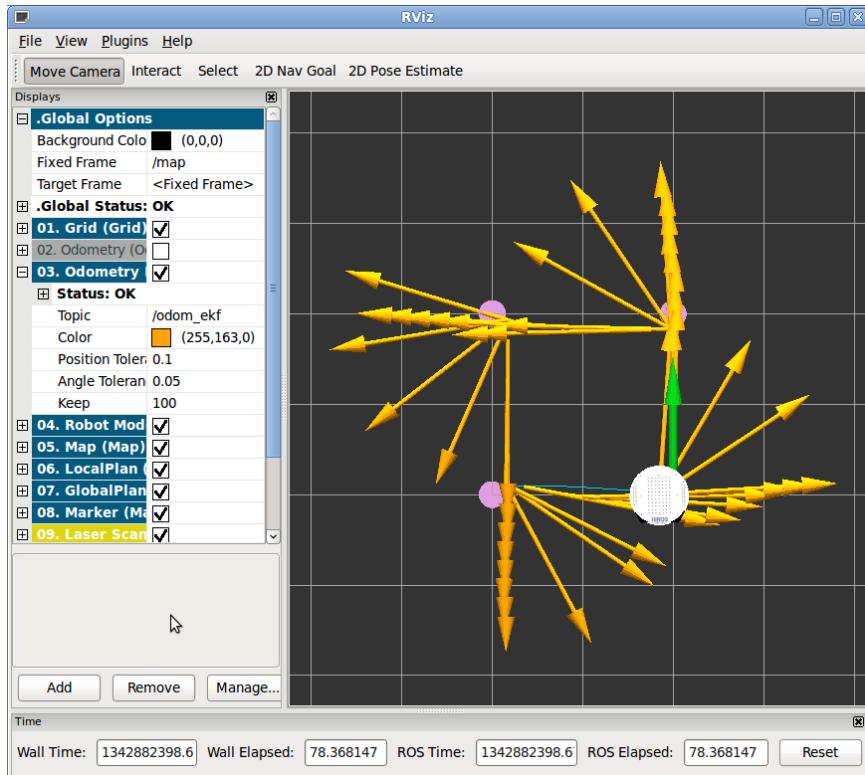
```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/nav_ekf_fuerte.vcg
```

Finally, run the `move_base_square.py` script. You can run this either on the robot's laptop or your desktop:

```
$ rosrun rbx1_nav move_base_square.py
```

If all goes well, your robot should move from one corner of the square to the next and then stop when it has come back to the start.

The following image shows the result when running my own TurtleBot on a low-ply carpet:



In the real world, the robot came within 18 cm of the starting position and approximately 5 degrees out of alignment.

8.3.2 Avoiding Obstacles using the TurtleBot's Fake Laser Scan

Our final test will use the TurtleBot's fake laser scan to detect obstacles so that `move_base` can plan a path around them while guiding the robot to a goal. If you look at the parameter file `costmap_common_params.yaml` in the `rbx1_nav/config/turtlebot` directory, you'll see the following pair of lines:

```
observation_sources: scan
scan: {data_type: LaserScan, topic: /scan, marking: true, clearing: true}
```

The first line tells the base local planner to expect sensor data from a source called "scan" and the second line indicates that the "scan" source is of type `LaserScan` and it publishes its data on the `/scan` topic. Setting the flags `marking` and `clearing` to `True` means that the laser data can be used to mark areas of the local cost map as occupied or free as the robot moves about.

If you have all the launch files running from the previous test, all we need to add is the TurtleBot's fake laser scan. Make sure your Kinect or Xtion is plugged into a USB port on the robot, then log into the TurtleBot's laptop and run:

```
$ roslaunch rbx1_bringup kinect_fuerte.launch
```

Back in `RViz`, and assuming there is at least one object within the camera's range, you should see the laser scan appear in the image. The config file we are using for `RViz` (`nav_ekf_fuerte.vcg`) includes a **Laser Scan** display which is set to the `/scan` topic by default. You can verify this by scrolling down the **Displays** panel on the left of `RViz`. The light blue areas around the laser scan reflect the inflation radius parameter we have set in the `common_costmap_params.yaml` file to provide a safety buffer around obstacles.

So now we are ready to test how well the robot can avoid obstacles on the way to a goal. Pick a point a few meters away from the robot and set the target pose in `RViz` using the mouse in as we have done previously. As the robot makes its way toward the goal, walk into its path a few feet ahead of it. As soon as you enter the view of the (fake) laser scan, the robot should veer to go around you, then continue on to the goal location.

Depending on the speed of your robot's computer, you may notice that the robot comes fairly close to your feet even with the inflation radius set to 0.5. There are two possible reasons for this. The first is the narrow field of view of the Kinect or Xtion cameras—about 57 degrees. As the robot begins moving past an obstacle, the object quickly passes out of the field of view, so the path planner figures it can start turning back toward the goal. Second, both RGB-D cameras are blind to depths within about 50cm (approx 2 feet) of the projector. This means it is possible for an obstacle to be completely invisible even if it is situated directly in front of the robot. A real laser scanner like a Hokuyo or the one found on the Neato XV-11 has a much wider field of view (240 – 360 degrees) and can sense objects as close as a few centimeters.

8.4 Map Building using the `gmapping` Package

Now that we understand how to use `move_base`, we can replace the blank map with a real map of the robot's environment. A map in ROS is simply a bitmap image representing an occupancy grid where white pixels indicate free space, black pixels represent obstacles, and grey pixels stand for "unknown". You can therefore draw a map yourself in any graphics program or use a map that someone else has created. However, if your robot is equipped with a laser scanner or depth camera, the robot can create its own map as it moves around the target area. If your robot has neither of these pieces of hardware, you can use the test map included in `rbx1_nav/maps`. In this case, you might want to skip directly to the next chapter on doing localization using an existing map.

The ROS [gmapping](#) package contains the `slam_gmapping` node that does the work of combining the data from laser scans and odometry into an occupancy map. The usual strategy is first to teleoperate the robot around an area while recording the laser and odometry data in a [rosbag](#) file. Then we run the `slam_gmapping` node against the recorded data to generate a map. The advantage of recording the data first is that you can generate any number of test maps later using the same data but with different parameters for `gmapping`. In fact, since we no longer need the robot at that point, you could do this testing anywhere you have a computer with ROS and your rosbag data.

Lets take each of these steps in turn.

8.4.1 Laser Scanner or Depth Camera?

To use the `gmapping` package, our robot needs either a laser scanner or a depth camera like the Kinect or Xtion.

If you have a laser scanner, you will need the ROS laser drivers which you can install using:

```
$ sudo apt-get install ros-fuerte-laser-drivers
```

In this case, your robot's startup files will need to launch the driver node for your scanner. For example, Pi Robot uses a Hokuyo laser scanner and the corresponding launch file looks like this:

```
<launch>
  <node name="hokuyo" pkg="hokuyo_node" type="hokuyo_node">
    <param name="min_ang" value="-1.7" />
    <param name="max_ang" value="1.7" />
    <param name="hokuyo_node/calibrate_time" value="true" />
    <param name="frame_id" value="/base_laser" />
  </node>
</launch>
```

You can find this `hokuyo.launch` file in the `rbx1_bringup/launch` subdirectory.

If you do not have a laser scanner but you do have a depth camera like on the TurtleBot, then you can use the "fake laser scanner" found in the `turtlebot_bringup` package. To see how it works, take a look at the TurtleBot's `kinect.launch` file as follows:

```
$ roscd turtlebot_bringup
$ more kinect.launch
```

Toward the end of the file, you will see the lines shown below:

```
<!-- Fake Laser (narrow one, for localization -->
<node pkg="nodelet" type="nodelet" name="kinect_laser_narrow" args="load point
cloud_to_laserscan/CloudToScan openni_manager" respawn="true">
```

```

<param name="output_frame_id" value="/camera_depth_frame"/>
<!-- heights are in the (optical?) frame of the kinect -->
<param name="min_height" value="-0.025"/>
<param name="max_height" value="0.025"/>
<remap from="cloud" to="/cloud_throttled"/>
<remap from="scan" to="/narrow_scan"/>
</node>

```

These lines bring up a ROS nodelet that converts a point cloud to an equivalent laser scan. The only catch is that the scan is rather narrow—about 57 degrees—which is the width of the Kinect's field of view. A typical laser scanner has a width around 240 degrees or more. Nonetheless, the fake scan can be used to create fairly good maps. If you are using a stock TurtleBot, you can just use the default `kinect.launch` file to bring up the camera driver and fake laser scan. If you're using a different robot but still have a Kinect or Xtion, you can use the `fake_laser_fuerte.launch` file found in the `rbx1_bringup/launch` subdirectory.

8.4.2 Collecting and Recording Scan Data

Whether using a laser scanner or depth camera, the strategy for collecting scan data is the same. First we fire up any launch files required to control our robot's mobile base. Then we launch the drivers for our laser scanner or depth camera together with a teleop node so we can remotely control the robot. Finally, we start recording data into a ROS bag file and proceed to drive the robot around the target area.

If you own a TurtleBot, you can simply follow the official [TurtleBot gmapping Tutorial](#). However, if you need a few more details, you can follow along here as well.

In the case of the TurtleBot, the procedure would go as follows. On the TurtleBot's laptop, run:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

Next, bring up the Kinect drivers and fake laser. Log into the TurtleBot using another terminal window and run the command:

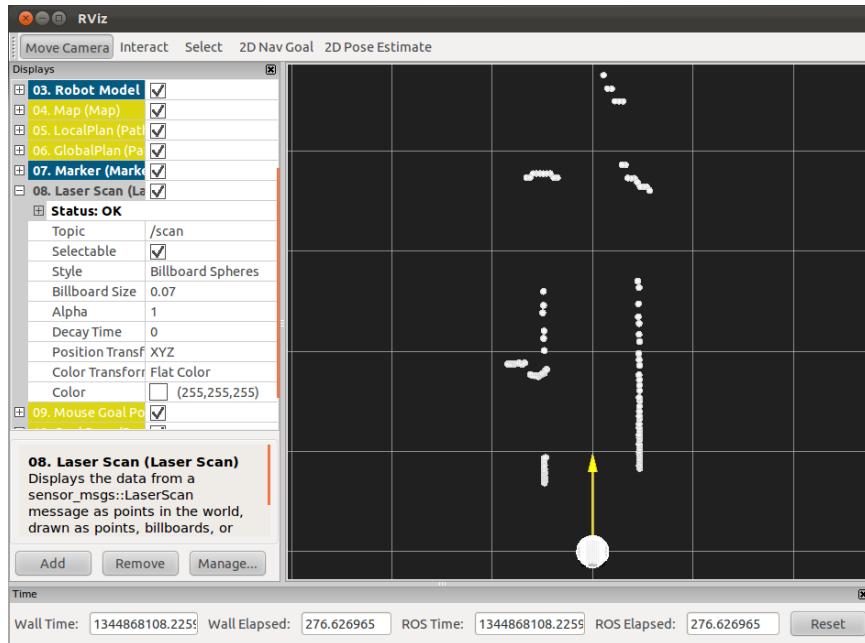
```
$ rosrun turtlebot_bringup kinect.launch
```

If you have a laser scanner, you would run its launch file here instead of the Kinect launch file.

Back on your desktop workstation, bring up `RViz` with the included gmapping config file:

```
$ rosrun rviz rviz -d `rospack find rbt1_nav`/gmapping_fuerte.vcg
```

If all goes well, you should see something like the following in RViz:



This particular scan was taken with the robot part way down a hallway with doorways on the left and right and another open door at the end of the hallway. Notice how we are subscribing to the `/scan` topic under the **Laser Scan** Display. If you don't see the scan points, click on the **Topic** field and check that the scan is being published and is visible on your workstation.

Next, launch a teleop node for either the keyboard or joystick depending on your hardware:

```
$ rosrun rbx1_nav keyboard_teleop.launch
```

or

```
$ rosrun rbx1_nav joystick_teleop.launch
```

Remember that the `joystick_teleop.launch` file needs to be launched on the computer physically connected to the joystick (or wireless receiver for something like a wireless game controller). This can be either the robot's laptop or your desktop.

Test out your connection to the robot by trying to move it with the keyboard or joystick. As the robot moves, the scan points in RViz should reflect the changing surroundings near the robot.

The final step is to start recording the data to a bag file. You can create the file anywhere you like, but there is a folder called `bag_files` in the `rbx1_nav` package for this purpose if you want to use it:

```
$ roscd rbx1_nav/bag_files
```

Now start the recording process:

```
$ rosbag record -O my_scan_data /scan /tf
```

where `my_scan_data` can be any filename you like. The only data we need to record is the scan data and the `tf` transforms. (The `tf` transform tree includes the transformation from the `/odom` frame to the `/base_link` or `/base_footprint` frame which gives us the needed odometry data.)

You are now ready to drive the robot around the area you'd like to map. Be sure to move the robot slowly, especially when rotating. Stay relatively close to walls and furniture so that there is always something within range of the scanner. Finally, plan to drive a closed loop and continue past the starting point for several meters to ensure a good overlap between the beginning and ending scan data.

When you are finished driving the robot, type `Ctrl-C` in the `rosbag` terminal window to stop the recording process. Also terminate your robot's startup nodes and the Kinect launch file.

Before running `gmapping` to create the map, you can watch the process in `RViz` by changing the **Frame** to `"/map"` in the **Global Options**. (You may have to type `/map` using the keyboard in the **Fixed Frame** field since it might not be one of the options in the pull down.)

Here is a video demonstrating the `gmapping` process using Pi Robot and a Hokuyo laser scanner: <http://youtu.be/7iIDdvCXIFM>

Back in your bag file directory, note the name of the bag file that was created above, then run the following commands to generate the map:

```
$ rosparam set use_sim_time true  
$ rosrun rbx1_nav gmapping.launch
```

```
$ rosrun rviz rviz -d /home/pi/.ros/meshes/kobuki.rviz
```

(If necessary, change the filename of the bag file in the last command above.)

If you look at the `gmapping.launch` file in the `rbx1_nav/launch` directory you will see many parameters that can be tweaked if needed. This particular launch file is a copied from the `turtlebot_navigation` package and the folks at Willow Garage have already dialed in the settings that should work for you. To learn more about each parameter, you can check out the [gmapping Wiki page](#).

When `rosbag` is finished playing the recorded data and exits, run the commands:

```
$ rosrun map_server map_saver -f my_map
```

where "my_map" can be any name you like. This will save the generated map into the current directory under the name you specified on the command line. If you look at the contents of the `rbx1_nav/maps` directory, you will see two new files: `my_map.pgm` which is the map image and `my_map.yaml` that describes the dimensions of the map. It is this latter file that you will point to in subsequent launch files when you want to use the map for navigation.

NOTE: Don't forget to reset the `use_sim_time` parameter after you are finished map building. Use the command:

```
$ rosparam set use_sim_time false
```

Now that your map is saved we will learn how to use it for localization in the next section.

8.4.3 Can I Extend or Modify an Existing Map?

The ROS `gmapping` package does not provide a way to start with an existing map and then modify it through additional mapping. However, you can always edit a map using your favorite graphics editor. For example, to keep your robot from entering a room, draw a black line across the doorway(s). (**NOTE:** There may be a bug in `move_base` that prevents this trick from working at the moment. You can also try setting all the pixels in forbidden region to mid-gray.) To remove a piece of furniture that has been moved, erase the corresponding pixels. In the next section we will find that localization is not terribly sensitive to the exact placement of pixels so it can handle small changes to the locations of objects. But if you have moved a large sofa from one side of a room to the other for example, the new arrangement might confuse your robot. In such a case, you could either move the corresponding pixels in your editor, or rebuild your map from scratch using new scan data.

8.5 Navigation and Localization using a Map and amcl

If you do not have the hardware to build a map using your own robot, you can use the test map in `rbx1_nav/maps` for this chapter. Otherwise, if you created a map of your own by following the instructions in the previous section you can use it here.

ROS uses the [amcl](#) package to localize the robot within an existing map using the current scan data coming from the robot's laser or depth camera. But before trying `amcl` on a real robot, let's try fake localization in the ArbotiX simulator.

8.5.1 Testing amcl with Fake Localization

Take a look at the launch file called `fake_amcl.launch` in the `rbx1_nav/launch` directory:

```
<launch>
  <!-- Set the name of the map yaml file: can be overridden on the command line. -->
  <arg name="map" default="test_map.yaml" />
  <!-- Run the map server with the desired map -->
  <node name="map_server" pkg="map_server" type="map_server" args="$(find
rbx1_nav)/maps/${arg map}"/>

  <!-- The move_base node -->
  <include file="$(find rbx1_nav)/launch/fake_move_base.launch" />

  <!-- Run fake localization compatible with AMCL output -->
  <node pkg="fake_localization" type="fake_localization"
name="fake_localization" output="screen" />

  <!-- For fake localization we need static transforms between /odom and /map
and /map and /world -->
  <node pkg="tf" type="static_transform_publisher" name="odom_map_broadcaster"
args="0 0 0 0 0 /odom /map 100" />
</launch>
```

As you can see from the launch file, first we load a map onto the map server, in this case the test map of a single floor house. The map name can be overridden on the command line as we will see below. Alternatively, you can edit the launch file and change the filename to your map so you do not have to type it on the command line.

Next we include the same `fake_move_base.launch` file that we used earlier. Finally, we fire up the `fake_localization` node. As you can read on the [fake_localization](#) ROS Wiki page, this node simply republishes the robot's odometry data in a form that is compatible with `amcl`.

To test it all out in the ArbotiX simulator, run the following commands—skip any commands that you already have running in various terminals:

```
$ roslaunch rbx1_bringup fake_turtlebot.launch
```

(Replace with your favorite fake robot if desired.)

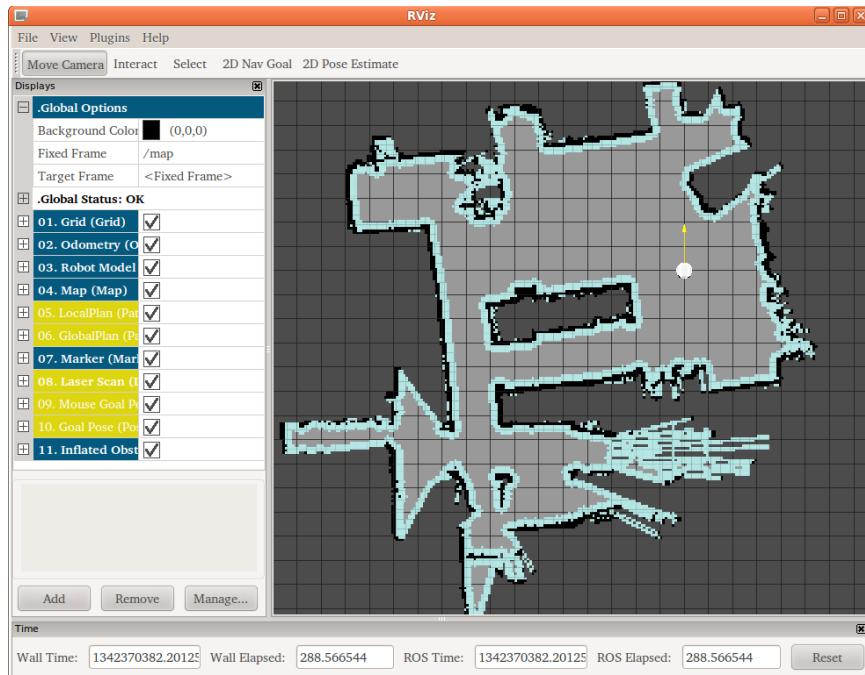
Next run the `fake_amcl.launch` file with the included test map or point it to your own map on the command line:

```
$ rosrun rbx1_nav fake_amcl.launch map:=test_map.yaml
```

Finally, if it's not running already, bring up `RViz` with the navigation config file:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/nav_fuerte.vcg
```

Once the map appears in `RViz`, you will probably have to zoom out a bit with your mouse scroll wheel to see more of the map. If you are using the test map, the image should look something like the following:



When you have a view you like, click on the **2D Nav Goal** button, then select a goal pose for the robot within the map. As soon as you release the mouse, `move_base` will take over to move the robot to the goal. Try a number of different goals to see how `amcl` and `move_base` work together to plan and implement a path for the robot.

8.5.2 Using amcl with a Real Robot

If your robot has a laser scanner or RGB-D camera like the Kinect or Xtion Pro, you can try out `amcl` in the real world. Assuming you have already created a map called `my_map.yaml` in the directory `rbx1_nav/maps`, follow these steps to start localizing your robot.

First, terminate any fake robots you may have running as well as the `fake_amcl.launch` file if you ran it in the previous section. It's also not a bad idea to shut down and restart your `roscore` process just to be sure we are starting with a clean slate.

If you have a TurtleBot, you can run through the official [TurtleBot SLAM Tutorial](#) on the ROS Wiki. You can also follow along here and get essentially the same result.

Next, launch your robot's startup files. For a TurtleBot, you would run the following on the robot's laptop computer:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

(Or use your own launch file if you have stored your calibration parameters in a different file.)

We also need an auxiliary script to be able to see the TurtleBot's combined odometry frame in `RViz`. You can skip this if you are not using a TurtleBot. The launch file should be run on the TurtleBot's laptop:

```
$ rosrun rbt_bringup odom_ekf.launch
```

Log in to the robot in yet another terminal and bring up the openni drivers and fake laser scan:

```
$ rosrun turtlebot_bringup kinect.launch
```

Alternatively, you can also use:

```
$ rosrun rbt_bringup kinect_fuerte.launch
```

The only difference between this launch file and the one in the `turtlebot_bringup` package is that the camera is run in QVGA mode instead of VGA mode which can be a little gentler on your robot's CPU. You can also set the resolution using `dynamic_reconfigure`.

Now launch the the `tb_amcl.launch` file with your map as an argument:

```
$ rosrun rbt1_nav tb_amcl.launch map:=my_map.yaml
```

If you don't already have `RViz` running with the `nav_ekf` config file, run it now:

```
$ rosrun rviz rviz -d `rospack find rbt1_nav`/nav_ekf_fuerte.vcg
```

When `amcl` first starts up, you have to give it the initial pose (position and orientation) of the robot as this is something `amcl` cannot figure out on its own. To set the initial pose, first click on the **2D Pose Estimate** button in `RViz`. Then click on the point in the map where you know your robot is located. While holding down the mouse button, a large green arrow should appear. Move the mouse to orient the arrow to match the orientation of your robot, then release the mouse.

With your robot's initial position set, you should be able to use the **2D Nav Goal** button in `RViz` to point-and-click navigation goals for your robot at different locations in the map. Use your mouse scroll-wheel to zoom out or in as necessary. As the robot moves about, you should see the laser scan points line up with walls and obstacle boundaries.

To test obstacle avoidance, start the robot toward a goal some distance away, then walk in front of the robot as it is moving. The base local planner should steer the robot around you and then continue on to the target location.

You can also teleoperate the robot at any time while `amcl` is running if you launch either a keyboard or joystick teleoperation node.

8.5.3 Fully Autonomous Navigation

Using your mouse to send a robot to any location in the house is pretty cool, especially when the robot will dynamically avoid obstacles along the way, but ultimately we want to be able to specify locations programmatically and have the robot move about autonomously. For instance, for a "Patrol Bot" application, we might select a series of locations for the robot to visit, then set the program running and walk away.

In this section we will look at a Python script that does precisely this. It was designed as a kind of navigation endurance test to see how long Pi Robot could autonomously navigate around the house without running into trouble. The file is called `nav_test.py` in the `rbt1_nav/nodes` directory and it executes the following steps:

- Initialize a set of goal locations with the map.
- Randomly select the next location. (The locations were sampled without replacement so that each location was visited equally often.)
- Send the appropriate `MoveBaseGoal` goal to the `move_base` action server.

- Record the success or failure of the navigation to the goal, as well as the elapsed time and distance traveled.
- Pause for a configurable number of seconds at each location.
- Rinse and repeat.

Before trying it out on a real robot, let's run it in the ArbotiX simulator.

8.5.4 Running the Navigation Test in Simulation

The entire set of nodes we need for the endurance test can be launched using the `fake_nav_test.launch` file. (This launch file is actually a good example of a complete ROS application: it launches the robot drivers, the `map_server`, the `move_base` node and the navigation test script.)

For this test, the robot will be approaching target locations from different directions depending on the previous location. Rather than force the robot to rotate to a particular orientation at each location, we can set the `yaw_goal_tolerance` parameter to 360 degrees (6.28 radians) which means that once the robot gets to a goal location, the base local planner will be happy with whatever orientation the robot has as it arrives. This results in a more natural motion of the robot from one location to the next. (Of course, for an actual Patrol Bot, you might have reasons for wanting the robot to face particular directions at specific locations.)

We can set this special `yaw_goal_tolerance` parameter in a separate config file and load the file to override the value we might normally used as specified in the `base_local_planner_params.yaml` file. In the `rbx1_nav/config` directory you will find the file `rbx1_nav/config/nav_test_params.yaml` that looks like this:

```
TrajectoryPlannerROS:  
  yaw_goal_tolerance: 6.28
```

As you can see, the file is simply a snippet of the `base_local_planner_params.yaml` file consisting of the namespace and the new yaw tolerance. This file is then loaded after the `base_local_planner_params.yaml` file in the `fake_nav_test.launch` file like this:

```
<!-- The move_base node -->  
<node pkg="move_base" type="move_base" respawn="false" name="move_base"  
output="screen">  
  <rosparam file="$(find rbx1_nav)/config/fake/costmap_common_params.yaml"  
command="load" ns="global_costmap" />  
  <rosparam file="$(find rbx1_nav)/config/fake/costmap_common_params.yaml"  
command="load" ns="local_costmap" />  
  <rosparam file="$(find rbx1_nav)/config/fake/local_costmap_params.yaml"  
command="load" />
```

```
<rosparam file="$(find rbx1_nav)/config/fake/global_costmap_params.yaml" command="load" />
<rosparam file="$(find rbx1_nav)/config/fake/base_local_planner_params.yaml" command="load" />
<rosparam file="$(find rbx1_nav)/config/nav_test_params.yaml" command="load" />
/>
</node>
```

where you see that the last `rosparam` line loads the `nav_test_params.yaml` file.

With these preliminaries out of the way, let's run the test. To make sure we are starting with a clean slate, kill any running launch files as well as `roscore`. Begin with a new `roscore`:

```
$ roscore
```

Next, fire up `rxconsole`. This allows us to view the status messages being output by the `nav_test.py` script. The same messages are shown in the terminal window used to run the the `fake_nav_test.launch` file, but `rxconsole` provides a nicer monitoring interface.

```
$ rxconsole
```

Now run the `fake_nav_test.launch` file:

```
$ roslaunch rbx1_nav fake_nav_test.launch
```

The `fake_nav_test.launch` file brings up the fake TurtleBot, the `map_server` node with the test map loaded, the `move_base` node with all the parameters tuned for the fake TurtleBot, the `fake_localization` node, and finally, the `nav_test.py` script itself.

The very last message in the output from the launch file should be:

```
*** Click the 2D Pose Estimate button in RViz to set the robot's initial pose...
```

At this point, fire up `RViz` with the `nav_test` configuration file:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/nav_test_fuerte.vcg
```

When `RViz` is up and the robot is visible, click on the **2D Pose Estimate** button to set the initial pose of the robot. Then click on the middle of the robot and align the green pose arrow with the yellow odometry arrow. As soon as you release the mouse, the navigation test will start.

The fake TurtleBot should now start moving in RViz from one location to another. For the fake test, the robot does not pause at each location. The simulation will run forever until you type Ctrl-C in the `fake_nav_test.launch` window.

As the test proceeds, bring the rxconsole window to the foreground and you can monitor the time elapsed, distance traveled, the number of goal locations attempted and the success rate.

8.5.5 Understanding the Navigation Test Script

Before running the navigation test on a real robot, let's make sure we understand the code that makes it work.

Link to SVN source: [nav_test.py](#)

```
1. #!/usr/bin/env python
2. import roslib; roslib.load_manifest('rbx1_nav')
3. import rospy
4. import actionlib
5. from actionlib_msgs.msg import *
6. from geometry_msgs.msg import Pose, PoseWithCovarianceStamped, Point,
   Quaternion, Twist
7. from move_base_msgs.msg import MoveBaseAction, MoveBaseGoal
8. from random import sample
9. from math import pow, sqrt
10.
11. class NavTest():
12.     def __init__(self):
13.         rospy.init_node('nav_test', anonymous=True)
14.
15.         rospy.on_shutdown(self.shutdown)
16.
17.         # How long in seconds should the robot pause at each location?
18.         self.rest_time = rospy.get_param("~rest_time", 10)
19.
20.         # Are we running in the fake simulator?
21.         self.fake_test = rospy.get_param("~fake_test", False)
22.
23.         # Goal state return values
24.         goal_states = ['PENDING', 'ACTIVE', 'PREEMPTED',
25.                        'SUCCEEDED', 'ABORTED', 'REJECTED',
26.                        'PREEMPTING', 'RECALLING', 'RECALLED',
27.                        'LOST']
28.
29.         # Set up the goal locations. Poses are defined in the map frame.
30.         # An easy way to find the pose coordinates is to point-and-click
31.         # Nav Goals in RViz when running in the simulator.
32.         # Pose coordinates are then displayed in the terminal
33.         # that was used to launch RViz.
34.         locations = dict()
35.
36.         locations['hall_foyer'] = Pose(Point(0.643, 4.720, 0.000),
37.                                         Quaternion(0.000, 0.000, 0.223, 0.975))
38.         locations['hall_kitchen'] = Pose(Point(-1.994, 4.382, 0.000),
```

```

39.                                     Quaternion(0.000, 0.000, -0.670, 0.743))
40.     locations['hall_bedroom'] = Pose(Point(-3.719, 4.401, 0.000),
41.                                         Quaternion(0.000, 0.000, 0.733, 0.680))
42.     locations['living_room_1'] = Pose(Point(0.720, 2.229, 0.000),
43.                                         Quaternion(0.000, 0.000, 0.786, 0.618))
44.     locations['living_room_2'] = Pose(Point(1.471, 1.007, 0.000),
45.                                         Quaternion(0.000, 0.000, 0.480, 0.877))
46.     locations['dining_room_1'] = Pose(Point(-0.861, -0.019, 0.000),
47.                                         Quaternion(0.000, 0.000, 0.892, -0.451))
48.
49.     # Publisher to manually control the robot (e.g. to stop it)
50.     self.cmd_vel_pub = rospy.Publisher('cmd_vel', Twist)
51.
52.     # Subscribe to the move_base action server
53.     self.move_base = actionlib.SimpleActionClient("move_base",
54.                                                   MoveBaseAction)
55.     rospy.loginfo("Waiting for move_base action server...")
56.
57.     # Wait 60 seconds for the action server to become available
58.     self.move_base.wait_for_server(rospy.Duration(60))
59.
60.     rospy.loginfo("Connected to move base server")
61.
62.     # A variable to hold the initial pose of the robot to be set by
63.     # the user in RViz
64.     initial_pose = PoseWithCovarianceStamped()
65.
66.     # Variables to keep track of success rate, running time,
67.     # and distance traveled
68.     n_locations = len(locations)
69.     n_goals = 0
70.     n_successes = 0
71.     i = n_locations
72.     distance_traveled = 0
73.     start_time = rospy.Time.now()
74.     running_time = 0
75.     location = ""
76.     last_location = ""
77.
78.     # Get the initial pose from the user
79.     rospy.loginfo("Click on the map in RViz to set the intial
80. pose...")
81.     rospy.wait_for_message('initialpose', PoseWithCovarianceStamped)
82.     self.last_location = Pose()
83.     rospy.Subscriber('initialpose', PoseWithCovarianceStamped,
84.                      self.update_initial_pose)
85.
86.     # Make sure we have the initial pose
87.     while initial_pose.header.stamp == "":
88.         rospy.sleep(1)
89.
90.     rospy.loginfo("Starting navigation test")
91.
92.     # Begin the main loop and run through a sequence of locations
93.     while not rospy.is_shutdown():
94.         # If we've gone through the current sequence,

```

```

93.          # start with a new random sequence
94.          if i == n_locations:
95.              i = 0
96.              sequence = sample(locations, n_locations)
97.              # Skip over first location if it is the same as
98.              # the last location
99.              if sequence[0] == last_location:
100.                  i = 1
101.
102.          # Get the next location in the current sequence
103.          location = sequence[i]
104.
105.          # Keep track of the distance traveled.
106.          # Use updated initial pose if available.
107.          if initial_pose.header.stamp == "":
108.              distance = sqrt(pow(locations[location].position.x
109.                               - locations[last_location].position.x, 2) +
110.                               pow(locations[location].position.y -
111.                                   locations[last_location].position.y, 2))
112.          else:
113.              rospy.loginfo("Updating current pose.")
114.              distance = sqrt(pow(locations[location].position.x
115.                               - initial_pose.pose.position.x, 2) +
116.                               pow(locations[location].position.y -
117.                                   initial_pose.pose.position.y, 2))
118.              initial_pose.header.stamp = ""
119.
120.          # Store the last location for distance calculations
121.          last_location = location
122.
123.          # Increment the counters
124.          i += 1
125.          n_goals += 1
126.
127.          # Set up the next goal location
128.          self.goal = MoveBaseGoal()
129.          self.goal.target_pose.pose = locations[location]
130.          self.goal.target_pose.header.frame_id = 'map'
131.          self.goal.target_pose.header.stamp = rospy.Time.now()
132.
133.          # Let the user know where the robot is going next
134.          rospy.loginfo("Going to: " + str(location))
135.
136.          # Start the robot toward the next location
137.          self.move_base.send_goal(self.goal)
138.
139.          # Allow 5 minutes to get there
140.          finished_within_time =
141.              self.move_base.wait_for_result(rospy.Duration(300))
142.
143.          # Check for success or failure
144.          if not finished_within_time:
145.              self.move_base.cancel_goal()
146.              rospy.loginfo("Timed out achieving goal")
147.          else:
148.              state = self.move_base.get_state()
149.              if state == GoalStatus.SUCCEEDED:

```

```

149.                 rospy.loginfo("Goal succeeded!")
150.                 n_successes += 1
151.                 distance_traveled += distance
152.             else:
153.                 rospy.loginfo("Goal failed with error code: " +
   str(goal_states[state]))
154.
155.             # How long have we been running?
156.             running_time = rospy.Time.now() - start_time
157.             running_time = running_time.secs / 60.0
158.
159.             # Print a summary success/failure, distance traveled and time
   elapsed
160.             rospy.loginfo("Success so far: " + str(n_successes) + "/" +
161.                           str(n_goals) + " = " +
162.                           str(100 * n_successes/n_goals) + "%")
163.             rospy.loginfo("Running time: " + str(trunc(running_time, 1)) +
164.                           " min Distance: " + str(trunc(distance_traveled,
   1)) + " m")
165.             rospy.sleep(self.rest_time)
166.
167. def update_initial_pose(self, initial_pose):
168.     self.initial_pose = initial_pose
169.
170. def shutdown(self):
171.     rospy.loginfo("Stopping the robot...")
172.     self.move_base.cancel_goal()
173.     rospy.sleep(2)
174.     self.cmd_vel_pub.publish(Twist())
175.     rospy.sleep(1)
176.
177. def trunc(f, n):
178.     # Truncates/pads a float f to n decimal places without rounding
179.     slen = len('%.%f' % (n, f))
180.     return float(str(f)[:slen])
181.
182. if __name__ == '__main__':
183.     try:
184.         NavTest()
185.         rospy.spin()
186.     except rospy.ROSInterruptException:
187.         rospy.loginfo("AMCL navigation test finished.")

```

Here are the key lines of the script and what they do.

```

17.     # How long in seconds should the robot pause at each location?
18.     self.rest_time = rospy.get_param("~rest_time", 10)
19.
20.     # Are we running in the fake simulator?
21.     self.fake_test = rospy.get_param("~fake_test", False)

```

Set the number of seconds to pause at each location before moving to the next. If the `fake_test` parameter is `True`, the `rest_time` parameter is ignored.

```

24.     goal_states = [ 'PENDING', 'ACTIVE', 'PREEMPTED',
25.                      'SUCCEEDED', 'ABORTED', 'REJECTED',
26.                      'PREEMPTING', 'RECALLING', 'RECALLED',
27.                      'LOST' ]

```

It's nice to have a human readable form of the various MoveBaseAction goal states.

```

34.     locations = dict()
35.
36.     locations['hall_foyer'] = Pose(Point(0.643, 4.720, 0.000),
37.                                         Quaternion(0.000, 0.000, 0.223, 0.975))
38.     locations['hall_kitchen'] = Pose(Point(-1.994, 4.382, 0.000),
39.                                         Quaternion(0.000, 0.000, -0.670, 0.743))
40.     locations['hall_bedroom'] = Pose(Point(-3.719, 4.401, 0.000),
41.                                         Quaternion(0.000, 0.000, 0.733, 0.680))
42.     locations['living_room_1'] = Pose(Point(0.720, 2.229, 0.000),
43.                                         Quaternion(0.000, 0.000, 0.786, 0.618))
44.     locations['living_room_2'] = Pose(Point(1.471, 1.007, 0.000),
45.                                         Quaternion(0.000, 0.000, 0.480, 0.877))
46.     locations['dining_room_1'] = Pose(Point(-0.861, -0.019, 0.000),
47.                                         Quaternion(0.000, 0.000, 0.892, -0.451))

```

The goal locations (poses) are stored as a Python dictionary. The Point and Quaternion values can be found by clicking on the **2D Nav Goal** button in RViz and noting the values displayed in the terminal that was used to launch RViz. Then copy and paste those values into your script.

```

83.         rospy.Subscriber('initialpose', PoseWithCovarianceStamped,
self.update_initial_pose)

```

Here we subscribe to the `initialpose` topic so that we can set the initial location and orientation of the robot within the map at the start of the test. When running the test on a real robot, the initial pose is set by the user in RViz. For a fake robot (`fake_test = True`), this variable is ignored since fake localization is already perfect.

```

91.     while not rospy.is_shutdown():

```

Run the test until the user aborts the application.

```

96.         sequence = sample(locations, n_locations)

```

We use the Python `sample()` function to generate a random sequence of goals from the set of locations.

```

127.         # Set up the next goal location
128.         self.goal = MoveBaseGoal()
129.         self.goal.target_pose.pose = locations[location]
130.         self.goal.target_pose.header.frame_id = 'map'
131.         self.goal.target_pose.header.stamp = rospy.Time.now()
132.
133.         # Let the user know where the robot is going next

```

```
134.         rospy.loginfo("Going to: " + str(location))
135.
136.         # Start the robot toward the next location
137.         self.move_base.send_goal(self.goal)
```

Finally, we set the goal location to the next location in the sequence and send it to the `move_base` action server.

8.5.6 Running the Navigation Test on a Real Robot

The procedure for running the navigation test with a real robot is nearly the same as with the simulation. However, you will of course need your own map of the area where you want the robot to run.

For this test, it is probably a good idea to run all nodes on the robot's computer except `rxconsole` and `RViz`. This will ensure that there are no timing issues between the robot and your desktop due to fluctuations in your wifi network.

The `rbx1_nav` directory includes a launch file called `tb_nav_test.launch` that should work with a TurtleBot but you will need to edit it first and point to your own map file. You can also supply the name of your map file on the command line as we did earlier and as we will illustrate below.

First terminate any simulations you might have running. If you really want to be on the safe side, shut down and restart `roscore` to make sure the entire parameter server is also cleared.

Next, fire up your robot's startup files. In the case of the TurtleBot, you would run the following launch files on the TurtleBot's laptop:

```
$ rosrun turtlebot Bringup turtlebot.launch
```

(Use your own launch file if you have saved your calibration parameters in a different file.)

```
$ rosrun turtlebot Bringup kinect.launch
```

Alternatively, you can also use:

```
$ rosrun rbx1 Bringup kinect_fuerte.launch
```

The only difference between these files is that the camera is run in QVGA mode instead of VGA mode which can be a little gentler on your robot's CPU. You can also set the resolution using `dynamic_reconfigure`.

If want to be able to monitor the combined odometry data computed by `robot_pose_ekf`, run the `odom_ekf.launch` file. You can skip this if you are not using a TurtleBot or you don't care about viewing this data:

```
$ rosrun rox1_bringup odom_ekf.launch
```

If it is not already running, bring up `rxconsole` to monitor status messages during the test. This can be run on your desktop:

```
$ rxconsole
```

Next, launch the `tb_nav_test.launch` file. Run the launch file on the robot's computer:

```
$ rosrun rox1_nav tb_nav_test.launch map:=my_map.yaml
```

You can leave off the map argument if you have edited your `tb_nav_test.launch` file. If you do supply the map on the command line, be sure to use your own map file.

Finally, if you don't already have `RViz` running with the `nav_test` config file, bring it up now on your desktop computer:

```
$ rosrun rviz rviz -d `rospack find rox1_nav`/nav_test_fuerte.vcg
```

If everything goes well, you should see the following message in `rxconsole` and in the terminal window used to launch the `tb_nav_test.launch` file:

```
*** Click the 2D Pose Estimate button in RViz to set the robot's initial pose...
```

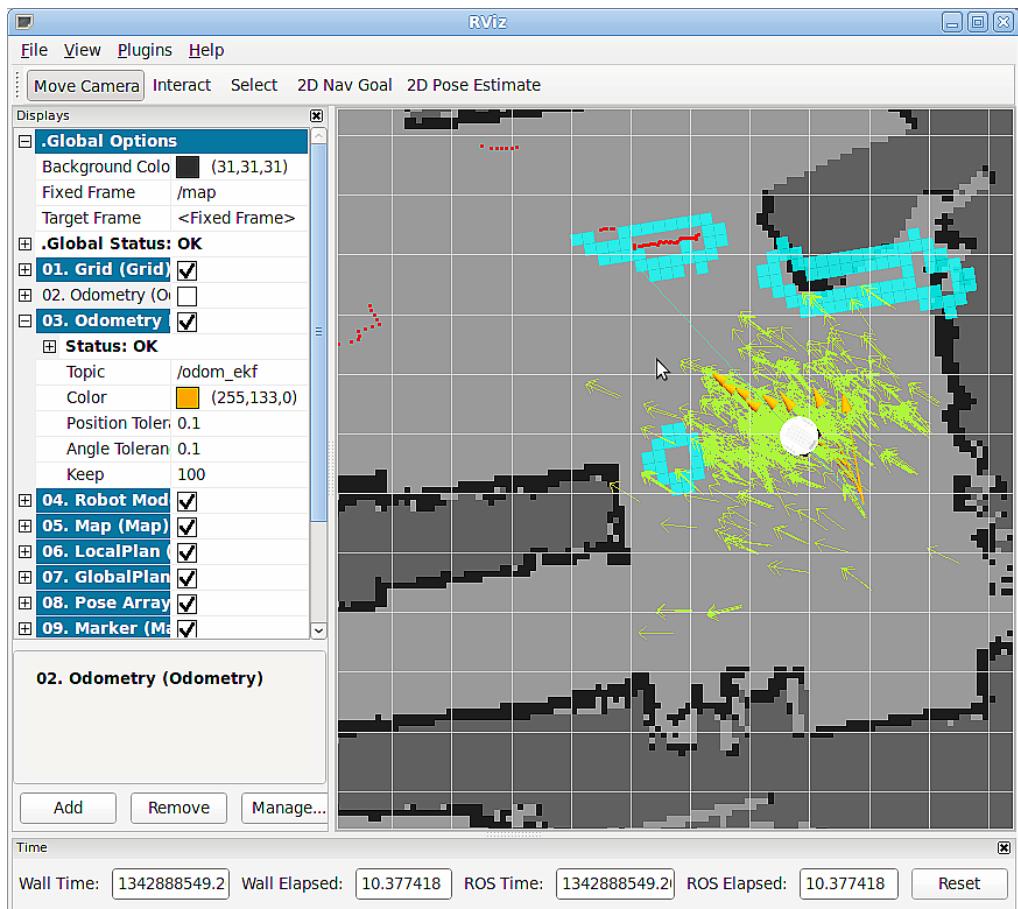
Before the navigation test will start, you need to set the initial pose of the robot. Click on the approximate starting location of the robot in `RViz`, and when the large green arrow appears, point the arrow to match the orientation of the robot. As soon as you release the mouse button, the robot should begin the test.

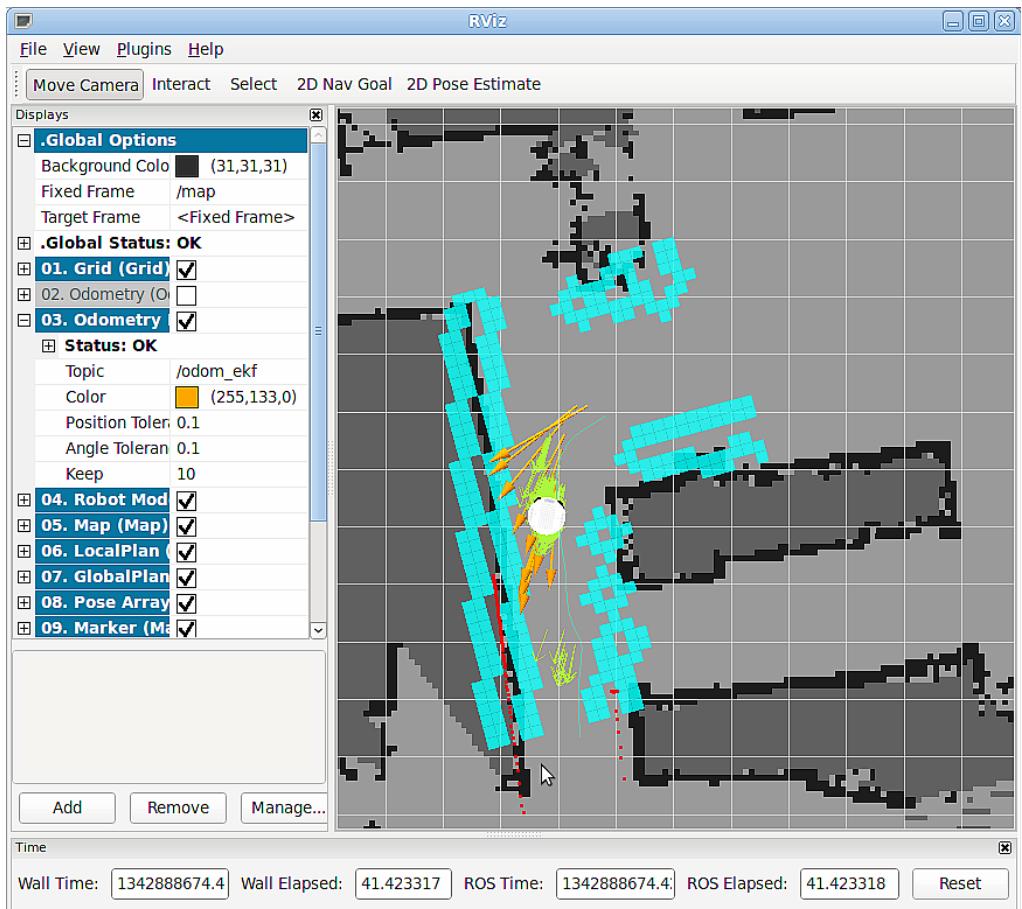
NOTE: To stop the robot (and the test) at any time, simply type `Ctrl-C` in the terminal window used to start the `nav_test.launch` file. If you are using a TurtleBot, you can also press the front bumper with your foot or hand and the robot will stop moving.

Probably the first thing you will notice in `RViz` is the cloud of light green arrows surrounding the robot. These arrows represent the range of poses returned by `amcl` and are being displayed because the `nav_test` config file we are using with `RViz` includes a **Pose Array** display type. (Look just below the **GlobalPlan** display in the left-hand panel in `RViz`.) The **Pose Array** topic is set to the `/particlecloud` topic which is the default topic on which `amcl` publishes its pose estimates for the robot. (See the [amcl](#))

[Wiki page](#) for details.) As the robot moves about the environment, this cloud should shrink in size as additional scan data allows `amcl` to refine its estimate of the robot's position and orientation.

Here are a couple of screen shots from a live test. The first was taken just after the test started and the second was taken a few minutes later:





Notice how the pose array in the first image is quite spread out. In the second image, the array has contracted around the robot but there is a small second cloud ahead of the robot that represents an alternative hypothesis about the robot's possible location. At this point in the test, the robot is running down a hallway and with the limited field of view of the Kinect, `amcl` cannot be 100% certain where in the hall the robot is located. Nonetheless, the larger probability is centered around the actual location of the robot.

8.5.7 What's Next?

This concludes the chapter on Navigation. You should now have the tools you need to program your own robot to autonomously navigation your home or office. To get started, you could try a few variations on the navigation test script. For example, instead of using a set of fixed target locations, try picking locations at random, or simply add some random variation around the primary locations. You could also have the robot rotate in place at each location as a Patrol Bot might do to scan the entire surroundings.

9. SPEECH RECOGNITION AND SYNTHESIS

Speech recognition and Linux have come a long way in the past few years, thanks mostly to the [CMU Sphinx](#) and [Festival](#) projects. We can also benefit from existing ROS packages for both speech recognition and text-to-speech. Consequently, it is quite easy to add speech control and voice feedback to your robot as we will now show.

In this chapter we will:

- Install and test the [pocketsphinx](#) package for speech recognition
- Learn how to create a custom vocabulary for speech recognition
- Teleoperate a real and simulated robot using voice commands
- Install and test the Festival text-to-speech system and the ROS [sound_play](#) package

9.1 Installing PocketSphinx for Speech Recognition

Thanks to Michael Ferguson from the University of Albany (and now at Willow Garage), we can use the ROS [pocketsphinx](#) package for speech recognition. The [pocketsphinx](#) package requires the installation of the Ubuntu package [gstreamer0.10-pocketsphinx](#) and we will also need the ROS sound drivers stack (in case you don't already have it) so let's take care of both first. You will be prompted to install the Festival packages if you don't already have them—answer "Y" of course:

```
$ sudo apt-get install gstreamer0.10-pocketsphinx  
$ sudo apt-get install ros-fuerte-audio-common  
$ sudo apt-get install libasound2
```

The [pocketsphinx](#) package is part of the University of Albany's [rharmony](#) stack so let's install the stack using the following commands. First move into your personal ROS directory (e.g. `~/ros_workspace`), then run:

```
$ svn checkout http://albany-ros-pkg.googlecode.com/svn/trunk/rharmony  
$ rosmake pocketsphinx
```

The key file in the `pocketsphinx` package is the Python script `recognizer.py` found in the `nodes` subdirectory. This script does all the hard work of connecting to the audio input stream of your computer and matching voice commands to the words or phrases in the current vocabulary. When the recognizer node matches a word or phrase, it publishes it on the `/recognizer/output` topic. Other nodes can subscribe to this topic to find out what the user has just said.

9.2 Testing the PocketSphinx Recognizer

You will get the best speech recognition results using a headset microphone, either USB, standard audio or Bluetooth. Once you have your microphone connected to your computer, make sure it is selected as the input audio device. (If you are using Ubuntu 10.04 go to the **System** menu, then select **Preferences→Sound**. If you are using Ubuntu 11.10 or higher, go to **System Settings** and click on the **Sound** control panel.) Once the Sound Preferences window opens, click on the **Input** tab and select your microphone device from the list (if more than one). Speak a few words into your microphone and you should see the volume meter respond. Then click on the **Output** tab, select your desired output device, and adjust the volume slider. Finally, close the **Sound Preferences** window.

NOTE: If you disconnect a USB or Bluetooth microphone and then reconnect it later, you will likely have to select it as the input again using the procedure described above.

Michael Ferguson includes a vocabulary file suitable for RoboCup@Home competitions that you can use to test the recognizer. Fire it up now by running:

```
$ roslaunch pocketsphinx robocup.launch
```

You should see a list of INFO messages indicating that the various parts of the recognition model are being loaded. The last few messages will look something like this:

```
INFO: ngram_search_fwdtree.c(195): Creating search tree
INFO: ngram_search_fwdtree.c(203): 0 root, 0 non-root channels, 26
single-phone words
INFO: ngram_search_fwdtree.c(325): max nonroot chan increased to 328
INFO: ngram_search_fwdtree.c(334): 77 root, 200 non-root channels, 6
single-phone words
```

Now say a few of the RoboCup phrases such as "bring me the glass", "go to the kitchen", or "come with me". The output should look something like this:

```
Partial: BRING
Partial: BRING ME
Partial: BRING IS
Partial: BRING ME THE
Partial: BRING ME THE GO
Partial: BRING ME THE THE
Partial: BRING ME THE GLASS
[INFO] [WallTime: 1318719668.724552] bring me the glass
Partial: THE
Partial: GO
Partial: GOOD
Partial: GO TO
Partial: GOOD IS
Partial: GO TO THE
Partial: GO TO THE TO
Partial: GO TO THE GET
Partial: GO TO THE KITCHEN
[INFO] [WallTime: 1318719670.184438] go to the kitchen
Partial: GO
Partial: COME
Partial: COME WITH
Partial: COME WITH THE
Partial: COME WITH ME
[INFO] [WallTime: 1318719671.835016] come with me
```

Congratulations—you can now talk to your robot! Here we see how the PocketSphinx recognizer builds the recognized phrase over the course of your utterance. To see just the final result, open another terminal, and echo the `/recognizer/output` topic:

```
$ rostopic echo /recognizer/output
```

Now try the same three phrases as above and you should see:

```
data: bring me the glass
---
data: go to the kitchen
---
data: come with me
---
```

For my voice, and using a Bluetooth over-the-ear microphone, the recognizer was surprisingly fast and accurate.

To see all the phrases you can use with the demo RoboCup vocabulary, run the following commands:

```
$ roscd pocketsphinx/demo
$ more robocup.corpus
```

Now try saying a phrase that is not in the vocabulary, such as "the sky is blue". In my case, the result on the `/recognizer/output` topic was "this go is room". As you can see, the recognizer will respond with something no matter what you say. This means that care must be taken to "mute" the speech recognizer if we don't want random conversation to be interpreted as speech commands. We will see how to do this below when we learn how to map speech recognition into actions.

9.3 Creating a Vocabulary

It is easy to create a new vocabulary or *corpus* as it is referred to in PocketSphinx. First, create a simple text file with one word or phrase per line. Here is a corpus that could be used to drive your robot around using voice commands. We will store it in a file called `nav_commands.txt` in the `config` subdirectory of the `rbx1_speech` package. To view its contents, run the commands:

```
$ roscd rbx1_speech/config  
$ more nav_commands.txt
```

You should see the following list of phrases (they will appear all in one column on your screen):

pause speech	come forward	stop
continue speech	come backward	stop now
move forward	come left	halt
move backward	come right	abort
move back	turn left	kill
move left	turn right	panic
move right	rotate left	help
go forward	rotate right	help me
go backward	faster	freeze
go back	speed up	turn off
go left	slower	shut down
go right	slow down	cancel
go straight	quarter speed	
	half speed	
	full speed	

You can also bring the file up in your favorite editor and add, delete or change some of these words or phrases before proceeding to the next step. When you enter your phrases, try not to mix upper and lower case and do not use punctuation marks. Also, if want to include a number such as 54, spell it out as "fifty four".

Before we can use this corpus with PocketSphinx, we need to compile it into special dictionary and pronunciation files. This can be done using the online CMU language model (**lm**) tool located at:

<http://www.speech.cs.cmu.edu/tools/lmtool-new.html>

Follow the directions to upload your `nav_commands.txt` file, click the **Compile Knowledge Base** button, then download the resulting compressed tarball that contains all the language model files. Extract these files into the `config` subdirectory of the `rbx1_speech` package. The files will all begin with the same number, such as `3026.dic`, `3026.lm`, etc. These files define your vocabulary as a language model that PocketSphinx can understand. You can rename all these files to something more memorable using a command like the following (the 4-digit number will likely be different in your case):

```
$ roscd rbx1_speech/config  
$ rename -f 's/3026/nav_commands/' *
```

Next, take a look at the `voice_nav_commands.launch` file found in the `rbx1_speech/launch` subdirectory. It looks like this:

```
<launch>  
  <node name="recognizer" pkg="pocketsphinx" type="recognizer.py"  
output="screen">  
    <param name="lm" value="$(find rbx1_speech)/config/nav_commands.lm"/>  
    <param name="dict" value="$(find rbx1_speech)/config/nav_commands.dic"/>  
  </node>  
</launch>
```

As you can see, the launch file runs the `recognizer.py` node from the `pocketsphinx` package and we point the `lm` and `dict` parameters to the files `nav_commands.lm` and `nav_commands.dic` created in the steps above. Note also that the parameter `output="screen"` is what allows us to see the real-time recognition results in the launch window.

Launch this file and test speech recognition by monitoring the `/recognizer/output` topic. First type `Ctrl-C` to terminate the earlier RoboCup demo if it is still running. Then run the commands:

```
$ rosrun rbx1_speech voice_nav_commands.launch
```

And in a separate terminal:

```
$ rostopic echo /recognizer/output
```

Try saying a few navigation phrases such as "move forward", "slow down" and "stop". You should see your commands echoed on the `/recognizer/output` topic.

9.4 A Voice-Control Navigation Script

The `recognizer.py` node in the `pocketsphinx` package publishes recognized speech commands to the `/recognizer/output` topic. To map these commands to robot actions, we need a second node that subscribes to this topic, looks for appropriate messages, then causes the robot to execute different behaviors depending on the message received. To get us started, Michael Ferguson includes a Python script called `voice_cmd_vel.py` in the `pocketsphinx` package that maps voice commands into `Twist` messages that can be used to control a mobile robot. We will use a slightly modified version of this script called `voice_nav.py` found in the `rbx1_speech/nodes` subdirectory.

Let's now look at the `voice_nav.py` script.

Link to SVN source: [voice_nav.py](#)

```
1  #!/usr/bin/env python
2
3 """
4     Based on the voice_cmd_vel.py script by Michael Ferguson in
5     the pocketsphinx ROS package.
6
7     See http://www.ros.org/wiki/pocketsphinx
8 """
9
10 import roslib; roslib.load_manifest('rbx1_speech')
11 import rospy
12 from geometry_msgs.msg import Twist
13 from std_msgs.msg import String
14 from math import copysign
15
16 class VoiceNav:
17     def __init__(self):
18         rospy.init_node('voice_nav')
19
20         rospy.on_shutdown(self.cleanup)
21
22         # Set a number of parameters affecting the robot's speed
23         self.max_speed = rospy.get_param("~max_speed", 0.4)
24         self.max_angular_speed = rospy.get_param("~max_angular_speed", 1.5)
25         self.speed = rospy.get_param("~start_speed", 0.1)
26         self.angular_speed = rospy.get_param("~start_angular_speed", 0.5)
27         self.linear_increment = rospy.get_param("~linear_increment", 0.05)
28         self.angular_increment = rospy.get_param("~angular_increment", 0.4)
29
30         # We don't have to run the script very fast
31         self.rate = rospy.get_param("~rate", 5)
32         r = rospy.Rate(self.rate)
33
34         # A flag to determine whether or not voice control is paused
35         self.paused = False
36
37         # Initialize the Twist message we will publish.
```

```

38         self.cmd_vel = Twist()
39
40         # Publish the Twist message to the cmd_vel topic
41         self.cmd_vel_pub = rospy.Publisher('cmd_vel', Twist)
42
43         # Subscribe to the /recognizer/output topic to receive voice commands.
44         rospy.Subscriber('/recognizer/output', String, self.speech_callback)
45
46         # A mapping from keywords or phrases to commands
47         self.keywords_to_command = {'stop': ['stop', 'halt', 'abort', 'kill',
48                                         'panic', 'off', 'freeze', 'shut down', 'turn off', 'help',
49                                         'help me'],
50                                         'slower': ['slow down', 'slower'],
51                                         'faster': ['speed up', 'faster'],
52                                         'forward': ['forward', 'ahead'],
53                                         'backward': ['back', 'backward', 'back
54                                         up'],
55                                         'rotate left': ['rotate left'],
56                                         'rotate right': ['rotate right'],
57                                         'turn left': ['turn left'],
58                                         'turn right': ['turn right'],
59                                         'quarter': ['quarter speed'],
59                                         'half': ['half speed'],
59                                         'full': ['full speed'],
59                                         'pause': ['pause speech'],
59                                         'continue': ['continue speech']}
60
61
62         rospy.loginfo("Ready to receive voice commands")
63
64         # We have to keep publishing the cmd_vel message if we want
65         # the robot to keep moving.
66         while not rospy.is_shutdown():
67             self.cmd_vel_pub.publish(self.cmd_vel)
68             r.sleep()
69
70     def get_command(self, data):
71         # Attempt to match the recognized word or phrase to the
72         # keywords_to_command dictionary and return the appropriate
73         # command
74         for (command, keywords) in self.keywords_to_command.iteritems():
75             for word in keywords:
76                 if data.find(word) > -1:
77                     return command
78
79     def speech_callback(self, msg):
80         # Get the motion command from the recognized phrase
81         command = self.get_command(msg.data)
82
83         # Log the command to the screen
84         rospy.loginfo("Command: " + str(command))
85
86         # If the user has asked to pause/continue voice control,
87         # set the flag accordingly
88         if command == 'pause':
89             self.paused = True
90         elif command == 'continue':
91             self.paused = False

```

```

91         # If voice control is paused, simply return without
92         # performing any action
93         if self.paused:
94             return
95
96         # The list of if-then statements should be fairly
97         # self-explanatory
98         if command == 'forward':
99             self.cmd_vel.linear.x = self.speed
100            self.cmd_vel.angular.z = 0
101
102        elif command == 'rotate left':
103            self.cmd_vel.linear.x = 0
104            self.cmd_vel.angular.z = self.angular_speed
105
106        elif command == 'rotate right':
107            self.cmd_vel.linear.x = 0
108            self.cmd_vel.angular.z = -self.angular_speed
109
110        elif command == 'turn left':
111            if self.cmd_vel.linear.x != 0:
112                self.cmd_vel.angular.z += self.angular_increment
113            else:
114                self.cmd_vel.angular.z = self.angular_speed
115
116        elif command == 'turn right':
117            if self.cmd_vel.linear.x != 0:
118                self.cmd_vel.angular.z -= self.angular_increment
119            else:
120                self.cmd_vel.angular.z = -self.angular_speed
121
122        elif command == 'backward':
123            self.cmd_vel.linear.x = -self.speed
124            self.cmd_vel.angular.z = 0
125
126        elif command == 'stop':
127            # Stop the robot! Publish a Twist message consisting of all
128            # zeros.
129            self.cmd_vel = Twist()
130
131        elif command == 'faster':
132            self.speed += self.linear_increment
133            self.angular_speed += self.angular_increment
134            if self.cmd_vel.linear.x != 0:
135                self.cmd_vel.linear.x += copysign(self.linear_increment,
136                self.cmd_vel.linear.x)
136            if self.cmd_vel.angular.z != 0:
137                self.cmd_vel.angular.z += copysign(self.angular_increment,
138                self.cmd_vel.angular.z)
139        elif command == 'slower':
140            self.speed -= self.linear_increment
141            self.angular_speed -= self.angular_increment
142            if self.cmd_vel.linear.x != 0:
143                self.cmd_vel.linear.x -= copysign(self.linear_increment,
144                self.cmd_vel.linear.x)

```

```

144         if self.cmd_vel.angular.z != 0:
145             self.cmd_vel.angular.z -= copysign(self.angular_increment,
146             self.cmd_vel.angular.z)
146
147         elif command in ['quarter', 'half', 'full']:
148             if command == 'quarter':
149                 self.speed = copysign(self.max_speed / 4, self.speed)
150
151             elif command == 'half':
152                 self.speed = copysign(self.max_speed / 2, self.speed)
153
154             elif command == 'full':
155                 self.speed = copysign(self.max_speed, self.speed)
156
157             if self.cmd_vel.linear.x != 0:
158                 self.cmd_vel.linear.x = copysign(self.speed,
159                 self.cmd_vel.linear.x)
159
160             if self.cmd_vel.angular.z != 0:
161                 self.cmd_vel.angular.z = copysign(self.angular_speed,
162                 self.cmd_vel.angular.z)
162
163         else:
164             return
165
166         self.cmd_vel.linear.x = min(self.max_speed, max(-self.max_speed,
167             self.cmd_vel.linear.x))
167         self.cmd_vel.angular.z = min(self.max_angular_speed, max(-
168             self.max_angular_speed, self.cmd_vel.angular.z))
168
169     def cleanup(self):
170         # When shutting down be sure to stop the robot!
171         twist = Twist()
172         self.cmd_vel_pub.publish(twist)
173         rospy.sleep(1)
174
175 if __name__ == "__main__":
176     try:
177         VoiceNav()
178         rospy.spin()
179     except rospy.ROSInterruptException:
180         rospy.loginfo("Voice navigation terminated.")

```

The script is fairly straightforward and heavily commented so we will only describe the highlights.

```

46         # A mapping from keywords or phrases to commands
47         self.keywords_to_command = {'stop': ['stop', 'halt', 'abort', 'kill',
48             'panic', 'off', 'freeze', 'shut down', 'turn off', 'help',
49             'help me'],
50             'slower': ['slow down', 'slower'],
51             'faster': ['speed up', 'faster'],
52             'forward': ['forward', 'ahead',
53             'straight'],
54             'backward': ['back', 'backward', 'back
55             up']},

```

```

52             'rotate left': ['rotate left'],
53             'rotate right': ['rotate right'],
54             'turn left': ['turn left'],
55             'turn right': ['turn right'],
56             'quarter': ['quarter speed'],
57             'half': ['half speed'],
58             'full': ['full speed'],
59             'pause': ['pause speech'],
60             'continue': ['continue speech']}
61

```

The `keywords_to_command` Python dictionary allows us to map different verbal works and phrases into the same action. For example, it is really important to be able to stop the robot once it is moving. However, the word "stop" is not always recognized by the PocketSphinx recognizer. So we provide a number of alternative ways of telling the robot to stop like "halt", "abort", "help", etc. Of course, these alternatives must be included in our original PocketSphinx vocabulary (corpus).

The `voice_nav.py` node subscribes to the `/recognizer/output` topic and looks for recognized keywords as specified in the `nav_commands.txt` corpus. If a match is found, the `keywords_to_commands` dictionary maps the matched phrase to an appropriate command word. Our callback function then maps the command word to the appropriate `Twist` action sent to the robot.

Another feature of the `voice_nav.py` script is that it will respond to the two special commands "pause speech" and "continue speech". If you are voice controlling your robot, but you would like to say something to another person without the robot interpreting your words as movement commands, just say "pause speech". When you want to continue controlling the robot, say "continue speech".

9.4.1 Testing Voice-Control in the ArbotiX Simulator

Before using voice navigation with a real robot, let's give it a try in the ArbotiX simulator. First fire up the fake TurtleBot as we have done before:

```
$ rosrun roslaunch rbx1 Bringup fake_turtlebot.launch
```

Next, bring up RViz with the simulation config file:

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/sim_fuerte.vcg
```

Let's also use rxconsole to more easily monitor the output of the voice navigation script. In particular, this will allow us to view the commands the script recognizes:

```
$ rxconsole
```

Before running the voice navigation script, check your **Sound Settings** as described earlier to make sure your microphone is still set as the **Input** device. Now run the `voice_nav_commands.launch` and `turtlebot_voice_nav.launch` files:

```
$ rosrun rbx1_speech voice_nav_commands.launch
```

and in another terminal:

```
$ rosrun rbx1_speech turtlebot_voice_nav.launch
```

You should now be able to use voice commands to move the fake TurtleBot around in RViz. For example, try the commands "rotate left", "move forward", "full speed", "halt", and so on. Here is the list of voice commands again for easy reference:

pause speech	come forward	stop
continue speech	come backward	stop now
move forward	come left	halt
move backward	come right	abort
move back	turn left	kill
move left	turn right	panic
move right	rotate left	help
go forward	rotate right	help me
go backward	faster	freeze
go back	speed up	turn off
go left	slower	shut down
go right	slow down	cancel
go straight	quarter speed	
	half speed	
	full speed	

You can also try the two special commands, "pause speech" and "continue speech" to see if you can turn voice control off and on again.

9.4.2 Using Voice-Control with a Real Robot

To voice control a TurtleBot, move the robot into an open space free of obstacles, then start the `turtlebot.launch` file on the TurtleBot's laptop:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

If it's not already running, bring up `rxconsole` to more easily monitor the output of the voice navigation script:

```
$ rxconsole
```

Before running the voice navigation script, check your **Sound Settings** as described earlier to make sure your microphone is still set as the **Input** device. On your

workstation computer, run the `voice_nav_commands.launch` and `turtlebot_voice_nav.launch` files:

```
$ rosrun rbx1_speech voice_nav_commands.launch
```

and in another terminal:

```
$ rosrun rbx1_speech turtlebot_voice_nav.launch
```

Try a relatively safe voice command first such as "rotate right". Refer to the list of commands above for different ways you can move the robot. The `turtlebot_voice_nav.launch` file includes parameters you can set that determine the maximum speed of the TurtleBot as well as the increments used when you say "go faster" or "slow down".

The following video presents a short demonstration of the script running on a modified TurtleBot: http://www.youtube.com/watch?v=10ysYZUX_jA

9.5 Installing and Testing Festival Text-to-Speech

Now that we can talk to our robot, it would be nice if it could talk back to us. Text-to-speech (TTS) is accomplished using the CMU Festival system together with the ROS `sound_play` package. If you have followed this chapter from the beginning, you have already done the following step. Otherwise, run it now. You will be prompted to install the Festival packages if you don't already have them—answer "Y" of course:

```
$ sudo apt-get install ros-fuerte-audio-common  
$ sudo apt-get install libasound2
```

The `sound_play` package uses the CMU Festival TTS library to generate synthetic speech. Let's test it out with the default voice as follows. First fire up the primary `sound_play` node:

```
$ rosrun sound_play soundplay_node.py
```

In another terminal, enter some text to be converted to voice:

```
$ rosrun sound_play say.py "Greetings Humans. Take me to your leader."
```

The default voice is called `kal_diphone`. To see all the English voices currently installed on your system:

```
$ ls /usr/share/festival/voices/english
```

To get a list of all basic Festival voices available, run the following command:

```
$ sudo apt-cache search --names-only festvox-*
```

To install the `festvox-don` voice (for example), run the command:

```
$ sudo apt-get install festvox-don
```

And to test out your new voice, add the voice name to the end of the command line like this:

```
$ rosrun sound_play say.py "Welcome to the future" voice_don_diphone
```

There aren't a huge number of voices to choose from, but a few additional voices can be installed [as described here](#) and [demonstrated here](#). Here are the steps to get and use two of those voices, one male and one female:

```
$ sudo apt-get install festlex-cmu
$ cd /usr/share/festival/voices/english/
$ sudo wget -c \
  http://www.speech.cs.cmu.edu/cmu_arctic/packed/cmu_us_clb_arctic\
-0.95-release.tar.bz2
$ sudo wget -c \
  http://www.speech.cs.cmu.edu/cmu_arctic/packed/cmu_us_bdl_arctic\
-0.95-release.tar.bz2
$ sudo tar jxfv cmu_us_clb_arctic-0.95-release.tar.bz2
$ sudo tar jxfv cmu_us_bdl_arctic-0.95-release.tar.bz2
$ sudo rm cmu_us_clb_arctic-0.95-release.tar.bz2
$ sudo rm cmu_us_bdl_arctic-0.95-release.tar.bz2
$ sudo ln -s cmu_us_clb_arctic cmu_us_clb_arctic_clunits
$ sudo ln -s cmu_us_bdl_arctic cmu_us_bdl_arctic_clunits
```

You can test these two voices like this:

```
$ rosrun sound_play say.py "I am speaking with a female C M U voice" \
  voice_cmu_us_clb_arctic_clunits
$ rosrun sound_play say.py "I am speaking with a male C M U voice" \
  voice_cmu_us_bdl_arctic_clunits
```

NOTE: If you don't hear the phrase on the first try, try re-running the command. Also, remember that a `sound_play` node must already be running in another terminal.

You can also use `sound_play` to play wave files or a number of built-in sounds. To play the R2D2 wave file in the `rbx1_speech/sounds` directory, use the command:

```
$ rosrun sound_play play.py `rospack find rbx1_speech`/sounds/R2D2a.wav
```

Note that the `play.py` script requires the absolute path to the wave file which is why we used '`rospack find`'. You could also just type out the full path name.

To hear one of the built-in sounds, use the `playbuiltin.py` script together with a number from 1 to 5; for example:

```
$ rosrun sound_play playbuiltin.py 4
```

9.5.1 Using Text-to-Speech within a ROS Node

So far we have only used the Festival voices from the command line. To see how to use text-to-speech from within a ROS node, let's take a look at the `talkback.py` script that can be found in the `rbx1_speech/nodes` directory.

Link to SVN source: [talkback.py](#)

```
1. #!/usr/bin/env python
2. import roslib; roslib.load_manifest('rbx1_speech')
3. import rospy
4. from std_msgs.msg import String
5. from sound_play.libsoundplay import SoundClient
6. import sys
7.
8. class TalkBack:
9.     def __init__(self, script_path):
10.         rospy.init_node('talkback')
11.
12.         rospy.on_shutdown(self.cleanup)
13.
14.         # Set the default TTS voice to use
15.         self.voice = rospy.get_param("~voice", "voice_don_diphone")
16.
17.         # Set the wave file path if used
18.         self.wavepath = rospy.get_param("~wavepath", script_path +
19.                                         "/../sounds")
20.
21.         # Create the sound client object
22.         self.soundhandle = SoundClient()
23.
24.         # Wait a moment to let the client connect to the
25.         # sound_play server
26.         rospy.sleep(1)
27.
28.         # Make sure any lingering sound_play processes are stopped.
29.         self.soundhandle.stopAll()
30.
31.         # Announce that we are ready for input
32.         self.soundhandle.playWave(self.wavepath + "/R2D2a.wav")
33.         rospy.sleep(1)
34.         self.soundhandle.say("Ready", self.voice)
```

```

35.         rospy.loginfo("Say one of the navigation commands...")
36.
37.         # Subscribe to the recognizer output and set the callback
38.         function
39.         rospy.Subscriber('/recognizer/output', String, self.talkback)
40.
41.     def talkback(self, msg):
42.         # Print the recognized words on the screen
43.         rospy.loginfo(msg.data)
44.
45.         # Speak the recognized words in the selected voice
46.         self.soundhandle.say(msg.data, self.voice)
47.
48.         # Uncomment to play one of the built-in sounds
49.         #rospy.sleep(2)
50.         #self.soundhandle.play(5)
51.
52.         # Uncomment to play a wave file
53.         #rospy.sleep(2)
54.         #self.soundhandle.playWave(self.wavepath + "/R2D2a.wav")
55.
56.     def cleanup(self):
57.         self.soundhandle.stopAll()
58.         rospy.loginfo("Shutting down talkback node...")
59.
60. if __name__ == "__main__":
61.     try:
62.         TalkBack(sys.path[0])
63.         rospy.spin()
64.     except rospy.ROSInterruptException:
65.         rospy.loginfo("AMCL navigation test finished.")

```

Let's look at the key lines of the script.

```
5. from sound_play.libsoundplay import SoundClient
```

The script talks to the `sound_play` server using the `SoundClient` class which we import from the `sound_play` library.

```
15.         self.voice = rospy.get_param("~voice", "voice_don_diphone")
```

Set the Festival voice for text-to-speech. This can be overridden in the launch file.

```
18.         self.wavepath = rospy.get_param("~wavepath", script_path +
19.                                         "../sounds")
```

Set the path for reading wave files. The `sound_play` client and server need the full path to wave files so we read in the `script_path` from the `sys.path[0]` environment variable (see the `"__main__"` block toward the end of the script.)

```
21.         self.soundhandle = SoundClient()
```

Create a handle to the `SoundClient()` object.

```
30.         self.soundhandle.playWave(self.wavepath + "/R2D2a.wav")
31.         rospy.sleep(1)
32.         self.soundhandle.say("Ready", self.voice)
```

Use the `self.soundhandle` object to play a short wave file (R2D2 sound) and speak "Ready" in the default voice.

```
40.     def talkback(self, msg):
41.         # Print the recognized words on the screen
42.         rospy.loginfo(msg.data)
43.
44.         # Speak the recognized words in the selected voice
45.         self.soundhandle.say(msg.data, self.voice)
```

This is our callback when receiving messages on the `/recognizer/output` topic. The `msg` variable holds the text spoken by the user as recognized by the PocketSphinx node. As you can see, we simply echo the recognized text back to the terminal as well as speak it using the default voice.

To learn more about the `SoundClient` object, take a look at the [libsoundplay API](#) on the ROS Wiki.

9.5.2 Testing the `talkback.py` script

You can test the script using the `talkback.launch` file. The launch file first brings up the PocketSphinx `recognizer` node and loads the navigation phrases. Then the `sound_play` node is launched, followed by the `talkback.py` script. So first terminate any `sound_play` node you might still have running, then run the command:

```
$ roslaunch rbx1_speech talkback.launch
```

Now try saying one of the voice navigation commands we used earlier such as "move right" and you should hear it echoed back by the TTS voice.

You should now be able to write your own script that combines speech recognition and text-to-speech. For example, see if you can figure out how to ask your robot the date and time and get back the answer from the system clock.

10. ROBOT VISION

One might say that we are living in a golden age for computer vision. Webcams are cheap and depth cameras like the Microsoft Kinect and Asus Xtion allow even a hobby roboticist to work with 3D vision without breaking the bank on an expensive stereo camera. But getting the pixels and depth values into your computer is just the beginning. Using that data to extract useful information about the visual world is a challenging mathematical problem. Fortunately for us, decades of research by thousands of scientists has yielded powerful vision algorithms from simple color matching to people detectors that we can use without having to start from scratch.

The overall goal of machine vision is to recognize the structure of the world behind the changing pixel values. Individual pixels are in a continual state of flux due to changes in lighting, viewing angle, object motion, occlusions and random noise. So computer vision algorithms are designed to extract more stable *features* from these changing values. Features might be corners, edges, blobs, colors, motion patches, etc. Once a set of robust features can be extracted from an image or video stream, they can be tracked or grouped together into larger patterns to support object detection and recognition.

10.1 OpenCV, OpenNI and PCL

The three pillars of computer vision in the ROS community are [OpenCV](#), [OpenNI](#) and [PCL](#). OpenCV is used for 2D image processing and machine learning. OpenNI provides drivers and a "Natural Interaction" library for skeleton tracking using depth cameras such as the Kinect and Xtion. And PCL, or Point Cloud Library, is the library of choice for processing 3D point clouds. In this book, we will focus on OpenCV but we will also provide a brief introduction to OpenNI and PCL. (For those readers already familiar with OpenCV and PCL, you might also be interested in [Ecto](#), a new vision framework from Willow Garage that allows one to access both libraries through a common interface.)

In this chapter we will learn how to:

- connect to a webcam or RGB-D (depth) camera using ROS
- use the ROS `cv_bridge` utility for processing ROS image streams with OpenCV
- write ROS programs to detect faces, track keypoints using optical flow, and follow objects of a particular color
- track a user's skeleton using an RGB-D camera and OpenNI

- detect the nearest person using PCL

10.2 A Note about Camera Resolutions

Most video cameras used in robotics can be run at various resolutions, typically 160x120 (QQVGA), 320x240 (QVGA), 640x480 (VGA) and sometimes as high as 1280x960 (SXGA). It is often tempting to set the camera to the highest resolution possible under the assumption that more detail is better. However, more pixels come at the cost of more computation per frame. For example, each frame of a 640x480 video contains four times as many pixels as a 320x240 video. That means four times as many operations per frame for most kinds of basic image processing. If your CPU and graphics processor are already maxed out when processing a 320x240 video at 20 frames per second (fps), you will be lucky to get 5 fps for a 640x480 video which is really too slow for most mobile robots.

Experience shows that a resolution of 320x240 (QVGA) produces a good balance between image detail and computational load. Anything less and functions like face detection tend to fail due to the lack of detail. Anything more and you will probably suffer from insufficient frame rates and delays in other processes you may need to run at the same time. Consequently, the camera launch files used in this book set the resolution to 320x240. Of course, if you have a ripping fast PC controlling your robot, by all means use the highest resolution that still gives you good performance.

10.3 Installing and Testing the ROS Camera Drivers

If you haven't done so already, install the drivers necessary for your camera following the instructions below.

10.3.1 Installing the OpenNI Drivers

To install the ROS OpenNI drivers for the Microsoft Kinect or Asus Xtion, use the command:

```
$ sudo apt-get install ros-fuerte-openni-kinect
```

That's all there is to it!

10.3.2 Installing Webcam Drivers

To use a typical USB webcam, there are a number of possible driver packages available. The one we will use here is from Eric Perko's repository. Type the following commands to move into your personal ROS directory, retrieve the source code, then make the package:

```
$ cd ~/ros_workspace  
$ sudo apt-get install git-core  
$ git clone https://github.com/ericperko/uvc_cam.git  
$ rosmake uvc_cam
```

IMPORTANT: If you were using an earlier version of the `uvc_cam` package with ROS Electric, be sure to get and rebuild the latest version as follows:

```
$ rosdep uvc_cam  
$ git pull  
$ rosmake --pre-clean
```

10.3.3 Testing your Kinect or Xtion Camera

Once you have the OpenNI driver installed, make sure you can see the video stream from the camera by using the ROS [image_view](#) package. For the Kinect or Xtion, first plug the camera in to any available USB port (and for the Kinect, make sure it has power through its 12V adapter or other means), then run the following launch file:

```
$ rosrun rbt_vision openni_node_fuerte.launch
```

If the connection to the camera is successful, you should see a series of diagnostic messages that look something like this:

```
[ INFO] [1351944239.583545882]: [/openni_launch] Number devices connected: 1  
[ INFO] [1351944239.583827140]: [/openni_launch] 1. device on bus 002:115 is a PrimeSense Device (600) from PrimeSense (1d27) with serial id ''  
[ WARN] [1351944239.586388840]: [/openni_launch] device_id is not set! Using first device.  
[ INFO] [1351944239.630797390]: [/openni_launch] Opened 'PrimeSense Device' on bus 2:115 with serial number ''  
[ INFO] [1351944239.655877799]: rgb_frame_id = 'camera_rgb_optical_frame'  
[ INFO] [1351944239.659900166]: depth_frame_id = 'camera_depth_optical_frame'
```

Next, use the ROS `image_view` utility to view the RGB video stream. We have set up our camera launch files so that the color video stream is published on the ROS topic `/camera/rgb/image_color`. To view the video, we therefore run:

```
$ rosrun image_view image_view image:=/camera/rgb/image_color
```

A small camera display window should pop up and after a brief delay, you should see the live video stream from your camera. Move something in front of the camera to verify that the image updates appropriately. Once you are satisfied, type `Ctrl-C` in the `image_view` window to close it.

You can also test the depth image from your camera using the ROS `disparity_view` node:

```
$ rosrun image_view disparity_view image:=/camera/depth/disparity
```

In this case, the resulting colors in the image represent depth, with yellow/green indicating points closer to the camera and blue/violet representing points further away.

10.3.4 Testing your USB Webcam

For a USB camera, we need to specify the video device we want to use. If your computer has an internal camera (as many laptop's do), it will likely be on `/dev/video0` while an externally attached USB camera will probably be on `/dev/video1`. Be sure to `Ctrl-C` out of the `openni_node_fuerte.launch` file from the previous section if it is still running, then run the appropriate command below depending on your webcam's video device:

```
$ roslaunch rbx1_vision uvc_cam.launch device:=/dev/video0
```

or

```
$ roslaunch rbx1_vision uvc_cam.launch device:=/dev/video1
```

depending on the camera you want use. If the connection is successful, you should see a stream of diagnostic messages describing various camera settings. Don't worry if some of these messages indicate that a parameter could not be set.

Next, use the ROS `image_view` utility to view the basic video stream. We have set up our camera launch files so that the color video stream is published on the ROS topic `/camera/rgb/image_color`. To view the video, we therefore run:

```
$ rosrun image_view image_view image:=/camera/rgb/image_color
```

A small camera display window should pop up and, after a brief delay, you should see the live video stream from your camera. Move something in front of the camera to verify that the image updates appropriately.

NOTE: By default, the `uvc_cam` node publishes the image on the topic `/camera/image_raw`. Our launch file `uvc_cam.launch` remaps the topic to `/camera/rgb/image_color` which is the topic used by the `openni` driver for depth cameras. This way we can use the same code below for either type of camera.

10.4 Installing OpenCV on Ubuntu Linux

The easiest way to install OpenCV under Ubuntu Linux is to get the Debian packages. At the time of this writing, the latest version is 2.4 which can be installed with the following command:

```
$ sudo apt-get install ros-fuerte-opencv2 ros-fuerte-vision-opencv
```

If you need a feature found only in the latest version, you can compile the library from source. Instructions can be found here:

<http://opencv.willowgarage.com/wiki/InstallGuide>.

To check your installation, try the following commands:

```
$ python
>>> from cv2 import cv
>>> quit()
```

Assuming you do not get an import error, you should be ready to go and you can skip to the next section. If instead you get an error of the form:

```
ImportError: No module named cv2
```

then either OpenCV is not installed properly or your Python path is not set correctly. The OpenCV Python library is stored in the file `cv2.so`. To verify that it is installed, run the command:

```
$ locate cv2.so | grep python
```

You should get an output similar to:

```
/usr/lib/pymodules/python2.7/cv2.so
/usr/lib/pyshared/python2.7/cv2.so
```

although the exact paths may be different. Next, make sure that at least one of these paths is in your `PYTHONPATH` environment variable. To see its current setting, run the command:

```
$ printenv PYTHONPATH
```

If the path includes one of the directories containing `cv2.so` then you should be OK. If not, edit your `~/.bashrc` file and add the appropriate directory to the `PYTHONPATH` variable. Then run the command:

```
$ source ~/.bashrc
```

and try the import test again as described above.

10.5 ROS to OpenCV: The `cv_bridge` Package

With the camera drivers up and running, we now need a way to process ROS video streams using OpenCV. ROS provides the `cv_bridge` utility to convert between ROS and OpenCV and image formats. The Python script `cv_bridge.demo.py` in the `rbx1_vision/nodes` directory demonstrates how to use `cv_bridge`. Before we look at the code, you can try it out as follows.

If you have a Kinect or Xtion, make sure you first run the OpenNI driver if it is not already running:

```
$ rosrun rbt_vision openni_node_fuerte.launch
```

or, for a webcam:

```
$ rosrun rbt_vision uvc_cam.launch device:=/dev/video0
```

(Change the video device is necessary.)

Now run the `cv_bridge_demo.py` node:

```
$ rosrun rbt_vision cv_bridge_demo.py
```

After a brief delay, you should see two image windows appear. The window on the top shows the live video after been converted to greyscale then sent through OpenCV blur and edge filters. The window on the bottom shows a greyscale depth image where white pixels are further away and dark grey pixels are closer to the camera. (This window will remain blank if you are using an ordinary webcam.) To exit the demo, either type the letter "q" with the mouse over one of the windows or `Ctrl-C` in the terminal where you launched the demo script.

Let's now look at the code to see how it works.

Link to SVN source: [cv_bridge_demo.py](#)

```
1.  #!/usr/bin/env python
2.  import roslib; roslib.load_manifest('rbt_vision')
3.  import rospy
4.  import sys
5.  import cv2
6.  import cv2.cv as cv
7.  from sensor_msgs.msg import Image, CameraInfo
8.  from cv_bridge import CvBridge, CvBridgeError
9.  import numpy as np
10.
11. class cvBridgeDemo():
12.     def __init__(self):
13.         self.node_name = "cv_bridge_demo"
```

```

14.         rospy.init_node(self.node_name)
15.
16.         # What we do during shutdown
17.         rospy.on_shutdown(self.cleanup)
18.
19.
20.         # Create the OpenCV display window for the RGB image
21.         self.cv_window_name = self.node_name
22.         cv.NamedWindow(self.cv_window_name, cv.CV_WINDOW_NORMAL)
23.         cv.MoveWindow(self.cv_window_name, 25, 75)
24.
25.         # And one for the depth image
26.         cv.NamedWindow("Depth Image", cv.CV_WINDOW_NORMAL)
27.         cv.MoveWindow("Depth Image", 25, 350)
28.
29.         # Create the cv_bridge object
30.         self.bridge = CvBridge()
31.
32.         # Subscribe to the camera image and depth topics and set
33.         # the appropriate callbacks
34.         self.image_sub = rospy.Subscriber("/camera/rgb/image_color",
35.                                         Image, self.image_callback)
36.         self.depth_sub = rospy.Subscriber("/camera/depth/image_raw",
37.                                         Image, self.depth_callback)
38.
39.         rospy.loginfo("Waiting for image topics...")
40.
41.     def image_callback(self, ros_image):
42.         # Use cv_bridge() to convert the ROS image to OpenCV format
43.         try:
44.             frame = self.bridge.imgmsg_to_cv(ros_image, "bgr8")
45.         except CvBridgeError, e:
46.             print e
47.
48.         # Convert the image to a Numpy array since most cv2 functions
49.         # require Numpy arrays.
50.         frame = np.array(frame, dtype=np.uint8)
51.
52.         # Process the frame using the process_image() function
53.         display_image = self.process_image(frame)
54.
55.         # Display the image.
56.         cv2.imshow(self.node_name, display_image)
57.
58.         # Process any keyboard commands
59.         self.keystroke = cv.WaitKey(5)
60.         if 32 <= self.keystroke and self.keystroke < 128:
61.             cc = chr(self.keystroke).lower()
62.             if cc == 'q':
63.                 # The user has press the q key, so exit
64.                 rospy.signal_shutdown("User hit q key to quit.")
65.
66.     def depth_callback(self, ros_image):
67.         # Use cv_bridge() to convert the ROS image to OpenCV format
68.         try:
69.             # The depth image is a single-channel float32 image
70.             depth_image = self.bridge.imgmsg_to_cv(ros_image, "32FC1")

```

```

71.         except CvBridgeError, e:
72.             print e
73.
74.             # Convert the depth image to a Numpy array since most cv2
functions
75.             # require Numpy arrays.
76.             depth_array = np.array(depth_image, dtype=np.float32)
77.
78.             # Normalize the depth image to fall between 0 and 1
79.             cv2.normalize(depth_array, depth_array, 0, 1, cv2.NORM_MINMAX)
80.
81.             # Process the depth image
82.             depth_display_image = self.process_depth_image(depth_array)
83.
84.             # Display the result
85.             cv2.imshow("Depth Image", depth_display_image)
86.
87.     def process_image(self, frame):
88.         # Convert to greyscale
89.         grey = cv2.cvtColor(frame, cv.CV_BGR2GRAY)
90.
91.         # Blur the image
92.         grey = cv2.blur(grey, (7, 7))
93.
94.         # Compute edges using the Canny edge filter
95.         edges = cv2.Canny(grey, 15.0, 30.0)
96.
97.         return edges
98.
99.     def process_depth_image(self, frame):
100.        # Just return the raw image for this demo
101.        return frame
102.
103.    def cleanup(self):
104.        print "Shutting down vision node."
105.        cv2.destroyAllWindows()
106.
107.    def main(args):
108.        try:
109.            cvBridgeDemo()
110.            rospy.spin()
111.        except KeyboardInterrupt:
112.            print "Shutting down vision node."
113.            cv.DestroyAllWindows()
114.
115.        if __name__ == '__main__':
116.            main(sys.argv)

```

Let's take a look at the key lines in this script.

```

5. import cv2
6. import cv2.cv as cv
7. from sensor_msgs.msg import Image, CameraInfo
8. from cv_bridge import CvBridge, CvBridgeError
9. import numpy as np

```

All of our OpenCV scripts will import the `cv2` library as well as the older pre-`cv2` functions found in `cv2.cv`. We will also usually need the ROS message types `Image` and `CameraInfo` from the `sensor_msgs` package. For a node that needs to convert ROS image format to OpenCV, we need the `CvBridge` and `CvBridgeError` classes from the ROS `cv_bridge` package. Finally, OpenCV does most of its image processing using Numpy arrays, so we almost always need access to the Python `numpy` module.

```
20.      # Create the OpenCV display window for the RGB image
21.      self.cv_window_name = self.node_name
22.      cv.NamedWindow(self.cv_window_name, cv.CV_WINDOW_NORMAL)
23.      cv.MoveWindow(self.cv_window_name, 25, 75)
24.
25.      # And one for the depth image
26.      cv.NamedWindow("Depth Image", cv.CV_WINDOW_NORMAL)
27.      cv.MoveWindow("Depth Image", 25, 350)
```

If you are already familiar with OpenCV, you'll recognize these statements that create named display windows for monitoring video streams; in this case, one window for the regular RGB video and one for the depth image if we are using an RGB-D camera. We also move the windows so that the depth window lies below the RGB window.

```
30.      self.bridge = CvBridge()
```

This is how we create the `CvBridge` object to be used later to convert ROS images to OpenCV format.

```
34.      self.image_sub = rospy.Subscriber("/camera/rgb/image_color",
35.                                         Image, self.image_callback)
36.      self.depth_sub = rospy.Subscriber("/camera/depth/image_raw",
37.                                         Image, self.depth_callback)
```

These are the two key subscribers, one for the RGB image stream and one for the depth image. Normally we would not hard code the topic names so that they can be remapped in the appropriate launch file but for the demo we'll use the default topic names used by the `openni` node. As with all subscribers, we assign the callback functions for doing the actual work on the images.

```
41.      def image_callback(self, ros_image):
42.          # Use cv_bridge() to convert the ROS image to OpenCV format
43.          try:
44.              frame = self.bridge.imgmsg_to_cv(ros_image, "bgr8")
45.          except CvBridgeError, e:
46.              print e
```

This is the start of our callback function for the RGB image. ROS provides the image as the first argument which we have called `ros_image`. The `try-except` block then uses the `imgmsg_to_cv` function to convert the image to OpenCV format assuming a blue/green/red 8-bit conversion.

```

50.         frame = np.array(frame, dtype=np.uint8)
51.
52.         # Process the frame using the process_image() function
53.         display_image = self.process_image(frame)
54.
55.         # Display the image.
56.         cv2.imshow(self.node_name, display_image)

```

Most OpenCV functions require the image to be converted to a Numpy array so we make the conversion here. Then we send the image array to the `process_image()` function which we will describe below. The result is a new image called `display_image` which is displayed in our previously-created display window using the OpenCV `imshow()` function.

```

58.         # Process any keyboard commands
59.         self.keystroke = cv.WaitKey(5)
60.         if 32 <= self.keystroke and self.keystroke < 128:
61.             cc = chr(self.keystroke).lower()
62.             if cc == 'q':
63.                 # The user has press the q key, so exit
64.                 rospy.signal_shutdown("User hit q key to quit.")

```

Finally, we look for keyboard input from the user. In this case, we only look for a key press of the letter "q" which signals that we want to terminate the script.

```

64.     def depth_callback(self, ros_image):
65.         # Use cv_bridge() to convert the ROS image to OpenCV format
66.         try:
67.             # The depth image is a single-channel float32 image
68.             depth_image = self.bridge.imgmsg_to_cv(ros_image, "32FC1")
69.         except CvBridgeError, e:
70.             print e

```

The depth callback begins similar to the image callback described earlier. The first difference we notice is that we use a conversion to a single-channel 32-bit float (32FC1) instead of the 3-channel 8 bit color conversion used for the RGB image.

```

76.         depth_array = np.array(depth_image, dtype=np.float32)
77.
78.         # Normalize the depth image to fall between 0 and 1
79.         cv2.normalize(depth_array, depth_array, 0, 1, cv2.NORM_MINMAX)

```

After converting the image to a Numpy array, we normalize to the interval [0, 1] since OpenCV's `imshow()` function can display greyscale images when the pixel values lie between 0 and 1.

```

82.         depth_display_image = self.process_depth_image(depth_array)
83.
84.         # Display the result
85.         cv2.imshow("Depth Image", depth_display_image)

```

The depth array is sent to the `process_depth_image()` function for further processing (if desired) and the result is displayed in the depth image window created earlier.

```
87.     def process_image(self, frame):
88.         # Convert to greyscale
89.         grey = cv2.cvtColor(frame, cv.CV_BGR2GRAY)
90.
91.         # Blur the image
92.         grey = cv2.blur(grey, (7, 7))
93.
94.         # Compute edges using the Canny edge filter
95.         edges = cv2.Canny(grey, 15.0, 30.0)
96.
97.         return edges
```

Recall that the image callback function in turn called the `process_image()` function in case we want to manipulate the image before displaying it back to the user. For the purposes of this demonstration, here we convert the image to greyscale, blur it using a Gaussian filter with a variance of 7 pixels in the x and y dimensions, then compute the Canny edges over the result. The edge image is returned to the callback where it is displayed to the user.

```
99.     def process_depth_image(self, frame):
100.         # Just return the raw image for this demo
101.         return frame
```

In this demo, we do nothing with the depth image and just return the original frame. Feel free to add your own set of OpenCV filters here.

10.6 The `ros2opencv2.py` Utility

Many of our ROS vision nodes will share a common set of functions such as converting from ROS to OpenCV image format using `cv_bridge`, drawing text on the screen, allowing the user to selection regions with the mouse and so on. We will therefore begin by programming a script that takes care of these common tasks and can be included in other nodes.

The file `ros2opencv2.py` found in the `rbx1_vision/src` subdirectory performs the following tasks:

- Subscribes to the raw image topic that is published by the camera driver. The format of this image is defined by the ROS `sensor_msgs/Image` message type.
- Creates an instance of the ROS `cv_bridge` utility that converts the ROS image format into OpenCV format.

- Creates an OpenCV display window for monitoring the image.
- Creates a callback for processing mouse clicks by the user; e.g., selecting a region to track.
- Creates a `process_image()` function that will do all the work of processing the image and returning the results.
- Creates a `process_depth_image()` function for processing a depth image.
- Publishes a region of interest (ROI) on the `/roi` topic that contains the pixels or keypoints that are returned by `process_image()`.
- Stores the currently detected target's location in the global variable `self.detect_box`.
- Stores the currently tracked target's location in the global variable `self.track_box`.

Other ROS nodes that we develop below will override the functions `process_image()` and/or `process_depth_image()` and detect specific features such as faces or colors as well as track keypoints found within the detected region.

Most of the code in this script is fairly straightforward and simply expands on the `cv_bridge_demo.py` script we saw earlier so we won't run through it line-by-line. (The script is heavily commented and should give you a good idea what each part does. You can also view it online [here](#):

Link to SVN source: [ros2opencv2.py](#)

But before moving on to more complex vision processing, let's test the `ros2opencv2.py` node on its own. With your camera's driver up and running, move to another terminal and run the `ros2opencv2.launch` file as follows:

```
$ roslaunch rbx1_vision ros2opencv2.launch
```

After a brief pause, you should see the OpenCV display window appear. By default, you will also see the processing speed (CPS = cycles per second) and the image resolution. (Cycles per second is the reciprocal of the time it takes to process a single frame. It is therefore an estimate of the *fastest* frame rate we could process.) You can resize the window by dragging one of the corners. If you click on a point in the image, a small circle will appear on the image in that location. If you drag across the image, a selection rectangle will be drawn in yellow until you release the mouse at which point it turns green and remains on the image. The green box represents your region of interest (ROI). To see the coordinates of the ROI, open another terminal and view the `/roi` topic:

```
$ rostopic echo /roi
```

Try drawing different rectangles on the image window and you will see the values of the ROI fields change accordingly. The meaning of these fields are:

- `x_offset`: x-coordinate of the upper left corner of the region
- `y_offset`: y-coordinate of the upper left corner of the region
- `height`: height of the region in pixels
- `width`: width of the region in pixels
- `do_rectify`: boolean value (True or False). Usually False which means that the ROI is defined with respect to the whole image. However, if True then the ROI is defined within a sub-window of the image.

Note that the offset coordinates are relative to the upper left corner of the image window which has coordinates (0, 0). Positive x values increase to the right while y values increase downward. The largest x value is `width-1` and the largest y value is `height-1`.

10.7 Processing Recorded Video

The `rbx1_vision` package also contains a node called `video2ros.py` for converting recorded video files into a ROS video stream so that you can use it instead of a live camera. To test the node, **terminate any camera drivers** you may have running in another terminal. Also terminate the `ros2opencv2.py` node if it is still running. Then run the following commands:

```
$ rosrun rbox1_vision cv_bridge_demo.py
```

```
$ rosrun rbox1_vision video2ros.launch input:=`rospack find \`rbox1_vision\`/videos/hide2.mp4`
```

(The test video comes courtesy of the [Honda/UCSD video database](#).)

You should see two active video display windows. (The depth video window will remain blank.) The display window called "Video Playback" allows you to control the recorded video: click anywhere on the window to bring it to the foreground, then hit the space bar to pause/continue the video and hit the "r" key to restart the video from the beginning. The other window displays the output from our `cv_bridge_demo.py` node which, as you will recall, computes the edge map of the input.

The `video2ros.py` script is heavily commented and fairly self-explanatory. You can find the source online at the following link:

Link to SVN source: [video2ros.py](#)

Now that our basic vision nodes are working, we are ready to try out a number of OpenCV's vision processing functions.

10.8 OpenCV: The Open Source Computer Vision Library

OpenCV was developed in 1999 by Intel to test CPU intensive applications and the code was released to the public in 2000. In 2008, primary development was taken over by Willow Garage. [OpenCV](#) is not as easy to use as some GUI-based vision packages such as [RoboRealm](#) for Windows. However, the functions available in OpenCV represent many state-of-the-art vision algorithms as well as methods for machine learning such as Support Vector Machines, artificial neural networks and Random Trees.

OpenCV can be run as a standalone library on Linux, Windows, MacOS X and Android. For those new to OpenCV, please note that we will only touch on a small fraction of OpenCV's capabilities. For a complete introduction to the library and all its features, please refer to [Learning OpenCV](#) by Gary Bradski and Adrian Kaehler. You can also refer to the complete [online manual](#) including a number of introductory tutorials.

10.8.1 Face Detection

OpenCV makes it relatively easy to detect faces in an image or video stream. And since this is a popular request for those interested in robot vision, it is a good place to start.

OpenCV's face detector uses a [Cascade Classifier with Haar-like features](#). You can learn more about cascade classifiers and Haar features at the provided link. For now, all we need to understand is that the OpenCV cascade classifier can be initialized with different XML files that define the object we want to detect. We will use two of these files to detect a face when seen directly from the front. Another file will allow us to detect a face when seen from the side (profile view). These files were created by training machine learning algorithms on hundreds or even thousands of images that either contain a face or do not. The learning algorithm is then able to extract the features that characterize faces and the results are stored in XML format. (Additional cascade files have been trained for detecting eyes and even whole people.)

A few of these XML files have been copied from the OpenCV source tree to the `rbx1_vision/data/haar_detectors` directory and we will use them in our scripts below.

Our ROS face detector node is located in the file `face_detector.py` in the `rbx1_vision/nodes` directory. Before we look at the code, let's give it a try.

To run the detector, first launch the appropriate video driver. For the Kinect or Xtion:

```
$ roslaunch rbx1_vision openni_node_fuerte.launch
```

Or for a webcam:

```
$ roslaunch rbx1_vision uvc_cam.launch device:=/dev/video0
```

(Change the video device if necessary.)

Now launch the face detector node:

```
$ roslaunch rbx1_vision face_detector.launch
```

If you position your face within the frame of the camera, you should see a green box around your face when the cascade detector finds it. When the detector loses your face, the box disappears and you will see the message "LOST FACE!" on the screen. Try turning your face from side to side and up and down. Also try moving your hand in front of your face. The "Hit Rate" number also displayed on the screen is the number of frames in which your face was detected divided by the total number of frames so far.

As you can see, the detector is pretty good, but it has limitations—the detector loses your face when you turn your head too far from either a frontal or side view. Nonetheless, since people (and robots) tend to interact while facing each other, the detector can get the job done in many situations.

Let's now take a look at the code.

Link to SVN source: [face_detector.py](#)

```
1.      #!/usr/bin/env python
2.      import roslib; roslib.load_manifest('rbx1_vision')
3.      import rospy
4.      import cv2
5.      import cv2.cv as cv
6.      from ros2opencv2 import ROS2OpenCV2
7.
8.      class FaceDetector(ROS2OpenCV2):
9.          def __init__(self, node_name):
10.              super(FaceDetector, self).__init__(node_name)
11.
12.              # Get the paths to the cascade XML files for the Haar detectors.
13.              # These are set in the launch file.
14.              cascade_1 = rospy.get_param("~cascade_1", "")
15.              cascade_2 = rospy.get_param("~cascade_2", "")
16.              cascade_3 = rospy.get_param("~cascade_3", "")
17.
18.              # Initialize the Haar detectors using the cascade files
19.              self.cascade_1 = cv2.CascadeClassifier(cascade_1)
```

```

20.         self.cascade_2 = cv2.CascadeClassifier(cascade_2)
21.         self.cascade_3 = cv2.CascadeClassifier(cascade_3)
22.
23.         # Set cascade parameters that tend to work well for faces.
24.         # Can be overridden in launch file
25.         self.haar_minSize = rospy.get_param("~haar_minSize", (20, 20))
26.         self.haar_maxSize = rospy.get_param("~haar_maxSize", (150, 150))
27.         self.haar_scaleFactor = rospy.get_param("~haar_scaleFactor", 1.3)
28.         self.haar_minNeighbors = rospy.get_param("~haar_minNeighbors", 1)
29.         self.haar_flags = rospy.get_param("~haar_flags",
30.                                         cv.CV_HAAR_DO_CANNY_PRUNING)
31.
32.         # Store all parameters together for passing to the detector
33.         self.haar_params = dict(minSize = self.haar_minSize,
34.                                 maxSize = self.haar_maxSize,
35.                                 scaleFactor = self.haar_scaleFactor,
36.                                 minNeighbors = self.haar_minNeighbors,
37.                                 flags = self.haar_flags)
38.
39.         # Do we should text on the display?
40.         self.show_text = rospy.get_param("~show_text", True)
41.
42.         # Initialize the detection box
43.         self.detect_box = None
44.
45.         # Track the number of hits and misses
46.         self.hits = 0
47.         self.misses = 0
48.         self.hit_rate = 0
49.
50.     def process_image(self, cv_image):
51.         # Create a greyscale version of the image
52.         grey = cv2.cvtColor(cv_image, cv2.COLOR_BGR2GRAY)
53.
54.         # Equalize the histogram to reduce lighting effects
55.         grey = cv2.equalizeHist(grey)
56.
57.         # Attempt to detect a face
58.         self.detect_box = self.detect_face(grey)
59.
60.         # Did we find one?
61.         if self.detect_box is not None:
62.             self.hits += 1
63.         else:
64.             self.misses += 1
65.
66.         # Keep tabs on the hit rate so far
67.         self.hit_rate = float(self.hits) / (self.hits + self.misses)
68.
69.     return cv_image
70.
71. def detect_face(self, input_image):
72.     # First check one of the frontal templates
73.     if self.cascade_1:
74.         faces = self.cascade_1.detectMultiScale(input_image,
**self.haar_params)

```

```

75.         # If that fails, check the profile template
76.         if len(faces) == 0 and self.cascade_3:
77.             faces =
self.cascade_3.detectMultiScale(input_image,**self.haar_params)
78.
79.         # If that also fails, check a the other frontal template
80.         if len(faces) == 0 and self.cascade_2:
81.             faces = self.cascade_2.detectMultiScale(input_image,
**self.haar_params)
82.
83.         # The faces variable holds a list of face boxes.
84.         # If one or more faces are detected, return the first one.
85.         if len(faces) > 0:
86.             face_box = faces[0]
87.         else:
88.             # If no faces were detected, print the "LOST FACE" message on
the screen
89.             if self.show_text:
90.                 font_face = cv2.FONT_HERSHEY_SIMPLEX
91.                 font_scale = 0.5
92.                 cv2.putText(self.marker_image, "LOST FACE!",
93.                             (int(self.frame_size[0] * 0.65),
int(self.frame_size[1] * 0.9)),
94.                             font_face, font_scale, cv.RGB(255, 50, 50))
95.             face_box = None
96.
97.         # Display the hit rate so far
98.         if self.show_text:
99.             font_face = cv2.FONT_HERSHEY_SIMPLEX
100.            font_scale = 0.5
101.            cv2.putText(self.marker_image, "Hit Rate: " +
102.                        str(trunc(self.hit_rate, 2)),
103.                        (20, int(self.frame_size[1] * 0.9)),
104.                        font_face, font_scale, cv.RGB(255, 255, 0))
105.
106.        return face_box
107.
108.    def trunc(f, n):
109.        '''Truncates/pads a float f to n decimal places without rounding'''
110.        slen = len('%.%f' % (n, f))
111.        return float(str(f)[:slen])
112.
113.    if __name__ == '__main__':
114.        try:
115.            node_name = "face_detector"
116.            FaceDetector(node_name)
117.            rospy.spin()
118.        except KeyboardInterrupt:
119.            print "Shutting down face detector node."
120.            cv2.destroyAllWindows()

```

Let's take a look at the key lines of the script.

```

6. from ros2opencv2 import ROS2OpenCV2
7.
8. class FaceDetector(ROS2OpenCV2):

```

```

9.     def __init__(self, node_name):
10.        super(FaceDetector, self).__init__(node_name)

```

First we must import the ROS2OpenCV2 class from the `ros2opencv2.py` script that we developed earlier. The face detector node is then defined as a class that extends the `ROS2OpenCV2` class. In this way it inherits all the housekeeping functions and variables from the `ros2opencv2.py` script such as user selections with the mouse, displaying a box around the ROI and so on. Whenever we extend a class, we have to initialize the parent class as well which is done with Python's `super()` function as shown in the last line above.

```

14.        cascade_1 = rospy.get_param("~cascade_1", "")
15.        cascade_2 = rospy.get_param("~cascade_2", "")
16.        cascade_3 = rospy.get_param("~cascade_3", "")

```

These three parameters store the path names to the XML files we want to use for the Haar cascade detector. The paths are specified in the launch file `rbx1_vision/launch/face_detector.launch`. The XML files themselves are not included in the OpenCV or ROS Fuerte Debian packages so they were copied from the OpenCV source to the `ros-by-example` repository and can be found in the directory `rbx1_vision/data/haar_detectors`.

```

19.        self.cascade_1 = cv2.CascadeClassifier(cascade_1)
20.        self.cascade_2 = cv2.CascadeClassifier(cascade_2)
21.        self.cascade_3 = cv2.CascadeClassifier(cascade_3)

```

These three lines create the OpenCV cascade classifiers based on the three XML files, two for frontal face views and one for side profiles.

```

25.        self.haar_minSize = rospy.get_param("~haar_minSize", (20, 20))
26.        self.haar_maxSize = rospy.get_param("~haar_maxSize", (150, 150))
27.        self.haar_scaleFactor = rospy.get_param("~haar_scaleFactor", 1.3)
28.        self.haar_minNeighbors = rospy.get_param("~haar_minNeighbors", 1)
29.        self.haar_flags = rospy.get_param("~haar_flags",
30.                                         cv.CV_HAAR_DO_CANNY_PRUNING)

```

The cascade classifiers require a number of parameters that determine their speed and the probability of correctly detecting a target. In particular, the `minSize` and `maxSize` parameters (specified in x and y pixel dimensions) set the smallest and largest target (faces in our case) that will be accepted. The `scaleFactor` parameter acts as a multiplier to change the image size as the detector runs from one scale to the next. The smaller this number (it must be > 1.0), the finer the scale pyramid used to scan for faces but the longer it will take on each frame. You can read up on the other parameters in the [OpenCV documentation](#).

```

32.        self.haar_params = dict(minSize = self.haar_minSize,
33.                               maxSize = self.haar_maxSize,

```

```

34.                     scaleFactor = self.haar_scaleFactor,
35.                     minNeighbors = self.haar_minNeighbors,
36.                     flags = self.haar_flags)

```

Here we stick all the parameters into a Python dictionary variable for easy reference later in the script.

```

49.     def process_image(self, cv_image):
50.         # Create a greyscale version of the image
51.         grey = cv2.cvtColor(cv_image, cv2.COLOR_BGR2GRAY)
52.
53.         # Equalize the histogram to reduce lighting effects
54.         grey = cv2.equalizeHist(grey)

```

Since the `FaceDetector` class extends the `ROS2OpenCV2` class, the `process_image()` function overrides the one defined in `ros2opencv2.py`. In this case, we begin by converting the image to greyscale. Many feature detection algorithms run on a greyscale version of the image and this includes the Haar cascade detector. We then equalize the histogram of the greyscale image. Histogram equalization is a standard technique for reducing the effects of changes in overall lighting.

```

56.         self.detect_box = self.detect_face(grey)
57.
58.         # Did we find one?
59.         if self.detect_box is not None:
60.             self.hits += 1
61.         else:
62.             self.misses += 1
63.
64.         # Keep tabs on the hit rate so far
65.         self.hit_rate = float(self.hits) / (self.hits + self.misses)

```

Here we send the pre-processed image to the `detect_face()` function which we will describe below. If a face is detected, the bounding box is returned to the variable `self.detect_box` which in turn is drawn on the image by the `ROS2OpenCV2` base class.

If a face is detected in this image frame, we increment the number of hits by 1, otherwise we add to the number of misses. The running hit rate is then updated accordingly.

```

70.     def detect_face(self, input_image):
71.         # First check one of the frontal templates
72.         if self.cascade_1:
73.             faces = self.cascade_1.detectMultiScale(input_image,
**self.haar_params)

```

Here we start the heart of the script—the `detect_face()` function. We run the input image through the cascade detector using the first XML template. The `detectMultiScale()` function searches the image across multiple scales and returns

any faces as a list of OpenCV rectangles in the form (x, y, w, h) where (x, y) are the coordinates of the upper left corner of the box and (w, h) are the width and height in pixels.

```
76.         if len(faces) == 0 and self.cascade_3:
77.             faces =
78.             self.cascade_3.detectMultiScale(input_image,**self.haar_params)
79.         # If that also fails, check a the other frontal template
80.         if len(faces) == 0 and self.cascade_2:
81.             faces = self.cascade_2.detectMultiScale(input_image,
**self.haar_params)
```

If a face is not detected using the first cascade, we try a second detector and then a third if necessary.

```
85.     if len(faces) > 0:
86.         face_box = faces[0]
```

If one or more faces are found, the `faces` variable will hold a list of face boxes (`cvRect`). We will only track the first face found so we set the `face_box` variable to `faces[0]`. If no faces are found in this frame, we set `face_box` to `None`. Either way, the result is returned to the calling function `process_image()`.

That completes the script. The `process_image()` and `detect_face()` functions are applied to every frame of the video. The result is that the detect box tracks your face as long as it can be found in the current frame. Don't forget that you can monitor the `/roi` topic to see the coordinates of the tracked face:

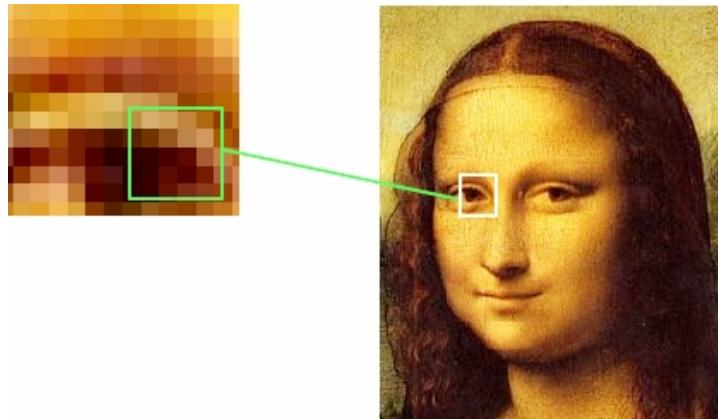
```
$ rostopic echo /roi
```

Tracking an object by running a detector over and over across the entire image is computationally expensive and can easily lose track of the object on any given frame. In the next two sections, we will show how to quickly detect and track a set of keypoints for any given region of an image. We will then combine the tracker with the face detector to make a better face tracker.

10.8.2 Keypoint Detection using GoodFeaturesToTrack

The Haar face detector scans an image for a specific type of object. A different strategy involves looking for smaller image features that are fairly easy to track from one frame to the next. These features are called **keypoints** or **interest points**. Keypoints tend to be regions where there are large changes in intensity in more than one direction.

Consider for example the images shown below:

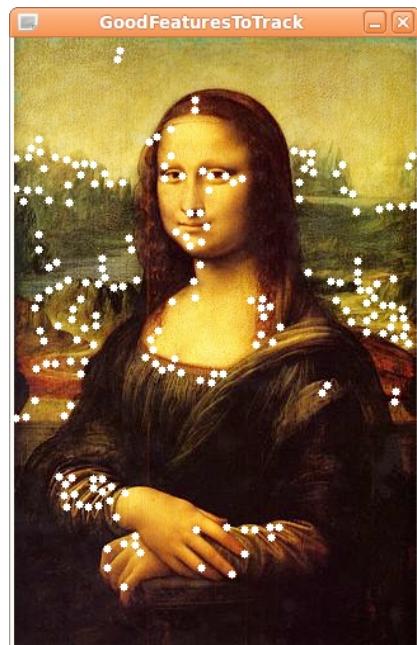


The image on the left shows the pixels from the left eye region from the image on the right. The square on the left indicates the region where the intensity changes the most in all directions. The center of such a region is a keypoint of the image and it is likely to be re-detected in the same location of the face regardless of its orientation or scale.

OpenCV 2.3 includes a number of keypoint detectors including `goodFeaturesToTrack()`, `cornerHarris()` and `SURF()`. We will use `goodFeaturesToTrack()` for our programming example. The image on the right illustrates the keypoints returned by `goodFeaturesToTrack()`.

As you can see, keypoints are concentrated in areas where the intensity gradients are largest. Conversely, areas of the painting which are fairly homogeneous have few or no keypoints. (To reproduce this image or find the keypoints in other images, take a look at the Python program called `script_good_features.py` in the `rbx1_vision/scripts` directory.)

We are now ready to detect keypoints on a live video stream. Our ROS node is called `good_features.py` and it can be found in the `rbx1_vision/nodes` subdirectory. The corresponding launch file is `good_features.launch` in the launch subdirectory. The launch file contains a number of parameters that affect the keypoints returned by `goodFeaturesToTrack()`:



- `maxCorners`: Puts an upper limit on how many keypoints are returned.
- `qualityLevel`: Reflects how strong a corner-like feature must be before it counts as a keypoint. Setting lower values returns more points.
- `minDistance`: The minimum number of pixels between keypoints.
- `blockSize`: The size of the neighborhood around a pixel used to compute whether or not there is a corner there.
- `useHarrisDetector`: Whether or not to use the original Harris corner detector or a minimum eigenvalue criterion.
- `k`: A free parameter for the Harris corner detector.

The `good_features.launch` file sets reasonable defaults for these parameters but try experimenting with them to see their effects.

To run the detector, first make sure the driver for your camera is up and running as described previously, then run:

```
$ roslaunch rbx1_vision good_features.launch
```

When the video appears, draw a rectangle with your mouse around some object in the image. A rectangle should indicate the selected region and you should see a number of green dots indicating the keypoints found in that region by `goodFeaturesToTrack()`. Try drawing a box around other areas of the image and see if you can guess where the keypoints will appear. Note that we are not yet tracking these keypoints—we are simply computing them for whatever patch of the scene lies within your select box.

You will probably notice that some of the keypoints jiggle around a bit even on a stationary part of the scene. This is due to noise in the video. Strong keypoints are less susceptible to noise as you can see by drawing your test box around the corner of a table or other high contrast point.

Let's now look at the code.

Link to SVN source: [good_features.py](#)

```

1.  #!/usr/bin/env python
2.  import roslib; roslib.load_manifest('rbx1_vision')
3.  import rospy
4.  import cv2
5.  import cv2.cv as cv
6.  from ros2opencv2 import ROS2OpenCV2
7.  import numpy as np
8.
```

```

9.     class GoodFeatures(ROS2OpenCV2):
10.        def __init__(self, node_name):
11.            super(GoodFeatures, self).__init__(node_name)
12.
13.            # Do we show text on the display?
14.            self.show_text = rospy.get_param("~show_text", True)
15.
16.            # How big should the feature points be (in pixels)?
17.            self.feature_size = rospy.get_param("~feature_size", 1)
18.
19.            # Good features parameters
20.            self.gf_maxCorners = rospy.get_param("~gf_maxCorners", 200)
21.            self.gf_qualityLevel = rospy.get_param("~gf_qualityLevel", 0.05)
22.            self.gf_minDistance = rospy.get_param("~gf_minDistance", 7)
23.            self.gf_blockSize = rospy.get_param("~gf_blockSize", 10)
24.            self.gf_useHarrisDetector =
rospy.get_param("~gf_useHarrisDetector", True)
25.            self.gf_k = rospy.get_param("~gf_k", 0.04)
26.
27.            # Store all parameters together for passing to the detector
28.            self.gf_params = dict(maxCorners = self.gf_maxCorners,
29.                                  qualityLevel = self.gf_qualityLevel,
30.                                  minDistance = self.gf_minDistance,
31.                                  blockSize = self.gf_blockSize,
32.                                  useHarrisDetector = self.gf_useHarrisDetector,
33.                                  k = self.gf_k)
34.
35.            # Initialize key variables
36.            self.keypoints = list()
37.            self.detect_box = None
38.            self.mask = None
39.
40.        def process_image(self, cv_image):
41.            # If the user has not selected a region, just return the image
42.            if not self.detect_box:
43.                return cv_image
44.
45.            # Create a greyscale version of the image
46.            grey = cv2.cvtColor(cv_image, cv2.COLOR_BGR2GRAY)
47.
48.            # Equalize the histogram to reduce lighting effects
49.            grey = cv2.equalizeHist(grey)
50.
51.            # Get the good feature keypoints in the selected region
52.            keypoints = self.get_keypoints(grey, self.detect_box)
53.
54.            # If we have points, display them
55.            if keypoints is not None and len(keypoints) > 0:
56.                for x, y in keypoints:
57.                    cv2.circle(self.marker_image, (x, y), self.feature_size,
(0, 255, 0, 0), cv.CV_FILLED, 8, 0)
58.
59.            # Process any special keyboard commands
60.            if 32 <= self.keystroke and self.keystroke < 128:
61.                cc = chr(self.keystroke).lower()
62.                if cc == 'c':
63.                    # Clear the current keypoints

```

```

64.                 keypoints = list()
65.                 self.detect_box = None
66.
67.             return cv_image
68.
69.     def get_keypoints(self, input_image, detect_box):
70.         # Initialize the mask with all black pixels
71.         self.mask = np.zeros_like(input_image)
72.
73.         # Get the coordinates and dimensions of the detect_box
74.         try:
75.             x, y, w, h = detect_box
76.         except:
77.             return None
78.
79.         # Set the selected rectangle within the mask to white
80.         self.mask[y:y+h, x:x+w] = 255
81.
82.         # Compute the good feature keypoints within the selected region
83.         keypoints = list()
84.         kp = cv2.goodFeaturesToTrack(input_image, mask = self.mask,
**self.gf_params)
85.         if kp is not None and len(kp) > 0:
86.             for x, y in np.float32(kp).reshape(-1, 2):
87.                 keypoints.append((x, y))
88.
89.         return keypoints
90.
91.     if __name__ == '__main__':
92.         try:
93.             node_name = "good_features"
94.             GoodFeatures(node_name)
95.             rospy.spin()
96.         except KeyboardInterrupt:
97.             print "Shutting down the Good Features node."
98.             cv.DestroyAllWindows()

```

Overall, we see that the script has the same structure as the `face_detector.py` node. We initialize a `GoodFeatures` class that extends the `ROS2OpenCV2` class. We then define a `process_image()` function that does most the work. Let's examine the more important lines of the script:

```

20.         self.gf_maxCorners = rospy.get_param("~gf_maxCorners", 200)
21.         self.gf_qualityLevel = rospy.get_param("~gf_qualityLevel", 0.02)
22.         self.gf_minDistance = rospy.get_param("~gf_minDistance", 7)
23.         self.gf_blockSize = rospy.get_param("~gf_blockSize", 10)
24.         self.gf_useHarrisDetector =
25.             rospy.get_param("~gf_useHarrisDetector", True)
26.         self.gf_k = rospy.get_param("~gf_k", 0.04)

```

As with the Haar detector, the Good Features detector takes a number of parameters to fine tune its behavior. Probably the two most important parameters above are `qualityLevel` and `minDistance`. Smaller values for `qualityLevel` will result in a

great number of feature points, but a number of them will be due to noise and not very consistent from one image frame to the next. Setting a higher value that is too high will yield only a few keypoints at the very strongest corners. Something on the order of 0.02 or so seems to strike a good balance for videos of natural scenes.

The `minDistance` parameter specifies the smallest distance in pixels we will allow between keypoints. The larger this value, the further apart keypoints must be resulting in fewer of them.

```
40.     def process_image(self, cv_image):
41.         # If the user has not selected a region, just return the image
42.         if not self.detect_box:
43.             return cv_image
44.
45.         # Create a greyscale version of the image
46.         grey = cv2.cvtColor(cv_image, cv2.COLOR_BGR2GRAY)
47.
48.         # Equalize the histogram to reduce lighting effects
49.         grey = cv2.equalizeHist(grey)
50.
51.         # Get the good feature keypoints in the selected region
52.         keypoints = self.get_keypoints(grey, self.detect_box)
```

As with the face detector node, we define a `process_image()` function which first converts the image to greyscale and equalizes the histogram. The resulting image is passed to the `get_keypoints()` function which does all the work of finding the Good Features.

```
69.     def get_keypoints(self, input_image, detect_box):
70.         # Initialize the mask with all black pixels
71.         self.mask = np.zeros_like(input_image)
72.
73.         # Get the coordinates and dimensions of the detect_box
74.         try:
75.             x, y, w, h = detect_box
76.         except:
77.             return None
78.
79.         # Set the selected rectangle within the mask to white
80.         self.mask[y:y+h, x:x+w] = 255
81.
82.         # Compute the good feature keypoints within the selected region
83.         keypoints = list()
84.         kp = cv2.goodFeaturesToTrack(input_image, mask = self.mask,
85.                                     **self.gf_params)
86.         if kp is not None and len(kp) > 0:
87.             for x, y in np.float32(kp).reshape(-1, 2):
88.                 keypoints.append((x, y))
89.
90.         return keypoints
```

The `get_keypoints()` function implements OpenCV's `GoodFeaturesToTrack` detector. Since we only want the keypoints within the box selected by the user (`detect_box`) we mask the image with the box by starting with a mask of all zeros

(black) and then filling in the detect box with all white pixels (255). The output from the `cv2.goodFeaturesToTrack()` function is a vector of keypoint coordinates. So we use a little numpy reshaping to turn it into a Python list of (x,y) pairs. The resulting list is returned to the `process_image()` function where the points are drawn on the image.

10.8.3 Tracking Keypoints using Optical Flow

Now that we can detect keypoints in an image, we can use them to track the underlying object from one video frame to the next by using OpenCV's Lucas-Kanade optical flow function `calcOpticalFlowPyrLK()`. A detailed explanation of the Lucas-Kanade method can be found on [Wikipedia](#). The basic idea is as follows.

We begin with the current image frame and the set of keypoints we have already extracted. Each keypoint has a location (x and y coordinates) and a neighborhood of surrounding image pixels. In the next image frame, the Lucas-Kanade algorithm uses a least squares method to solve for a small constant-velocity transformation that maps a given neighborhood of pixels from the first frame to the next. If the least squares error for a given neighborhood does not exceed some threshold, we assume it is the same neighborhood as in the first frame and we assign it the same keypoint to that location; otherwise the keypoint is discarded. Note that we are *not* extracting new keypoints in subsequent frames. Instead, `calcOpticalFlowPyrLK()` calculates new positions for the original keypoints. In this manner, we can extract the keypoints in the first frame, then follow them from frame to frame as the underlying object or camera moves over time.

After a number of frames, tracking will degrade for two reasons: keypoints will be dropped when the tracking error is too high between frames, and nearby keypoints will take the place of those in the original set as the algorithms makes errors in predictions. We will look at ways to overcome these limitations in later sections.

Our new node, `lk_tracker.py`, combines our earlier keypoint detector (using `goodFeaturesToTrack()`) with this optical flow tracking. To launch the node, run:

```
$ roslaunch rbx1_vision lk_tracker.launch
```

When the video window appears, draw a rectangle with your mouse around an object of interest. As in the previous section, keypoints will appear over the image as green dots. Now try moving the object or the camera and the keypoints should follow the object. In particular, try drawing a box around your face. You should see keypoints attach to various parts of your face. Now move your head around and the keypoints should move with it. Notice how much faster the CPS value is compared to running the Haar face detector. On my machine, tracking keypoints using the LK method is fully twice as fast as using the Haar face detector. It is also much more reliable in that it continues to track the face keypoints under a greater range of movement. You can best see this by turning on "night mode" (hit the "n" key when the video window is in the foreground.)

Remember that the base class ROS2OpenCV2 publishes the bounding box around the tracked points on the /roi topic. So if you run the command:

```
$ rostopic echo /roi
```

while using the lk_tracker node, you should see the ROI move as the points move. This means that if you have another node that needs to follow the location of the tracked points, it only has to subscribe to the /roi topic to follow them in real time.

Now let's look at the code:

Link to SVN source: [lk_tracker.py](#)

```

1.  #!/usr/bin/env python
2.  import roslib; roslib.load_manifest('rbxl_vision')
3.  import rospy
4.  import cv2
5.  import cv2.cv as cv
6.  import numpy as np
7.  from good_features import GoodFeatures
8.
9.  class LKTracker(GoodFeatures):
10.     def __init__(self, node_name)
11.         super(LKTracker, self).__init__(node_name)
12.
13.         self.show_text = rospy.get_param("~show_text", True)
14.         self.feature_size = rospy.get_param("~feature_size", 1)
15.
16.         # LK parameters
17.         self.lk_winSize = rospy.get_param("~lk_winSize", (10, 10))
18.         self.lk_maxLevel = rospy.get_param("~lk_maxLevel", 2)
19.         self.lk_criteria = rospy.get_param("~lk_criteria",
20. (cv2.TERM_CRITERIA_EPS | cv2.TERM_CRITERIA_COUNT, 20, 0.01))
21.         self.lk_derivLambda = rospy.get_param("~lk_derivLambda", 0.1)
22.
23.         self.lk_params = dict( winSize = self.lk_winSize,
24.                               maxLevel = self.lk_maxLevel,
25.                               criteria = self.lk_criteria,
26.                               derivLambda = self.lk_derivLambda )

```

```

27.         self.detect_interval = 1
28.         self.keypoints = list()
29.
30.         self.detect_box = None
31.         self.track_box = None
32.         self.mask = None
33.         self.grey = None
34.         self.prev_grey = None
35.
36.     def process_image(self, cv_image):
37.         # If we don't yet have a detection box (drawn by the user
38.         # with the mouse), keep waiting
39.         if self.detect_box is None:
40.             return cv_image
41.
42.         # Create a greyscale version of the image
43.         self.grey = cv2.cvtColor(cv_image, cv2.COLOR_BGR2GRAY)
44.
45.         # Equalize the grey histogram to minimize lighting effects
46.         self.grey = cv2.equalizeHist(self.grey)
47.
48.         # If we haven't yet started tracking, set the track box to the
49.         # detect box and extract the keypoints within it
50.         if self.track_box is None or not
51.             self.is_rect_nonzero(self.track_box):
52.                 self.track_box = self.detect_box
53.                 self.keypoints = list()
54.                 self.keypoints = self.get_keypoints(self.grey,
55.                                         self.track_box)
56.             else:
57.                 if self.prev_grey is None:
58.                     self.prev_grey = self.grey
59.
60.                 # Now that have keypoints, track them to the next frame
61.                 # using optical flow
62.                 self.track_box = self.track_keypoints(self.grey,
63.                                         self.prev_grey)
64.
65.                 # Process any special keyboard commands for this module
66.                 if 32 <= self.keystroke and self.keystroke < 128:
67.                     cc = chr(self.keystroke).lower()
68.                     if cc == 'c':
69.                         # Clear the current keypoints
70.                         self.keypoints = list()
71.                         self.track_box = None
72.                         self.detect_box = None
73.                         self.classifier_initialized = True
74.
75.                         self.prev_grey = self.grey
76.
77.             return cv_image
78.
79.     def track_keypoints(self, grey, prev_grey):
80.         try:
81.             # We are tracking points between the previous frame and the
82.             # current frame

```

```

81.             img0, img1 = prev_grey, grey
82.
83.             # Reshape the current keypoints into a numpy array required
84.             # by calcOpticalFlowPyrLK()
85.             p0 = np.float32([p for p in self.keypoints]).reshape(-1, 1,
86.                           2)
87.
88.             # Calculate the optical flow from the previous frame
89.             # to the current frame
90.             p1, st, err = cv2.calcOpticalFlowPyrLK(img0, img1, p0,
91.             None, **self.lk_params)
92.
93.             # Do the reverse calculation: from the current frame
94.             # to the previous frame
95.             p0r, st, err = cv2.calcOpticalFlowPyrLK(img1, img0, p1,
96.             None, **self.lk_params)
97.
98.             # Compute the distance between corresponding points
99.             # in the two flows
100.            d = abs(p0-p0r).reshape(-1, 2).max(-1)
101.
102.            # If the distance between pairs of points is < 1 pixel, set
103.            # a value in the "good" array to True, otherwise False
104.            good = d < 1
105.
106.            # Initialize a list to hold new keypoints
107.            new_keypoints = list()
108.
109.            # Cycle through all current and new keypoints and only keep
110.            # those that satisfy the "good" condition above
111.            for (x, y), good_flag in zip(p1.reshape(-1, 2), good):
112.                if not good_flag:
113.                    continue
114.                new_keypoints.append((x, y))
115.
116.            # Draw the keypoint on the image
117.            cv2.circle(self.marker_image, (x, y),
118.                      self.feature_size, (0, 255, 0, 0), cv.CV_FILLED, 8, 0)
119.
120.            # Set the global keypoint list to the new list
121.            self.keypoints = new_keypoints
122.
123.            # If we have >6 points, find the best ellipse around them
124.            if len(self.keypoints) > 6:
125.                self.keypoints_matrix = cv.CreateMat(1,
126.                len(self.keypoints), cv.CV_32SC2)
127.                i = 0
128.                for p in self.keypoints:
129.                    cv.Set2D(self.keypoints_matrix, 0, i, (int(p[0]),
130.                        int(p[1])))
131.                    i = i + 1
132.                track_box = cv.FitEllipse2(self.keypoints_matrix)
133.            else:
134.                # Otherwise, find the best fitting rectangle
135.                track_box = cv2.boundingRect(self.keypoints_matrix)
136.            except:
137.                track_box = None

```

```

132.         return track_box
134.
135.
136.     if __name__ == '__main__':
137.         try:
138.             node_name = "lk_tracker"
139.             LKTracker(node_name)
140.             rospy.spin()
141.         except KeyboardInterrupt:
142.             print "Shutting down LK Tracking node."
143.             cv.DestroyAllWindows()

```

Let's look at the key lines of the script.

```

7.  from good_features import GoodFeatures
8.
9.  class LKTracker(GoodFeatures):
10.    def __init__(self, node_name):
11.        super(LKTracker, self).__init__(node_name)

```

The overall structure of the script is once again similar to the `face_detector.py` node. However, this time we import `good_features.py` and define the `LKTracker` class as an extension of the `GoodFeatures` class rather than the `ROS2OpenCV2`. Why? Because the keypoints we will track are precisely those we obtained from the `GoodFeatures` class in the previous section. And since the `GoodFeatures` class itself extends the `ROS2OpenCV2` class, we are covered.

```

36.    def process_image(self, cv_image):
...
53.            self.keypoints = self.get_keypoints(self.grey,
self.track_box)
...
61.            self.track_box = self.track_keypoints(self.grey,
self.prev_grey)

```

The `process_image()` function is very similar to the one we used in the `good_features.py` script. The key lines are 53 and 61 above. In line 53 we are using the `get_keypoints()` function from the `GoodFeatures` class to get the initial keypoints. And in line 61, we track those keypoints using the new `track_keypoints()` function which we will now describe.

```

77.    def track_keypoints(self, grey, prev_grey):
78.        try:
79.            # We are tracking points between the previous frame and the
80.            # current frame
81.            img0, img1 = prev_grey, grey
82.
83.            # Reshape the current keypoints into a numpy array required

```

```
84.         # by calcOpticalFlowPyrLK()
85.         p0 = np.float32([p for p in self.keypoints]).reshape(-1, 1,
2)
```

To track the keypoints, we begin by storing the previous greyscale image and the current greyscale image in a couple of variables. We then store the current keypoints using a numpy array format required by the `calcOpticalFlowPyrLK()` function.

```
89.         p1, st, err = cv2.calcOpticalFlowPyrLK(img0, img1, p0, None,
**self.lk_params)
```

In this line we use the OpenCV `calcOpticalFlowPyrLK()` function to predict the next set of keypoints from the current keypoints and the two greyscale images.

```
93.         p0r, st, err = cv2.calcOpticalFlowPyrLK(img1, img0, p1, None,
**self.lk_params)
```

And in this line, we make the *reverse* calculation: here we predict the previous points from the future points we just computed. This allows us to do a consistency check since we can compare the actual previous points (the keypoints we started with) with these reverse-predicted points.

```
97.         d = abs(p0-p0r).reshape(-1, 2).max(-1)
```

Next we compute the distances between pairs of reverse-predicted points (`p0r`) and our original keypoints (`p0`). The result, `d`, is an array of these distances. (Python can seemly awfully compact sometimes.)

```
101.        good = d < 1
```

And here we define a new array (`good`) that is a set of `True` or `False` values depending on whether or not the distance between a pair of points is less than 1 pixel.

```
108.         for (x, y), good_flag in zip(p1.reshape(-1, 2), good):
109.             if not good_flag:
110.                 continue
111.             new_keypoints.append((x, y))
```

Finally, we drop any keypoints that are more than 1 pixel away from their reverse-predicted counterpart.

```
117.         self.keypoints = new_keypoints
```

The result becomes our new global set of keypoints that we send through the next tracking cycle.

10.8.4 Building a Better Face Tracker

We now have the ingredients we need to improve on our original face detector. Recall that the `face_detector.py` node attempts to detect a face over and over on every frame. This is not only CPU-intensive, but it can also fail to detect a face at all fairly often. A better strategy is to first detect the face, then use `goodFeaturesToTrack()` to extract keypoints from the face region and then use `calcOpticalFlowPyrLK()` to track those features from frame to frame. In this way, detection is only done once to originally acquire the face region.

Our processing pipeline looks like this:

```
detect_face() → get_keypoints() → track_keypoints()
```

In terms of the nodes we have developed so far, the pipeline becomes:

```
face_detector.py() → good_features.py() → lk_tracker.py()
```

Our new node, `face_tracker.py` implements this pipeline. To try it out, make sure you have launched the driver to your camera, then run:

```
$ rosrun rbox1_vision face_tracker.launch
```

If you move your face into view of the camera, the Haar face detector should find it. After the initial detection, the keypoints are computed over the face region and then tracked through subsequent frames using optical flow.

Let's now look at the code.

Link to SVN source: [face_tracker.py](#)

```
1.  #!/usr/bin/env python
2.  import roslib
3.  roslib.load_manifest('rbox1_vision')
4.  import rospy
5.  import cv2
6.  import cv2.cv as cv
7.  import numpy as np
8.  from face_detector import FaceDetector
9.  from lk_tracker import LKTracker
10.
11. class FaceTracker(FaceDetector, LKTracker):
12.     def __init__(self, node_name):
13.         super(FaceTracker, self).__init__(node_name)
14.
15.         self.n_faces = rospy.get_param("~n_faces", 1)
16.         self.show_text = rospy.get_param("~show_text", True)
17.         self.feature_size = rospy.get_param("~feature_size", 1)
18.
19.         self.keypoints = list()
20.         self.detect_box = None
```

```

21.         self.track_box = None
22.
23.         self.grey = None
24.         self.prev_grey = None
25.
26.     def process_image(self, cv_image):
27.         # Create a greyscale version of the image
28.         self.grey = cv2.cvtColor(cv_image, cv2.COLOR_BGR2GRAY)
29.
30.         # Equalize the grey histogram to minimize lighting effects
31.         self.grey = cv2.equalizeHist(self.grey)
32.
33.         # STEP 1: Detect the face if we haven't already
34.         if self.detect_box is None:
35.             self.detect_box = self.detect_face(self.grey)
36.
37.         else:
38.             # Step 2: If we aren't yet tracking keypoints, get them now
39.             if self.track_box is None or not
40.                 self.is_rect_nonzero(self.track_box):
41.                     self.track_box = self.detect_box
42.                     self.keypoints = self.get_keypoints(self.grey,
43.                         self.track_box)
44.
45.                     # Step 3: If we have keypoints, track them using optical flow
46.                     if len(self.keypoints) > 0:
47.                         # Store a copy of the current grey image used for LK
48.                         tracking
49.                         if self.prev_grey is None:
50.                             self.prev_grey = self.grey
51.
52.                         self.track_box = self.track_keypoints(self.grey,
53.                             self.prev_grey)
54.                         else:
55.                             # We have lost all keypoints so re-detect the face
56.                             self.detect_box = None
57.
58.                             # Process any special keyboard commands for this module
59.                             if 32 <= self.keystroke and self.keystroke < 128:
60.                                 cc = chr(self.keystroke).lower()
61.                                 if cc == 'c':
62.                                     self.keypoints = list()
63.                                     self.track_box = None
64.                                     self.detect_box = None
65.
66.                                     # Set store a copy of the current image used for LK tracking
67.                                     self.prev_grey = self.grey
68.
69.                                     return cv_image
70.
71.     if __name__ == '__main__':
72.         try:
73.             node_name = "face_tracker"
74.             FaceTracker(node_name)
75.             rospy.spin()
76.         except KeyboardInterrupt:
77.             print "Shutting down face tracker node."

```

```
74.         cv.DestroyAllWindows()
```

The `face_tracker` node essentially combines two nodes we have already developed: the `face_detector` node and the `lk_tracker` node. The `lk_tracker` node in turn depends on the `good_features` node. The following breakdown explains how we combine these Python classes.

```
8.  from face_detector import FaceDetector
9.  from lk_tracker import LKTracker
10.
11. class FaceTracker(FaceDetector, LKTracker):
12.     def __init__(self, node_name):
13.         super(FaceTracker, self).__init__(node_name)
```

To use the `face_detector` and `lk_tracker` code we developed earlier, we first have to import their classes, `FaceDetector` and `LKTracker`. We then define our new `FaceTracker` class as extending both classes. In Python this is called multiple inheritance. As before, we then use the `super()` function to initialize our new class which also takes care of initializing the parent classes.

```
26.     def process_image(self, cv_image):
27.         # Create a greyscale version of the image
28.         self.grey = cv2.cvtColor(cv_image, cv2.COLOR_BGR2GRAY)
29.
30.         # Equalize the grey histogram to minimize lighting effects
31.         self.grey = cv2.equalizeHist(self.grey)
```

As we did with our other nodes, we begin the `process_image()` function by converting the image to greyscale and equalizing the histogram to minimize lighting effects.

```
33.     # STEP 1: Detect the face if we haven't already
34.     if self.detect_box is None:
35.         self.detect_box = self.detect_face(self.grey)
```

Step 1 is to detect the face if we haven't already. The `detect_face()` function comes from the `FaceDetector` class we imported.

```
38.     # STEP 2: If we aren't yet tracking keypoints, get them now
39.     if self.track_box is None or not
40.         self.is_rect_nonzero(self.track_box):
41.             self.track_box = self.detect_box
42.             self.keypoints = self.get_keypoints(self.grey, self.track_box)
```

Once we have detected a face, Step 2 is to get the keypoints from the face region using the `get_keypoints()` function we imported from the `LKTracker` class, which in turn actually gets the function from the `GoodFeatures` class that it imports.

```
43.     # STEP 3: If we have keypoints, track them using optical flow
44.     if len(self.keypoints) > 0:
```

```
45.          # Store a copy of the current grey image used for LK tracking
46.          if self.prev_grey is None:
47.              self.prev_grey = self.grey
48.
49.          self.track_box = self.track_keypoints(self.grey,
self.prev_grey)
```

Once we have the keypoints, Step 3 starts tracking them using the `track_keypoints()` function that we imported from the `LKTracker` class.

```
1. else:
2.     # We have lost all keypoints so re-detect the face
3.     self.detect_box = None
```

If during tracking the number of keypoints dwindle to zero, we set the detect box to `None` so that we can re-detect the face in Step 1.

In the end, you can see that the overall script is essentially just a combination of our earlier nodes.

10.8.5 Dynamically Adding and Dropping Keypoints

If you play with the face tracker for a little bit, you will notice that the keypoints can drift onto other objects besides your face. You will also notice that the number of keypoints shrinks over time as the optical flow tracker drops them due to a low tracking score.

We can easily add new keypoints and drop bad ones during the tracking process. To add keypoints, we run `goodFeaturesToTrack()` every once in awhile over the region we are tracking. To drop keypoints, we can run a simple statistical clustering test on the collection of keypoints and remove the outliers.

The node `face_tracker2.py` incorporates these improvements. You can try it using the following command:

```
$ roslaunch rbx1_vision face_tracker2.launch
```

You should now see improved tracking of your face as keypoints are added and dropped to reflect the movements of your head. To actually see the points that are added and dropped, as well as the region around the face from which new keypoints are drawn, hit the "d" key over the image window. The expanded keypoint region is shown by a yellow box. Added keypoints will flash briefly in light blue and dropped points will flash briefly in red before they disappear. Hit the "d" key again to turn off the display.

The code for `face_tracker2.py` is nearly the same as the first `face_tracker.py` script so we won't describe it in detail again. The full source can be found here:

Link to SVN source: [face_tracker2.py](#)

The two new functions are `add_keypoints()` and `drop_keypoints()` which should be fairly self-explanatory from the comments in the code. However, it is worth briefly describing the new parameters that control when points are dropped and added. These can be found in the launch file `face_tracker2.launch` in the `rbxl_vision/launch` directory. Let's look at those parameters now. The default values are in parentheses:

- `use_depth_for_tracking: (False)` If you are using a depth camera, setting this value to `True` will drop keypoints that fall too far away from the face plane.
- `min_keypoints: (20)` The minimum number of keypoints before we will add new ones.
- `abs_min_keypoints: (6)` The absolute minimum number of keypoints before we consider the face lost and try to re-detect it.
- `add_keypoint_distance: (10)` A new keypoint must be at least this distance (in pixels) from any existing keypoint.
- `std_err_xy: (2.5)` The standard error (in pixels) for determining whether or not a keypoint is an outlier.
- `pct_err_z: (0.42)` The depth threshold (as a percent) that determines when we drop a keypoint for falling too far off the face plane.
- `max_mse: (10000)` The maximum total mean squared error in the current feature cluster before we start over and re-detect the face.
- `expand_roi: (1.02)` When looking for new keypoints, the expansion factor to grow the ROI on each cycle.
- `add_keypoints_interval: (1)` How often do we attempt to add new keypoints. A value of 1 means every frame, 2 every other frame and so on.
- `drop_keypoints_interval: (1)` How often do we attempt to drop keypoints. A value of 1 means every frame, 2 every other frame and so on.

Most of the defaults should work fairly well but of course feel free to try different values.

10.8.6 Color Blob Tracking (*CamShift*)

So far we have not made any use of color information to track the object of interest. OpenCV includes the [CamShift](#) filter which allows us to track a selected region of the

image based on the color histogram of that region. For an excellent explanation of how the CamShift filter works, be sure to check out Robin Hewitt's article on [How OpenCV's Face Tracker Works](#). In short, the CamShift filter scans successive frames of the video stream and assigns each pixel a probability of belonging to the original color histogram. The collection of pixels with the highest probability of "belonging" becomes the new target region to be tracked.

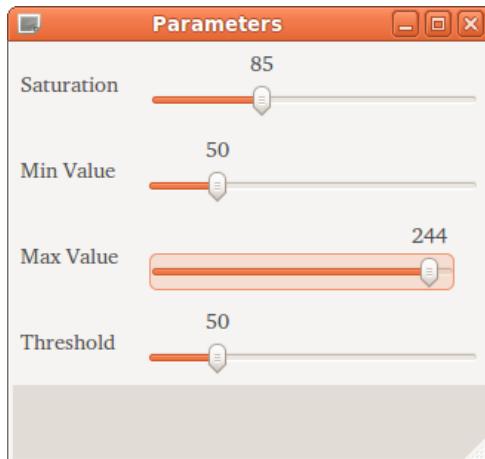
Before we look at the code, you can try it out as follows. Tracking works best with brightly colored objects. So first find an object such as a plastic ball that is fairly uniform in color and stands out from any background colors.

Next be sure to run the appropriate camera driver for the camera you are using. Then launch the CamShift node with the following command:

```
$ rosrun rbx1_vision camshift.launch
```

When the video window appears, hold the target object in front of the camera and draw a rectangle around it. The CamShift node will immediately begin to follow the object as best it can based on the color histogram computed from the selected region. Notice how the tracked region actually fills out the object even if you only select a smaller piece of it. This is because the CamShift algorithm is adaptively matching a *range* of colors in the selected region, not just a single RGB value.

Two other windows will be present on the screen. The first is a group of slider controls that look like this:



These controls determine the selectivity of the CamShift filter. For brightly colored objects like a green tennis ball, the default values should work fairly well. However, for natural colors like faces, you may have to turn down the **Saturation** and **Min Value**

settings and tweak the **Threshold** parameter slightly. Once you find a group of settings that work for your camera, you can set them in the `camshift.launch` file.

The second window shows the "back projection" of the histogram probabilities back onto the image. The result is a greyscale image where white pixels represent a high probability of belonging to the histogram and grey or black pixels represent lower probabilities. It is useful to have the back projection window visible when adjusting the slider controls: the goal is to have mostly white pixels over the target and black elsewhere.

The following video demonstrates the CamShift filter in action:

<http://www.youtube.com/watch?v=rDTun7A6HO8&feature=plcp>

Let's now look at the code.

Link to SVN source: [camshift.py](#)

```
1.  #!/usr/bin/env python
2.  import roslib; roslib.load_manifest('rbxl_vision')
3.  import rospy
4.  import cv2
5.  from cv2 import cv as cv
6.  from ros2opencv2 import ROS2OpenCV2
7.  from std_msgs.msg import String
8.  from sensor_msgs.msg import Image
9.  import numpy as np
10.
11. class CamShiftNode(ROS2OpenCV2):
12.     def __init__(self, node_name):
13.         ROS2OpenCV2.__init__(self, node_name)
14.
15.         self.node_name = node_name
16.
17.         # The minimum saturation of the tracked color in HSV space,
18.         # as well as the min and max value (the V in HSV) and a
19.         # threshold on the backprojection probability image.
20.         self.smin = rospy.get_param("~smin", 85)
21.         self.vmin = rospy.get_param("~vmin", 50)
22.         self.vmax = rospy.get_param("~vmax", 254)
23.         self.threshold = rospy.get_param("~threshold", 50)
24.
25.         # Create a number of windows for displaying the histogram,
26.         # parameters controls, and backprojection image
27.         cv.NamedWindow("Histogram", cv.CV_WINDOW_NORMAL)
28.         cv.MoveWindow("Histogram", 700, 50)
29.         cv.NamedWindow("Parameters", 0)
30.         cv.MoveWindow("Parameters", 700, 325)
31.         cv.NamedWindow("Backproject", 0)
32.         cv.MoveWindow("Backproject", 700, 600)
33.
34.         # Create the slider controls for saturation, value and threshold
35.         cv.CreateTrackbar("Saturation", "Parameters", self.smin, 255,
self.set_smin)
```

```

36.         cv.CreateTrackbar("Min Value", "Parameters", self.vmin, 255,
self.set_vmin)
37.         cv.CreateTrackbar("Max Value", "Parameters", self.vmax, 255,
self.set_vmax)
38.         cv.CreateTrackbar("Threshold", "Parameters", self.threshold, 255,
self.set_threshold)
39.
40.         # Initialize a number of variables
41.         self.hist = None
42.         self.track_window = None
43.         self.show_backproj = False
44.
45.         # These are the callbacks for the slider controls
46.         def set_smin(self, pos):
47.             self.smin = pos
48.
49.         def set_vmin(self, pos):
50.             self.vmin = pos
51.
52.         def set_vmax(self, pos):
53.             self.vmax = pos
54.
55.         def set_threshold(self, pos):
56.             self.threshold = pos
57.
58.         # The main processing function computes the histogram and
backprojection
59.         def process_image(self, cv_image):
60.             # First blue the image
61.             frame = cv2.blur(cv_image, (5, 5))
62.
63.             # Convert from RGB to HSV space
64.             hsv = cv2.cvtColor(frame, cv2.COLOR_BGR2HSV)
65.
66.             # Create a mask using the current saturation and value parameters
67.             mask = cv2.inRange(hsv, np.array((0., self.smin, self.vmin)),
np.array((180., 255., self.vmax)))
68.
69.             # If the user is making a selection with the mouse,
70.             # calculate a new histogram to track
71.             if self.selection is not None:
72.                 x0, y0, w, h = self.selection
73.                 x1 = x0 + w
74.                 y1 = y0 + h
75.                 self.track_window = (x0, y0, x1, y1)
76.                 hsv_roi = hsv[y0:y1, x0:x1]
77.                 mask_roi = mask[y0:y1, x0:x1]
78.                 self.hist = cv2.calcHist([hsv_roi], [0], mask_roi, [16], [0,
180] )
79.                 cv2.normalize(self.hist, self.hist, 0, 255, cv2.NORM_MINMAX);
80.                 self.hist = self.hist.reshape(-1)
81.                 self.show_hist()
82.
83.             if self.detect_box is not None:
84.                 self.selection = None
85.
86.             # If we have a histogram, tracking it with CamShift

```

```

87.         if self.hist is not None:
88.             # Compute the backprojection from the histogram
89.             backproject = cv2.calcBackProject([hsv], [0], self.hist, [0,
180], 1)
90.
91.             # Mask the backprojection with the mask created earlier
92.             backproject &= mask
93.
94.             # Threshold the backprojection
95.             ret, backproject = cv2.threshold(backproject, self.threshold,
255, cv.CV_THRESH_TOZERO)
96.
97.             x, y, w, h = self.track_window
98.             if self.track_window is None or w <= 0 or h <=0:
99.                 self.track_window = 0, 0, self.frame_width - 1,
self.frame_height - 1
100.
101.            # Set the criteria for the CamShift algorithm
102.            term_crit = ( cv2.TERM_CRITERIA_EPS | cv2.TERM_CRITERIA_COUNT,
10, 1 )
103.
104.            # Run the CamShift algorithm
105.            self.track_box, self.track_window = cv2.CamShift(backproject,
self.track_window, term_crit)
106.
107.            # Display the resulting backprojection
108.            cv2.imshow("Backproject", backproject)
109.
110.            return cv_image
111.
112.        def show_hist(self):
113.            bin_count = self.hist.shape[0]
114.            bin_w = 24
115.            img = np.zeros((256, bin_count*bin_w, 3), np.uint8)
116.            for i in xrange(bin_count):
117.                h = int(self.hist[i])
118.                cv2.rectangle(img, (i*bin_w+2, 255), ((i+1)*bin_w-2, 255-h),
(int(180.0*i/bin_count), 255, 255), -1)
119.                img = cv2.cvtColor(img, cv2.COLOR_HSV2BGR)
120.                cv2.imshow("Histogram", img)
121.
122.
123.        def hue_histogram_as_image(self, hist):
124.            """ Returns a nice representation of a hue histogram """
125.            histimg_hsv = cv.CreateImage((320, 200), 8, 3)
126.
127.            mybins = cv.CloneMatND(hist.bins)
128.            cv.Log(mybins, mybins)
129.            (_, hi, _, _) = cv.MinMaxLoc(mybins)
130.            cv.ConvertScale(mybins, mybins, 255. / hi)
131.
132.            w,h = cv.GetSize(histimg_hsv)
133.            hdims = cv.GetDims(mybins)[0]
134.            for x in range(w):
135.                xh = (180 * x) / (w - 1) # hue sweeps from 0-180 across the
image
136.                val = int(mybins[int(hdims * x / w)] * h / 255)

```

```

137.             cv2.rectangle(histimg_hsv, (x, 0), (x, h-val), (xh,255,64),
-1)
138.             cv2.rectangle(histimg_hsv, (x, h-val), (x, h), (xh,255,255),
-1)
139.
140.         histimg = cv2.cvtColor(histimg_hsv, cv.CV_HSV2BGR)
141.
142.         return histimg
143.
144.
145.     if __name__ == '__main__':
146.         try:
147.             node_name = "camshift"
148.             CamShiftNode(node_name)
149.             try:
150.                 rospy.init_node(node_name)
151.             except:
152.                 pass
153.             rospy.spin()
154.         except KeyboardInterrupt:
155.             print "Shutting down vision node."
156.             cv.DestroyAllWindows()

```

Let's look at the key lines in the script.

```

20.     self.smin = rospy.get_param("~smin", 85)
21.     self.vmin = rospy.get_param("~vmin", 50)
22.     self.vmax = rospy.get_param("~vmax", 254)
23.     self.threshold = rospy.get_param("~threshold", 50)

```

These are the parameters that control the color sensitivity of the CamShift algorithm. The algorithm will not work at all without setting these to the right values for your camera. The defaults should be close but you will want to play with the slider controls (which appear after launching the program) to find good values for your setup. Once you are satisfied with your numbers, you can enter them in the launch file to override the defaults.

The `smin` value controls the minimum *saturation* in the HSV image (Hue, Saturation, Value). It is a measure of the "richness" of a color. The `vmin` and `vmax` parameters determine the minimum and maximum *value* (brightness) a color needs to have. Finally, the `threshold` parameter is applied after the backprojection is computed to filter out low-probability pixels from the result.

```

35. cv.CreateTrackbar("Saturation", "Parameters", self.smin, 255,
    self.set_smin)
36. cv.CreateTrackbar("Min Value", "Parameters", self.vmin, 255,
    self.set_vmin)
37. cv.CreateTrackbar("Max Value", "Parameters", self.vmax, 255,
    self.set_vmax)
38. cv.CreateTrackbar("Threshold", "Parameters", self.threshold, 255,
    self.set_threshold)

```

Here we use OpenCV's trackbar function to create slider controls on the "Parameters" window. The last three arguments of the `CreateTrackbar()` function specify the minimum, maximum and default values for each trackbar.

```
59.     def process_image(self, cv_image):
60.         # First blur the image
61.         frame = cv2.blur(cv_image, (5, 5))
62.
63.         # Convert from RGB to HSV space
64.         hsv = cv2.cvtColor(frame, cv2.COLOR_BGR2HSV)
```

The main processing loop begins by blurring the image, then converting it from blue-green-red (BGR) to hue-saturation-value (HSV). Blurring helps wash out some of the color noise in typical video images. Working in HSV space is a common practice when processing color images. In particular, the hue dimension maps nicely into what we (i.e. humans) consider different colors such as red, orange, yellow, green, blue, etc. The saturation dimension maps into how "rich" versus "washed out" a color appears to us, and the value dimension maps into how bright the color appears.

```
67.         mask = cv2.inRange(hsv, np.array((0., self.smin, self.vmin)),
68.                               np.array(180., 255., self.vmax)))
```

The OpenCV `inRange()` function turns our saturation and value limits into a mask so that we process only those pixels that fall within our color parameters. Note that we are not filtering on hue—so we are still accepting any color at this point. Instead, we are selecting only those colors that have a fairly high saturation and value.

```
71.     if self.selection is not None:
72.         x0, y0, w, h = self.selection
73.         x1 = x0 + w
74.         y1 = y0 + h
75.         self.track_window = (x0, y0, x1, y1)
76.         hsv_roi = hsv[y0:y1, x0:x1]
77.         mask_roi = mask[y0:y1, x0:x1]
```

In this block we take a selection from the user (made with the mouse) and turn it into a region of interest for computing a color histogram and a mask.

```
78.         self.hist = cv2.calcHist([hsv_roi], [0], mask_roi, [16], [0,
79.                                   180])
80.         cv2.normalize(self.hist, self.hist, 0, 255, cv2.NORM_MINMAX);
81.         self.hist = self.hist.reshape(-1)
82.         self.show_hist()
```

Here we use the OpenCV `calcHist()` function to calculate a histogram over the hues in the selected region. Note that the region is also masked with `mask_roi`. We then normalize the histogram so that the maximum value is 255. This allows us to display the result as an 8-bit color image which is done with the last two lines using the helper function `show_hist()` defined later in the script.

```

89.         backproject = cv2.calcBackProject([hsv], [0], self.hist, [0,
180], 1)
90.
91.         # Mask the backprojection with the mask created earlier
92.         backproject &= mask
93.
94.         # Threshold the backprojection
95.         ret, backproject = cv2.threshold(backproject, self.threshold,
255, cv.CV_THRESH_TOZERO)

```

Once we have a histogram to track, we use the OpenCV `calcBackProject()` function to assign a probability to each pixel in the image of belonging to the histogram. We then mask the probabilities with our earlier mask and threshold it to eliminate low probability pixels.

```

102.        term_crit = (cv2.TERM_CRITERIA_EPS | cv2.TERM_CRITERIA_COUNT,
10, 1)
103.
104.        # Run the CamShift algorithm
105.        self.track_box, self.track_window = cv2.CamShift(backproject,
self.track_window, term_crit)

```

With the masked and thresholded backprojection in hand, we can finally run the CamShift algorithm itself which converts the probabilities into a new location of the track window.

The whole process is repeated on every frame (without any further selection from the user of course) and the track window follows the pixels that have the highest probability of belonging to the original histogram. If you find your target object is not being followed very well, start with a brightly colored ball or other uniformly colored object. You will also probably have to tweak the saturation and value slider controls to get the result you want.

10.9 OpenNI and Skeleton Tracking

Perhaps the earliest and best known robotics application using a Kinect is skeleton tracking. The ROS [openni_tracker](#) package can use the depth data from a Kinect or Asus Xtion to track the joint positions of a person standing in front of the camera. Using this data, one can program a robot to follow gesture commands signaled by the user. One example of how to do this using ROS and Python can be found in the [pi_tracker](#) package.

While we won't go into a lot of detail on the use of skeleton tracking, let's at least take a look at the basics.

10.9.1 Viewing Skeletons in RViz

The ROS [openni_tracker](#) package connects to a PrimeSense device such as a Kinect or Asus Xtion and broadcasts a ROS frame transform for each skeleton joint detected in front of the camera. The `tf` transforms are defined relative to the `openni_depth_frame` which is embedded inside the camera behind the depth sensor.

To view the skeleton frames in `RViz`, perform the following steps. First, plug in your Kinect or Asus camera and in the case of the Kinect, make sure it has power as well. Terminate any `openni` launch files you might already have running. Then run the `openni_tracker.launch` file:

```
$ rosrun rviz rviz -d `rospack find \`  
rbx1_vision`/skeleton_frames_fuerte.vcg`
```

Bring up `RViz` with the included `skeleton_frames_fuerte.vcg` config file:

```
$ rosrun rviz rviz -d `rospack find \`  
rbx1_vision`/skeleton_frames_fuerte.vcg`
```

Keep your eye on `RViz` and stand back from the camera at least a 5 or 6 feet while assuming the "Psi pose". (See the [openni_tracker](#) page for a picture.) Once the tracker locks onto you, you should see your skeleton `tf` frames appear in `RViz`. At this point you can move around as you like in front of the camera and the skeleton in `RViz` should mimic your actions.

10.9.2 Accessing Skeleton Frames in your Programs

Since the `openni_tracker` node makes the skeleton joints available as ROS `tf` frames, we can use a `tf TransformListener` to find the current position of a given joint. An example of how this works can be found in the [skeleton_markers](#) package. You can install it by first moving into your personal ROS directory, then running the commands:

```
$ svn co http://pi-robot-ros\  
-pkg.googlecode.com/svn/trunk/skeleton_markers  
$ rosmake skeleton_markers
```

Let's try it out before looking at the code. First terminate any instances of `openni_tracker` and `RViz` you may have launched in the previous section. Next, run the commands:

```
$ rosrun skeleton_markers markers_from_tf_fuerte.launch  
$ rosrun rviz rviz -d `rospack find \`  
skeleton_markers`/markers_from_tf_fuerte.vcg`
```

Now assume the "Psi Pose" in front of the camera while keeping an eye on RViz until calibration is complete and tracking begins. Once the tracker locks onto you, you should see the green skeleton markers appear in RViz. At this point you can move around as you like in front of the camera and the skeleton in RViz should follow your actions.

Before we look at the code, let's be sure we understand the launch file `markers_from_tf.launch` listed below:

```
<launch>
  <arg name="tf_prefix" value="/skeleton" />

  <include file="$(find openni_camera)/launch/openni_node.launch" />

  <node pkg="openni_tracker" name="openni_tracker" type="openni_tracker"
output="screen">
    <param name="tf_prefix" value="$(arg tf_prefix)" />
  </node>

  <node pkg="skeleton_markers" name="markers_from_tf" type="markers_from_tf.py"
output="screen">
    <rosparam file="$(find skeleton_markers)/params(marker_params.yaml"
command="load" />
    <param name="tf_prefix" value="$(arg tf_prefix)" />
  </node>
</launch>
```

Note how we define a `tf_prefix` and set it to `"/skeleton"`. The reason for this is that you might have all sorts of frame transforms lying around, such as those defined by your robot's URDF model. By instructing the `openni_tracker` node to publish all its transforms under a single prefix, we can extract them more easily in our script. We then set the same `tf_prefix` for the `markers_from_tf.py` node.

Let's now look at the `markers_from_tf.py` script.

Link to SVN source: [markers_from_tf.py](#)

```
1  #!/usr/bin/env python
2  import roslib; roslib.load_manifest('skeleton_markers')
3  import rospy
4  from visualization_msgs.msg import Marker
5  from geometry_msgs.msg import Point
6  import tf
7
8  class SkeletonMarkers():
9      def __init__(self):
10          rospy.init_node('markers_from_tf')
11
12          rospy.loginfo("Initializing Skeleton Markers Node...")
13
14          rate = rospy.get_param('~rate', 20)
15          r = rospy.Rate(rate)
16
```

```

17      # The tf_prefix needs to be set in the launch file for both
18      # the openni_tracker node and the markers_from_tf node
19      self.tf_prefix = rospy.get_param('~tf_prefix', '/skeleton')
20
21      # There is usually no need to change the fixed frame from the default
22      self.fixed_frame = rospy.get_param('~fixed_frame',
23      'openni_depth_frame')
24
25      # We need to prepend the tf_prefix to the fixed frame
26      self.fixed_frame = self.tf_prefix + '/' + self.fixed_frame
27
28      # Initialize the tf listener
29      tf_listener = tf.TransformListener()
30
31      # Define a marker publisher
32      marker_pub = rospy.Publisher('skeleton_markers', Marker)
33
34      # Initialize the markers
35      self.initialize_markers()
36
37      # Make sure we see the openni_depth_frame
38      tf_listener.waitForTransform(self.fixed_frame, self.fixed_frame,
rospy.Time(), rospy.Duration(60.0))
39
40      # Begin the main loop
41      while not rospy.is_shutdown():
42          # Get the list of all skeleton frames from tf
43          skeleton_frames = [f for f in tf_listener.getFrameStrings() if
f.startswith(self.tf_prefix)]
44
45          # If we don't have any frames yet, wait and try again
46          if len(skeleton_frames) == 0:
47              r.sleep()
48              continue
49
50          # Set the markers header
51          self.markers.header.stamp = rospy.Time.now()
52
53          # Clear the markers point list
54          self.markers.points = list()
55
56          # Loop through the skeleton frames
57          for frame in skeleton_frames:
58              if frame == self.fixed_frame:
59                  continue
60
61              # Find the position of the frame's origin relative to the
62              # fixed frame.
63              try:
64                  position = Point()
65
66                  # Get the transformation from the fixed frame to the
67                  # skeleton frame
68                  (trans, rot) =
tf_listener.lookupTransform(self.fixed_frame, frame, rospy.Time(0))
69                  position.x = trans[0]
70                  position.y = trans[1]

```

```

68             position.z = trans[2]
69
70             # Set a marker at the origin of this frame
71             self.markers.points.append(position)
72             except (tf.Exception, tf.ConnectivityException,
73 tf.LookupException):
74                 rospy.logerr("tf error when looking up " + frame + ' and '
+ self.fixed_frame)
75                 continue
76
77             # Publish the set of markers
78             marker_pub.publish(self.markers)
79             r.sleep()
80
81     def initialize_markers(self):
82         # Set various parameters
83         scale = rospy.get_param('~scale', 0.07)
84         lifetime = rospy.get_param('~lifetime', 0) # 0 is forever
85         ns = rospy.get_param('~ns', 'skeleton_markers')
86         id = rospy.get_param('~id', 0)
87         color = rospy.get_param('~color', {'r': 0.0, 'g': 1.0, 'b': 0.0, 'a':
1.0})
88
89         # Initialize the marker points list
90         self.markers = Marker()
91         self.markers.header.frame_id = self.fixed_frame
92         self.markers.ns = ns
93         self.markers.id = id
94         self.markers.type = Marker.POINTS
95         self.markers.action = Marker.ADD
96         self.markers.lifetime = rospy.Duration(lifetime)
97         self.markers.scale.x = scale
98         self.markers.scale.y = scale
99         self.markers.color.r = color['r']
100        self.markers.color.g = color['g']
101        self.markers.color.b = color['b']
102        self.markers.color.a = color['a']
103 if __name__ == '__main__':
104     try:
105         SkeletonMarkers()
106     except rospy.ROSInterruptException:
107         pass

```

Let's examine the key lines:

```

19         self.tf_prefix = rospy.get_param('~tf_prefix', '/skeleton')
20
21         # There is usually no need to change the fixed frame from the default
22         self.fixed_frame = rospy.get_param('~fixed_frame',
23 'openni_depth_frame')
24
25         # We need to prepend the tf_prefix to the fixed frame
26         self.fixed_frame = self.tf_prefix + '/' + self.fixed_frame

```

Here we read in the `tf_prefix` we discussed earlier. We also set the fixed frame to be the default used by the `openni_tracker` node. We then glue the `tf_prefix` in front of the fixed frame.

```
27      # Initialize the tf listener
28      tf_listener = tf.TransformListener()
29
30      # Define a marker publisher
31      marker_pub = rospy.Publisher('skeleton_markers', Marker)
```

Next we create a `TransformListener` from the ROS `tf` library and set up a publisher for the visualization markers.

```
34      self.initialize_markers()
```

This line calls a function (defined later in the script) to initialize the markers. We won't discuss markers in this volume but you can probably follow the initializing function fairly easily. You can also look at the [Markers Tutorial](#) on the ROS Wiki, although the examples are in C++.

```
37      tf_listener.waitForTransform(self.fixed_frame, self.fixed_frame,
rospy.Time(), rospy.Duration(60.0))
```

Before we start looking for skeleton frames, we make sure we can at least see the camera's fixed frame and we allow 60 seconds before we time out.

```
40      while not rospy.is_shutdown():
41          # Get the list of all skeleton frames from tf
42          skeleton_frames = [f for f in tf_listener.getFrameStrings() if
f.startswith(self.tf_prefix)]
43
44          # If we don't have any frames yet, wait and try again
45          if len(skeleton_frames) == 0:
46              r.sleep()
47              continue
```

We finally enter the main loop of the script. First we create a list of all the `tf` frames that match the `tf_prefix`. If we don't yet have any skeleton frames, we wait for one cycle then try again.

```
56      for frame in skeleton_frames:
57          if frame == self.fixed_frame:
58              continue
```

Once we have some skeleton frames, we are ready to get their transformations. However, we can skip the fixed frame.

```
61          try:
62              position = Point()
```

```

63                         # Get the transformation from the fixed frame to the
64                         skeleton frame
65                         (trans, rot) =
66                         tf_listener.lookupTransform(self.fixed_frame, frame, rospy.Time(0))
67                         position.x = trans[0]
68                         position.y = trans[1]
69                         position.z = trans[2]
70
71                         # Set a marker at the origin of this frame
72                         self.markers.points.append(position)
73                         except (tf.Exception, tf.ConnectivityException,
74                         tf.LookupException):
75                             rospy.logerr("tf error when looking up " + frame + ' and '
76                             + self.fixed_frame)
77                             continue

```

For each frame in the skeleton list, we attempt to look up the transform between it and the fixed frame using the `tf` listener's `lookupTransform()` function. If the lookup is successful, the translation and rotation are returned separately. If the lookup fails, an exception is generated which we catch with the `try-catch` block. With a successful lookup, we only care about the translation component (the location of the frame's origin relative to the fixed frame) and therefore set the x, y and z components of a `Point()` variable called `position`. This point is then appended to the list of markers.

```

77             marker_pub.publish(self.markers)
78             r.sleep()

```

Once we have a marker for each frame, we publish the whole set of markers and then wait for one rate cycle before starting a new loop.

10.10 PCL Nodelets and 3D Point Clouds

The [Point Cloud Library](#), or PCL, is an expansive project including many powerful algorithms for processing point clouds. It is especially useful for robots equipped with an RGB-D camera like the Kinect at Xtion Pro or even a more traditional stereo camera. While the details of using PCL are beyond the scope of this volume, we can at least touch on some of the basics.

At the time of this writing, the primary API for PCL is available only in C++. If you are already an experienced C++ programmer, you can start right away with the [excellent tutorials](#) on the PCL website. At the moment, there are not any official Python bindings for PCL (although at least [one developer](#) has made a start). In the meantime, the `pcl_ros` package provides a number of `nodelets` for processing point clouds using PCL without having to write any code at all. For this reason, we will take a brief look at a couple of functions we can perform on point clouds using `pcl_ros`. (You can also find a complete list of `pcl_ros` nodelets in the [pcl_ros tutorials](#) on the ROS Wiki.)

10.10.1 The PassThrough Filter

The first PCL nodelet we will look at is the [PassThrough filter](#). This filter is handy if you want to restrict your attention to the part of the image that falls within a certain depth range. We will use this filter in our Person Follower application in the next chapter since we will want the robot to follow only those objects that are located within a certain distance.

Before trying out the filter, let's look at the launch file `passthrough.launch` in the `rbx1_vision/launch` directory:

```
<launch>
  <node pkg="nodelet" type="nodelet" name="pcl_manager" args="manager"
output="screen" />

  <!-- Run a passthrough filter to clean NaNs -->
  <node pkg="nodelet" type="nodelet" name="passthrough" args="load
pcl/PassThrough pcl_manager" output="screen">
    <remap from="~input" to="/camera/rgb/points" />
    <remap from="~output" to="/passthrough" />
    <rosparam>
      filter_field_name: z
      filter_limit_min: 1.0
      filter_limit_max: 1.25
      filter_limit_negative: False
    </rosparam>
  </node>
</launch>
```

The launch file first loads the `pcl_manager` nodelet and then the `passthrough` nodelet. The `passthrough` nodelet takes a number of parameters described as follows:

- `filter_field_name`: Typically this will be either `x`, `y` or `z` to indicate the optical axis that should be filtered. By "filtered" we mean that only points within the min and max limits (defined next) will be kept.
- `filter_limit_min`: The minimum value (in meters) we will accept.
- `filter_limit_max`: The maximum value (in meters) we will accept.
- `filter_limit_negative`: If set to `True`, then only keep what lies *outside* the filter limits.

In the sample launch file, we have set the min and max limits to 1.0 and 1.25 meters, respectively. This means that only points that fall between about 3 feet and 4 feet from the camera will be retained.

Note that the launch file sets the input point cloud topic to `/camera/rgb/points` and the output topic to `/passthrough`. This output topic name is needed when you want to view the results in `RViz`.

To see the result, start by launching the `openni_node` (if it isn't already):

```
$ rosrun rbx1_vision openni_node_fuerte.launch
```

Then run the command:

```
$ rosrun rbx1_vision passthrough.launch
```

Next, bring up `RViz` with the provided PCL config file:

```
$ rosrun rviz rviz -d `rospack find rbx1_vision`/pcl_fuerte.vcg
```

When `RViz` is up, look in the **Displays** panel on the left. By default, the **Original PointCloud** should be checked and you should see a color-coded point cloud in the main display. To see the result of the `Passthrough` filter, un-check the **Original PointCloud** display and check the **PassThrough** display. The **PassThrough** display topic should be set to `/passthrough`. If not, click on the **Topic** field and select it from the list.

Since we have set the distance limits to a fairly narrow window, do not be alarmed if you do not see any points in `RViz` when selecting the **PassThrough** display. However, stand in front of the camera and move toward and away from it and you should see the image of yourself appear and disappear as you pass through the filter limits.

To try different values of the minimum and maximum limits as well as the `filter_limit_negative` parameter, bring up `dynamic_reconfigure` and select the `passthrough` node. If you check the checkbox beside `filter_limit_negative`, you should now find a "hole" in between the distance limits. Now everything *outside* your limits should be visible but as you move through the hole, you will disappear.

By the way, you can change how depth is displayed for a given point cloud topic by changing the **Color Transformer** from the pull down list. For example, selecting `RGB8` instead of `Axis` will display the actual pixel color values while the `Axis` setting uses a color-coded depth map. The recommended setting for the **Style** setting is `Points`. You can try other options here but you will likely find that they slow down your computer significantly unless you have a very powerful machine.

10.10.2 Combining More than One `PassThrough` Filter

We can combine more than one `PassThrough` filter in a single launch file. In particular, we can put limits on all three dimensions and create a box such that only points inside the box are visible. The result is a kind of 3D focus of attention. If we set the `filter_limit_negative` parameter to `True` for each filter, only points outside the box will be visible.

As an example, take a look at the launch file `passthrough2.launch` in the directory `rbx1_vision/launch`. The launch file includes three instances of the `passthrough` nodelet, one for each optical dimension x, y and z. Note that each nodelet must have a unique name so we have called them `passthrough_x`, `passthrough_y` and `passthrough_z`. We then set min/max distance limits on each filter to create a box of the desired size. Note how the input topic of a subsequent filter is set to be the output topic of the one before it. The final result of all three filters is still published on the `/passthrough` topic so you can use the same `RViz` config file to see it. Terminate the previous `passthrough.launch` file and run:

```
$ roslaunch rbx1_vision passthrough2.launch
```

You should be able to play with the settings in `dynamic_reconfigure` to create filter boxes of different size.

10.10.3 The `VoxelGrid` Filter

The second filter we will look at is the [VoxelGrid filter](#). Point clouds from high resolution cameras contain a very large number of points and can take a lot of CPU power to process. To reduce the load and ensure faster frame rates, the `VoxelGrid` filter does a downsampling of the input cloud using parameters specified in the launch file. The result is a new point cloud with many fewer points. Let's take a look at the launch file `voxel.launch` found in the `rbx1_vision/launch` directory:

```
<launch>
  <node pkg="nodelet" type="nodelet" name="pcl_manager" args="manager"
output="screen" />

  <!-- Run a VoxelGrid filter to clean NaNs and downsample the data -->
  <node pkg="nodelet" type="nodelet" name="voxel_grid" args="load pcl/VoxelGrid
pcl_manager" output="screen">
    <remap from="~input" to="/camera/rgb/points" />
    <remap from="~output" to="/voxel_grid" />
    <rosparam>
      filter_field_name: z
      filter_limit_min: 0.01
      filter_limit_max: 3.5
      filter_limit_negative: False
      leaf_size: 0.05
    </rosparam>
  </node>
</launch>
```

Notice that the first four parameters are identical to the `PassThrough` filter and they behave the same way. The fourth parameter, `leaf_size`, determines the coarseness of the sampling grid. A value of 0.05 means that the original point cloud is sampled every 5cm to produce the output cloud.

If you are still running a `passthrough` launch file from the previous section, terminate it now. If you don't still have the `openni` node running, bring it up now:

```
$ rosrun rbox1_vision openni_node_fuerte.launch
```

If you don't already have `RViz` running with the `pcl_fuerte.vcg` config file, run it now:

```
$ rosrun rviz rviz -d `rospack find rbox1_vision`/pcl_fuerte.vcg
```

Finally, fire up the `VoxelGrid` filter:

```
$ rosrun rbox1_vision voxel.launch
```

To view the result of the `VoxelGrid` filter, un-check both the **Original PointCloud** and **PassThrough** displays in `RViz` and check the box beside **VoxelGrid**. You should see a fairly sparse cloud. This is especially apparent if you zoom in on the cloud using your mouse scroll wheel. You also use `dynamic_reconfigure` to change the `leaf_size` on the fly and observe the result in `RViz`.

To get an idea of the reduction of the number of points in the Voxel-filtered point cloud, click the checkbox beside the **Original PointCloud** display to activate it again. Then click the + sign beside **Original PointCloud** which should reveal the **Status** field at the top. Finally, click the + sign beside **Status** and you can see the number of points being displayed. The `openni_node_fuerte.launch` file used above loads the camera driver in 320x240 mode (QVGA) which yields as many as 76,800 points depending how much of the image is within the camera's depth range. (Selecting a resolution of 640x480 bumps this number up 4x to 307,200 points.)

Now un-check the **Original** PointCloud display and repeat the steps above for the **VoxelGrid** display. Depending on the leaf size, you should see many fewer points under the **Status** field. You will probably also notice that `RViz` is much more responsive as you rotate the cloud around with your mouse due to the smaller load on the CPU and graphics processor.

11. COMBINING VISION AND BASE CONTROL

Now that we have a handle on basic vision processing and motion control in ROS, we are ready to put them together into a full ROS application. In this chapter we will look at two such applications: object tracking and person following.

11.1 A Note about Camera Coordinate Axes

ROS assumes that the optical coordinate frame attached to a given camera is oriented with the z-axis pointing outward from the camera and perpendicular to the image plane. Within the image plane, the x-axis points horizontally to the right and the y-axis points vertically downward.

Note that this frame differs from the one typically attached to a mobile base which, as we saw earlier, has the z-axis pointing upward, the x-axis pointing forward, and the y-axis point to the left. While we won't have to worry too much about this difference in this volume, it is important to keep in mind that when we talk about "depth" in the context of an RGB-D camera such as the Kinect, we are talking about the camera's z-axis which points outward from the camera.

11.2 Object Tracker

In the chapter on Robot Vision, we learned how to use OpenCV to track faces, keypoints and colors. In all cases, the result is a region of interest (ROI) that follows the object and is published on the ROS topic `/roi`. If the camera is mounted on a mobile robot, we can use the `x_offset` coordinate of the `/roi` to keep the object centered in the field of view by rotating the robot to compensate for the offset. In this way, the robot will track the object as it moves to the left or right in front of the camera. (We will deal with depth in the next application.)

An example of this kind of tracking can be found in the `object_tracker.py` script located in the directory `rbx1_apps/nodes`. Before we review the code, let's test the tracking as follows.

11.2.1 Testing the Object Tracker with `rxplot`

First, make sure your camera is plugged in, then run the openni driver:

```
$ roslaunch rbx1_vision openni_node_fuerte.launch
```

Next, launch the `face_tracker` node we developed earlier:

```
$ roslaunch rbx1_vision face_tracker2.launch
```

Now bring up the object_tracker node:

```
$ roslaunch rbx1_apps object_tracker.launch
```

Finally, run rxplot to view the angular component of the /cmd_vel topic:

```
$ rxplot -p 15 /cmd_vel/angular/z
```

Now look at the camera and when the face tracker detects your face, move your head left and right. As you do so, you should see the angular velocity in rxplot vary between roughly 2 and -2 radians per second. The further away from center you move your face, the larger the velocity value on rxplot. If these values were being sent to a robot, the robot would rotate accordingly.

11.2.2 Testing the Object Tracker with a Simulated Robot

Instead of rxplot, we can use the ArbotiX simulator to test the functionality of the object tracker code. The procedure is the same as the preceding section except that instead of running rxplot as the last step, bring up the simulator and RViz as we have done before:

```
$ roslaunch rbx1_bringup fake_turtlebot.launch
```

```
$ rosrun rviz rviz -d `rospack find rbx1_nav`/sim_fuerte.vcg
```

You should see the simulated TurtleBot in RViz. If you now move your head left or right in front of the camera, the TurtleBot should rotate in the corresponding direction. The further left/right you move, the faster it should rotate. Note that the robot will continue to rotate as long as your face is off-center since the simulation cannot line up with your real face.

11.2.3 Understanding the Object Tracker Code

Before running the tracking application on a real robot, let's take a look at the code.

Link to SVN source: [object_tracker.py](#)

```
1 #!/usr/bin/env python
2 import roslib; roslib.load_manifest('rbx1_apps')
3 import rospy
4 from sensor_msgs.msg import RegionOfInterest, CameraInfo
5 from geometry_msgs.msg import Twist
6
7
8 class ObjectTracker():
9     def __init__(self):
```

```

10     rospy.init_node("object_tracker")
11
12     # Set the shutdown function (stop the robot)
13     rospy.on_shutdown(self.shutdown)
14
15     # How often should we update the robot's motion?
16     self.rate = rospy.get_param("~rate", 10)
17     r = rospy.Rate(self.rate)
18
19     # The maximum rotation speed in radians per second
20     self.max_rotation_speed = rospy.get_param("~max_rotation_speed", 2.0)
21
22     # The minimum rotation speed in radians per second
23     self.min_rotation_speed = rospy.get_param("~min_rotation_speed", 0.5)
24
25     # Sensitivity to target displacements. Setting this too high
26     # can lead to oscillations of the robot.
27     self.gain = rospy.get_param("~gain", 2.0)
28
29     # The x threshold (% of image width) indicates how far off-center
30     # the ROI needs to be in the x-direction before we react
31     self.x_threshold = rospy.get_param("~x_threshold", 0.1)
32
33     # Publisher to control the robot's movement
34     self.cmd_vel_pub = rospy.Publisher('/cmd_vel', Twist)
35
36     # Initialize the movement command
37     self.move_cmd = Twist()
38
39     # We will get the image width and height from the camera_info topic
40     self.image_width = 0
41     self.image_height = 0
42
43     # Set flag to indicate when the ROI stops updating
44     self.target_visible = False
45
46     # Wait for the camera_info topic to become available
47     rospy.loginfo("Waiting for camera_info topic...")
48     rospy.wait_for_message('camera_info', CameraInfo)
49
50     # Subscribe the camera_info topic to get the image width and height
51     rospy.Subscriber('camera_info', CameraInfo, self.get_camera_info)
52
53     # Wait until we actually have the camera data
54     while self.image_width == 0 or self.image_height == 0:
55         rospy.sleep(1)
56
57     # Subscribe to the ROI topic and set the callback to
58     # update the robot's motion
59     rospy.Subscriber('roi', RegionOfInterest, self.set_cmd_vel)
60
61     # Wait until we have an ROI to follow
62     rospy.wait_for_message('roi', RegionOfInterest)
63
64     rospy.loginfo("ROI messages detected. Starting tracker...")
65     # Begin the tracking loop

```

```

66     while not rospy.is_shutdown():
67         # If the target is not visible, stop the robot
68         if not self.target_visible:
69             self.move_cmd = Twist()
70         else:
71             # Reset the flag to False by default
72             self.target_visible = False
73
74             # Send the Twist command to the robot
75             self.cmd_vel_pub.publish(self.move_cmd)
76
77             # Sleep for 1/self.rate seconds
78             r.sleep()
79
80     def set_cmd_vel(self, msg):
81         # if the ROI width or height is 0, we have lost the target
82         if msg.width == 0 or msg.height == 0:
83             return
84
85         # If the ROI stops updating this next statement will not happen
86         self.target_visible = True
87
88         # Compute the displacement of the target from the center of the image
89         target_x_offset = msg.x_offset + (msg.width / 2.0) - (self.image_width
90 / 2.0)
91
92         try:
93             percent_x_offset = float(angular_offset) /
94 (float(self.image_width) / 2.0)
95         except:
96             percent_x_offset = 0
97
98         # Rotate the robot only if the displacement of the
99         # target exceeds the threshold
100        if abs(percent_x_offset) > self.x_threshold:
101            # Set the rotation speed proportional to the
102            # displacement of the target
103            try:
104                speed = self.gain * percent_x_offset
105                if speed < 0:
106                    direction = -1
107                else:
108                    direction = 1
109                self.move_cmd.angular.z = -direction *
110 max(self.min_rotation_speed, min(self.max_rotation_speed, abs(speed)))
111            except:
112                self.move_cmd = Twist()
113
114        else:
115            # Otherwise stop the robot
116            self.move_cmd = Twist()
117
118    def shutdown(self):
119        rospy.loginfo("Stopping the robot...")

```

```

118     self.cmd_vel_pub.publish(Twist())
119     rospy.sleep(1)
120
121 if __name__ == '__main__':
122     try:
123         ObjectTracker()
124         rospy.spin()
125     except rospy.ROSInterruptException:
126         rospy.loginfo("Object tracking node terminated.")

```

By this point in the book, the script will probably be fairly self-explanatory. However, let's run through the key lines. Keep in mind the overall goal of the tracker application: we want to monitor the /roi topic for any change in the position of the target to either the left or right of the camera's center of view. We will then rotate the robot in the appropriate direction to compensate.

```

19     # The maximum rotation speed in radians per second
20     self.max_rotation_speed = rospy.get_param("~max_rotation_speed", 2.0)
21
22     # The minimum rotation speed in radians per second
23     self.min_rotation_speed = rospy.get_param("~min_rotation_speed", 0.5)

```

When controlling a mobile robot, it is always a good idea to set a maximum speed. Setting a minimum speed as well can ensure that the robot does not struggle against its own weight and friction when trying to move too slowly.

```
27     self.gain = rospy.get_param("~gain", 2.0)
```

Most feedback loops require a gain parameter to control how fast we want the system to respond to displacements of the target from the neutral point. In our case, the gain parameter will determine how quickly the robot reacts to movements of the target away from the center of view.

```
31     self.x_threshold = rospy.get_param("~x_threshold", 0.05)
```

We don't want the robot to be draining its battery chasing every tiny movement of the target. So we set a lower threshold on the horizontal displacement of the target to which the robot will respond. In this case, the threshold is specified as a percentage (0.05 = 5%) of the image width.

```
44     self.target_visible = False
```

If the target is lost (e.g. goes out of the field of view), we want the robot to stop. So we will use a flag to indicate when the target is visible or not.

```
51     rospy.Subscriber('camera_info', CameraInfo, self.get_camera_info)
```

Rather than hard code the video resolution into the program, we can get it dynamically from the appropriate `camera_info` topic. The actual name of this topic is mapped in the launch file `object_tracker.launch`. In the case of a Kinect or Xtion camera driven by the OpenNI node, the topic name is usually `/camera/rgb/camera_info`. The callback function `self.get_camera_info` (defined later in the script) simply sets the global variables `self.image_width` and `self.image_height` from the `camera_info` messages.

```
58      rospy.Subscriber('roi', RegionOfInterest, self.set_cmd_vel)
```

Here we subscribe to the `/roi` topic and set the callback function to `self.set_cmd_vel` which will set the `Twist` command to send to the robot when the position of the target changes.

```
66      while not rospy.is_shutdown():
67          # If the target is not visible, stop the robot
68          if not self.target_visible:
69              self.move_cmd = Twist()
70          else:
71              # Reset the flag to False by default
72              self.target_visible = False
73
74          # Send the Twist command to the robot
75          self.cmd_vel_pub.publish(self.move_cmd)
76
77          # Sleep for 1/self.rate seconds
78          r.sleep()
```

This is our main control loop. First we test to see if the target is still visible. If not we stop the robot by setting the movement command to the empty `Twist` message. Otherwise, we set the `target_visible` flag back to `False` (the safe default) and then publish the current movement command as set in the `set_cmd_vel()` callback described next.

```
80  def set_cmd_vel(self, msg):
81      # if the ROI width or height is 0, we have lost the target
82      if msg.width == 0 or msg.height == 0:
83          return
84
85      # If the ROI stops updating this next statement will not happen
86      self.target_visible = True
```

The `set_cmd_vel()` callback gets triggered whenever there is a new message on the `/roi` topic. The first thing to check is that neither the width nor height of the ROI is zero. If so, the target has probably been lost so we return immediately to the main loop which will stop the robot from rotating. Otherwise, we set the `target_visible` flag to `True` so that the robot will react to the target's position.

```

89         target_x_offset = msg.x_offset + (msg.width / 2.0) - (self.image_width
/ 2.0)
90
91     try:
92         percent_offset = float(target_x_offset) / (float(self.image_width)
/ 2.0)
93     except:
94         percent_offset = 0

```

Before we can determine how the robot should move, we compute the displacement of the target from the center of the camera image. Recall that the `x_offset` field in an ROI message specifies the x-coordinate of the upper left corner of the region, so to find the center of the region we add half the width. Then to find the displacement from the center of the image we subtract half the width of the image. With the displacement computed in pixels, we then get the displacement as a fraction of the image width. The `try-catch` block ensures we trap any attempt to divide by zero which can happen if the `camera_info` topic hiccups and sends us an `image_width` value of 0.

```

97     if abs(percent_x_offset) > self.x_threshold:
98         # Set the rotation speed proportional to the displacement of the
target
99         try:
100             speed = self.gain * percent_x_offset
101             if speed < 0:
102                 direction = -1
103             else:
104                 direction = 1
105             self.move_cmd.angular.z = -direction *
max(self.min_rotation_speed, min(self.max_rotation_speed, abs(speed)))
106         except:
107             self.move_cmd = Twist()
108     else:
109         # Otherwise stop the robot
110         self.move_cmd = Twist()

```

Finally we compute the rotation speed of the robot to be proportional to the displacement of the target where the multiplier is the parameter `self.gain`. If the target offset does not exceed the `x_threshold` parameter, we set the movement command to the empty `Twist` message to stop the robot (or keep it stopped).

11.2.4 Object Tracking on a Real Robot

We're now ready to try the object tracker on a real robot. Since the robot will only be rotating left and right, you shouldn't have to worry about it running into anything, but move it into a clear area anyway.

If you are using a TurtleBot with its fixed camera location, you might have to get on your hands and knees to do face tracking. Alternatively, you can run the CamShift

tracker and hold a colored object in front of the robot to test tracking. To get it all rolling, follow these steps.

First terminate any launch files you might have running from the previous section. Then start up your robot's launch files. For the TurtleBot we would run:

```
$ rosrun turtlebot_bringup turtlebot.launch
```

```
$ rosrun turtlebot_bringup kinect.launch
```

Next launch either the face tracker or CamShift tracker:

```
$ rosrun rbt1_vision face_tracker2.launch
```

or

```
$ rosrun rbt1_vision camshift.launch
```

Finally, bring up the object tracker node:

```
$ rosrun rbt1_apps object_tracker.launch
```

With all the nodes up and running, move in front of your robot's camera so your face is in the field of view, wait for your face to be detected, then move to the left or right. If you launched the Camshift tracker instead, move a colored object in front of the camera and adjust the parameters so you get good isolation of the target. Your robot should rotate to keep your face or the object centered in the image frame.

Try adjusting the parameters in the `object_tracker.launch` file to get the response sensitivity you desire.

11.3 Person Follower

Our second application is designed to make our robot follow a person as they walk around the room. If you have a TurtleBot, you can use the most excellent [turtlebot_follower](#) application by [Tony Pratkanis](#) that uses PCL and is written in C++. Our goal will be to write a similar application in Python where we don't have access to the PCL API.

While the ROS Python API defines a class for the `PointCloud2` data type, it does not provide an easy way to access the depth values. Fortunately, Tim Field has contributed a [Python module](#) to fill this gap. The file is called `point_cloud2.py` and is included in the `rbt1_apps/src` directory. We will see how to use it a little later.

Tony Pratkanis' `turtlebot_follower` program doesn't really know what a person looks like. Instead, it uses the following strategy to detect a "person-like blob" in front of it and then keep that object within a certain distance:

- First, define the minimum and maximum size of the blob in the x, y and z dimensions. This way the robot won't tend to fixate on pieces of furniture or chair legs.
- Next, define how close we want the robot to stay to the blob (person). For a depth camera, the z-coordinate is the relevant dimension here.
- Start the main loop:
 - If the robot is too far or too close to the person, move forward or backward accordingly.
 - If the person is to the left or right of the robot, rotate right or left appropriately.
 - Publish the corresponding movement as a `Twist` message on the `/cmd_vel` topic.

Let's now program a similar ROS application in Python.

11.3.1 Testing the Follower Application in Simulation

The Python script that implements the follower application is called `follower.py` in the `rbx1_apps/nodes` directory. Before looking at the code, you can try it out in the ArbotiX simulator.

First, make sure your camera is plugged in, then run the `openni` driver:

```
$ rosrun rbt1_vision openni_node_fuerte.launch
```

Next, launch the follower application:

```
$ rosrun rbt1_apps follower.launch
```

Finally, bring up the simulator and `RViz` as we have done before:

```
$ rosrun rbt1_bringup fake_turtlebot.launch
```

```
$ rosrun rviz rviz -d `rospack find rbt1_nav`/sim_fuerte.vcg
```

You should see the simulated TurtleBot in RViz. If you now move your body toward or away from the camera, the TurtleBot should move forward or backward. If you move to the right or left, the robot should rotate to track you. Since your body is not actually part of the simulation, the robot will continue to move as long as you are not centered or at the goal distance from the camera.

11.3.2 Understanding the Follower Script

Let's now take a look at the follower code.

Link to SVN source: [follower.py](#)

```
1  #!/usr/bin/env python
2  import roslib; roslib.load_manifest('rbxl_apps')
3  import rospy
4  from sensor_msgs.msg import PointCloud2
5  from geometry_msgs.msg import Twist
6  from math import copysign
7  import point_cloud2
8
9  class Follower():
10     def __init__(self):
11         rospy.init_node("follower")
12
13         # Set the shutdown function (stop the robot)
14         rospy.on_shutdown(self.shutdown)
15
16         # The dimensions (in meters) of the box in which we will search
17         # for the person (blob). These are given in camera coordinates
18         # where x is left/right, y is up/down and z is depth (forward/backward)
19         self.min_x = rospy.get_param("~min_x", -0.2)
20         self.max_x = rospy.get_param("~max_x", 0.2)
21         self.min_y = rospy.get_param("~min_y", -0.3)
22         self.max_y = rospy.get_param("~max_y", 0.5)
23         self.max_z = rospy.get_param("~max_z", 1.2)
24
25         # The goal distance (in meters) to keep between the robot
26         # and the person
26         self.goal_z = rospy.get_param("~goal_z", 0.6)
27
28         # How far away from the goal distance (in meters) before the robot
29         reacts
30         self.z_threshold = rospy.get_param("~z_threshold", 0.05)
31
32         # How far away from being centered (x displacement) on the person
33         # before the robot reacts
33         self.x_threshold = rospy.get_param("~x_threshold", 0.1)
34
35         # How much do we weight the goal distance (z) when making a movement
36         self.z_scale = rospy.get_param("~z_scale", 1.0)
37
38         # How much do we weight x-displacement of the person when
38         # making a movement
```

```

39         self.x_scale = rospy.get_param("~x_scale", 2.5)
40
41     # The maximum rotation speed in radians per second
42     self.max_angular_speed = rospy.get_param("~max_angular_speed", 2.0)
43
44     # The minimum rotation speed in radians per second
45     self.min_angular_speed = rospy.get_param("~min_angular_speed", 0.0)
46
47     # The max linear speed in meters per second
48     self.max_linear_speed = rospy.get_param("~max_linear_speed", 0.3)
49
50     # The minimum linear speed in meters per second
51     self.min_linear_speed = rospy.get_param("~min_linear_speed", 0.1)
52
53     # Publisher to control the robot's movement
54     self.cmd_vel_pub = rospy.Publisher('/cmd_vel', Twist)
55
56     rospy.Subscriber('point_cloud', PointCloud2, self.set_cmd_vel)
57
58     # Wait for the point cloud topic to become available
59     rospy.wait_for_message('point_cloud', PointCloud2)
60
61 def set_cmd_vel(self, msg):
62     # Initialize the centroid coordinates and point count
63     x = y = z = n = 0
64
65     # Read in the x, y, z coordinates of all points in the cloud
66     for point in point_cloud2.read_points(msg, skip_nans=True):
67         pt_x = point[0]
68         pt_y = point[1]
69         pt_z = point[2]
70
71         # Keep only those points within our designated boundaries
72         # and sum them up
73         if -pt_y > self.min_y and -pt_y < self.max_y and pt_x <
74             self.max_x and pt_x > self.min_x and pt_z < self.max_z:
75             x += pt_x
76             y += pt_y
77             z += pt_z
78             n += 1
79
80         # Stop the robot by default
81         move_cmd = Twist()
82
83         # If we have points, compute the centroid coordinates
84         if n:
85             x /= n
86             y /= n
87             z /= n
88
89             # Check our movement thresholds
90             if (abs(z - self.goal_z) > self.z_threshold) or (abs(x) >
91                 self.x_threshold):
92                 # Compute the linear and angular components of the movement
93                 linear_speed = (z - self.goal_z) * self.z_scale
94                 angular_speed = -x * self.x_scale

```

```

93             # Make sure we meet our min/max specifications
94             linear_speed = copysign(max(self.min_linear_speed,
95                                         min(self.max_linear_speed,
96                                             abs(linear_speed))), linear_speed)
97             angular_speed = copysign(max(self.min_angular_speed,
98                                         min(self.max_angular_speed,
99                                             abs(angular_speed))), angular_speed)
100            move_cmd.linear.x = linear_speed
101            move_cmd.angular.z = angular_speed
102
103        # Publish the movement command
104        self.cmd_vel_pub.publish(move_cmd)
105
106    def shutdown(self):
107        rospy.loginfo("Stopping the robot...")
108        self.cmd_vel_pub.publish(Twist())
109        rospy.sleep(1)
110
111    if __name__ == '__main__':
112        try:
113            Follower()
114            rospy.spin()
115        except rospy.ROSInterruptException:
116            rospy.loginfo("Follower node terminated.")

```

The overall strategy behind the script is fairly simple. First, sample all the points in the depth cloud that lie within a search box in front of the robot. From those points, compute the centroid of the region; i.e. the average x, y and z value for all the points. If there is a person in front of the robot, the z-coordinate of the centroid tells us how far away they are and the x-coordinate reflects whether they are to the right or left. From these two numbers we can compute an appropriate Twist message to keep the robot near the person.

Let's now look at the key lines of the script.

```
7 import point_cloud2
```

To access the points in the depth cloud, we import Tim Field's `point_cloud2` library that you can find in the `rbx1_apps/src` directory. Will will use the library in the point cloud callback.

The long list of parameters should be fairly self-explanatory from the comments in the code. The heart of the script is the `set_cmd_vel()` callback on the point cloud topic:

```
56     rospy.Subscriber('point_cloud', PointCloud2, self.set_cmd_vel)
```

Note how we use a generic topic name ('`point_cloud`') in the `Subscriber` statement. This allows us to remap the cloud topic in the launch file. Typically we will use the

default topic `/camera/rgb/points` but if we filter the cloud beforehand, we might use a different topic.

```
61     def set_cmd_vel(self, msg):
62         # Initialize the centroid coordinates and point count
63         x = y = z = n = 0
```

Each time we receive a message on the `point_cloud` topic, we begin the `set_cmd_vel` callback by zeroing the centroid coordinates and point count.

```
66     for point in point_cloud2.read_points(msg, skip_nans=True):
67         pt_x = point[0]
68         pt_y = point[1]
69         pt_z = point[2]
```

Here we use the `point_cloud2` library to cycle through all the points in the cloud. The `skip_nans` parameter is handy since a NaN (not a number) can occur when the point is inside or outside the camera's depth range.

```
72         if -pt_y > self.min_y and -pt_y < self.max_y and pt_x <
    self.max_x and pt_x > self.min_x and pt_z < self.max_z:
73             x += pt_x
74             y += pt_y
75             z += pt_z
76             n += 1
```

For each point in the cloud message, we check to see if it falls within the search box. If so, add its x, y and z coordinates to the centroid sums and increment the point count.

```
79     move_cmd = Twist()
```

Initialize the movement command to the empty `Twist` message which will stop the robot by default.

```
82     if n:
83         x /= n
84         y /= n
85         z /= n
```

Assuming we found at least one non-NaN point, we compute the centroid coordinates by dividing by the point count. If there is a person in front of the robot, these coordinates should give us a rough idea of how far away they are and whether they are to the left or right.

```
88         if (abs(z - self.goal_z) > self.z_threshold) or (abs(x) >
    self.x_threshold):
89
90             linear_speed = (z - self.goal_z) * self.z_scale
91             angular_speed = -x * self.x_scale
```

If the person is closer or further than the goal distance by more than the `z_threshold`, or the left/right displacement exceeds the `x_threshold`, set the robot's linear and angular speed appropriately, weighing each by the `z_scale` and `x_scale` parameters.

```
103     self.cmd_vel_pub.publish(move_cmd)
```

Finally, publish the movement command to move (or stop) the robot.

11.3.3 Running the Follower Application on a TurtleBot

If you have a TurtleBot, you can compare our Python follower node to the C++ version by Tony Pratkanis which is found in the `turtlebot_follower` package. In either case, start with your robot in the middle of a large room as far away from walls, furniture, or other people as possible.

Next, make sure the TurtleBot is powered on and startup launch files are running:

```
$ roslaunch turtlebot_bringup turtlebot.launch
```

```
$ roslaunch turtlebot_bringup kinect.launch
```

To run our Python follower script, issue the command:

```
$ roslaunch rbx1_apps follower.launch
```

Then move in front of the robot to see if you can get it to follow you. You can adjust the robot's behavior by changing the parameters in the launch file. Note that if you move too close to a wall or another object, the robot will just as likely lock onto it and you might have to pick it up and rotate it back toward you.

To try the C++ version, terminate both the `kinect.launch` file and the `follower.launch` file from above. Then run:

```
$ roslaunch turtlebot_follower follower.launch
```

(The launch file for the C++ version runs both an OpenNI node to connect to the camera and the follower node itself.)

11.3.4 Running the Follower Node on a Filtered Point Cloud

In our current `follower.py` script, we test every point in the cloud to see if it falls within the search box. You might be wondering, why not use the `PassThrough` nodelet we learned about earlier to pre-filter the cloud so this test isn't necessary? Indeed, this is a viable alternative and an implementation can be found in the `follower2.launch`

file. This file runs a `VoxelGrid` filter plus a number of `PassThrough` filters to create the search box, then launches the `follower2.py` node. This new script is very similar to the original but now we can skip the test to see if a point falls within the search box.

By this point in the book, you can probably follow both the `follower2.launch` file and the `follower2.py` script on your own so we will leave it to the reader as an exercise. To test the script on a TurtleBot, follow the same instructions as in the previous section but run the `follower2.launch` file instead of `follower.launch`:

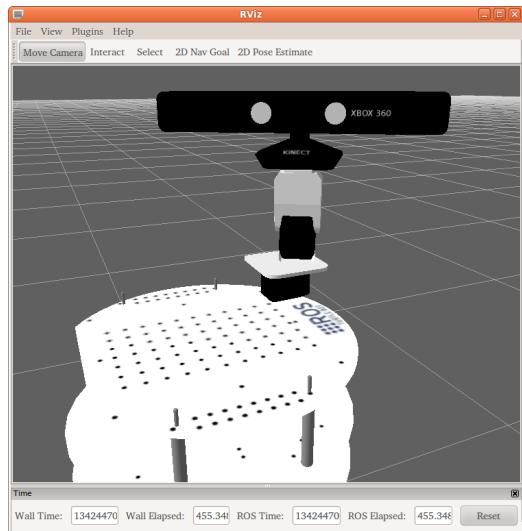
```
$ rosrun rbx1_apps follower2.launch
```


12. DYNAMIXEL SERVOS AND ROS

It is hard to beat a pan-and-tilt head for adding life-like behavior to your robot. With just two servos, the robot can track your face or other moving objects, or simply look around without having to rotate its entire body. Indeed, you don't even need a robot for this chapter: just a camera mounted on a pair of servos.

A number of third-party ROS packages provide all the tools we need to get started with joint control. At the time of this writing, our only choice of servo is the [Robotis Dynamixel](#), primarily because these servos provides real-time feedback for position, speed and torque which is key to the way that ROS manages robot joints. A pair of the low-end [AX-12](#) servos are generally sufficient to support the weight of a Kinect or Asus Xtion Pro camera.

However, the Kinect is heavy enough that the tilt servo should not be held too far away from the vertical position for more than a few minutes at a time to prevent overheating.



In this chapter we will cover the following topics:

- Adding a pan-and-tilt head to a TurtleBot
- Choosing a Dynamixel controller and ROS package
- Understanding the ROS `JointState` message type
- Using basic joint control commands
- Connecting the hardware controller and setting the servo IDs
- Configuring the launch files and parameters
- Testing the servos
- Programming a head tracking node
- Combining head tracking with face tracking

12.1 A TurtleBot with a Pan-and-Tilt Head

For this chapter, we will use a modified TurtleBot with the Kinect placed on top of a pair of pan and tilt Dynamixel servos as shown in the picture above. (An Asus Xtion would work as well.)

If you have a TurtleBot and would like to add a pan-and-tilt head using Dynamixel servos, you can find a detailed hardware tutorial on the [TurtleBot Make Projects](#) website. Alternatively, if you have more money than time, you might pick up a [PhantomX](#) pan-and-tilt kit from Trossen Robotics. Note that this kit comes with an ArbotiX controller which we will not actually be using in this chapter. (We will be using a [USB2Dynamixel](#) controller instead.)

To test the URDF model of the modified TurtleBot, make sure you terminate any other launch files that might be running, then run the following commands:

```
$ rosrun rviz rviz -d `rospack find rbx1_description`/urdf_fuerte.vcg
```

and then in another terminal:

```
$ rosrun rviz rviz -d `rospack find rbx1_description`/urdf_fuerte.vcg
```

If all goes well, you should see the robot in RViz as it appears in the picture at the start of the chapter. In addition, a small pop-up window will appear with a number of slider controls that allow you to test the movement of the servos. Try moving the sliders and make sure the servos rotate the head appropriately. (See if you can use the right-hand rule to figure out why a positive tilt rotates the camera forward and a positive pan causes the head to rotate counter-clockwise.)

Type Ctrl-C in the `test_turtlebot_with_head.launch` window when you are finished.

12.2 Choosing a Dynamixel Hardware Controller

There are two Dynamixel hardware controllers that work well with ROS: the [ArbotiX](#) controller from Vanadium Labs used on the [Mini Max](#) and [Maxwell](#) robots, and the Robotis [USB2Dynamixel](#) controller used with the Crustcrawler [Smart Arm](#). We will use the USB2Dynamixel controller since we don't need the onboard base controller that is also provided by the ArbotiX. You can find existing tutorials for using the ArbotiX controller on the [Mini Max](#) Wiki page.

You will also need a way to power the servos. The USB2Dynamixel controller does not itself have a power connection so you will need something like the [SMPs2Dynamixel](#) together with a 12V power supply.

12.3 A Note Regarding Dynamixel Hardware

While Dynamixel servos are very sophisticated pieces of hardware, the cable connections between the servos need to be secured with tie wraps or other methods to ensure reliability. Even a slight movement of the connectors in the sockets can cause a loss of signal which in turn can cause the software drivers to crash. In such cases, power cycling the servos and restarting the driver is often necessary. The same precautions should be taken for the power connection between the battery source and the SMPS2Dynamixel device.

12.4 Choosing a ROS Dynamixel Package

The two most actively developed ROS Dynamixel projects are the [arbotix](#) stack by Michael Ferguson and the [dynamixel_motor](#) stack by Antons Rebguns. Both stacks can be used with a USB2Dynamixel controller while the `arbotix` stack can also be used with the [ArbotiX](#) controller. However, we will use the `dynamixel_motor` stack to be consistent with earlier tutorials on the Pi Robot website. More importantly, we will need to control the speed of the servos when it comes to our head tracking application later in this chapter and this capability is currently only available in the `dynamixel_motor` stack.

To install the `dynamixel_motor` stack, run the command:

```
$ sudo apt-get install ros-fuerte-dynamixel-motor
```

That's all there is to it!

12.5 Understanding the ROS `JointState` Message Type

The ROS `JointState` message type is designed to keep track of all of the joints on a robot. As with all message types, we can display its fields using the `rosmsg` command:

```
$ rosmsg show sensor_msgs/JointState
```

which should produce the following output:

```
Header header
  uint32 seq
  time stamp
  string frame_id
  string[] name
  float64[] position
  float64[] velocity
  float64[] effort
```

As you can see, the `JointState` message includes a standard ROS Header component made up of a sequence number (`seq`), a timestamp (`stamp`) and a `frame_id`. This is followed by four arrays: a string array called `name` to hold the names of the joints, then three float arrays to hold the `position`, `velocity` and `effort` (usually torque) for each joint.

We can now see why Dynamixel servos are a good fit with ROS: namely, we can query each servo for its current position, velocity and torque which is exactly the data we need to fill in the `JointState` message. Once we have chosen a hardware controller for the Dynamixel servos, a ROS driver for that controller would be expected to publish the servo states as a `JointState` message on some topic. This topic is typically called `/joint_states` and other nodes can subscribe to the topic to find out the current state of all the joints.

While most joints used on robots are *revolute* like servos, ROS can also deal with linear joints which are referred to as *prismatic*. A prismatic joint can be used to move a robot's torso up and down like on the PR2, or to extend or retract an arm. In either case, the position, velocity and torque of a prismatic joint can be specified in the same way as a servo-type joint and so ROS can easily handle both.

12.6 Controlling Joint Position, Speed and Torque

Setting the position, speed and torque of a servo or linear joint in ROS is done using topics and services as we would expect. The `dynamixel_motor` stack contains the [`dynamixel_controllers`](#) package that works in a manner similar to the one used on the Willow Garage PR2: first a controller manager node is launched that connects to the Dynamixel bus (in our case a USB2Dynamixel controller). The controller node then launches a number of individual controllers, one for each servo.

Each controller uses a topic to control the servo's position and a collection of services for setting the servo's speed, torque, and other Dynamixel properties. Fortunately, the authors of the `dynamixel_motor` stack (Antons Rebguns, Cody Jorgensen and Cara Slutter) have nicely documented their package on the ROS Wiki. The part of the documentation we are interested in right now can be found on the [`dynamixel_controllers`](#) page. Click on the link and then click on the **electric** button at the top of the page to see the documentation. Finally, click on the link called "Common Joint Controller Interface" in the table of contents. Here is a screen shot of that part of the page:

2.4 Common Joint Controller Interface

2.4.1 Subscribed Topics

`<joint_controller_name>/command (std_msgs/Float64)`

Listens for a joint angle (in radians) to be sent to the controller.

`motor_states/<serial_port_name> (dynamixel_msgs/MotorStateList)`

Listens for motor status feedback published by low level driver.

2.4.2 Published Topics

`<joint_controller_name>/state (dynamixel_msgs/JointState)`

Provides current joint status information (current goal, position, velocity, load, etc.)

2.4.3 Services

`<joint_controller_name>/set_speed (dynamixel_controllers/SetSpeed)`

Change the current velocity of the joint (specified in radians per second).

`<joint_controller_name>/torque_enable (dynamixel_controllers/TorqueEnable)`

Turn joint torque on or off.

`<joint_controller_name>/set_compliance_slope (dynamixel_controllers/SetComplianceSlope)`

Change the level of torque near goal position (see [Dynamixel documentation](#) for more details).

`<joint_controller_name>/set_compliance_margin (dynamixel_controllers/SetComplianceMargin)`

Change allowable error between goal position and present position (see [Dynamixel documentation](#) for more details).

`<joint_controller_name>/set_compliance_punch (dynamixel_controllers/SetCompliancePunch)`

Change minimum amount of torque at goal position (see [Dynamixel documentation](#) for more details).

`<joint_controller_name>/set_torque_limit (dynamixel_controllers/SetTorqueLimit)`

Change the maximum amount of torque (see [Dynamixel documentation](#) for more details).

The topics and services listed here allow us to control many aspects of the servos. The ones we are interested in for now are setting position, speed and torque.

12.6.1 Setting Servo Position

To set a servo's position in radians from center, we publish the desired position on the topic called:

`<joint_controller_name>/command`

So if the controller for moving a head pan servo is called `head_pan_joint`, then we would use the following command to set the position of the servo to 1.0 radians clockwise from center:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- -1.0
```

The pair of hyphens (--) before the position value is required when publishing a negative value so that `rostopic` does not think we are supplying an option like `-r`. We can also use them when publishing positive values but they are not required. To position the servo 1.0 radians *counter-clockwise* from center, we would use the command:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- 1.0
```

or without the hyphens:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 1.0
```

12.6.2 Setting Servo Speed

To set a servo's speed in radians per second, use the `set_speed` service called:

`<joint_controller_name>/set_speed`

So to set the speed of the head pan servo to 0.5 radians per second, we would use the command:

```
$ rosservice call /head_pan_joint/set_speed 0.5
```

12.6.3 Controlling Servo Torque

The `dynamixel_controllers` package provides two services related to torque: `torque_enable` and `set_torque_limit`. The `torque_enable` service allows us to relax the torque completely or to turn it back on. Starting your robot with the servos in the relaxed state conveniently allows you to position the joints by hand before running any tests.

To relax the head pan servo, we would use the following command:

```
$ rosservice call /head_pan_joint/torque_enable False
```

And to turn it back on:

```
$ rosservice call /head_pan_joint/torque_enable True
```

The `set_torque_limit` service allows you to set how hard you want the servo to work against a load. For example, if your robot has a multi-jointed arm, you might want the torque limits set just high enough to lift the arm's own weight. This way if the arm

bumps against a person or object, the servos won't mindlessly attempt to push through the obstacle. The following command would set the head pan servo torque limit to 0.1:

```
$ rosservice call /head_pan_joint/set_torque_limit 0.1
```

This is a relatively low limit and when we try it out on a real servo later in the chapter, we will find that you can still rotate the servo by hand but now it will rotate back to its starting position when you let go.

12.7 Checking the USB2Dynamixel Connection

To check the connection to the USB2Dynamixel controller, first make sure that the micro switch on the side of the device is moved to the correct setting. For 3-pin AX-12, AX-18 or the new "T" series servos (e.g. MX-28T), you want the TTL setting. For any of the 4-pin or "R" series servos (e.g. MX-28R, RX-28, EX-106+), you need the RS-485 setting.

Next, unplug any other USB devices from your computer if possible, then connect your controller to a USB port. You can also connect it to a USB hub that is connected to your computer. Once connected, a red LED on the controller should illuminate. Then issue the following command to see what USB ports you have connected:

```
$ ls /dev/ttyUSB*
```

Hopefully you will see something like the following output:

/dev/ttyUSB0

If instead you get back the message:

```
ls: cannot access /dev/ttyUSB*: No such file or directory
```

then your USB2Dynamixel has not been recognized. Try plugging it into a different USB port, use a different cable, or check your USB hub.

If you have no other USB devices attached, your USB2Dynamixel should be on /dev/ttyUSB0. If you need to have other USB devices connected at the same time, plug in the USB2Dynamixel first so that it gets assigned the device /dev/ttyUSB0. If it has to be on a different device, e.g. /dev/ttyUSB1, simply make a note of it for the following configuration sections.

12.8 Setting the Servo Hardware IDs

If you have already set the hardware IDs of your Dynamixel servos, you can skip this section. Otherwise, read on.

All Dynamixels are shipped with an ID of 1 so if you are using more than one servo on the bus, at least one ID has to be changed. In the case of our pan-and-tilt head, we'll assume we want the ID for the pan servo to be 1 and 2 for the tilt servo. You can set them to be whatever you like but be sure to remember your choices for the next section on configuration.

If both servos still have their default value of 1, connect the tilt servo to the bus on its own. In other words, disconnect the pan servo from the bus if it is already connected. Then power up the servo. Assuming your USBDynamixel is still plugged into your computer from the previous section, bring up the `arbotix_python terminal.py` script as follows:

```
$ rosrun arbotix_python terminal.py /dev/ttyUSB0 1000000
```

Note the device name `/dev/ttyUSB0` on the command line. If your controller is using a different device, such as `/dev/ttyUSB1`, use that instead. The second parameter is the baud rate of the USB2Dynamixel which is always 1000000.

If all goes well, you should see the following on your screen:

```
ArbotiX Terminal --- Version 0.1
Copyright 2011 Vanadium Labs LLC
>>
```

To list the servos on the bus, run the `ls` command at the `>>` prompt. Hopefully your screen will then look something like this:

```
ArbotiX Terminal --- Version 0.1
Copyright 2011 Vanadium Labs LLC
>> ls
 1 .... .... .... .... .... .... ....
.... .... .... .... .... .... .... ....
>>
```

Notice the 1 before all the characters. This indicates that a servo with an ID of 1 was found on the bus. If no IDs are shown, run the `ls` command a second time. If still no IDs are displayed, check the connection between your servo and the USB2Dynamixel controller. Also double-check that the servo has power.

To change this servo's ID from 1 to 2, use the `mv` command:

```
>> mv 1 2
```

then issue the `ls` command again. If all goes well, you should see that the servo now has ID 2:

```
>> ls  
.... 2 .... .... .... ....  
.... .... .... .... .... ....
```

Next, disconnect the tilt servo and connect the pan servo instead, again ensuring that it has power. Run the `ls` command to find its current ID. If it is already set to 1, you can leave it as is. Otherwise, use the `mv` command to set it to 1.

Finally, connect both servos at the same time and run the `ls` command. The result should be:

```
>> ls  
1 2 .... .... .... .... ....  
.... .... .... .... .... ....
```

To exit the `terminal.py` program, type `Ctrl-C`.

12.9 Configuring and Launching `dynamixel_controllers`

In this section we will learn how to interpret the servo configuration file and examine the `dynamixel_controllers` launch file.

12.9.1 The `dynamixel_controllers` Configuration File

The servo configuration parameters are stored in the file `dynamixel_params.yaml` found in the `rbx1_dynamixels/config` subdirectory and looks like this:

```
joints: ['head_pan_joint', 'head_tilt_joint']

head_pan_joint:
    controller:
        package: dynamixel_controllers
        module: joint_position_controller
        type: JointPositionController
    joint_name: head_pan_joint
    joint_speed: 2.0
    motor:
        id: 1
        init: 512
        min: 0
        max: 1024

head_tilt_joint:
    controller:
        package: dynamixel_controllers
        module: joint_position_controller
        type: JointPositionController
```

```

joint_name: head_tilt_joint
joint_speed: 2.0
motor:
  id: 2
  init: 512
  min: 300
  max: 800

```

First we define a list parameter called `joints` that contains the names of our servos. Next, we have a block for each servo controller beginning with the controller name. In our case, the two controllers are called `head_pan_joint` and `head_tilt_joint`. These are the names that are used in the topics and services we learned about in the previous section.

For each servo controller, we specify the type of controller (`JointPositionController`), as well as its hardware ID, the initial position value and its minimum and maximum position values. If your servo IDs are different than 1 and 2, edit this file accordingly.

The `init/min/max` numbers are given in servo ticks which vary from 0 to 1023 for the AX-12's. In the configuration above, we give the head tilt controller less than full range since it cannot go all the way forward or back without hitting the mounting plate. (We also specify these limits in the robot's URDF file but using radians instead of servo ticks.)

12.9.2 The dynamixel_controllers Launch File

The file `dynamixels.launch` in the `rbx1_dynamixels/launch` directory illustrates how to fire up the servo controllers when we have a USB2Dynamixel controller on device `/dev/ttyUSB0` and two Dynamixel servos on the bus with hardware IDs 1 and 2. Let's take a look at it now:

```

<launch>
  <param name="/use_sim_time" value="false" />

  <!-- Load the URDF/Xacro model of our robot -->
  <param name="robot_description" command="$(find xacro)/xacro.py '$(find
rbx1_description)/urdf/turtlebot_with_head.xacro'" />

  <!-- Publish the robot state -->
  <node name="robot_state_publisher" pkg="robot_state_publisher"
type="state_publisher">
    <param name="publish_frequency" value="20.0"/>
  </node>

  <!-- Start the Dynamixel low-level driver manager with parameters -->
  <node name="dynamixel_manager" pkg="dynamixel_controllers"
type="controller_manager.py" required="true" output="screen">
    <rosparam>
      namespace: turtlebot_dynamixel_manager
      serial_ports:
        dynamixel_ax12:
    </rosparam>
  </node>

```

```

        port_name: "/dev/ttyUSB0"
        baud_rate: 1000000
        min_motor_id:  1
        max_motor_id: 2
        update_rate: 20
    
```

```

</rosparam>
</node>

<!-- Load the joint controller configuration from a YAML file -->
<rosparam file="$(find rbt_dynamixels)/config/dynamixel_params.yaml"
command="load"/>

<!-- Start the head pan and tilt controllers -->
<node name="dynamixel_controller_spawner_ax12" pkg="dynamixel_controllers"
type="controller_spawner.py"
args="--manager=turtlebot_dynamixel_manager
      --port=dynamixel_ax12
      --type=simple
      head_pan_joint
      head_tilt_joint"
      output="screen" />

<!-- Start the Dynamixel Joint States Publisher -->
<node name="dynamixel_joint_states_publisher" pkg="rbx1_dynamixels"
type="dynamixel_joint_state_publisher.py" output="screen" />

<!-- Start all Dynamixels in the relaxed state -->
<node pkg="rbx1_dynamixels" type="relax_all_servos.py"
name="relax_all_servos" />

</launch>
```

If your USB2Dynamixel controller is on a device other than `/dev/ttyUSB0` and/or your servo IDs are other than 1 and 2, edit this file now before going any further.

The launch file first loads the URDF model for the robot and runs a `robot_state_publisher` node to publish the state of the robot to `tf`. We then launch the `controller_manager.py` node, load the `dynamixels_param.yaml` file we looked at earlier, then spawn a pair of joint controllers, one for each servo.

The next node launched is called `dynamixel_joint_state_publisher.py` and is found in the `rbx1_dynamixels/nodes` directory. This is not part of the `dynamixel_controllers` package but is necessary to correct one inconsistency in the way the package publishes joint states. Rather than use the standard ROS `JointState` message type that we introduced earlier, the `dynamixel_controllers` package uses a custom message type to publish the joint states including some additional useful information such as servo temperature. If you look at the code in the `dynamixel_joint_state_publisher.py` node, you will see that it simply republishes the custom joint state information as a standard `JointState` message on the `/joint_states` topic.

Finally, the launch file runs the `relax_all_servos.py` node found in the `rbx1_dynamixels/nodes` directory which relaxes the torque on each servo and sets a reasonable default speed and torque limit. (More on this below.)

12.10 Testing the Servos

To test the pan and tilt servos, first connect your servos and USB2Dynamixel to a power source, then make sure your USB2Dynamixel is connected to a USB port on your computer.

12.10.1 Starting the Controllers

Before running the next command, be sure to terminate the `test_turtlebot_with_head.launch` file we used in the previous section if you haven't already.

Next fire up the `dynamixels.launch` file:

```
$ rosrun dynamixels dynamixels.launch
```

You should see a number of startup messages that look something like this:

```
process[robot_state_publisher-1]: started with pid [11415]
process[dynamixel_manager-2]: started with pid [11416]
process[dynamixel_controller_spawner_ax12-3]: started with pid [11417]
process[fake_pub-4]: started with pid [11418]
process[dynamixel_joint_states_publisher-5]: started with pid [11424]
process[relax_all_servos-6]: started with pid [11426]
process[world_base_broadcaster-7]: started with pid [11430]
[INFO] [WallTime: 1340671865.017257] Pinging motor IDs 1 through 2...
[INFO] [WallTime: 1340671865.021896] Found motors with IDs: [1, 2].
[INFO] [WallTime: 1340671865.054116] dynamixel_ax12 controller_spawner:
waiting for controller_manager turtlebot_dynamixel_manager to startup in
global namespace...
[INFO] [WallTime: 1340671865.095946] There are 2 AX-12+ servos connected
[INFO] [WallTime: 1340671865.096249] Dynamixel Manager on port
/dev/ttyUSB0 initialized
[INFO] [WallTime: 1340671865.169167] Starting Dynamixel Joint State
Publisher at 20Hz
[INFO] [WallTime: 1340671865.363797] dynamixel_ax12 controller_spawner:
All services are up, spawning controllers...
[INFO] [WallTime: 1340671865.468773] Controller head_pan_joint
successfully started.
[INFO] [WallTime: 1340671865.530030] Controller head_tilt_joint
successfully started.
[dynamixel_controller_spawner_ax12-3] process has finished cleanly.
```

NOTE: If one of the startup messages gives an error containing the message:

```
serial.serialutil.SerialException: could not open port /dev/ttyUSB0:
```

then try the following. First, power-cycle the USB2Dynamixel controller (unplug the power supply and plug it back it again), then unplug the USB cable from your computer and plug it back in again. This will fix this error 9 times out of 10.

12.10.2 Monitoring the Robot in RViz

To view the robot in `RViz` and observe the motion of the servos as we start testing below, bring up `RViz` now as follows:

```
$ rosrun rviz rviz -d `rospack find rbx1_dynamixels`/rviz_fuerte.vcg
```

12.10.3 Listing the Controller Topics and Monitoring Joint States

Once the `dynamixels.launch` file is up and running, bring up another terminal and list the active topics:

```
$ rostopic list
```

Among the topics listed, you should see the following dynamixel-related topics:

```
/diagnostics
/head_pan_joint/command
/head_pan_joint/state
/head_tilt_joint/command
/head_tilt_joint/state
/joint_states
/motor_states/dynamixel_ax12
```

For now, the topics we will look at are:

```
/head_pan_joint/command
/head_tilt_joint/command
/head_pan_joint/state
/head_tilt_joint/state
/joint_states
```

The two `command` topics are for setting the servo positions as we saw earlier and we will test them below. The `/joint_states` topic (which is actually published by our auxiliary node `dynamixel_joint_state_publisher.py`) holds the current state of the servos as a `JointState` message. Use the `rostopic echo` command to see the messages:

```
$ rostopic echo /joint_states
```

which should yield a stream of messages that look something like the following:

```

header:
  seq: 11323
  stamp:
    secs: 1344138755
    nsecs: 412811040
  frame_id: ''
name: ['head_pan_joint', 'head_tilt_joint']
position: [-0.5266667371740702, 0.08692557798018634]
velocity: [0.0, 0.0]
effort: [0.0, 0.0]

```

Here we see the header with the sequence number and timestamp, a blank `frame_id` (which is typical for joint states) and then the four arrays for `name`, `position`, `velocity` and `effort`. Since our servos are not moving, the velocities are 0 and since they are not under load, the effort (torque) is 0.

While the messages are still streaming on the screen, try moving the servos by hand. You should immediately see the position, velocity and effort values change to match your movements. You should also see the movements in RViz.

Returning to the full list of dynamixel topics above, the two controller `state` topics are useful for monitoring the servo temperatures and other parameters. Try viewing the messages on the `state` topic for the head pan controller:

```
$ rostopic echo /head_pan_joint/state
```

A typical message looks like this:

```

header:
  seq: 25204
  stamp:
    secs: 1344221332
    nsecs: 748966932
  frame_id: ''
name: head_pan_joint
motor_ids: [1]
motor_temps: [37]
goal_pos: 0.0
current_pos: -0.00511326929295
error: -0.00511326929295
velocity: 0.0
load: 0.0
is_moving: False

```

Perhaps the most important number here is the servo temperature listed in the `motor_temps` field. A value of 37 degrees is fairly typical for a resting AX-12 servo. When the temperature starts getting up around 50 degrees or higher, it's probably a good idea to give it rest. To visually monitor the temperatures of both servos, you could keep a running plot using rxplot:

```
$ rxplot /head_pan_joint/state/motor_temps[0], \
          /head_tilt_joint/state/motor_temps[0]
```

(We have to index the `motor_temps` fields since the `dynamixel_controllers` package uses an array variable for this field to accommodate joints that use more than one motor.)

Since you now know the topics that include servo temperatures, you could subscribe to these topics in your scripts and relax the servos or move them to a neutral position if the temperature gets too high. A more sophisticated approach uses ROS [diagnostics](#) which is outside the scope of this volume.

12.10.4 Listing the Controller Services

We can also list the services used by the `dynamixel_controllers` package. To list all currently active services, use the `rosservice list` command:

```
$ rosservice list
```

Among the topics listed, you should see the following `dynamixel_controllers` services:

```
/head_pan_joint/set_speed
/head_pan_joint/set_torque_limit
/head_pan_joint/torque_enable
/head_tilt_joint/set_speed
/head_tilt_joint/set_torque_limit
/head_tilt_joint/torque_enable
```

(There are quite a few additional services provided by `dynamixel_controllers` but we will not be using them in this book.)

These are just the services we have already met in an earlier section. Let's now test the position command topic and these services on the live servos.

12.10.5 Setting Servo Position, Speed and Torque

Once the dynamixel controllers are up and running, bring up a new terminal and send a couple of simple pan and tilt commands. The first command should pan the head fairly slowly to the left (counter-clockwise) through 1 radian or about 57 degrees:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- 1.0
```

Re-center the servo with the command:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- 0.0
```

Now try tilting the head downward half a radian (about 28 degrees):

```
$ rostopic pub -1 /head_tilt_joint/command std_msgs/Float64 -- 0.5
```

And bring it back up:

```
$ rostopic pub -1 /head_tilt_joint/command std_msgs/Float64 -- 0.0
```

To change the speed of the head pan servo to 1.0 radians per second, use the `set_speed` service:

```
$ rosservice call /head_pan_joint/set_speed 1.0
```

Then try panning the head again at the new speed:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- -1.0
```

To relax a servo so that you can move it by hand, use the `torque_enable` service:

```
$ rosservice call /head_pan_joint/torque_enable False
```

Now try rotating the head by hand. Note that relaxing a servo does not prevent it from moving when it receives a new position command. For example, re-issue the last panning command:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- -1.0
```

The position command will automatically re-enable the torque and move the servo. To re-enable the torque manually, run the command:

```
$ rosservice call /head_pan_joint/torque_enable True
```

And try again rotating the servo by hand (but don't force it!)

Finally, set the torque limit to a small value:

```
$ rosservice call /head_pan_joint/set_torque_limit 0.1
```

Now try rotating the head by hand. This time you should feel a little more resistance compared to a completely relaxed servo. Furthermore, when you release your grip, the servo will return to the position it held before you moved it.

Now set the torque limit back to a moderate value:

```
$ rosservice call /head_pan_joint/set_torque_limit 0.5
```

Note: If the torque limit is set very low, you will find that there is also a limit to how fast you can move the servo regardless of how high you set the speed using the `set_speed` service.

12.10.6 Using the `relax_all_servos.py` Script

To relax all the servos at once, use the `relax_all_servos.py` utility script which is included in the `rbx1_dynamixels/nodes` directory:

```
$ rosrun rbx1_dynamixels relax_all_servos.py
```

If you examine the `relax_all_servos.py` script, you will see that relaxing is done by using a `torque_enable(False)` service call to each servo. The `set_speed` service is also used to set the servo speeds to a relatively low value (0.5 rad/s) so that we are not surprised by a fast motion the first time a position command is sent. Finally, the `set_torque_limit` service is called on each servo to set the maximum torque to a moderate value (0.5). You can edit this script to set your own defaults as desired.

After running the script, sending a position command to a servo will automatically re-enable its torque so there is no need to explicitly turn the torque back on when you want to move the servo.

The `relax_all_servos.py` script is run from the `dynamixels.launch` file we used earlier to start up the servo controllers.

12.11 Tracking a Visual Target

In the chapter on Robot Vision, we developed a number of nodes for tracking a visual target including faces, keypoints, and colors. We now have all the ingredients we need to program a head tracking node that will move the robot's pan-and-tilt camera to follow a moving object.

The script that does the job is called `head_tracker.py` and can be found in the `rbx1_dynamixels/nodes` directory. Before looking at the code, you can try it out with our earlier face tracking node.

12.11.1 Tracking a Face

First make sure your camera driver is up and running. For a Kinect or Xtion Pro:

```
$ roslaunch rbx1_vision openni_node_fuerte.launch
```

or if you are using a webcam:

```
$ roslaunch rbx1_vision uvc_cam.launch device:=/dev/video0
```

(Change the video device if necessary.)

Next, make sure your servos are powered up and the USB2Dynamixel controller is plugged into a USB port. If you have already launched the `dynamixels.launch` file, you can skip this step:

```
$ roslaunch rbx1_dynamixels dynamixels.launch
```

Make sure your servos are connected by testing the pan servo with the commands:

```
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- 1.0  
$ rostopic pub -1 /head_pan_joint/command std_msgs/Float64 -- 0.0
```

With the servos good to go, fire up the face tracking node we developed earlier:

```
$ roslaunch rbx1_vision face_tracker2.launch
```

When the video window appears, move your face in front of the camera and make sure the tracking is working. Remember that you can hit the 'c' key to clear tracking and have your face re-detected.

We are now ready to launch the head tracking node with the command:

```
$ roslaunch rbx1_dynamixels head_tracker.launch
```

Assuming the face tracking node still has a lock on your face, the pan and tilt servos should now keep the camera centered on your face as you move in front of the camera. If your face is lost for a long enough period of time, the servos will re-center the camera. If you Ctrl-C out of the `head_tracker.launch` process, the servos will also re-center before the node shuts down. If the keypoints in the face tracker window start drifting onto other objects, hit the 'c' key to clear the points and re-detect your face.

The following video demonstrates the behavior using a printout of the Mona Lisa as the target face: <http://youtu.be/KHJL09BTnIY>

12.11.2 The Head Tracker Script

The `head_tracker.py` script is rather long but straightforward. The overall process is as follows:

- Initialize the servos.
- Subscribe to the `/roi` topic.

- If the `/roi` moves away from the center of view, command the servos to move the camera in a direction to re-center it.
- If the `/roi` is lost for a given amount of time, re-center the servos to protect them from overheating.

To track the target, the script uses a kind of "speed tracking". If you move the camera to the position where the tracked object is *now*, it may have moved by the time the camera gets there. You might think you could just update the camera's target position at a high rate and therefore keep up with the object. However, this kind of position tracking will result in a jerky staccato-like motion of the camera. A better strategy is to always aim the camera *ahead* of the target, but adjust the servo speeds to be proportional to the displacement of the target from the center of view. This results in much smoother camera motion and will ensure that it moves quickly if the target is far off-center and more slowly if the displacement is small. When the target is centered, the servo speeds will be zero and so the camera will not move.

The `head_tracker.py` script is a little long to display in its entirety, so let's take a look at just the key sections of the code. You can see the entire source file at the following link:

Link to SVN source: [head_tracker.py](#)

Here now are the key lines.

```
namespace = rospy.get_namespace()

# The joints parameter needs to be set by the servo controller
self.joints = rospy.get_param(namespace + '/joints', '')
```

Remember that the names of the servos are defined by the `joints` parameter in the `dynamixel_params.yaml` file found in the `rbx1_dynamixels/config` directory, and this file is loaded when we start up the servos with the `dynamixels.launch` file. (Some servo controllers place the `joints` parameter under their own namespace so we read in the current namespace and use it as a prefix.)

```
# Initialize the servo services and publishers
self.init_servos()
```

The initialization of the servos is tucked away in the `init_servos()` function. Let's look at it first.

```
def init_servos(self):
    # Create dictionaries to hold the speed, position and torque controllers
    self.servo_speed = dict()
    self.servo_position = dict()
    self.torque_enable = dict()
```

First we define three Python dictionaries to store the servo controllers for speed, position and torque.

```
for controller in sorted(self.joints):
```

We then loop through all the joints listed in the `self.joints` parameter. In our case, there are only two servos named `head_pan_joint` and `head_tilt_joint`.

```
try:  
    # The set_speed services  
    set_speed_service = '//' + controller + '/set_speed'  
    rospy.wait_for_service(set_speed_service)  
    self.servo_speed[name] = rospy.ServiceProxy(set_speed_service,  
SetSpeed, persistent=True)
```

NOTE: We will see a number of other `try-except` blocks throughout the script. The reason for this is that it is possible to run into hardware glitches with the AX-12 servos, their cable connections, or the USB2Dynamixel controller, and these glitches will sometimes require restarting the `head_tracker.py` node and possibly even power-cycling the servos.

Recall that the `dynamixel_controller` package uses a `set_speed` service for each servo to set the servo's speed. We therefore connect to the `set_speed` service for each servo controller. Using the `persistent=True` argument in the `ServiceProxy` statement is important. Otherwise `rospy` has to reconnect to the `set_speed` service every time we want to adjust the speed of a servo. Since we will be updating servo speeds continuously during tracking, we want to avoid this connection delay.

```
# Initialize the servo speed to the default_joint_speed  
self.servo_speed[name](self.default_joint_speed)
```

Once we are connected to the `set_speed` services, we can initialize each servo speed to the default speed.

```
# Torque enable/disable control for each servo  
torque_service = '//' + controller + '/torque_enable'  
rospy.wait_for_service(torque_service)  
self.torque_enable[name] = rospy.ServiceProxy(torque_service,  
TorqueEnable)  
  
# Start each servo in the disabled state so we can move them by hand  
self.torque_enable[name](False)
```

In a similar manner, we connect to the `torque_enable` service for each servo and initialize them to the relaxed state so we can move them by hand if necessary.

```
# The position controllers  
self.servo_position[name] = rospy.Publisher('//' + controller +  
'/' + command, Float64)
```

The position controller uses a ROS publisher rather than service so we define one for each servo. This completes servo initialization.

```
# Subscribe to roi topics and set the callback
rospy.Subscriber('roi', RegionOfInterest, self.set_joint_cmd)
```

We assume that the position of the target is published on the /roi topic as it will be if we are using any of our earlier vision nodes. The callback function `set_joint_cmd()` will set the servo speeds and target positions to track the target.

```
self.joint_state = JointState()
rospy.Subscriber('joint_states', JointState, self.update_joint_state)
```

We also keep tabs on the current servo positions by subscribing to the /joint_states.

```
while not rospy.is_shutdown():
    # If we have lost the target, stop the servos
    if not self.target_visible:
        self.pan_speed = 0
        self.tilt_speed = 0
        # Keep track of how long the target is lost
        self.target_lost_count += 1
    else:
        self.target_visible = False
        self.target_lost_count = 0
```

This is the start of the main tracking loop. We use a variable named `self.target_visible` to indicate if we have lost the ROI. (We'll see how we set this variable below.) If the target is lost, we stop the servos by setting their speed to 0 and increment a counter to keep track of how many cycles the target remains lost.

```
# If the target is lost long enough, center the servos
if self.target_lost_count > self.max_target_lost_count:
    self.center_head_servos()
```

If the target is lost long enough, recenter the servos by calling the `center_head_servos()` function defined later in the script. This not only prevents the servos from overheating but also places the camera in a more central position to reacquire the target.

```
else:
    try:
        # Only update the pan speed if it differs from the last value
        if self.last_pan_speed != self.pan_speed:
            self.set_servo_speed(self.head_pan_joint, self.pan_speed)
            self.last_pan_speed = self.pan_speed
        self.set_servo_position(self.head_pan_joint, self.pan_position)
```

Here we finally update the servo speeds and positions. In this case we are updating the pan servo. The variables `self.pan_speed` and `self.pan_position` are set in the `set_joint_cmd()` callback which we will look at next. If the servo speed has not

changed since the last cycle, we skip the call to the `set_servo_speed()` function to avoid unnecessarily overwhelming the `set_speed` service.

```
except:  
    # If there are exceptions, momentarily stop the servo  
    try:  
        current_pan_position =  
seself.tilt_speedlf.joint_state.position[self.joint_state.name.index(self.head_p  
an_joint)]  
        self.set_servo_position(self.head_pan_joint,  
current_pan_position)  
        rospy.loginfo("Servo SetSpeed Exception!")  
        rospy.loginfo(sys.exc_info())  
    except:  
        pass
```

If we run into any exceptions, temporarily stop the servo by setting the target position to the current position. We do this rather than setting the speed to 0 since in this case the exception might have been caused by the `set_speed` service itself.

These two blocks are then repeated for the tilt servo.

Finally, let's look at the `set_joint_cmd()` callback function which fires whenever we receive a message on the `/roi` topic.

```
def set_joint_cmd(self, msg):  
    # If the ROI stops updating this next statement will not happen  
    self.target_visible = True
```

The first thing we do is set the `target_visible` flag to `True` since we wouldn't be here if we hadn't just received a message on the `/roi` topic. As we saw earlier in the main program loop, the flag is reset to `False` on each cycle.

```
# Compute the displacement of the ROI from the center of the image  
target_offset_x = msg.x_offset + msg.width / 2 - self.image_width / 2  
target_offset_y = msg.y_offset + msg.height / 2 - self.image_height / 2
```

Next, we compute how far off-center the middle of ROI lies. Recall that the `x_offset` and `y_offset` fields in an ROI message specify coordinates of the upper left corner of the ROI.

```
try:  
    percent_offset_x = float(target_offset_x) / (float(self.image_width) /  
2.0)  
    percent_offset_y = float(target_offset_y) / (float(self.image_height) /  
2.0)  
except:  
    percent_offset_x = 0  
    percent_offset_y = 0
```

To accommodate different image resolutions, it is better to work in relative displacements. The `try-except` block is used since the `camera_info` topic can sometimes hiccup and send us a value of 0 for the image width and height.

```
# Pan the camera only if the x target offset exceeds the threshold
if abs(percent_offset_x) > self.pan_threshold:
    # Set the pan speed proportion to the target offset
    self.pan_speed = trunc(min(self.max_joint_speed, max(0,
self.gain_pan * abs(percent_offset_x))), 2)
```

If the horizontal displacement of the target exceeds our threshold, we set the pan servo speed proportional to the displacement. The `trunc()` function (defined later in the script) simply truncates the speed (given in radians per second) to two decimal places so that we don't chase very small changes in speed and overwhelm the `set_speed` service.

```
# Set the target position ahead or behind the current position
current_pan =
self.joint_state.position[self.joint_state.name.index(self.head_pan_joint)]

if target_offset_x > 0:
    self.pan_position = max(self.min_pan, current_pan -
self.lead_target_angle)
else:
    self.pan_position = min(self.max_pan, current_pan +
self.lead_target_angle)
```

To set the servo's target position, we first get its current position (thanks to the callback we have running on the `joint_states` topic.) We then set the target position ahead or behind the current position depending on whether the target is to the left or right of center.

The process is then repeated for the tilt servo, setting its speed and target position depending on the vertical displacement of the target.

And that completes the most important parts of the script. The rest should be fairly self-explanatory from the comments in the code.

12.11.3 Tracking Colored Objects

We can use the same `head_tracker.py` node to track colored objects or arbitrary objects selected using the mouse. The head tracker script simply follows the coordinates published on the `/roi` topic, so any node that publishes `RegionOfInterest` messages on that topic can control the movement of the camera.

To track a colored object, simply launch the CamShift node we developed earlier instead of the face tracker node used in the first head tracking example.

The complete sequence of steps would be as follows. Skip any launch files that you already have running. But `Ctrl-C` out of the face tracker launch if it is still running.

First make sure your camera driver is up and running. For a Kinect or Xtion Pro:

```
$ roslaunch rbx1_vision openni_node_fuerte.launch
```

or if you are using a webcam:

```
$ roslaunch rbx1_vision uvc_cam.launch device:=/dev/video0
```

(Change the video device if necessary.) Now fire up the servos:

```
$ roslaunch rbx1_dynamixels dynamixels.launch
```

Launch the CamShift node:

```
$ roslaunch rbx1_vision camshift.launch
```

When the CamShift video window appears, select the target region with your mouse and adjust the hue/value slider controls as necessary to isolate the target from the background. When you are finished, bring up the head tracker node:

```
$ roslaunch rbx1_dynamixels head_tracker.launch
```

The servos should now move the camera to track the colored target.

12.11.4 Tracking Manually Selected Targets

Recall that the `lk_tracker.py` node allows us to select an object with the mouse and the script will then use keypoints and optical flow to track the object. Since the coordinates of the tracked object are published on the `/roi` topic, we can use the head tracker node just as we did with faces and colors.

This demo works best if the target object has a highly textured surface with robust keypoints such as the cover of a book or other graphic. It also helps if the background is fairly homogeneous such as a wall.

The complete sequence of steps would be as follows. Skip any launch files that you already have running. But `Ctrl-C` out of either the CamShift or face tracker if it is still running.

First make sure your camera driver is up and running. For a Kinect or Xtion Pro:

```
$ roslaunch rbx1_vision openni_node_fuerte.launch
```

or if you are using a webcam:

```
$ roslaunch rbx1_vision uvc_cam.launch device:=/dev/video0
```

(Change the video device if necessary.)

Fire up the servos:

```
$ roslaunch rbx1_dynamixels dynamixels.launch
```

Launch the lk_tracker.py node:

```
$ roslaunch rbx1_vision lk_tracker.launch
```

When the video window appears, select the target object with your mouse then bring up the head tracker node:

```
$ roslaunch rbx1_dynamixels head_tracker.launch
```

The servos should now move the camera to track the selected target. There will be a limit to how fast you can move the target otherwise the optical flow tracker will not keep up. Also, you can re-select the target region at any time with your mouse.

12.12 A Complete Head Tracking ROS Application

The last three examples all have 3 out of 4 launch files in common. We can create a single launch file that includes the three common files and then selects the particular vision launch file we want based on a user provided argument.

Take a look at the head_tracker_app_fuerte.launch file in the rbx1_apps/launch directory and reproduced below:

```
<launch>
  <!-- For a Kinect or Xtion, set the depth_camera arg = True.
      For a webcam, set the value = False -->
  <arg name="depth_camera" default="True" />

  <!-- These arguments determine which vision node we run -->
  <arg name="face" default="False" />
  <arg name="color" default="False" />
  <arg name="keypoints" default="False" />

  <!-- Launch the appropriate camera drivers based on the depth_camera arg -->
  <include if="$(arg depth_camera)" file="$(find rbx1_vision)/launch/openni_node_fuerte.launch" />
  <include unless="$(arg depth_camera)" file="$(find rbx1_vision)/launch/uvc_cam.launch" />

  <include if="$(arg face)" file="$(find rbx1_vision)/launch/face_tracker2.launch" />
  <include if="$(arg color)" file="$(find rbx1_vision)/launch/camshift.launch" />
  <include if="$(arg keypoints)" file="$(find rbx1_vision)/launch/lk_tracker.launch" />

  <include file="$(find rbx1_dynamixels)/launch/dynamixels.launch" />

  <include file="$(find rbx1_dynamixels)/launch/head_tracker.launch" />
</launch>
```

The launch file uses a number of arguments to control which other launch files are included in any particular run. The depth_camera argument determines whether we

load the OpenNI drivers for a Kinect or Xtion or the UVC drivers for a webcam. The default value of `True` will load the OpenNI drivers as we will see later in the launch file.

The next three arguments, `face`, `color`, and `keypoints` determine which vision node we will run. All three default to `False` so we must set one of them to `True` on the command line.

Following the argument definitions, we run either the `openni_node_fuerte.launch` file or the `uvc_camera.launch` file depending on the value of `depth_camera`.

One of the next three lines is run depending on which vision argument we set to `True` on the command line. For example, if we set the `color` argument to `True`, then the `camshift.launch` file will be run.

Next we run the `dynamixels.launch` file to fire up the servos. And finally, we run the `head_tracker_app_fuerte.launch` file to start the head tracking.

Using our new launch file, we can now start the entire head tracking application to track either faces, colors or keypoints with a single command. For example, to track a face using either a Kinect or Xtion camera (the default), we would run:

```
$ roslaunch rbx1_apps head_tracker_app_fuerte.launch face:=True
```

To track colors instead, we would run:

```
$ roslaunch rbx1_apps head_tracker_app_fuerte.launch color:=True
```

Or to use a webcam and keypoint tracking:

```
$ roslaunch rbx1_apps head_tracker_app_fuerte.launch \
depth_camera:=False keypoints:=True
```

One final note: if you forget to select one of the vision modes on the command line, you can always run its launch file afterward. In other words, the command:

```
$ roslaunch rbx1_apps head_tracker_app_fuerte.launch face:=True
```

is equivalent to running:

```
$ roslaunch rbx1_apps head_tracker_app_fuerte.launch
```

followed by:

```
$ roslaunch rbx1_vision face_tracker2.launch
```

13. WHERE TO GO NEXT?

Hopefully this book has provided enough examples to help you get a good start on programming your own ROS applications. You should now have the tools you need to write applications that combine computer vision with speech recognition, text-to-speech, robot navigation and servo control. For example, how about writing an application that periodically scans the room for a person's face and when someone is detected, speaks a greeting of some sort, moves toward the person, then asks if they need any help? Or how about placing an object on your robot and using a voice command to take it to a person in another room?

As we mentioned in the introduction, there are still many areas of ROS to explore including:

- Controlling a multi-jointed arm like the [TurtleBot arm](#).
- 3-D image processing using [PCL](#) (Point Cloud Library).
- Identifying and grasping [objects on a table top](#). (Or how about [playing chess](#)?)
- Identifying your friends and family using [face_recognition](#).
- Creating a [URDF robot model](#) for your own robot.
- Adding [sensors](#) such as a gyro, sonar, IR, or laser scanner to your robot.
- Running realistic simulations with [Gazebo](#).
- Programming state machines using [SMACH](#).
- Building knowledge bases with [knowrob](#).
- Recognizing arbitrary 3-D objects using [roboearth](#).
- Learning from experience using [reinforcement_learning](#).
- Many additional options to explore using OpenCV including [template matching](#), [motion analysis](#), and [machine learning](#).

There are now over 2000 packages and libraries available for ROS. Click on the [Browse Software](#) link at the top of the ROS Wiki for a list of all ROS packages and stacks that have been submitted for indexing. When you are ready, you can contribute your own package(s) back to the ROS community. Welcome to the future of robotics. Have fun and good luck!

Notes

