Intro to Robot Operating System

by Siddharth Patel

ROS

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Ashokbhai Babubhai Patel

Intro to Robot Operating System - Using ROS in Python

Learn to program Robots using the famous Robot Operating System (ROS) framework in Python

Siddharth Patel

September 28, 2024

Preface

One vivid memory from my childhood is the time when LED TVs were gaining popularity in India. I constantly wondered how the images were displayed and what those tiny, intricate components—like miniature buildings—were doing inside. I soon realized that the failure of even one small part could stop the entire system from working. This taught me an important lesson: there are countless ways for a circuit to fail, but only a few precise combinations that allow it to function flawlessly. That insight stayed with me and shaped my approach to problem-solving in electronics.

Through these early experiences, I came to a deeper realization about how computers, electronics, and even machines like water pipes all share something fundamental: they behave like laborers—obedient, yet extremely limited laborers. Why do I call them "super-dumb"? Because they only follow instructions without question or deviation. Take, for example, a green LED and a blue LED. Neither knows how to collaborate or blend their light to create a cyan color on their own. They simply light up when the correct voltage is applied. The intelligence to make them work together, to adjust their brightness and achieve the desired color, lies with us. We design the circuit, we provide the instructions, and it's through our guidance that these "laborers" fulfill their purpose.

I applied this same principle early on, combining different circuits and components to create devices with new, unique functions. This hands-on experimentation not only fueled my creativity but also expanded my knowledge of circuits, integrated circuits (ICs), sensors, and eventually coding. However, in 2023, I discovered something that took my understanding to the next level—a development by two visionary minds, Keenan Wyrobek and Eric Berger. These two pioneers, who shared my passion for robotics and scientific innovation, were far ahead of me in their realization of just how challenging robotics development can be. With so many components at play, countless things can go wrong, and only a few will function as intended. They referred to this ongoing struggle as "reinventing the wheel"—a concept that resonated deeply with my

own experiences in building and troubleshooting complex systems.

Imagine if, every time you made a pizza, you had to buy a farm, grow the grains, make the dough, and ferment the cheese yourself. It would take forever! Instead, we buy ingredients from the store and make the pizza. Wyrobek and Berger applied the same logic to robotics by creating ROS (Robot Operating System), which allows different parts (or ”laborers”) to communicate with each other. The best part is that you don't need to reinvent the wheel—someone else has already created it, and you can focus on putting the parts together to build complex systems or robots.

In 2023, I started working with my professor, Prof. Dr.-Ing. Jan Hanno Carstens, on developing a robot for his company. I was forced to learn ROS because we were using it for our project. It took me a long time, partly because I found the ROS documentation a bit overwhelming, and I wasn't sure where to start. So, during my vacation, I decided to document everything I had learned in this book, using one of my favorite approaches to learning.

Let me explain my approach with a great example that I used in another area of my life. When I came to Germany, I had to learn the German language to study at a prestigious German university. Learning a language was a big challenge for me because my mind works logically, If something doesn't make sense, I find it hard to learn. Languages don't have formulas you can memorize and then pass an exam the next day. You need to invest time every day for at least a year or two to become fluent.

But I didn't have that kind of time, so I developed a strategy. I realized that while German may have thousands of verbs, only a few hundred are used in daily conversation, especially in an engineering context. By focusing on these 200–300 verbs, I was able to learn the language quickly. This approach worked—I earned a scholarship, got a job at my university, and competed successfully with native German speakers.

That's exactly what I'm doing with this book. I've compiled all the most common ROS commands and concepts you'll need to get started quickly. This book is for people who want to learn ROS but don't have a year to study—they have a job starting next week! By going through this book, they can probably manage just fine.

In my next book, I plan to present 10 ROS projects that I created,

ranging from simple to complex, to show you how to apply ROS in real-world scenarios.

Abstract

This book is designed to offer an accelerated yet comprehensive introduction to the Robot Operating System (ROS), aimed at individuals who, like myself, may not have the luxury of years to master a complex system. Whether you're a researcher, engineer, or hobbyist, ROS provides a powerful framework that allows you to focus on innovation without constantly "reinventing the wheel."

ROS emerged from a fundamental need to streamline the development of robotics systems—a challenge that has resonated with roboticists for years. In this book, I trace the origins of ROS, from its creation by Keenan Wyrobek and Eric Berger as a solution to the inefficiency of duplicating low-level code for every new robotics project, to its present status as a global standard in the field. The opening chapters explain how ROS was born from a desire to enable developers to focus on building intelligent algorithms, rather than repeatedly coding the same infrastructure from scratch.

At its core, ROS is a middleware—a system that sits between the robot's hardware and the software, providing modular tools that allow components to communicate seamlessly. The book introduces key concepts like nodes, topics, services, and actions, explaining how each element plays a role in building complex systems with reusable, scalable, and efficient components. By drawing on these building blocks, you'll learn how to write robotics software that's both powerful and adaptable, without needing to start from scratch for every project.

After introducing the ROS framework, the book walks you through setting up your ROS development environment, using step-by-step instructions that focus on simplicity and clarity. You'll learn how to install ROS Noetic, create workspaces, and develop your first ROS publisher and subscriber scripts. These initial projects will get you up and running quickly, providing practical experience in managing nodes, publishing data to topics, and processing messages in real-time.

Moving beyond the basics, the book delves into more advanced concepts such as ROS services and actions, parameter servers, and how to record and play back data using ROS bag files. Each concept is broken down with clear explanations and practical examples, ensuring that you

can apply these tools in real-world scenarios.

Throughout the book, my goal is to minimize the steep learning curve that often comes with ROS. Drawing from my own experience, I've compiled a list of essential commands, functions, and best practices that will help you navigate the ROS ecosystem efficiently. The final chapters explore how to use launch files to simplify the process of running multiple nodes, and how to manage your workspace in a way that scales as your projects grow more complex.

With the help of this book, you'll not only grasp the fundamentals of ROS but also gain the confidence to start applying your knowledge immediately. In much the same way I approached learning German by focusing on its most essential elements, this book offers a targeted approach to learning ROS—distilling the vast and often complex documentation into the core concepts and commands that will get you up and running quickly.

For those eager to move beyond the basics, stay tuned for my next book, where I will dive into 10 real-world ROS projects—demonstrating how to build everything from simple robots to fully autonomous systems using the power of ROS.

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What is ROS?

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1.1 History of ROS

ROS (Robot Operating System) has become a standard in the field of robotics, widely adopted by researchers, hobbyists, and even large robotics companies. But the path to its current success was not straightforward. The history of ROS goes back to the mid-2000s, and its beginnings were humble, born out of the need to solve a common problem in robotics.

1.1.1 The Stanford Period

ROS started as a personal project of Keenan Wyrobek and Eric Berger while they were at Stanford University. During that time, robotics development faced a serious challenge: developers had to spend too much time reinventing basic software infrastructure, such as sensor drivers and actuator controllers, for every new project. As a result, there was little time left for developing advanced robotic intelligence.

Even within the same organizations, developers would re-implement these core systems for each project. This situation was frustrating for robotics engineers, including Keenan and Eric, who wanted to focus on developing complex robotic algorithms instead of constantly rebuilding the wheel.

What does ”Reinventing the Wheel” Mean?

”Reinventing the wheel” refers to the unnecessary duplication of work by recreating something that already exists. In the case of robotics, this meant writing the same code for basic robot functionality over and over again, instead of building upon previous work.

Analogy: Reinventing the Wheel

Imagine your father plants a tree and waters it every day for his entire life. By the time he's 60, the tree is large and bears delicious fruit. However, instead of continuing to nurture this tree, you decide to plant your own tree from scratch. This new tree takes years to grow, while your father's tree could have been even more fruitful with a little extra care.
This is the essence of what ROS aimed to solve. Instead of each robotics project starting from scratch, developers could build upon the infrastructure created by others, allowing them to focus on creating smarter, more complex robots.

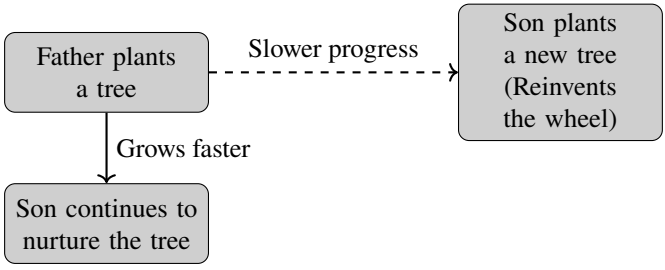


Figure 1.1: Analogy of Reinventing the Wheel vs. Building on Existing Work

In 2006, Keenan and Eric founded the **Stanford Personal Robotics Program** to address this issue. Their goal was to create a framework that allowed different processes (nodes) to communicate with each other and provide tools to help build code on top of this foundation. The testbed for this framework was a robot they built, known as the *Personal Robot*. They created 10 of these robots and distributed them to universities for development and testing purposes.

1.1.2 Building the Foundation

The Stanford Personal Robotics Program laid the foundation for ROS. The key idea was to have a common framework where developers could

share software components, such as drivers and communication systems. This would allow roboticists to focus on creating smarter, more innovative applications rather than rewriting basic infrastructure. ROS was designed to scale and adapt to different robots and environments.

The Foundation of ROS

The Stanford Personal Robotics Program aimed to create a universal framework for robot development. This framework allowed different robot processes to communicate seamlessly, and it came with tools to build code on top of the existing infrastructure. The robot built for this program, the *Personal Robot*, was distributed to universities to promote ROS development.

The idea was simple but revolutionary: let roboticists collaborate and build on top of each other's work. Much like the analogy of the father's tree, ROS would allow developers to nurture and grow from the work already done by others, avoiding the pitfalls of reinvention.

The development of ROS during the Stanford Period is well documented. The vision was clearly laid out in a fundraising deck from 2006, which highlighted the need to stop reinventing the wheel and instead build a reusable framework for robotics software.

1.2 Challenges in Robotics Development

Building robots is inherently complex due to the wide range of hardware and software involved. Historically, roboticists often faced the challenge of writing every piece of the operating code from scratch, typically in low-level languages like C. Even simple tasks, such as making a light blink, could take weeks of effort due to the numerous components involved.

Example: Imagine trying to code a blinking light indicator for your robot. You would need to:

Challenges in Coding a Blinking Light Indicator

- **Create the firmware controller:** Write the low-level code to manage the microcontroller.
- **Manage serial communications:** Ensure the microcontroller can communicate with a host computer.
- **Create higher-level software nodes:** Build logic to decide when the light should blink.
- **Develop debugging and visualization tools:** Ensure all the sensors, actuators, and code are functioning correctly.

This entire process represents a significant time and effort investment for what should be a simple task.

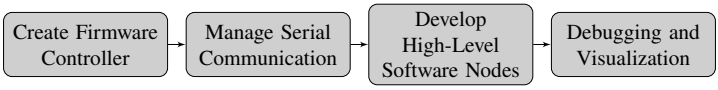


Figure 1.2: Robotic Development Workflow: Even a simple task like a blinking light requires numerous steps.

The complexity doesn't stop here. For each new project or robot, engineers often had to repeat these steps. This process of "reinventing the wheel" for every project significantly slowed down the pace of robotics development, which led to the birth of ROS.

1.3 The Birth of ROS

The challenge of re-implementing basic robotic functionality for every project led to the creation of ROS (Robot Operating System). Born as an **open-source middleware**, ROS provides a set of standardized tools and libraries that drastically reduce the time needed to develop robotic systems.

Initially developed at Stanford University in 2006 as part of the **Stanford Personal Robotics Program**, ROS was created with the goal of offering reusable software infrastructure, enabling researchers and

developers to focus on building intelligent systems, instead of wasting time on reimplementing low-level drivers and communication protocols.

ROS simplifies robotic development by providing:

Key Benefits of ROS

- **Open-source:** Freely accessible, allowing for global collaboration.
- **Reduced development time:** Built-in tools, drivers, and libraries for common robotics tasks.
- **Modular design:** Promotes reusable components and allows for easy system scaling.
- **Platform independence:** Initially developed for Linux, ROS now has experimental support for macOS and Windows.

1.4 What ROS Is and Isn't

ROS is often misunderstood as a traditional operating system, but it is more accurately described as a **meta-operating system** or **middleware**.

Key Benefits of ROS is:

- An **open-source middleware** that sits on top of a traditional operating system (like Ubuntu).
- A **development environment** with tools for building robotic systems, including visualization (Rviz), communication libraries, and introspection tools.
- A **packaging system** that supports the distribution of robot software in reusable modules. ROS uses the **colcon** command to build and manage these packages.

ROS is not:

- A **computer operating system**. It is not a replacement for Linux, macOS, or Windows. It runs on top of these OSs.
- A **programming language**. ROS programs are written in languages like C++ and Python. Other experimental languages include Java, Lisp, and Octave.
- A **hard real-time environment**. ROS is not suitable for systems requiring hard real-time constraints.
- A **development environment**. ROS is used with existing IDEs or text editors like Sublime or VSCode.

1.5 Why Learn ROS?

ROS has emerged as the standard framework for developing robotic systems due to several key advantages.

1.5.1 Open Source

ROS is entirely **open-source**, which means the community is constantly contributing to and improving the software. The collaborative nature of ROS allows developers to share their work, learn from each other, and continuously improve robotic development worldwide.

1.5.2 Reusability and Modularity

With ROS, you don't have to start from scratch every time. The framework provides numerous **open-sourced tools** and libraries, which allow developers to easily contribute, adapt, and share software.

1.5.3 Support for Development Tools

ROS comes with built-in tools to assist with development. For example:

Development Tools Examples:

- **Rviz:** A 2D/3D visualization tool for representing robot data like sensor information and environments.
- **Gazebo:** A simulation tool that allows you to test robotic systems in a virtual environment before deploying on actual hardware.

1.5.4 Rapid Testing and Prototyping

ROS provides a platform where you can quickly prototype robotic systems using simulators like Gazebo or test data using bag files (rosbags). This allows you to refine your system design before deploying it to the physical robot.

1.6 Languages Supported by ROS

ROS natively supports several programming languages, providing flexibility to developers based on their needs.

1.6.1 Officially Supported Languages

ROS is primarily used with:

Officially Supported Languages

- **C++:** Often used for performance-critical tasks in robotics due to its speed and control over hardware.
- **Python:** Highly popular for writing simple and quick scripts, offering ease of use and rapid development.
- **Lisp:** Historically supported but less commonly used in modern ROS applications.

1.6.2 Community-Driven Libraries

ROS also has community-driven support for additional languages, enabling greater flexibility for developers.

Community-Driven Libraries

- **Java:** Enables the integration of robotics into Java-based systems.
- **JavaScript:** Can be used in web-based applications for robotics control.
- **Lua:** A lightweight scripting language useful for specific robotic tasks.

1.7 Conclusion

With the vast amount of existing ROS 1 libraries and new features in ROS 2, roboticists can leverage these tools to develop powerful and scalable robotic systems. ROS is already a major player in the robotics field, and learning it will significantly enhance your ability to create and deploy robotics solutions efficiently.

Let's dive deeper into ROS and explore its capabilities!

Environment Setup

2

2.1 Introduction

Setting up an environment for ROS can be a bit tricky depending on the machine you're using. The first requirement for ROS is Ubuntu 20.04. If you already have a machine running Ubuntu 20.04, you can directly proceed to downloading ROS Noetic. However, if not, you will first need to install the operating system. In this section, we'll explore various options for setting up Ubuntu, followed by ROS installation.

2.2 Installing Ubuntu

There are two main methods for installing Ubuntu on your current machine: using a virtual machine or dual booting, as discussed earlier. The process can vary based on whether you're using Windows or macOS.

2.2.1 Windows Setup

If you're using Windows, you can take advantage of open-source virtual machine software such as VirtualBox or VMware Player. These tools allow you to install Ubuntu 20.04 as a virtual environment, running side by side with your main OS.

2.2.2 macOS Setup

For macOS users, the process depends on whether you're using an Intel or Apple Silicon chip:

- **Intel-based macOS**: You can use VirtualBox or UTM to install Ubuntu 20.04. This is relatively straightforward and allows you to run Ubuntu on your machine.

- **Apple Silicon-based macOS**: Installing Ubuntu can be trickier. You will need to download the Ubuntu 20.04 Live Server version first, then use the terminal to download the Ubuntu desktop environment. Tools like UTM are commonly used for virtualization on Apple Silicon, but the performance may vary.

2.3 Other Installation Methods

There are also alternative ways to set up the ROS environment. For example, using a Raspberry Pi, a high-level microcontroller, you can install Ubuntu 20.04 as the base OS and directly start coding your ROS projects. This is an excellent option for developers looking to run lightweight projects on dedicated hardware.

2.4 Installing a Code Editor

When working with ROS, you will need a text editor to write and modify your code. There are several options available, such as Visual Studio Code, Atom, and Sublime Text, among many others. Each editor has its own unique features, so feel free to choose one based on your personal preference.

As an example, let's go through the process of installing Sublime Text on Ubuntu 20.04. Sublime Text is a popular, minimalist code editor that is well-known for its clean interface and ease of use.

To install Sublime Text, open a terminal and run the following commands:

Step 1: Add GPG Key for Sublime

```
wget -q0 - https://download.sublimetext.com/sublimehq-pub.gpg | sudo
apt-key add -
```

Step 2: Add Sublime to the Sources List

```
echo "deb https://download.sublimetext.com/ apt/stable/" | sudo tee
/etc/apt/sources.list.d/sublime-text.list
```

Step 3: Update Package List

```
sudo apt-get update
```

Step 4: Install Sublime Text

```
sudo apt-get install sublime-text
```

Once installed, you can open Sublime Text by clicking the *Show Applications* button and typing *Sublime*, then clicking the icon.

Sublime Text is well-known for its iconic Monokai syntax theme, which offers a clean and visually appealing coding experience. While Sublime has been a favored editor for many developers, tools like Atom and Visual Studio Code have become popular alternatives due to their additional features and extensibility. The choice of editor is up to you, and this guide merely uses Sublime as one example of what you can install on your system.

2.5 Conclusion

Setting up the environment for ROS will vary depending on your hardware and personal preferences. Whether you choose to use virtual machines, dual boot, or even Raspberry Pi, the key is ensuring that Ubuntu 20.04 is installed correctly. Once this is done, we can proceed to install ROS Noetic and begin the exciting part—coding with ROS!

Installing ROS Noetic

3

3.1 Introduction

In this chapter, we will walk through the step-by-step process of installing ROS Noetic on Ubuntu 20.04. For the most up-to-date instructions, please visit the official ROS Noetic installation page.

3.2 Installation

Step 1: Configure Ubuntu Repositories

By default, your Ubuntu repositories should be correctly configured. To verify this:

1. Open the *Software and Updates* application from the app menu.
2. Ensure that the options for *restricted*, *universe*, and *multiverse* repositories are checked.
3. Close the window once verified.

Step 2: Set Up Sources List

The sources list allows Ubuntu to locate and download software packages. To add the ROS Noetic repository, open a terminal and run the following command:

```
sudo sh -c 'echo "deb http://packages.ros.org/ros/ubuntu
     $(lsb_release -sc) main" >
     /etc/apt/sources.list.d/ros-latest.list'
```

This command adds ROS Noetic to the Ubuntu sources list, enabling your system to access ROS packages.

Step 3: Add ROS GPG Keys

ROS keys are necessary to authenticate and verify downloaded packages. Use the following command to add the required keys:

```
sudo apt-key adv --keyserver 'hkp://keyserver.ubuntu.com:80'
     --recv-key C1CF6E31E6BADE8868B172B4F42ED6FBAB17C654
```

Once successfully added, you can proceed to the next step.

Step 4: Update Package Index

After configuring the repositories and adding the keys, update your package index to reflect the changes:

```
sudo apt update
```

Step 5: Install ROS Noetic

Now, it's time to install ROS Noetic. For a full desktop installation (which includes simulation tools), use the following command:

```
sudo apt install ros-noetic-desktop-full
```

This installation will include all the essential ROS tools and packages.

Step 6: Source Your Environment

To make sure ROS commands are recognized by your terminal, source the ROS setup file:

```
source /opt/ros/noetic/setup.bash
```

Why Do We Source the Environment?
Sourcing is a crucial step after installing ROS because it allows your terminal to access the newly installed ROS packages and tools. When you install ROS, it adds a number of commands and configurations that need to be loaded into your terminal session. Without sourcing, your terminal will not know where the ROS executables and libraries are located, and any ROS-related command you try to run will fail.
By running the `source /opt/ros/noetic/setup.bash` command, you tell the terminal to load the ROS environment variables, enabling it to recognize and execute ROS commands.
To automate this process for future terminal sessions, add the sourcing command to your `.bashrc` file:

```
echo "source /opt/ros/noetic/setup.bash" >> ~/.bashrc

source ~/.bashrc
```

Step 7: Test Your ROS Installation

Finally, test your ROS installation by starting the ROS Master:

```
roscore
```

If the ROS Master starts successfully, your installation is complete. You can terminate it by pressing `Ctrl`+`C`.

3.3 Conclusion

Congratulations! You have successfully installed ROS Noetic on Ubuntu 20.04. In the following chapters, we will explore the structure of ROS and how to use it for developing robotic systems.

ROS Framework Overview

4

4.1 Introduction

In this chapter, we will explore the core components of the ROS (Robot Operating System) framework. ROS provides various tools and abstractions to simplify robotics programming, and understanding its key concepts is essential for developing effective robotics systems. We will discuss important ROS features like the ROS Master, Nodes, Topics, Services, Actions, the Parameter Server, Bag Files, and Packages.

4.2 ROS Master

The ROS Master acts as the central server in the ROS framework. It manages the registration of nodes, topics, services, and parameters. Without the Master, nodes would not be able to locate each other or communicate.

Role of ROS Master

ROS Master:

- Keeps track of active nodes.
- Manages topics, services, and parameters.
- Enables nodes to discover each other and exchange messages.

4.3 Nodes

Nodes are the fundamental building blocks in ROS. Each node is an executable program that performs a specific task. Nodes can represent any computational process in the robot, such as controlling a motor, reading sensor data, or processing images from a camera. Nodes are designed to be modular, meaning that they are single-purpose, reusable, and easily maintainable. Each node runs independently but can communicate with other nodes in the system through topics, services, or actions.

The idea behind nodes is to break down complex systems into smaller, manageable pieces. This allows different parts of a robotic system to be developed and debugged independently.

4.3.1 How Nodes Communicate

Nodes can communicate in different ways:

Node communication methods

- **Topics:** A node can publish messages to a topic, and other nodes can subscribe to that topic to receive those messages.
- **Services:** Nodes can communicate synchronously by sending a request to another node and waiting for a response.
- **Actions:** Similar to services but more suitable for long-running tasks. Nodes can request an action, receive feedback during the execution, and finally get a result.

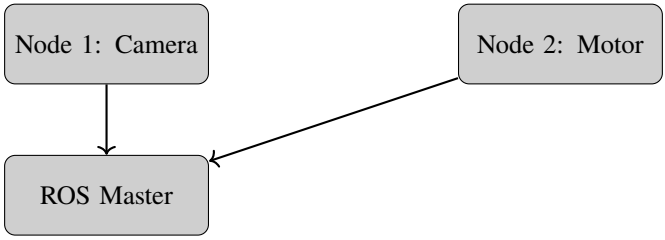


Figure 4.1: Nodes communicate through the ROS Master

In a basic robot setup, we can have multiple nodes working together to perform different tasks:

Example of Nodes in a Simple Robot:

- **Sensor Node:** A node responsible for reading data from a sensor (e.g., temperature sensor) and publishing the data to other nodes.
- **Motor Control Node:** A node that controls the motors to move the robot, receiving commands from other nodes.
- **Decision-Making Node:** A node that subscribes to the sensor data, processes it, and sends commands to the motor control node based on the sensor readings.

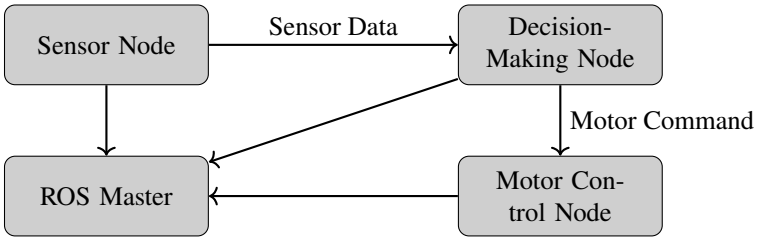


Figure 4.2: Nodes Communicating with Each Other through the ROS Master

Explanation of Node Interactions:

- The **Sensor Node** publishes data (e.g., temperature) to a topic that other nodes can subscribe to.
- The **Decision-Making Node** subscribes to the sensor data, processes it (e.g., checking if the temperature exceeds a threshold), and sends commands to the **Motor Control Node**.
- The **Motor Control Node** receives the motor commands and drives the robot accordingly (e.g., stopping the robot if the temperature is too high).

4.3.2 Node Lifecycle

Each node in ROS goes through a lifecycle from initialization to shutdown. Below are the typical steps a node follows:

Step 1: Initialization

The node is created and registers with the ROS Master.

Step 2: Running

The node performs its assigned task, such as publishing sensor data or subscribing to a topic.

Step 3: Shutdown

The node completes its task and shuts down gracefully, unregistering itself from the ROS Master.

Figure 4.3: Node Lifecycle in ROS

4.4 Topics

Topics in ROS allow nodes to communicate asynchronously. The communication model for topics follows a **publish/subscribe** pattern, where one or more nodes can publish messages to a topic, and other nodes can subscribe to that topic to receive the messages. This is ideal for broadcasting sensor data like camera images, GPS coordinates, or motor commands, where multiple subscribers may need access to the same information.

4.4.1 How Topics Work

A topic in ROS is a named bus over which nodes exchange messages. A node that produces data **publishes** it on a specific topic, while nodes that are interested in this data **subscribe** to that topic to receive the published messages. Nodes don't need to know each other's existence; they only communicate through the topic they publish or subscribe to.

Publisher/Subscriber Example

- **Publisher:** The sensor node publishes data (e.g., temperature) to the `/sensor_data` topic. [6]
- **Subscriber:** The decision-making node subscribes to the `/sensor_data` topic to receive and process the data. [7]

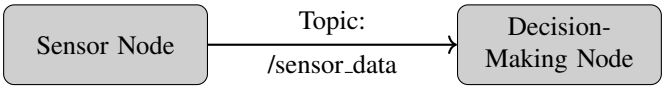


Figure 4.4: Publisher-Subscriber Communication in ROS

4.4.2 Example of Topics in Action

Let's use the previous example of our robot with sensor data and motor control:

Example

- The **Sensor Node** publishes data from the robot's sensor (e.g., temperature) to the `/sensor_data` topic.
- The **Decision-Making Node** subscribes to the `/sensor_data` topic to receive the sensor readings and makes decisions based on the data (e.g., stopping the robot if the temperature exceeds a threshold).
- The **Motor Control Node** subscribes to a topic called `/cmd_vel` to receive velocity commands and adjusts the robot's speed accordingly.
- The **GPS Node** publishes the robot's current position to the `/gps_data` topic, which can be used by other nodes for navigation or monitoring.

This architecture allows multiple nodes to communicate through topics without needing direct knowledge of each other.

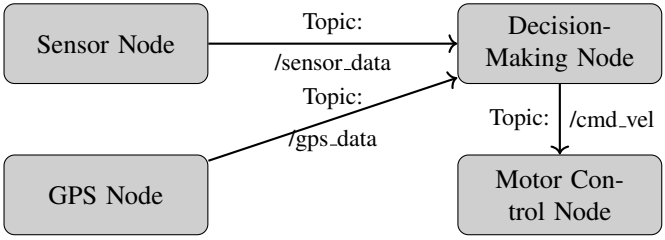


Figure 4.5: Multiple Nodes Communicating via Topics in ROS

4.4.3 Node vs Topic: Key Differences

- **Nodes:** Are independent programs that perform specific tasks. They are the building blocks of a ROS system, and multiple nodes can be executed at once.
- **Topics:** Are named channels through which nodes exchange messages. Topics enable asynchronous communication between

nodes.

4.4.4 Analogy: Nodes and Topics

Think of nodes as different departments in a company, each performing a specific task (e.g., HR, Marketing, Engineering). These departments do not directly interact with each other but instead communicate through email or reports (i.e., topics). A topic is like an internal mailing system where each department can subscribe to certain newsletters or reports that are relevant to them.

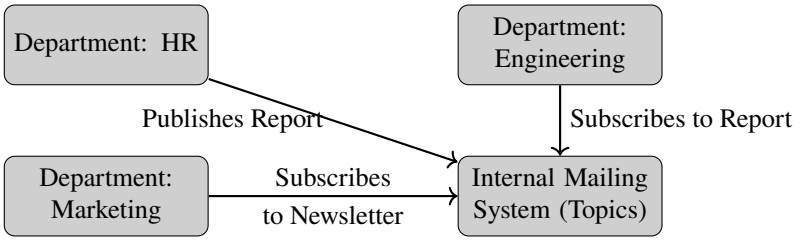


Figure 4.6: Analogy: Departments (Nodes) Communicate Through Mailing System (Topics)

4.5 Services

Services provide synchronous communication between nodes. Unlike Topics, which allow continuous data streaming, Services follow a request/response model. One node sends a request, and another node processes the request and sends back a response. Services are useful for tasks like turning a robot's camera or triggering a one-time event.

Service Example

Service Request:

- **Request:** A node requests the robot to turn its camera 45 degrees.
- **Response:** The service node returns the updated camera image.

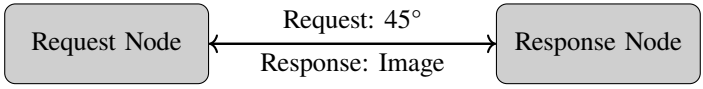


Figure 4.7: Client-Server Communication for Services

More about ROS Services will be covered in the upcoming chapter. [18]

4.6 Actions

Actions in ROS are used for tasks that take a longer duration to complete and may require continuous feedback. The Action framework allows a client to send a goal to an Action Server, which processes the goal and provides periodic feedback. Once the goal is reached, the server sends a result back to the client.

Action Example

Action Workflow:

- **Goal:** A node sends a goal for the robot to move to a specific coordinate.
- **Feedback:** The robot node continuously sends feedback about its distance from the goal.
- **Result:** Once the goal is reached, the robot node sends the time taken to achieve the goal.

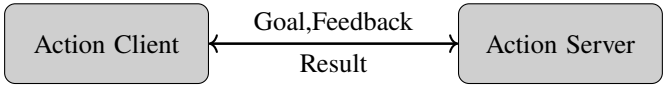


Figure 4.8: Action Client-Server Communication

More about ROS Actions will be covered in the upcoming chapter. [19]

4.7 Parameter Server

The Parameter Server is a shared, multi-variate dictionary that is accessible globally. It stores parameters that nodes can retrieve or modify during execution. This is useful for defining settings like the robot's wheel size, sensor calibration data, or environment-specific constants.

Parameter Server Example

- **Use case:** Instead of hard-coding the wheel size in the robot's control nodes, store it on the Parameter Server and access it from different nodes.

More about the ROS Parameter Server will be covered in the upcoming chapter. [11]

4.8 Bag Files

Bag Files are used for recording ROS message data during robot operation. You can record topics, services, or action communications in a bag file for later playback. This is especially useful for debugging and analyzing sensor data, robot movements, or for testing algorithms with pre-recorded data.

Bag File Example

- **Use case:** Record all sensor data during a robot's patrol and play it back later to simulate the robot's environment for testing purposes.

More about ROS Bagfiles will be covered in the upcoming chapter. [16]

4.9 Packages

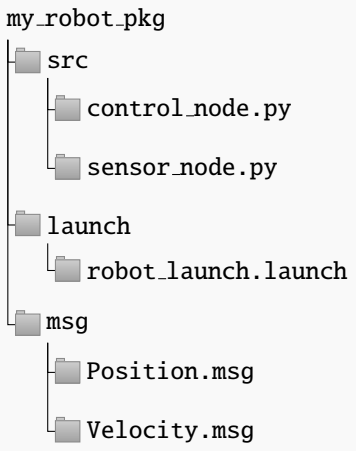
ROS organizes code into packages. A package contains all the necessary code and configuration files to implement a specific functionality. Packages can be easily shared, reused, and distributed among different robotics projects.

Package Example

Package Structure:

- `src/` - Contains the source code.
- `launch/` - Contains launch files for starting multiple nodes.
- `msg/` - Contains message definitions.

ROS Package Directory Structure



More about ROS Packages will be covered in the upcoming chapter. [17]

4.10 Conclusion

This chapter provided an overview of the ROS framework and its key components, including the ROS Master, Nodes, Topics, Services, Actions, Parameter Server, Bag Files, and Packages. Each of these elements plays a vital role in simplifying robotics programming and enabling modular, reusable code. Understanding these concepts is essential for building scalable, maintainable robotics systems using ROS. we will explore each of these topics in greater depth in the following chapters.

ROS Workspace Setup

5

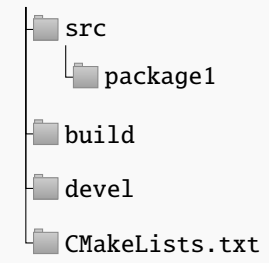
5.1 Introduction

In this chapter, we will explore how to set up a ROS workspace to organize development files efficiently. A ROS workspace is essential for managing packages, code, and dependencies. Let's begin by understanding the workspace structure and setting it up in Ubuntu.

5.2 Understanding ROS Workspace Structure

The ROS workspace typically follows a standard structure:

Workspace Structure



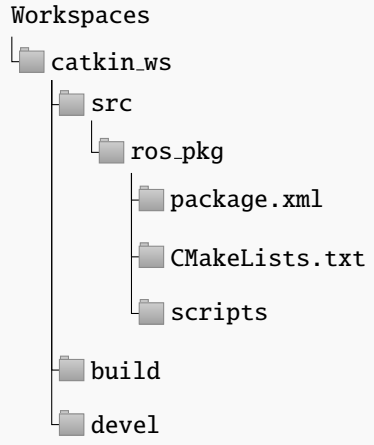
Explanation:

- **Source Folder (src)**: This is where all packages will reside.
- **Build Folder**: Auto-generated after running the `catkin_make` command. Contains compiled files.
- **Devel Folder**: Also generated by `catkin_make`. Contains development resources such as executable files.

5.3 Visualizing Workspace Structure

Below is a visual representation of a typical ROS workspace structure using a folder tree.

Workspace Structure



5.4 Creating the Workspace in Ubuntu

Let's walk through the steps to set up a ROS workspace in Ubuntu.

5.4.1 Step 1: Create Workspace Directory

First, we need to create the workspace folder. We recommend organizing multiple projects under a single "Workspaces" directory.

Step 1: Create Workspaces Directory

```
mkdir -p ~/Workspaces/catkin_ws/src
```

5.4.2 Step 2: Create a ROS Package

After navigating to the workspace's `src` folder, create a ROS package using the `catkin_create_pkg` command. We will create a package named `ros_pkg` with some basic dependencies.

Step 2: Create ROS Package

```
cd ~/Workspaces/catkin_ws/src

catkin_create_pkg ros_pkg roscpp rospy std_msgs sensor_msgs
```

5.4.3 Step 3: Create Scripts Folder

Since we will write our code in Python, create a `scripts` folder inside the package.

Step 3: Create Scripts Folder

```
mkdir ~/Workspaces/catkin_ws/src/ros_pkg/scripts
```

5.5 Compiling the Workspace

Once the package is ready, we need to compile the workspace to generate the `build` and `devel` folders. Go back to the workspace directory and run the following command:

Step 4: Compile the Workspace

```
cd ~/Workspaces/catkin_ws

catkin_make
```

5.6 Final Workspace Structure

After compilation, you should see the following structure:

Final Workspace Structure

5.7 Recap

To summarize the process of creating a ROS workspace:

1. Create the workspace and source folders.
2. Create a ROS package using `catkin_create_pkg`.
3. Add dependencies for Python and C++ development.
4. Compile the workspace using `catkin_make`.

In the next chapter, we will begin writing ROS nodes and working with the communication between nodes in ROS.

Coding a ROS Publisher

6

6.1 Introduction

In this chapter, we will develop a simple ROS publisher using Python. This publisher will send a message that prints ”hello world” along with a counter that increments each time the message is published. We will break down each step of the code, define the functions used, and explain the ROS commands involved.

6.2 Writing the Publisher Script

The ROS publisher script will be responsible for initializing a node, creating a publisher, and sending messages at a defined rate. We will go through each section of the code and explain how to create a functional publisher in Python.

6.2.1 Importing ROS Libraries

To work with ROS in Python, we first need to import the `rospy` library. This provides access to all the ROS-related functionalities in Python.

Python Code with Explanation

```
import rospy
```

Explanation:

- `rospy`: This module allows Python scripts to interface with ROS nodes. It provides functionality for creating publishers, subscribers, services, and more.

6.2.2 Creating the Main Function

The main section of the script is responsible for managing the execution of the node and handling exceptions. Here’s how we set it up:

Python Code with Explanation

```
if __name__ == '__main__':
        try:
                hello_world_pub()

        except rospy.ROSInterruptException:
                pass
```

Explanation:

- `if __name__ == "__main__"`: Ensures that the script runs only when executed directly, not when imported as a module.
- `try-except`: Handles exceptions, such as interruptions during node execution.
- `rospy.ROSInterruptException`: Triggered when the node is shut down or interrupted by external signals like `Ctrl+C`.

6.2.3 Initializing the ROS Node

In the function `hello_world_pub()`, we first initialize our ROS node.

Python Code with Explanation

```
def hello_world_pub():
        rospy.init_node('hello_world_pub_node')
```

Explanation:

- `rospy.init_node()`: Initializes a ROS node. In this case, the node is called `hello_world_pub_node`.

6.2.4 Creating a ROS Publisher

Now, we create a publisher that will send messages to a specific topic. The publisher needs to know the topic name, message type, and queue size.

Python Code with Explanation

```
pub = rospy.Publisher('hello_world', String, queue_size=10)
```

Explanation:

- `rospy.Publisher()`: Creates a publisher. It takes three main arguments:
  - **Topic Name**: `'hello_world'` is the name of the topic.
  - **Message Type**: `String` is the type of message being published.
  - **Queue Size**: Limits the number of messages stored in the buffer.

6.2.5 Setting the Publish Rate

We control how fast the messages are sent by setting a publishing rate.

Python Code with Explanation

```
rate = rospy.Rate(5)  # 5 Hz
```

Explanation:

- `rospy.Rate(5)`: Sets the publish rate to 5 Hz, meaning the message will be published 5 times per second.

6.2.6 Publishing the Message

The publisher sends messages within a `while` loop that runs until the node is shut down.

Python Code with Explanation

```
i = 0
rate = rospy.Rate(5)  # 5 Hz
while not rospy.is_shutdown():
        pub.publish(f"Hello World {i}")
        i += 1
        rate.sleep()
```

Explanation:

- `i = 0`: Initializes a counter.
- `rospy.is_shutdown()`: Ensures the loop continues as long as the node is active.
- `pub.publish()`: Sends the message, incrementing the counter on each loop iteration.
- `rate.sleep()`: Delays the loop to maintain the publish rate.

6.2.7 Importing the Required Message Type

We need to import the `String` message type to publish text data.

Python Code with Explanation

```
from std_msgs.msg import String
```

Explanation:

- `from std_msgs.msg import String`: Imports the `String` message type from the standard ROS messages library.

6.3 Summary Table of Functions

Summary of ROS Publisher Functions

Function	Description	Input	Output
`rospy.init_node(name)`	Initializes a ROS node	`name`: string	Initializes the node
`rospy.Publisher(topic, type, queue_size)`	Creates a publisher for a topic	`topic`: string, `type`: message, `queue_size`: int	Publishes data on the topic
`rospy.Rate(hz)`	Controls the message publishing rate	`hz`: int	Sets the publish rate
`rospy.is_shutdown()`	Checks if the node is shutting down	None	Returns True if the node is shutting down
`pub.publish(data)`	Publishes data on the topic	`data`: string	Sends data to the ROS topic
`rate.sleep()`	Pauses the loop to maintain the publish rate	None	Delays the loop

6.4 Verifying the Publisher with ROS Commands

After running your ROS publisher script, you can use the following ROS commands in separate terminals to verify that everything is working as expected.

6.4.1 Listing Active Nodes

This command lists all active nodes in your ROS system. It should include the node you just created (i.e., `/hello_world_pub_node`).

Bash Command with Explanation

```
rosnode list
```

Explanation:

- `rosnode list`: Lists all running ROS nodes in the system. You should see `/hello_world_pub_node` in the output if your publisher node is active.

6.4.2 Listing Topics

This command lists all active topics in the ROS system. You should see the `/hello_world` topic created by your publisher.

Bash Command with Explanation

```
rostopic list
```

Explanation:

- `rostopic list`: Displays all the topics currently available in the ROS system. The `/hello_world` topic should be listed here, indicating that your publisher is active.

6.4.3 Echoing Topic Messages

To see the messages being published on the `/hello_world` topic, use the following command:

Bash Command with Explanation

```
rostopic echo /hello_world
```

Explanation:

- `rostopic echo /hello_world`: Displays the messages being published to the `/hello_world` topic in real time. You should see the ”Hello World” messages along with the counter incrementing.

6.4.4 Getting Topic Information

To get more detailed information about the `/hello_world` topic, including its message type and the publishing rate, use the following command:

Bash Command with Explanation

```
rostopic info /hello_world
```

Explanation:

- `rostopic info /hello_world`: Provides detailed information about the topic, including the type of message being published, the node that is publishing it, and any subscribers.

6.4.5 Monitoring Publish Rate

To monitor the publishing rate of the `/hello_world` topic, use the `rostopic hz` command. This will show the rate at which messages are being published.

Bash Command with Explanation

```
rostopic hz /hello_world
```

Explanation:

- `rostopic hz /hello_world`: Displays the frequency (in Hz) at which messages are being published to the `/hello_world` topic. This should match the rate you set in the script (5 Hz in this case).

6.4.6 Stopping the Publisher

To stop the ROS publisher, simply use `Ctrl+C` in the terminal where the script is running. This will safely shut down the ROS node.

Bash Command with Explanation

```
Ctrl+C
```

Explanation:

- `Ctrl+C`: Terminates the running ROS node and safely shuts down the publisher.

6.5 Summary Table of ROS Commands

Summary of ROS Commands

Command	Description	Output
`rosnode list`	Lists all active ROS nodes	Displays node names including `/hello_world_pub_node`
`rostopic list`	Lists all active ROS topics	Shows available topics including `/hello_world`
`rostopic echo /hello_world`	Displays messages published to the topic	Prints ”Hello World” messages with counter
`rostopic info /hello_world`	Provides information about the topic	Details on publisher, message type, and subscribers
`rostopic hz /hello_world`	Monitors the publishing rate of the topic	Shows frequency (Hz) of messages
`Ctrl+C`	Stops the ROS node	Shuts down the publisher

Coding a ROS Subscriber

7

7.1 Introduction

In this chapter, we will develop a simple ROS subscriber in Python. This subscriber will listen to the messages being published on the same topic as our previous publisher, printing them to the terminal. Like with the publisher, we will break down each part of the code step by step, explaining the ROS commands involved.

7.2 Writing the Subscriber Script

To write a subscriber, we will follow similar steps to our previous publisher, but instead of publishing messages, we will listen for and process them. Below are the instructions and code snippets to create the `simple_subscriber.py` script in the `scripts` folder of our ROS package.

7.2.1 Importing ROS Libraries

Just like in the publisher, we need to import the `rospy` library, along with the message type `String`, which will allow us to process the published messages.

Python Code with Explanation

```
import rospy
from std_msgs.msg import String
```

Explanation:

- `rospy`: The module that interfaces with ROS nodes in Python.
- `String`: The message type from `std_msgs` package that we will subscribe to.

7.2.2 Defining the Main Function

In the main function, we will create our subscriber and ensure the script continues running using `rospy.spin()`.

Python Code with Explanation

```
if __name__ == '__main__':
        create_subscriber()
        rospy.spin()
```

Explanation:

- `rospy.spin()`: This keeps the node running until it is shut down, preventing the script from exiting immediately after the subscriber is created.

7.2.3 Initializing the ROS Node

Just like with the publisher, we need to initialize the ROS node for our subscriber.

Python Code with Explanation

```
def create_subscriber():
        rospy.init_node('hello_world_sub_node')
```

Explanation:

- `rospy.init_node()`: Initializes the subscriber node with the name `hello_world_sub_node`.

7.2.4 Creating a ROS Subscriber

The next step is to create the actual subscriber that listens to the `hello_world` topic, and specify the callback function that will process the incoming messages.

Python Code with Explanation

```
rospy.Subscriber('hello_world', String, process_hello_world_message)
```

Explanation:

- `rospy.Subscriber()`: Creates a subscriber for the `hello_world` topic. It takes three arguments:
  - **Topic Name**: The name of the topic to subscribe to.
  - **Message Type**: The type of messages being subscribed to, in this case, `String`.
  - **Callback Function**: The function that processes the incoming messages.

7.2.5 Defining the Callback Function

The callback function processes the incoming messages. Here, we'll print the contents of the received message.

Python Code with Explanation

```
def process_hello_world_message(data):
        print(f"Message␣received:␣{data.data}")
```

Explanation:

- `data`: This parameter holds the message data received from the publisher.
- `data.data`: The actual string content of the message is accessed via `data.data`.

7.3 Summary Table of ROS Subscriber Functions

Summary of ROS Subscriber Functions

Function	Description	Input	Output
`rospy.init_node(name)`	Initializes a ROS node	`name`: string	Initializes the node
`rospy.Subscriber(topic, type, callback)`	Creates a subscriber for a topic	`topic`: string, `type`: message, `callback`: function	Subscribes to messages on the topic
`rospy.spin()`	Keeps the subscriber node running	None	Prevents the script from closing
`process_hello_world_message(data)`	Callback function to process received messages	`data`: message	Prints the message content

ROS Message Types

8

8.1 Introduction

In this chapter, we will explore various ROS message types. In the previous chapters, we used the `String` message type for our publisher and subscriber. However, ROS provides many other built-in message types that allow for more complex data processing and communication between nodes. We will cover some commonly used message types and how to implement them in a ROS publisher or subscriber.

For more detailed information about message types, refer to the following resources:

Resources

- ROS Message Types: https://wiki.ros.org/msg
- ROS Noetic ‘sensor_msgs‘ API: https://docs.ros.org/en/noetic/api/sensor_msgs/html/index-msg.html
- ROS 2 Galactic ‘geometry_msgs‘ API: https://docs.ros2.org/galactic/api/geometry_msgs/index-msg.html

8.2 Overview of ROS Message Types

ROS message types are used to define the structure of data that is transmitted between nodes. These message types can represent simple data like integers or strings, as well as more complex structures like sensor data or geometric coordinates.

8.2.1 Standard Message Types

ROS comes with a library of standard message types, which include primitive data types such as `Bool`, `Float64`, and `Int32`, as well as arrays of these types. These message types can be easily integrated into ROS publishers and subscribers, just as we did with the `String` message type.

Example: Publishing a Boolean Message

```
from std_msgs.msg import Bool

def boolean_publisher():
        pub = rospy.Publisher('bool_topic', Bool, queue_size=10)
        rospy.init_node('boolean_publisher_node')

        rate = rospy.Rate(10)  # 10 Hz
        while not rospy.is_shutdown():
                bool_msg = Bool(data=True)
                pub.publish(bool_msg)
                rate.sleep()
```

Explanation:

- `from std_msgs.msg import Bool`: Imports the `Bool` message type from the standard messages library.
- `Bool(data=True)`: Creates a message of type `Bool` with the value `True`.

8.2.2 Custom Message Types

While standard message types cover many use cases, sometimes it's necessary to create custom message types. These can be defined by the user to match specific requirements, such as combining multiple primitive data types into a single message.

8.3 Using Sensor Message Types

`sensor_msgs` is a library in ROS that provides message types for common sensor data, such as cameras, LiDARs, and IMUs. These messages are essential for robotics applications where sensor data needs to be transmitted between nodes.

8.3.1 Example: Publishing LaserScan Data

The `LaserScan` message is used to represent data from a LiDAR sensor, which provides distance measurements around the robot.

Example: Publishing LaserScan Data

```
from sensor_msgs.msg import LaserScan

def lidar_publisher():
        pub = rospy.Publisher('lidar_scan', LaserScan, queue_size=10)
        rospy.init_node('lidar_publisher_node')

        rate = rospy.Rate(10)  # 10 Hz
        while not rospy.is_shutdown():
                scan_msg = LaserScan()
                scan_msg.header.stamp = rospy.Time.now()
                scan_msg.ranges = [1.0, 1.2, 0.9]  # Example
     distances
                pub.publish(scan_msg)
                rate.sleep()
```

Explanation:

- `from sensor_msgs.msg import LaserScan`: Imports the `LaserScan` message type.
- `scan_msg.ranges`: Defines an array of distances measured by the LiDAR sensor.
- `scan_msg.header.stamp = rospy.Time.now()`: Sets the timestamp for the message.

8.4 Using Geometry Message Types

The `geometry_msgs` package provides messages for representing geometric information such as points, vectors, and poses. These messages are crucial for transmitting information related to the robot's position, orientation, and movement.

8.4.1 Example: Using Vector3 Message

The `Vector3` message represents a vector in 3D space. It is often used for conveying velocity, acceleration, or force.

Example: Publishing Vector3 Data

```
from geometry_msgs.msg import Vector3

def vector_publisher():
        pub = rospy.Publisher('vector_topic', Vector3, queue_size=10)
        rospy.init_node('vector_publisher_node')

        rate = rospy.Rate(10)  # 10 Hz
        while not rospy.is_shutdown():
                vector_msg = Vector3(x=1.0, y=2.0, z=3.0)
                pub.publish(vector_msg)
                rate.sleep()
```

Explanation:

- `from geometry_msgs.msg import Vector3`: Imports the `Vector3` message type.
- `Vector3(x=1.0, y=2.0, z=3.0)`: Creates a message representing a vector in 3D space.
- `pub.publish(vector_msg)`: Publishes the vector data to the topic.

8.5 4. Summary Table of Functions

Summary of ROS Message Types and Functions

Function	Description	Input	Output
`rospy.Publisher(topic, type, queue_size)`	Creates a publisher for a topic	`topic`: string, `type`: message, `queue_size`: int	Publishes data on the topic
`rospy.init_node`	Initializes a ROS node	`name`: string	Initializes the node
`LaserScan()`	Creates a LaserScan message	None	Data structure for laser range data
`Vector3(x, y, z)`	Creates a Vector3 message	`x, y, z`: floats	Vector in 3D space
`rospy.spin()`	Keeps the subscriber node active	None	Loops continuously

8.6 Conclusion

In this chapter, we explored some of the key ROS message types, including `sensor_msgs` for sensor data and `geometry_msgs` for representing geometric information. These message types enable efficient data exchange between nodes in a ROS system and are essential for building advanced robotics applications. As you continue working with ROS, you will encounter a variety of other message types, but the ones covered here will serve as a strong foundation.

Your First Project in ROS

9

9.1 Introduction

In this chapter, we will create our first complete project in ROS. This project will require the use of Python skills we learned in previous chapters, along with some basic mathematics and physics knowledge. Specifically, we will focus on the mechanics of a differential drive robot and apply transformation matrices to calculate the robot's velocity based on the angular velocities of its wheels.

9.2 Project Overview

The task is to build a differential drive robot with two wheels (left and right motors). We will write two Python scripts for this:

Python script overview

- A **Publisher** script that generates random angular velocities (in RPM) for the left and right wheels and publishes them to a ROS topic.
- A **Subscriber** script that subscribes to the published velocities, converts them into radians per second (rad/s), and calculates the robot's resultant velocity in meters per second (m/s).

9.2.1 Mathematical Concept: Transformation Matrix

To compute the robot's velocity, we will use the transformation matrix for a differential drive robot. The matrix is shown below:

Transformation Matrix

$$\vec{V} = \frac{R}{2} \begin{bmatrix} 1 & 1 \\ -\frac{1}{L} & \frac{1}{L} \end{bmatrix} \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix}$$

Where:

- $\vec{V}$ is a 2D vector containing v (linear velocity) and ω (angular velocity),
- R is the radius of the wheels.
- L is the distance between the two wheels (also called the axle length).
- ω_L and ω_R are the angular velocities of the left and right wheels in rad/s.

For a more detailed explanation of differential drive robots and the transformation matrix, refer to the https://en.wikipedia.org /wiki/Differential_wheeled_robot.

9.3 Creating the ROS Package and Workspace

To implement this project, we will first set up a new ROS workspace and package. Follow the steps below:

Step-by-Step Instructions

1. **Create a New Workspace:** Open a terminal and run the following commands: [5.4], [5.4.1]

```
mkdir -p ~/catkin_ws/src

cd ~/catkin_ws/

catkin_make

source devel/setup.bash
```

2. **Create a New ROS Package:** Inside the `src` folder of your workspace, create a new ROS package: [5.4.2]

```
cd src/

catkin_create_pkg robot_velocity rospy std_msgs
```

3. **Build the Package:** Go back to the root of the workspace and run: [5.5]

```
cd ~/catkin_ws/

catkin_make

source devel/setup.bash
```

4. **Create a `scripts` Folder:** Navigate to the package folder and create a `scripts` directory to store Python scripts:

```
cd ~/catkin_ws/src/robot_velocity/

mkdir scripts
```

9.4 Project Breakdown

Now that we have set up the workspace and package, let's break down the two main components of the project:

Python script usage

- **Publisher:** This script will generate and publish random angular velocities for the left and right wheels in RPM.
- **Subscriber:** This script will subscribe to the published velocities, convert them to rad/s, and calculate the resultant velocity of the robot.

In the next chapter, we will implement these scripts step by step and explain the underlying calculations in detail.

Solution to Your First Project

10

10.1 Introduction

In this chapter, we will implement the two Python scripts for our ROS project. The first script will act as the publisher, generating random angular velocities for the left and right wheels of the robot. The second script will subscribe to these velocities and compute the resultant velocity using the transformation matrix introduced earlier.

10.2 Writing the Publisher Script

We will begin by writing the publisher script, which publishes random angular velocities for the robot's wheels.

10.2.1 Importing Required Libraries

We need to import the `rospy` library and the standard message type `Float64`, which we will use to publish the angular velocities.

Python Code with Explanation

```
import rospy
from std_msgs.msg import Float64
```

Explanation:

- `rospy`: The ROS client library for Python.
- `Float64`: Message type for publishing float data (angular velocities in RPM).

10.2.2 Initializing the Publisher Node

We will now create and initialize the ROS node and the publisher.

Python Code with Explanation

```
def publisher():
        rospy.init_node('wheel_velocity_publisher', anonymous=True)
        left_wheel_pub = rospy.Publisher('left_wheel_rpm', Float64,
      queue_size=10)
        right_wheel_pub = rospy.Publisher('right_wheel_rpm',
      Float64, queue_size=10)
        rate = rospy.Rate(1)  # 1 Hz
```

Explanation:

- `rospy.init_node()`: Initializes the ROS node named `wheel_velocity_publisher`.
- `rospy.Publisher()`: Creates two publishers for the topics `left_wheel_rpm` and `right_wheel_rpm`, both using `Float64` message type.
- `rospy.Rate(1)`: Sets the publishing rate to 1 Hz.

10.2.3 Publishing Random Velocities

We will now implement the logic to generate random velocities for both wheels and publish them.

Python Code with Explanation

```
while not rospy.is_shutdown():
                left_wheel_rpm = random.uniform(10.0, 50.0)
                right_wheel_rpm = random.uniform(10.0, 50.0)

                rospy.loginfo(f"Left␣wheel␣RPM:␣{left_wheel_rpm},␣
     Right␣wheel␣RPM:␣{right_wheel_rpm}")

                left_wheel_pub.publish(left_wheel_rpm)
                right_wheel_pub.publish(right_wheel_rpm)

                rate.sleep()
```

Explanation:

- `random.uniform(10.0, 50.0)`: Generates random RPM values for both wheels in the range 10.0 to 50.0.
- `rospy.loginfo()`: Logs the published RPM values to the console.
- `left_wheel_pub.publish()`: Publishes the left wheel's RPM.
- `right_wheel_pub.publish()`: Publishes the right wheel's RPM.
- `rate.sleep()`: Pauses the loop to maintain the 1 Hz rate.

10.2.4 Complete Publisher Script

Here's the full publisher script:

Complete Python Code

```
import rospy
from std_msgs.msg import Float64

def publisher():
        rospy.init_node('wheel_velocity_publisher', anonymous=True)
        left_wheel_pub = rospy.Publisher('left_wheel_rpm', Float64,
     queue_size=10)
        right_wheel_pub = rospy.Publisher('right_wheel_rpm',
     Float64, queue_size=10)
        rate = rospy.Rate(1)  # 1 Hz

while not rospy.is_shutdown():
        left_wheel_rpm = 30
        right_wheel_rpm = 40

        rospy.loginfo(f"Publishing -> Left wheel RPM: 
     {left_wheel_rpm}, Right wheel RPM: {right_wheel_rpm}")

        left_wheel_pub.publish(left_wheel_rpm)
        right_wheel_pub.publish(right_wheel_rpm)

        rate.sleep()

if __name__ == '__main__':
        try:
                publisher()
        except rospy.ROSInterruptException:
        pass
```

10.3 Writing the Subscriber Script

Now, we will write the subscriber script that subscribes to the wheel velocities and calculates the resultant robot velocity.

10.3.1 Importing Required Libraries

We will import the necessary libraries for ROS and mathematical calculations.

Python Code with Explanation

```
import rospy
from std_msgs.msg import Float64
import math
```

Explanation:

- `rospy`: The ROS client library for Python.
- `Float64`: Message type for receiving angular velocities.
- `math`: Python's built-in math library for mathematical functions.

10.3.2 Transformation Matrix and Velocity Calculations

To compute the linear velocity v and angular velocity ω of the robot, we use the following transformation matrix:

Transformation Matrix

$$\vec{V} = \frac{R}{2} \begin{bmatrix} 1 & 1 \\ -\frac{1}{L} & \frac{1}{L} \end{bmatrix} \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix}$$

where:

- $\vec{V}$ is a 2D vector containing v (linear velocity) and ω (angular velocity),
- R is the radius of the wheels,
- L is the wheelbase of the robot,
- ω_L and ω_R are the angular velocities of the left and right wheels, respectively.

Step 1: Matrix Multiplication We perform the matrix multiplication to obtain the linear and angular velocities:

$$\vec{V} = \frac{R}{2} \begin{bmatrix} 1 & 1 \\ -\frac{1}{L} & \frac{1}{L} \end{bmatrix} \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix}$$

Performing the multiplication:

$$\vec{V} = \frac{R}{2} \begin{bmatrix} \omega_L + \omega_R \\ \frac{\omega_R - \omega_L}{L} \end{bmatrix}$$

Thus, the linear velocity v and angular velocity ω are given by:

$$v = \frac{R}{2} (\omega_L + \omega_R)$$

$$\omega = \frac{R}{L} (\omega_R - \omega_L)$$

Step 2: Conversion from RPM to Radians per Second Before using these formulas, we must convert the wheel velocities from RPM (revolutions per minute) to radians per second using the following equation:

$$\omega = \text{RPM} \times \frac{2\pi}{60}$$

This conversion allows us to input the wheel velocities in radians per second into the matrix equation.

Step 3: Final Velocity Calculation Given the RPM values for both wheels, we can calculate the final linear velocity v and angular velocity ω using the above formulas.

Let's assume the following values:

- Left wheel RPM: 30
- Right wheel RPM: 40
- Wheel radius R: 0.05 m
- Wheel base L: 0.3 m

Using the formulas, we can convert the RPM values to radians per second:

$$\omega_{left} = 30 \times \frac{2\pi}{60} = 3.14\,\text{rad/s}$$
$$\omega_{right} = 40 \times \frac{2\pi}{60} = 4.19\,\text{rad/s}$$

Now, we compute the linear velocity v:

$$v = \frac{0.05}{2}\,(3.14 + 4.19) = 0.18\,\text{m/s}$$

And the angular velocity ω:

$$\omega = \frac{0.05}{0.3}\,(4.19 - 3.14) = 0.17\,\text{rad/s}$$

Thus, the robot's linear velocity is 0.18 m/s and angular velocity is 0.17 rad/s.

10.3.3 Defining the Subscriber Callback Function

The callback function will calculate the resultant velocity using the transformation matrix.

Python Code with Explanation

```
def calculate_velocity(left_rpm, right_rpm, wheel_radius,
     wheel_base):

        left_rad_s = math.radians(left_rpm)
        right_rad_s = math.radians(right_rpm)

        velocity = (wheel_radius / 2) * (left_rad_s + right_rad_s)
        angular_velocity = (wheel_radius / wheel_base) *
     (right_rad_s - left_rad_s)

        return velocity, angular_velocity
```

Explanation:

- `math.radians()`: Converts RPM to radians per second.
- `velocity`: Calculates the linear velocity based on the transformation matrix.
- `angular_velocity`: Calculates the angular velocity of the robot.

10.3.4 Complete Subscriber Script

Here's the complete subscriber script that calculates the velocity and angular velocity of the robot.

Complete Python Code

```
import rospy
from std_msgs.msg import Float64
import math

wheel_radius = 0.05  # in meters
wheel_base = 0.3  # in meters

def calculate_velocity(left_rpm, right_rpm, wheel_radius,
     wheel_base):
        # Convert RPM to rad/s
        left_rad_s = (left_rpm * 2 * math.pi) / 60.0
        right_rad_s = (right_rpm * 2 * math.pi) / 60.0

        # Calculate linear velocity (v) and angular velocity (w)
        velocity = (wheel_radius / 2) * (left_rad_s + right_rad_s)
        angular_velocity = (wheel_radius / wheel_base) *
     (right_rad_s - left_rad_s)

        return velocity, angular_velocity

def subscriber():
        rospy.init_node('velocity_subscriber', anonymous=True)
        rate = rospy.Rate(1)  # 1 Hz

while not rospy.is_shutdown():
        # Get the latest messages from each topic
        left_rpm = rospy.wait_for_message('left_wheel_rpm',
     Float64).data
        right_rpm = rospy.wait_for_message('right_wheel_rpm',
     Float64).data

        # Calculate and print the velocities
        velocity, angular_velocity = calculate_velocity(left_rpm,
     right_rpm, wheel_radius, wheel_base)
        rospy.loginfo(f"Linear velocity: {velocity:.2f} m/s, Angular
     velocity: {angular_velocity:.2f} rad/s")

        rate.sleep()

if __name__ == '__main__':
        try:
                subscriber()
        except rospy.ROSInterruptException:
                pass
```

10.4 Conclusion

In this chapter, we developed a complete ROS project involving a differential drive robot. We created a publisher that generates random angular velocities for the wheels and a subscriber that computes the robot's linear and angular velocities using a transformation matrix.

ROS Parameters

11

11.1 Introduction

In this chapter, we will explore how to use the ROS parameter server in Python. The ROS parameter server provides a centralized location for storing values related to the physical attributes of our robot. This allows us to easily accommodate changes in hardware without having to modify multiple scripts across our project. We will also discuss how to interact with the parameter server from the terminal, as well as how to integrate it into our Python code using `rospy.get_param()`.

11.2 Why Use the ROS Parameter Server?

In our previous project, we hard-coded the wheel radius of our robot. While this is manageable in small projects, it becomes cumbersome when we need to modify this value across multiple scripts. Using the ROS parameter server, we can store values like the wheel radius in one place and easily retrieve them within our code. This approach saves time, especially in larger projects.

11.3 Interacting with the Parameter Server from the Terminal

Before we modify our Python code, let's learn how to interact with the ROS parameter server from the terminal.

11.3.1 Listing Parameters

We can start by checking which parameters are currently available using the following command:

Terminal Command

```
rosparam list
```

This command will list all the active ROS parameters. For example, you might see a default parameter like `/rosdistro`, which indicates the version of ROS you're using (e.g., `noetic`).

11.3.2 Setting and Getting Parameters

You can view the value of a parameter using:

Terminal Command

```
rosparam get /rosdistro
```

To set a new parameter, such as the wheel radius for our robot, use:

Terminal Command

```
rosparam set /wheel_radius 0.05
```

After setting the parameter, you can confirm that it has been added by running:

Terminal Command

```
rosparam get /wheel_radius
```

11.4 Saving and Loading Parameters

It is possible to save and load parameter values using YAML files. This is useful if you want to save the current parameter settings and reload them later.

11.4.1 Dumping Parameters

To save the current parameters to a YAML file, use the `rosparam dump` command. This "dumps" the current parameters from the ROS parameter server into a YAML file, which can be useful if you want to save your configuration for future use or backup.

Terminal Command

```
rosparam dump params.yaml
```

This command will create a `params.yaml` file in your current working directory, which contains all the current parameters.

11.4.2 Loading Parameters

You can edit the `params.yaml` file and reload it into the ROS parameter server using the `rosparam load` command. This "loads" the parameter values from the YAML file back into the parameter server, making it useful when restarting or changing configurations.

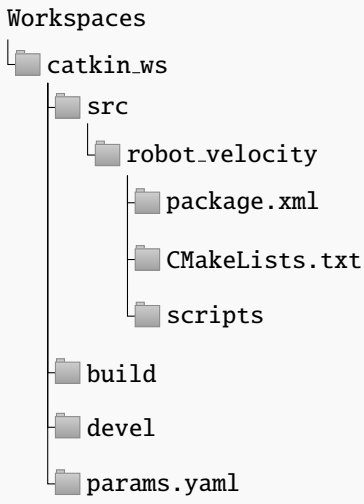
Terminal Command

```
rosparam load params.yaml
```

11.4.3 When to Use Dump and Load

Dumping and loading parameters is especially useful when you want to persist configuration settings across sessions or deployments. For instance, you can dump the parameters of a robot's configuration and then load it into another system to replicate the setup.

Final Workspace Structure



11.5 Integrating ROS Parameters into Python Code

Let's now modify our Python code to retrieve the wheel radius from the ROS parameter server instead of hard-coding it. We will use the `rospy.get_param()` function to retrieve the value of `/wheel_radius`.

11.5.1 Using `rospy.get_param` in `subscriber_script.py`

Similarly, we will modify the `subscriber_script.py` to use the wheel radius value from the parameter server within the callback function.

Python Code with Explanation

```
import rospy
from std_msgs.msg import Float64
import math

wheel_radius = rospy.get_param('/wheel_radius',0.05)  # in meters
wheel_base = 0.3  # in meters

def calculate_velocity(left_rpm, right_rpm, wheel_radius,
     wheel_base):
       wheel_radius = rospy.get_param('/wheel_radius',0.05)  #
     Default to 0.05 if param not set

       # Convert RPM to rad/s
       left_rad_s = (left_rpm * 2 * math.pi) / 60.0
       right_rad_s = (right_rpm * 2 * math.pi) / 60.0

       # Calculate linear velocity (v) and angular velocity (w)
       velocity = (wheel_radius / 2) * (left_rad_s + right_rad_s)
       angular_velocity = (wheel_radius / wheel_base) *
     (right_rad_s - left_rad_s)
       return velocity, angular_velocity

       #rest of the code...
```

Explanation:

- `rospy.get_param('/wheel_radius', 0.05)`: Retrieves the wheel radius from the parameter server.

11.6 Summary Table of ROS Parameter Functions

Summary of ROS Parameter Functions

Function	Description	Input	Output
`rospy.get_param(param, default)`	Retrieves a parameter from the server	`param`: string, `default`: value	Parameter value
`rosparam set`	Sets a parameter on the server	`name`: string, `value`: value	Sets the parameter
`rosparam get`	Retrieves a parameter from the server	`name`: string	Parameter value
`rosparam dump`	Saves parameters to a YAML file	`filename`: string	Saves the file
`rosparam load`	Loads parameters from a YAML file	`filename`: string	Loads the parameters

ROS Basics

12

12.1 Introduction

In this chapter, we will cover several fundamental concepts essential for running ROS nodes effectively. These include:

Overview

- Sourcing a workspace and why it's necessary
- The `rosrun` command and package structure
- Making Python scripts executable using `chmod +x`
- Resolving Python version errors with ROS
- Running `roscore` in a parallel terminal

Understanding these elements will help ensure that your ROS environment functions smoothly, particularly when working with Python scripts.

12.2 Sourcing a Workspace

When you create a new terminal session, ROS does not automatically know about your workspace or the packages within it. This is why we must "source" the workspace, making it known to the ROS environment.

12.2.1 The Need for Sourcing

When we source a workspace, we tell ROS to use the environment variables and configuration of our workspace. This is done with the `source` command, typically like this:

Source Command

```
source ~/catkin_ws/devel/setup.bash
```

12.2.2 Making Sourcing Automatic

To avoid running the `source` command every time you open a new terminal, you can add the command to your `.bashrc` file. Here's how to do it:

1. First, open your terminal and navigate to your home directory (if not already there) by typing:

Navigate to Home Directory

```
cd ~
```

2. Next, open the `.bashrc` file in Sublime by typing the following command:

Open .bashrc in Sublime

```
subl ~/.bashrc
```

3. If you cannot see hidden files in Sublime's file dialog, press `Ctrl + H` to show hidden files.

4. Scroll to the bottom of the file and add the following line, making sure to replace `catkin_ws` with your workspace name:

Adding to .bashrc

```
source ~/catkin_ws/devel/setup.bash
```

5. After saving the file, apply the changes by typing:

Source .bashrc

```
source ~/.bashrc
```

This will automatically source your workspace every time a terminal is opened.

12.3 Running ROS Nodes with `rosrun`

The `rosrun` command allows us to run a specific node from a package without needing to manually navigate to its location. The general syntax is as follows:

rosrun Command Syntax

```
rosrun <package_name> <executable_file>
```

For instance, after sourcing your workspace, you can run a Python script from the `ros_pkg` package:

Example

```
rosrun ros_pkg publisher_script.py
```

12.3.1 Why Tab Completion May Not Work

If you notice that tab completion doesn't work after typing `rosrun <package_name>`, it might be because the Python script is not marked as executable.

12.4 Making Python Scripts Executable

In Linux, a script must be marked as ”executable” for ROS to recognize it when using `rosrun`. You can check if a file is executable by listing the files in your directory:

Check File Permissions

```
ls -l
```

Files that are not executable will appear in white. To make them executable, use the `chmod +x` command:

Making Files Executable

```
chmod +x publisher_script.py
```

After running this command, the file will become executable, allowing it to be run with `rosrun`.

12.4.1 Python Version Error

Now that we have successfully made our Python script executable, and ROS recognizes the file, you might expect everything to work perfectly. However, when you attempt to run the following command:

Executing ROS Script

```
rosrun ros_pkg publisher_script.py
```

You may encounter a Python version error, which prevents the script from running correctly. This error typically looks something like this:

Python Version Error

```
ImportError: No module named 'rospy'
```

This occurs because the script is being executed in the wrong Python environment. By default, ROS uses Python 2, but your script might require Python 3. This mismatch causes the import error as ROS tries to run the script with an incorrect version of Python.

In the next section, we will go over how to resolve this Python version issue and ensure ROS runs the script in the proper environment.

12.5 Dealing with Python Version Errors

ROS may not know which version of Python to use when running your script. By default, ROS may attempt to use Python 2.x, which could cause issues if your script is written for Python 3.x. To specify the Python version, add the following ”shebang” line at the top of your Python script:

Python Shebang for Version Control

```
#!/usr/bin/env python3
```

This line ensures that Python 3 is used to run the script.

12.5.1 Example of Updating a Script

Here is an updated version of our `publisher_script.py` file that uses Python 3:

Updated Python Script

```
#!/usr/bin/env python3

import rospy
from std_msgs.msg import String

def example():


if __name__ == '__main__':
        example()
```

12.6 Starting `roscore` in a Parallel Terminal

After making your Python script executable and specifying the correct Python version, you may encounter an error related to the ROS master node. This error usually looks like:

Common Error

```
Unable to register with master node...
```

This happens because `roscore` is not running. You need to start `roscore` in a parallel terminal:

Start roscore

```
roscore
```

Once `roscore` is running, your node will be able to connect to the master, and the error will be resolved.

12.7 Summary

Below is a table summarizing the key commands and concepts introduced in this chapter.

Key Commands and Concepts in ROS Node Execution

Command/Concept	Description
`source <file>`	Source a workspace to make it known to ROS.
`rosrun <package> <file>`	Run a node from a package.
`chmod +x <file>`	Make a Python script executable.
Shebang (`#!/usr/bin/env python3`)	Specify Python 3 as the interpreter for your script.
`roscore`	Start the ROS master node.

12.8 Conclusion

By understanding these core concepts—sourcing workspaces, running executable Python scripts, and starting `roscore`—you are well on your way to mastering ROS node execution. These steps form the foundation for more complex ROS projects.

Using Launch Files in ROS

13

13.1 Introduction

In this chapter, we will simplify the process of launching ROS nodes by using launch files. Instead of manually running `roscore` and individual ROS nodes in separate terminals, we will create a launch file that automates this process, making it more efficient. Launch files help in managing multiple nodes and setting up complex configurations, all with a single command.

13.2 Creating the Launch Folder

First, let's keep our ROS package organized by creating a launch folder where we will store our launch files. This folder will be located inside the `src` directory of your ROS workspace, specifically in the package directory.

Creating a Launch Folder

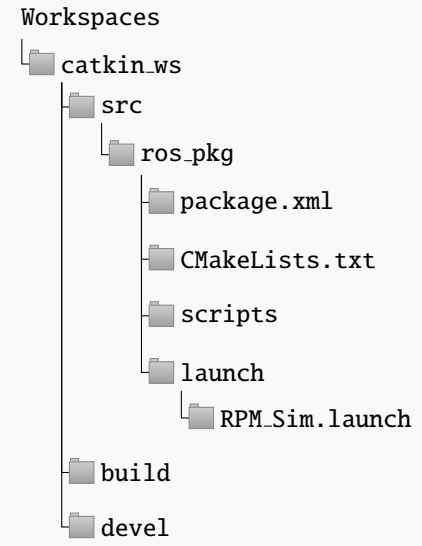
```
mkdir ~/workspace/catkin_ws/src/ros_pkg/launch
```

Now that the `launch` folder is created, we can move on to creating the actual launch file.

13.3 Where to Place the Launch File

The launch file should be placed inside the `launch` folder that we just created within the package. The following file structure diagram shows the correct place to store the launch file within your ROS workspace:

Launch File Placement



Description:

- `ros_pkg`: The ROS package where your launch file will be placed.
- `launch`: The folder where we will store the `RPM_Sim.launch` file.
- `RPM_Sim.launch`: The launch file that will be used to run your ROS nodes.

13.4 Understanding the Structure of a Launch File

A launch file in ROS uses XML syntax to specify which nodes to launch, parameters to set, and other configurations. Below is a simple structure of a launch file, which we will modify for our project.

Sample Launch File

```
<launch>}
<node name="node_name" pkg="package_name" type="script_name.py"
      output="screen" />
</launch>
```

13.4.1 Tags in Launch Files

Here are some important tags used in launch files:

- `<launch>`: The root tag, wrapping the entire launch file.
- `<node>`: Launches a specific node. Takes attributes like `name`, `pkg` (package name), and `type` (the script name).
- `<param>`: Sets ROS parameters, useful for configuring nodes.
- `<include>`: Includes another launch file within the current one.

For more details, refer to the ROS Wiki page on https://wiki.ros.org/roslaunch/XML.

13.5 Creating the Launch File

Now, let's create the launch file to run our `publisher_script.py` node. Navigate to the `launch` folder and create a file named `publisher.launch`.

Creating the Launch File

```
touch ~/workspace/catkin_ws/src/ros_pkg/launch/publisher.launch
```

13.6 Modifying the Launch File

We will now modify the launch file to launch our publisher node.

Modifying the Launch File

```
<launch>
<node name="wheel_velocity_publisher" pkg="ros_pkg"
      type="publisher_script.py" output="screen" />
</launch>
```

Explanation:

- `name`: This is the name of the node, which we initialize as `wheel_velocity_publisher`.
- `pkg`: This is the ROS package where our node is located, in this case, `ros_pkg`.
- `type`: This is the Python script we want to run, `publisher_script.py`.
- `output`: The `screen` option ensures that the output is displayed on the terminal.

13.7 Running the Launch File

To run the launch file, we use the `roslaunch` command. Make sure to source your workspace and then execute the following:

Running the Launch File

```
source ~/workspace/catkin_ws/devel/setup.bash

roslaunch ros_pkg publisher.launch
```

This command will automatically start `roscore` and run the `publisher_script.py` node, all with one command.

13.8 Conclusion

In this chapter, we learned how to simplify the process of launching ROS nodes by using launch files. We created a `launch` folder in our package, wrote a simple launch file, and executed it with a single command. Launch files are crucial for managing complex robot configurations where multiple nodes need to be started together. In the next chapter, we will extend this project by creating a launch file for both the publisher and subscriber nodes.

Summary of ROS Launch File Commands

Command/Concept	**Description**
`roslaunch <package> <file>`	Launch a ROS launch file and start all nodes.
`<launch>`	The root tag in a ROS launch file.
`<node>`	Launches a specific node within the launch file.
`<param>`	Sets ROS parameters in the launch file.
`source <file>`	Source the workspace to make it known to ROS.

Your Second Project

14

14.1 Project Overview

In this project, we will create a new `launch` file that will automate several steps, allowing us to run the `roscore`, set parameters for the robot's `wheel_radius`, and run both the `publisher_script.py` and `subscriber_script.py` nodes simultaneously. This is a practical way to organize and manage multiple ROS nodes efficiently, saving time and reducing errors.

The goal is to create a launch file within the `launch` folder of your ROS workspace that accomplishes the following tasks:

Launch File Functions

- Start `roscore`, the ROS master node.
- Set the `wheel_radius` parameter for the robot.
- Launch the `publisher_script.py` to publish wheel velocities.
- Launch the `subscriber_script.py` to calculate the robot's velocity.

The result will be a fully automated system that launches the necessary components with a single command.

14.2 Visualizing the Project Workflow

Below is a graphical representation of the project workflow. It shows how different components interact within the ROS framework when using the launch file.

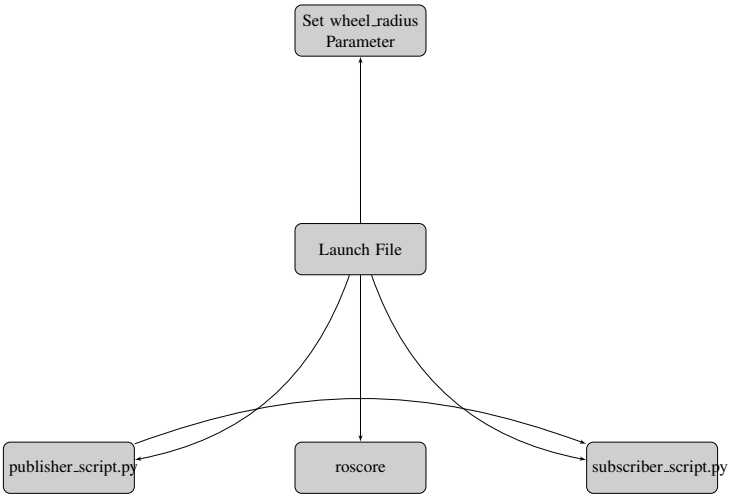


Figure 14.1: Project Workflow Diagram

The launch file will start `roscore`, set the `wheel_radius` parameter, and run both the `publisher` and `subscriber` scripts. The `publisher_script.py` sends wheel velocity data, which is received by `subscriber_script.py` to calculate the robot's velocity.

14.3 Project Requirements

To complete this project, ensure you have the following:

Requirements

- A properly configured ROS workspace with the `ros_pkg` package.
- The `publisher_script.py` and `subscriber_script.py` nodes, as developed in previous chapters.
- A `launch` folder within the `ros_pkg` package.

14.4 Things to Take Care of While Doing This Project

Before you proceed, there are a few important things to remember to ensure the launch file works correctly:

14.4.1 Sourcing Your ROS Workspace

Make sure your workspace is properly sourced so ROS can recognize the packages and nodes. You can reference the sourcing section [12.2]in Chapter [12] for more details.

Command to Source the Workspace

```
source ~/workspace/catkin_ws/devel/setup.bash
```

14.4.2 Making Python Scripts Executable

Ensure your Python scripts are marked as executable. You can refer to Section [12.4] for instructions on how to make Python files executable.

Command to Make Python Scripts Executable

```
chmod +x publisher_script.py
chmod +x subscriber_script.py
```

14.4.3 Specifying Python 3 in Your Scripts

Add the following shebang line at the top of each Python script to ensure that ROS runs the script using Python 3. For more details, check out Section [12.5] on dealing with Python version errors.

Python 3 Shebang Line

```
#!/usr/bin/env python3
```

14.4.4 Starting roscore in a Parallel Terminal

Remember that `roscore` needs to be running in a parallel terminal for your ROS nodes to communicate with each other. You can refer to Section [12.6] for a detailed explanation on running `roscore` in a separate terminal.

Starting roscore

```
roscore
```

14.5 Conclusion

In this chapter, we outlined the steps to create a new `launch` file for running a complete ROS project. This project aims to automate the process of starting `roscore`, setting the `wheel_radius` parameter, and running both the `publisher_script.py` and `subscriber_script.py` nodes. In the next chapter, we will implement the solution and provide the actual `launch` file and necessary code.

Solution to Second Project

15

15.1 Introduction

In this chapter, we will implement a launch file to automate the process of running the ROS master, setting the parameter for the wheel radius, and launching both the `publisher_script.py` and `subscriber_script.py` nodes. This will allow us to start the entire project with a single command, making it much more convenient than running multiple terminal commands manually.

15.2 Creating the Launch File

We will now create the `publisher.launch` file, which will reside in the `launch` folder of the `ros_pkg` package.

15.2.1 Basic Structure of the Launch File

The `launch` file uses XML syntax to define nodes and parameters. Let's start with the basic structure:

Launch File Structure

```
<launch>
        <!-- Set the wheel radius parameter -->
        <param name="wheel_radius" value="0.05" />

        <!-- Start the publisher node -->
        <node pkg="ros_pkg" type="publisher_script.py"
     name="wheel_velocity_publisher" output="screen" />

        <!-- Start the subscriber node -->
        <node pkg="ros_pkg" type="subscriber_script.py"
     name="velocity_subscriber" output="screen" />
</launch>
```

Explanation:

- `<launch>`: The root tag that defines the launch file.
- `<param>`: Defines the parameter `wheel_radius`, which is set to `0.05`.

- <node>: Specifies the nodes to be launched. We include the publisher and subscriber nodes from the `ros_pkg` package.
- `output="screen"`: This ensures that log output is printed to the terminal for debugging purposes.

15.2.2 Setting Parameters

The `param` tag allows us to set parameters in the ROS parameter server. In this case, we are setting the `wheel_radius` parameter, which is used in our subscriber node to calculate the velocity.

Parameter Setting in Launch File

```
<param name="wheel_radius" value="0.05" />
```

Explanation:

- `name="wheel_radius"`: The name of the parameter we want to set.
- `value="0.05"`: The value of the parameter, in this case, the radius of the robot's wheels (in meters).

15.2.3 Launching the Publisher Node

Next, we define the `publisher_script.py` node. This script publishes random RPM values for the left and right wheels of the robot.

Launching the Publisher Node

```
<node pkg="ros_pkg" type="publisher_script.py"
     name="wheel_velocity_publisher" output="screen" />
```

Explanation:

- `pkg="ros_pkg"`: Specifies the package where the node is located.

- `type="publisher_script.py"`: The name of the Python script that acts as the publisher.
- `name="wheel_velocity_publisher"`: The name of the node when it runs.
- `output="screen"`: Displays the output from the node in the terminal.

15.2.4 Launching the Subscriber Node

Finally, we include the subscriber node `subscriber_script.py`, which calculates the robot's velocity and angular velocity based on the RPM values published by the `publisher_script.py`.

Launching the Subscriber Node

```
<node pkg="ros_pkg" type="subscriber_script.py"
      name="velocity_subscriber" output="screen" />
```

Explanation:

- `pkg="ros_pkg"`: Specifies the package where the node is located.
- `type="subscriber_script.py"`: The name of the Python script that acts as the subscriber.
- `name="velocity_subscriber"`: The name of the node when it runs.
- `output="screen"`: Displays the output from the node in the terminal.

15.2.5 Complete Launch File

Here's the full `RPM_Sim.launch` file:

Launch File Structure

```
<launch>
        <!-- Set the wheel radius parameter -->
        <param name="wheel_radius" value="0.05" />

        <!-- Start the publisher node -->
        <node pkg="ros_pkg" type="publisher_script.py"
     name="wheel_velocity_publisher" output="screen" />

        <!-- Start the subscriber node -->
        <node pkg="ros_pkg" type="subscriber_script.py"
     name="velocity_subscriber" output="screen" />
</launch>
```

15.3 Things to Keep in Mind [14.4]

Before running the launch file, there are a few important points to remember:

- Make sure your ROS workspace is sourced. Refer to Chapter 12 for details on how to source the workspace. [12.2]
- Ensure both `publisher_script.py` and `subscriber_script.py` are marked as executable. You can review Section [12.4] to see how to make Python files executable.
- Check that the Python shebang line (`#!/usr/bin/env python3`) is added at the top of both Python scripts. If you encounter Python version errors, consult Section [12.5] for troubleshooting steps.

15.4 Testing the Launch File

To test the launch file, you can run the following command in your terminal:

Running the Launch File

```
roslaunch ros_pkg publisher.launch
```

This command will launch both the publisher and subscriber nodes, start `roscore`, and set the `wheel_radius` parameter. You can verify the output using `rostopic echo`.

15.5 Summary of Key Commands and Concepts

Summary of ROS Launch Commands

Command/Concept	Description
`roslaunch <package> <file>`	Launches a ROS launch file, starting all nodes and roscore.
`param name="wheel_radius"`	Sets the wheel radius parameter to be used in nodes.
`<node>`	Defines a node to be launched within the ROS package.
`output="screen"`	Prints the node output to the terminal.

15.6 Conclusion

In this chapter, we walked through the process of creating and running a launch file. This file automates the execution of our publisher and subscriber nodes, along with setting the necessary parameters. By using the `roslaunch` command, we can now run the entire project with a single command. In the next chapter, we will work on more advanced projects, further exploring the capabilities of ROS.

ROS Bag Files

16

16.1 Introduction

In this chapter, we will explore the concept of ROS bag files, their purpose, and their applications. ROS bag files are a way to record and playback ROS topics, making them incredibly useful for data analysis, debugging, and testing without needing live hardware. To understand how to create and work with bag files, we will walk through a simple ROS project: a temperature sensor simulation. This project will help illustrate the use of bag files in a real-world scenario.

16.2 What are ROS Bag Files?

ROS bag files store message data that flows through ROS topics. This data can be saved during a live session and played back later, simulating real-time execution. Bag files are useful for:

- Debugging and testing systems when live data is unavailable.
- Recording sensor data for analysis.
- Simulating scenarios for machine learning or other applications.

In the following project, we will simulate a temperature sensor and demonstrate how to record and analyze the temperature data using a ROS bag file.

16.3 Project Overview: Temperature Sensor Simulation

Our project consists of two scripts: a publisher script and a subscriber script. The publisher will simulate a temperature sensor that periodically publishes temperature data. The subscriber will monitor this data and compare it to a threshold value, triggering an alert if the temperature exceeds the threshold.

16.3.1 Things to Keep in Mind

Before diving into the solution, ensure the following:

- Make sure the workspace is sourced (refer to the earlier chapter on automatic sourcing). [12.2]
- The Python scripts must be executable by running `chmod +x <filename>`. [12.4]
- Make sure that your Python scripts include the shebang line to specify the Python 3 environment: `#!/usr/bin/env python3`. [12.5]
- Ensure that `roscore` is running, or launch it via a launch file. [12.6]

16.4 Writing the Publisher Script

Let's start by writing the `temperature_publisher.py` script, which simulates the temperature sensor and publishes the temperature data to the `current_temperature` topic.

16.4.1 Importing Required Libraries

We need to import the `rospy` library and the `Float32` message type for publishing temperature data.

Python Code with Explanation

```
import rospy
from std_msgs.msg import Float32
import time
```

Explanation:

- `rospy`: The ROS client library for Python.
- `Float32`: The message type used to represent floating-point temperature values.
- `time`: Built-in Python library used to simulate delays.

16.4.2 Initializing the Publisher Node

We will initialize the ROS node and create a publisher that will publish random temperature values in the range of 15°C to 45°C. The values will increase steadily until they reach 45°C, then reset back to 15°C.

Python Code with Explanation

```
def publisher():
        rospy.init_node('temperature_publisher', anonymous=True)
        temp_pub = rospy.Publisher('current_temperature', Float32,
     queue_size=10)
        rate = rospy.Rate(1)  # 1 Hz
```

Explanation:

- `rospy.init_node()`: Initializes the ROS node with the name `temperature_publisher`.
- `rospy.Publisher()`: Creates a publisher for the `current_temperature` topic, using `Float32` as the message type.
- `rospy.Rate(1)`: Sets the publishing rate to 1 Hz (one message per second).

16.4.3 Publishing Temperature Values

The temperature values will increment from 15°C to 45°C, then reset back to 15°C. The publisher will continuously publish these values.

Python Code with Explanation

```
temp = 15.0
while not rospy.is_shutdown():
        temp_pub.publish(temp)
        temp += 1.0
        if temp > 45.0:
                temp = 15.0
        rate.sleep()
```

Explanation:

- `temp_pub.publish(temp)`: Publishes the current temperature.
- The temperature starts at 15°C and increments by 1°C each second. When it reaches 45°C, it resets to 15°C.

16.4.4 Complete Publisher Script

Here is the complete `temperature_publisher.py` script:

Complete Python Code

```
#!/usr/bin/env python3

import rospy
from std_msgs.msg import Float32

def publisher():
        rospy.init_node('temperature_publisher', anonymous=True)
        temp_pub = rospy.Publisher('current_temperature', Float32,
     queue_size=10)
        rate = rospy.Rate(1)  # 1 Hz

        temp = 15.0
        while not rospy.is_shutdown():
                temp_pub.publish(temp)
                temp += 1.0
                if temp > 45.0:
                        temp = 15.0
                rate.sleep()

if __name__ == '__main__':
        try:
                publisher()
        except rospy.ROSInterruptException:
                pass
```

16.5 Writing the Subscriber Script

Next, we'll write the `temperature_subscriber.py` script. The subscriber will listen to the temperature data and publish a new topic with the current temperature, threshold temperature, and whether an alert is triggered.

16.5.1 Importing Required Libraries

We need to import the necessary libraries, including `Float32` for temperature data and `String` for publishing a list of values.

Python Code with Explanation

```
import rospy
from std_msgs.msg import Float32, String
```

Explanation:

- `Float32`: Used for subscribing to temperature data.
- `String`: Used to publish the current temperature, threshold, and alert state as a string.

16.5.2 Defining the Callback Function

The callback function will compare the current temperature to a threshold, and publish the current temperature, threshold, and alert status as a string to a new topic.

Python Code with Explanation

```
def temperature_callback(data):
        threshold_temp = rospy.get_param('/threshold_temp', 30.0)
        alert = "ALERT" if data.data > threshold_temp else "OK"
        status_str = f"{data.data},{threshold_temp},{alert}"
        alert_pub.publish(status_str)
```

Explanation:

- `threshold_temp`: Retrieves the threshold temperature from the ROS parameter server.
- `alert`: Checks if the current temperature exceeds the threshold and sets the status to ”ALERT” or ”OK”.
- `status_str`: A formatted string with the current temperature, threshold, and alert status.
- `alert_pub.publish(status_str)`: Publishes the status string.

16.5.3 Complete Subscriber Script

Here is the complete `temperature_subscriber.py` script:

Complete Python Code

```
import rospy
from std_msgs.msg import Float32, String

def temperature_callback(data):
        threshold_temp = rospy.get_param('/threshold_temp', 30.0)
        alert = "ALERT" if data.data > threshold_temp else "OK"
        status_str = f"{data.data},{threshold_temp},{alert}"
        alert_pub.publish(status_str)

def subscriber():
        rospy.init_node('temperature_subscriber', anonymous=True)
        global alert_pub
        alert_pub = rospy.Publisher('temperature_status', String,
     queue_size=10)

        rospy.Subscriber('current_temperature', Float32,
     temperature_callback)
        rospy.spin()

if __name__ == '__main__':
        try:
                subscriber()
        except rospy.ROSInterruptException:
                pass
```

16.6 Recording a ROS Bag File

Now that we have our `temperature_status` topic publishing temperature data, let's learn how to record this data into a ROS bag file. A ROS bag file is essentially a log file that records the messages published on specified topics. This is particularly useful for saving sensor data, debugging, or testing.

16.6.1 What Does it Mean to Record a Bag File?

Recording a bag file means capturing the messages that are being published on ROS topics. This allows you to save and analyze data later, rather than needing to run the ROS system live each time. Bag files

can be used to simulate sensor data in a controlled environment, making them ideal for debugging and testing purposes.

16.6.2 Recording the Temperature Status Topic

We will record the `temperature_status` topic, which contains the current temperature, threshold temperature, and alert status. We will also vary the `threshold_temp` parameter to capture different scenarios in our bag file.

To start recording, open a new terminal, ensure that `roscore` is running, and run the following command:

Terminal Command

```
rosbag record -a -o test.bag
```

Explanation:

- `rosbag record`: The command used to record ROS topics into a bag file.
- `-a`: Records all active topics.
- `-o test.bag`: Saves the output to a file named `test.bag`.

While recording, you can change the `threshold_temp` parameter to capture different alert scenarios. Use the following command in a separate terminal:

Terminal Command

```
rosparam set /threshold_temp 35.0
```

Now, adjust the threshold temperature during the recording process to see how the alert status changes. You can verify the topics are being recorded by echoing the `temperature_status` topic:

Terminal Command

```
rostopic echo /temperature_status
```

Once you are done recording, press `Ctrl + C` to stop the recording. The `test.bag` file will now contain all the data from the ROS topics that were active during the recording session.

16.7 Playing a ROS Bag File

After recording the bag file, we can play it back to simulate the real-time execution of the system. This is useful when you want to replay sensor data, test algorithms, or visualize past events without needing live data.

16.7.1 What Does it Mean to Play a Bag File?

Playing a bag file replays the recorded messages as if they were being published live in ROS. This allows you to simulate previous conditions or test the behavior of the system in response to the same data.

16.7.2 Playing the Test Bag File

To play the bag file that we just created, use the following command:

Terminal Command

```
rosbag play -l test.bag
```

Explanation:

- `rosbag play`: The command used to play a recorded ROS bag file.
- `-l`: Loops the playback, continuously replaying the bag file.
- `test.bag`: The bag file we previously recorded.

While the bag file is playing, you can verify the data by echoing the `temperature_status` topic:

Terminal Command

```
rostopic echo /temperature_status
```

This will display the same temperature, threshold, and alert data that was recorded earlier.

16.7.3 Modifying Playback Speed

You can also control the playback speed of the bag file using the `-r` flag. For example, to play the bag file at twice the speed, you can run:

Terminal Command

```
rosbag play -r 2.0 test.bag
```

Explanation:

- `-r 2.0`: Plays the bag file at twice the normal speed.

16.7.4 Inspecting the Bag File

If you want to inspect the contents of a bag file (i.e., see which topics are recorded), you can use the following command:

Terminal Command

```
rosbag info test.bag
```

This will display details about the recorded topics, their message types, and the time duration of the recording.

16.8 Summary Table of ROS Bag Commands

Summary of ROS Bag Commands

Command	Description
`rosbag record -a -o <file>`	Records all topics into a bag file.
`rosbag play <file>`	Plays the recorded bag file.
`rosbag play -l <file>`	Plays the bag file in a continuous loop.
`rosbag play -r <rate> <file>`	Plays the bag file at a specified rate.
`rosbag info <file>`	Displays information about the contents of a bag file.

16.9 Conclusion

In this chapter, we explored ROS bag files, their importance in data recording, and their usefulness in testing and debugging. We built a simple temperature sensor project, recorded the sensor data in a bag file,

and demonstrated how to play back the recorded data. Bag files are an essential tool in any ROS developer's toolkit, enabling efficient testing and simulation in robotics projects.

Exploring ROS Packages

17

17.1 Introduction

In this chapter, we will take a break from developing our own ROS package and explore how to install and use an existing package created by other developers. Specifically, we will be working with the `usb_cam` package, which interfaces with a USB camera and publishes images as sensor messages. This example will demonstrate how we can easily integrate pre-built packages into our ROS workspace and use them for various tasks, like capturing images.

17.2 Why Use ROS Packages?

We have been organizing our code into ROS packages since the beginning of this course, as it provides a standardized way to manage and share code. By using packages created by others, we can easily extend the functionality of our ROS projects. Packages often come with tools for controlling robots, interacting with sensors, and visualizing data, allowing us to leverage the work of others for our own projects.

In this chapter, we will explore how to install and use the `usb_cam` package to capture and display images from a USB camera in ROS.

17.3 Installing the USB Camera Package

The `usb_cam` package is available in the official ROS package repositories, and we can install it using the `apt-get` command.

17.3.1 Installing the Package via `sudo apt-get install`

To install the `usb_cam` package, open a terminal and run the following command:

Terminal Command

```
sudo apt-get install ros-noetic-usb-cam
```

Explanation:

- `sudo apt-get install`: The command used to install packages in Ubuntu.
- `ros-noetic-usb-cam`: Specifies the ROS Noetic version of the USB camera package.

After running the command, ROS will install the `usb_cam` package, allowing us to access its features in our workspace.

17.4 Verifying the Installation

Once the package is installed, we can verify it using the following methods:

17.4.1 Using `roscd`

The `roscd` command allows us to navigate to the package directory. To check if the `usb_cam` package was installed successfully, run the following:

Terminal Command

```
roscd usb_cam
```

If the package was installed correctly, this command will take you to the `usb_cam` directory.

17.4.2 Using `rospack list-names`

We can also list all installed packages using the `rospack` command:

Terminal Command

```
rospack list-names
```

Scroll through the list to confirm that `usb_cam` is included among the installed packages.

17.5 Running the USB Camera Node

Now that the package is installed, let's run the `usb_cam` node to start capturing images from the camera.

17.5.1 Starting `roscore`

Before we run the camera node, we need to make sure that the ROS master node (`roscore`) is running. Open a new terminal and run:

Terminal Command

```
roscore
```

17.5.2 Running the `usb_cam` Node

With `roscore` running, open a new terminal tab and run the `usb_cam` node:

Terminal Command

```
rosrun usb_cam usb_cam_node
```

Explanation:

- `rosrun`: Runs a node from a ROS package.
- `usb_cam`: The package name.
- `usb_cam_node`: The node that captures images from the USB camera.

If everything is set up correctly, the node will begin running, and you will see messages related to the camera output in the terminal. Don't worry if you see warnings like "deprecation pixel format"; these messages can usually be ignored.

17.6 Viewing Camera Output in ROS

Now that the USB camera node is running, let's visualize the camera output using ROS tools.

17.6.1 Checking Available Topics

To view the topics published by the USB camera node, open a new terminal and run:

Terminal Command

```
rostopic list
```

You should see several topics related to the USB camera, including:

```
/usb_cam/image_raw
/usb_cam/image_raw/compressed
```

Explanation:

- `/usb_cam/image_raw`: The raw image data from the camera.
- `/usb_cam/image_raw/compressed`: A compressed version of the image.

17.6.2 Echoing the Camera Data

We can view the raw data being published by the USB camera using the `rostopic echo` command. In the terminal, run the following to display the raw image data:

Terminal Command

```
rostopic echo /usb_cam/image_raw
```

17.7 Visualizing the Camera Output in RViz

Seeing the raw data in the terminal is useful, but it's even more helpful to visualize the image in a graphical window. For this, we will use RViz, ROS's built-in visualization tool.

17.7.1 Starting RViz

Open a new terminal tab and run the following command to launch RViz:

Terminal Command

```
rosrun rviz rviz
```

Explanation:

- `rviz`: The ROS visualization tool.

In RViz, you can add a display to visualize the camera image by adding a `Camera` type display and selecting the `/usb_cam/image_raw` topic.

17.8 Using Launch Files for the USB Camera

Running `rosrun` and manually opening RViz each time can become tedious. Fortunately, the developers of the `usb_cam` package provided a launch file that simplifies this process.

17.8.1 Running the Launch File

To use the provided launch file, run the following command in a new terminal tab:

Terminal Command

```
roslaunch usb_cam usb_cam-test.launch
```

Explanation:

- `roslaunch`: Command to launch a file.
- `usb_cam`: The package name.
- `usb_cam-test.launch`: The provided launch file that runs the camera node and opens RViz automatically.

When you run this command, RViz will launch, and the camera feed will appear in a separate window.

17.9 Troubleshooting USB Camera Issues

If you encounter issues with the USB camera, the following steps may help resolve them:

- Check if your camera is correctly recognized by your system using the command:

  Terminal Command

  ```
  ls /dev/video*
  ```

  This command lists all video devices. Your USB camera should appear as `/dev/video0` or `/dev/video1`.

- Use the `dmesg` command to view the device logs and confirm that the camera is correctly detected by your system.

17.10 Summary of Commands

Summary of ROS Package Commands

Command	Description
`sudo apt-get install ros-noetic-usb-cam`	Install the USB camera package in ROS.
`roscd usb_cam`	Change directory to the `usb_cam` package.
`rospack list-names`	List all installed ROS packages.
`rosrun usb_cam usb_cam_node`	Run the USB camera node.
`roslaunch usb_cam usb_cam-test.launch`	Launch the USB camera node and RViz for visualization.
`rostopic echo /usb_cam/image_raw`	Display the raw image data from the camera.

17.11 Conclusion

In this chapter, we explored how to use the `usb_cam` ROS package to interface with a USB camera. We learned how to install the package, run the node, visualize the camera output in RViz, and troubleshoot common issues. By leveraging existing ROS packages, we can add powerful functionality to our projects with minimal effort.

Services in ROS

18

18.1 Introduction to Services in ROS

In this chapter, we will explore one of the essential communication mechanisms in ROS: **Services**. While we've already covered `Topics`, which provide a continuous flow of data between nodes, **Services** allow for *request-response* communication, which is useful when a node needs to request data or an action from another node, and then wait for a response.

18.2 What is a Service in ROS?

In simple terms, a **Service** in ROS is a communication method where one node sends a *request* to another node, which processes the request and sends back a *response*. Unlike topics, which are used for continuous data streams, services are ideal for tasks that require a specific action or information on demand. For example, you might use a service to:

- Instruct a robot to move to a specific location and wait for confirmation.
- Request the status of a sensor or device.
- Start or stop specific operations (like starting a video recording or activating a sensor).

The service mechanism follows a **client-server** model:

- The **service client** sends a request to the service.
- The **service server** processes the request and sends back a response.

This model ensures that the client waits until it receives a response, which can be particularly useful in robotics for tasks that need to be sequential or dependent on the success of previous tasks.

18.3 How Do Services Differ from Topics?

One of the core distinctions between **Services** and **Topics** is the nature of communication:

- **Topics**: Used for *continuous* data flow, where nodes publish and subscribe to data without waiting for acknowledgment. Topics are ideal for real-time sensor data, like camera feeds or IMU data.
- **Services**: Follow a *request-response* pattern, where a node sends a specific request and waits for a reply. This is useful for actions like querying the current state or performing a single action, such as opening a door.

Key Differences Between Topics and Services

Topic	**Service**
Continuous data exchange (publish-subscribe)	On-demand communication (request-response)
No guarantee of message delivery or acknowledgment	Client waits for server response
Best for real-time data streams like sensor data	Best for actions like querying or controlling processes
Data is continuously published whether it's needed or not	Action occurs only when requested

18.4 Why Are Services Useful?

The request-response nature of services makes them ideal for situations where actions need to be taken sequentially or where confirmation of the action is required. Here are a few key scenarios where services are beneficial:

- **Task control**: You can use services to control tasks that require sequential operations. For example, you might send a service request to a node controlling a robotic arm to move to a specific position. The node will respond once the task is complete.

- **Querying states**: Services are useful when a node needs to retrieve specific information. For instance, a node might send a service request to another node asking for the current battery status or the temperature of a sensor.
- **Performing single actions**: Services are perfect for triggering specific actions, like opening a door or starting a process (e.g., activating a sensor or enabling a motor).

Service Example Scenario

Imagine you have a mobile robot with a robotic arm. You want the robot to pick up an object. Here's how services would be used:

- **Service request:** The main node sends a service request to the robotic arm to move to the object's location.
- **Service response:** The arm's controller node processes the request, moves the arm to the location, and sends a response when the task is complete.

The service ensures that the main node waits for the arm to complete its task before moving on to the next step.

18.5 ROS Services vs Other Programming Tools

While the service mechanism may seem familiar, it differs significantly from typical request-response models in traditional programming. Here's why:

- **ROS services are decentralized:** Unlike web services or API calls where a central server manages requests, in ROS, any node can be a service server. The decentralized nature of ROS means that multiple nodes can offer different services, giving more flexibility to distributed systems.
- **Built for real-time systems:** Services in ROS are designed to handle real-time robotics operations where actions must be triggered with precise timing.

- **Simplified communication:** Unlike other tools that require extensive configuration (such as setting up REST APIs), ROS services are easy to set up within the ROS ecosystem. They are tightly integrated with the ROS middleware, which handles messaging and service requests.

18.6 Diagram: Client-Server Communication in ROS Services

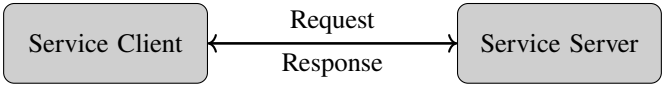


Figure 18.1: Client-Server Communication Diagram

In the next section, we will begin exploring how to implement a basic ROS service in Python.

18.7 Creating a Simple Service: Sum of Two Numbers

In this section, we will create a simple ROS service to illustrate how services work in practice. Our task is to build a system where the **service client** will request the sum of two numbers, and the **service server** will compute and return the result. This will give us hands-on experience with service creation and provide insight into how clients and servers interact within ROS.

18.7.1 Project Overview

The project will consist of two components:

- A **service client**, which will send a request with two numbers to the service server.
- A **service server**, which will receive the request, calculate the sum of the two numbers, and return the result to the client.

The service client will wait until it receives the server's response before proceeding. This type of communication is useful in scenarios where you need to execute an operation and wait for its completion before continuing with other tasks.

18.7.2 Creating the Service Definition

Before we can write the Python scripts for the client and server, we need to define the structure of our service. The service definition specifies the **request** and **response** formats. In our case, the request will contain two numbers (integers), and the response will return their sum.

Service Definition

We need to create a custom `.srv` file that defines the inputs and outputs for our service. Here's what the file will look like:

```
int64 a
int64 b
---
int64 sum
```

Explanation:

- The `int64 a` and `int64 b` lines define the two integers that will be sent as the request.
- The `---` separates the request from the response.
- The `int64 sum` line defines the integer response, which is the sum of `a` and `b`.

18.7.3 Setting Up the ROS Package

To organize the files for this project, we will create a new ROS package. The package will contain the service definition and the Python scripts for the client and server.

Creating a New ROS Package

To create the package, use the following command in your terminal:

```
catkin_create_pkg sum_two_numbers rospy std_msgs
```

Explanation:

- `sum_two_numbers` is the name of the new package.
- `rospy` and `std_msgs` are the dependencies that the package requires.

After running this command, you will see a new folder named `sum_two_numbers` inside your workspace. Navigate to this folder:

```
cd ~/catkin_ws/src/sum_two_numbers
```

18.7.4 Creating the Service Definition File

Once the package is created, we need to add the custom service definition. The service definition file (`SumTwoInts.srv`) will specify the request and response format for the service.

Steps to Add the Service Definition File

1. Inside the `sum_two_numbers` package directory, create a new directory for service definitions:

```
mkdir srv
```

2. Navigate into the `srv` directory and create the service file:

```
cd srv

touch SumTwoInts.srv
```

3. Open `SumTwoInts.srv` in your favorite text editor (for example, Sublime):

```
subl SumTwoInts.srv
```

4. Copy the following service definition into the file:

```
int64 a
int64 b
---
int64 sum
```

18.7.5 Modifying the CMakeLists.txt and package.xml Files

To use the custom service in ROS, we need to modify the `CMakeLists.txt` and `package.xml` files **in our package**.

Updating CMakeLists.txt

To enable our custom service, make the following changes in CMakeLists.txt:

- Add the following lines under the find_package section to enable service generation:

```
find_package(catkin REQUIRED COMPONENTS
        rospy
        std_msgs
        message_generation
)
```

- Uncomment the add_service_files() section to specify the custom service file:

```
add_service_files(
        FILES
        SumTwoInts.srv
)
```

- Uncomment the generate_messages() section to generate the service messages:

```
generate_messages(
        DEPENDENCIES
        std_msgs
)
```

- Ensure that the catkin_package() section is also uncommented.

Updating `package.xml`

In the `package.xml` file, we need to ensure that the necessary dependencies are listed for message generation. Add the following lines:

```
<build_depend>message_generation</build_depend>
<exec_depend>message_runtime</exec_depend>
```

18.7.6 Building the Package

After updating the configuration files, we need to build the package to generate the service files.

Building the Package

Run the following commands to build the package and source your workspace:

```
cd ~/catkin_ws

catkin_make

source devel/setup.bash
```

Once the package is built, ROS will write the necessary python service script files based on the `SumTwoInts.srv` definition.

18.8 Writing the Python Service Scripts

Now that we've set up the service definition, it's time to write the Python scripts for both the **service server** and the **service client**. The service server will receive the two numbers from the client and return their sum, while the client will send a request to the server and display the response.

18.8.1 Writing the Service Server Script

The service server is responsible for waiting for client requests, processing them, and sending back the response. Let's break down the `server.py` script into simple parts.

Importing Required Libraries

First, we import the necessary ROS libraries and the service definition.

Python Code

```
import rospy
from sum_two_numbers.srv import SumTwoInts, SumTwoIntsResponse
```

Explanation:

- `rospy`: This imports the Python library to interact with ROS.
- `SumTwoInts` and `SumTwoIntsResponse`: These are the custom service message types defined in the `srv` file. `SumTwoInts` defines the request (two integers), and `SumTwoIntsResponse` defines the response (the sum).

Defining the Callback Function

Next, we define a callback function that processes the incoming service requests and returns the sum of the two numbers.

Python Code

```
def handle_sum_request(req):
        sum_result = req.a + req.b
        return SumTwoIntsResponse(sum_result)
```

Explanation:

- `def handle_sum_request(req)`: This function handles the incoming request. The `req` parameter contains the two integers, `req.a` and `req.b`.
- `return SumTwoIntsResponse(sum_result)`: This sends the sum result back as a response to the client.

Setting Up the ROS Service

Now, we set up the ROS node and create the service.

Python Code

```
def sum_server():
        rospy.init_node('sum_server')
        service = rospy.Service('sum_two_ints', SumTwoInts,
     handle_sum_request)
        rospy.spin()
```

Explanation:

- `rospy.init_node('sum_server')`: Initializes the ROS node with the name `'sum_server'`.
- `rospy.Service('sum_two_ints', SumTwoInts, handle_sum_request)`: This creates the service named `'sum_two_ints'`, using the `SumTwoInts` service type.
- `rospy.spin()`: Keeps the service running, waiting for incoming requests.

Running the Server

Finally, we ensure the server runs when the script is executed.

Python Code

```
if __name__ == "__main__":
        sum_server()
```

Explanation:

- This block runs the service when the script is executed.
- If the service is interrupted (e.g., by `Ctrl+C`), it exits cleanly.

Complete Service Server Script

Here's the full `server.py` script:

Complete Python Code

```
import rospy
from sum_two_numbers.srv import SumTwoInts, SumTwoIntsResponse

def handle_sum_request(req):
        sum_result = req.a + req.b
        return SumTwoIntsResponse(sum_result)

def sum_server():
        rospy.init_node('sum_server')
        service = rospy.Service('sum_two_ints', SumTwoInts,
     handle_sum_request)
        rospy.spin()

if __name__ == "__main__":
        sum_server()
```

18.8.2 Writing the Service Client Script

Next, we write the client script, which will request the sum of two numbers from the server.

Importing Required Libraries

We begin by importing the necessary ROS libraries and the service definition.

Python Code

```
import rospy
from sum_two_numbers.srv import SumTwoInts
```

Explanation:

- `SumTwoInts`: This is the custom service type we defined earlier, which will be used for the request and response.

Defining the Client Function

Now, we define the function that will send the request to the service.

Python Code

```
def sum_client(x, y):
        rospy.wait_for_service('sum_two_ints')
        try:
                sum_two_ints = rospy.ServiceProxy('sum_two_ints',
     SumTwoInts)
                response = sum_two_ints(x, y)
                return response.sum
        except rospy.ServiceException:
                pass
```

Explanation:

- `rospy.wait_for_service('sum_two_ints')`: The client waits until the service `'sum_two_ints'` is available.
- `rospy.ServiceProxy('sum_two_ints', SumTwoInts)`: This creates a proxy to communicate with the service.
- `response = sum_two_ints(x, y)`: This sends the request to the service with the two numbers `x` and `y`, and stores the response.

Running the Client with User Input

Let's modify the client to accept user input for the two integers.

Python Code

```
if __name__ == "__main__":
        rospy.init_node('sum_client')

        # Prompt user for input
        x = int(input("Enter the first number: "))
        y = int(input("Enter the second number: "))

        # Call the service
        result = sum_client(x, y)
        print(f"The sum of {x} and {y} is {result}")
```

Explanation:

- `x = int(input("Enter the first number: "))`: This prompts the user to input the first number.
- `y = int(input("Enter the second number: "))`: This prompts the user to input the second number.
- `sum_client(x, y)`: Sends the user input to the service and returns the sum.
- `print(f"The sum of x and y is result")`: Prints the result of the service call.

Complete Service Client Script

Here's the full `client.py` script with user input:

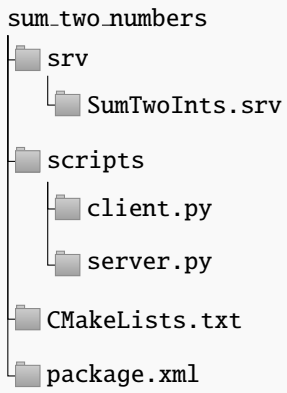
Complete Python Code

```
import rospy
from sum_two_numbers.srv import SumTwoInts

def sum_client(x, y):
        rospy.wait_for_service('sum_two_ints')
        try:
                sum_two_ints = rospy.ServiceProxy('sum_two_ints',
     SumTwoInts)
                response = sum_two_ints(x, y)
                return response.sum
        except rospy.ServiceException:
                pass

if __name__ == "__main__":
        rospy.init_node('sum_client')

        # Prompt user for input
        x = int(input("Enter the first number: "))
        y = int(input("Enter the second number: "))

        # Call the service
        result = sum_client(x, y)
        print(f"The sum of {x} and {y} is {result}")
```

18.8.3 File Organization and Structure

Before we move to testing, make sure both scripts are placed in the `scripts` directory of your package. Here's the structure of the package:

Package Structure



In the next section, we will test our service using ROS commands and verify that the server and client communicate correctly.

18.9 Testing the Service

Now that we have our service server and client scripts ready, it's time to test them using ROS commands. We will use several service-related commands to ensure our server and client are communicating properly.

18.9.1 Things to Keep in Mind

Before testing the service, it's important to ensure that several essential steps are followed to avoid errors:

- **Source Your Workspace**: Don't forget to source your workspace using the `source devel/setup.bash` command or set up automatic sourcing. Refer to Section [12.2], for more details.

- **Make Python Scripts Executable**: Ensure both the `server.py` and `client.py` scripts are executable. Refer to the section [12.4] in Chapter [12] for detailed instructions on how to use the `chmod +x` command.

- **Shebang on Top of Python Scripts**: Ensure you have the shebang line `#!/usr/bin/env python3` at the top of your Python scripts to avoid any version mismatch errors. This was discussed in Section [12.5] under *Dealing with Python Version Errors*.

- **Run `roscore`**: Before running any ROS nodes, make sure `roscore` is running in a separate terminal. If you need help, see Section [12.6].

18.9.2 Running the Service Server

After following the above steps, you can start the service server by running the following command in a new terminal:

Terminal Command

```
rosrun sum_two_numbers server.py
```

Once the server is running, we can verify that the service is up and ready for requests.

18.9.3 Verifying the Service

You can list all active services and check if `/sum_two_ints` is available by using the following command:

Terminal Command

```
rosservice list
```

Explanation:

- `rosservice list`: Lists all available services in ROS. If `/sum_two_ints` is listed, it means your server is running successfully.

18.9.4 Checking Service Type

You can inspect the service type of `/sum_two_ints` using:

Terminal Command

```
rosservice type /sum_two_ints
```

Explanation:

- `rosservice type /sum_two_ints`: This command outputs the service type, which is `sum_two_numbers/SumTwoInts`.

18.9.5 Inspecting the Service Definition

To view the structure of the service, use the `rossrv` command:

Terminal Command

```
rossrv show sum_two_numbers/SumTwoInts
```

This will display the structure of the service message, showing the input (two integers) and the output (sum).

18.9.6 Calling the Service Manually

To manually call the service and send a request for the sum of two numbers, use the `rosservice call` command:

Terminal Command

```
rosservice call /sum_two_ints 7 8
```

This will send a request with the integers 7 and 8 to the server, and the response will be their sum (15).

18.9.7 Running the Client

Now, run the client script to make a service request automatically:

Terminal Command

```
rosrun sum_two_numbers client.py
```

This will trigger the client script, which sends a request to the `/sum_two_ints` service and retrieves the sum of two numbers.

18.9.8 Summary of Service Commands and Functions

Summary of ROS Service Commands

Command/Function	Description
`rosservice list`	Lists all active ROS services.
`rosservice type <service>`	Displays the type of the specified service.
`rossrv show <service type>`	Shows the definition of the service type.
`rosservice call <service> <args>`	Calls the service and passes arguments for the request.
`rospy.Service`	Used in Python to create a ROS service.
`rospy.ServiceProxy`	Used to create a client that calls a service in Python.
`rospy.wait_for_service`	Waits for a service to become available.

18.10 Conclusion

In this chapter, we learned about ROS services and how they enable nodes to communicate synchronously in a request-response model. We walked through an example project to create a simple service that adds two integers. Then, we explored various ROS commands for listing, inspecting, and calling services, and tested our service using both manual and client calls.

With this knowledge, you can now implement your own ROS services to enable request-response interactions in your robotic systems, adding another layer of flexibility to your projects.

Actions in ROS

19

19.1 Introduction

In this chapter, we will explore **Actions** in ROS, a powerful mechanism designed for handling long-running tasks that require feedback and the ability to be preempted. Actions are crucial for robotic applications where tasks take time to complete, such as navigating to a point, controlling a robotic arm, or monitoring complex sensors.

While **Topics** and **Services** are helpful, Actions add flexibility by allowing continuous feedback and control over tasks that take longer to complete. This section introduces the structure of Actions in ROS, their purpose, and how they differ from other communication mechanisms.

19.2 What Are Actions in ROS?

Actions enable nodes to send a goal to another node and receive continuous feedback during the goal's execution. Unlike **Services**, which are synchronous and expect an immediate response, Actions are asynchronous, allowing clients to perform other tasks while the goal is being processed.

Key Features of Actions in ROS

- **Asynchronous Communication**: The client can send a goal to the server and continue working while waiting for the result.
- **Continuous Feedback**: The server provides ongoing updates to the client, allowing real-time monitoring of the task.
- **Preemption**: The client can cancel the goal before it is completed, offering more control over the task.
- **Result Handling**: Once the task is completed, the server sends the final result to the client.

19.2.1 Basic Flow of Actions

The flow of Actions in ROS involves several steps:

1. The **client** sends a **goal** to the **server**.
2. The **server** starts processing the goal and provides **feedback** to the client.
3. The client can decide to **preempt** or cancel the goal at any time.
4. Once the task is done, the server sends the **result** back to the client.

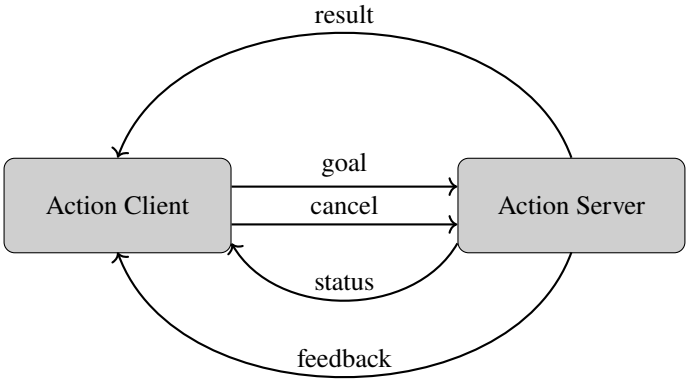


Figure 19.1: Action Communication Workflow

19.3 Comparing Actions with Services and Topics

To understand the unique role of Actions, let's compare them with other ROS communication mechanisms: **Services** and **Topics**.

19.3.1 Topics

Topics are used for continuous, asynchronous data streams between nodes. A publisher sends data, and multiple subscribers can receive it.

However, topics are not suitable for scenarios where a task needs to be initiated, monitored, and completed because there is no concept of goals or feedback.

19.3.2 Services

Services, on the other hand, are designed for one-time, synchronous communication between a client and a server. The client sends a request, the server processes it, and the result is returned. Services are quick and efficient for short operations, but they are not suitable for long-running tasks because they block the client until a response is received.

19.3.3 Actions

Actions combine the best of both worlds:

- **Like Topics**, they provide continuous feedback while a task is being performed.

- **Like Services**, they allow a client to send a specific request (goal) to the server and receive the result when the task is done.

- Unlike Services, Actions allow the client to cancel the request before the task completes, and unlike Topics, they can handle complex tasks that need feedback and final results.

Comparing Actions Services and Topics

Mechanism	Purpose	Example Use Case	Feedback /Preemption?
Topics	Continuous data streams	Sensor data, robot status	No
Services	One-time synchronous requests	Requesting sensor value, triggering an action	No
Actions	Asynchronous tasks with feedback	Navigation, robotic arm control	Yes

19.4 Why Are Actions Important?

Actions are vital in robotic applications where tasks are complex and take time to complete. Some examples include:

- **Robot Navigation**: Sending a goal to the robot, like moving from one point to another, with continuous feedback on the progress.
- **Robotic Arm Control**: Setting up a task where the arm manipulates objects while giving feedback on its position and status.
- **Task Sequences**: Performing a series of operations that rely on sensor feedback to adjust the task as it progresses.

Why Use Actions?

- **Feedback**: Actions provide real-time feedback, allowing for better monitoring and control.
- **Preemption**: Tasks can be canceled or modified while in progress, providing greater flexibility.
- **Control**: Actions offer more control for long-running tasks that require continuous adjustments.

Actions are a powerful communication mechanism in ROS, suitable for complex, long-running tasks that require feedback and the ability to adjust mid-process. In the next sections, we will dive into a practical example to demonstrate how Actions can be implemented in a real-world scenario.

19.5 Project Overview: Robot Navigation Using Actions

In this part of the chapter, we will explore an example project to demonstrate the power of Actions in ROS. The project involves navigating a robot in a coordinate space to a goal location. The robot will provide feedback on its progress, such as the distance to the goal, and will return the time it took to reach the goal.

The task can be summarized as follows:

- We will define a goal, which is a specific point in a coordinate space (x, y, z).
- The robot will navigate to this goal, providing feedback on how far away it is.
- Once the robot reaches the goal, the Action Server will return the total time taken to reach the goal.

19.5.1 Conceptual Approach

To complete this task, we will create three ROS nodes:

- **Action Server Node**: The server will receive a goal (target position), provide feedback on the distance to the goal, and return the elapsed time to reach the goal.

- **Action Client Node**: The client will send the goal (desired position) to the server and handle the response (elapsed time).

- **Robot State Publisher Node**: This node will simulate the robot's current position and publish updates that the Action Server will use to calculate feedback.

We will also need to define a custom action message to handle the communication between the Action Client and Action Server.

19.5.2 Defining the Action File

Actions in ROS require an `.action` file that defines the structure of the goal, result, and feedback. In our case, we will define the following:

- **Goal**: The point (x, y, z) that represents the robot's target destination.

- **Result**: The elapsed time taken to reach the goal.

- **Feedback**: The distance from the robot's current position to the goal.

The `.action` file for this project would look like this:

Action File: `MoveToPoint.action`

```
# Goal
geometry_msgs/Point point
---
# Result
float32 elapsed_time
---
# Feedback
float32 distance_to_point
```

Explanation:

- `Goal:` We define the goal as a `geometry_msgs/Point`, which represents the target position (x, y, z).
- `Result:` The result is a `float32` representing the elapsed time it took the robot to reach the goal.
- `Feedback:` The feedback is a `float32` value representing the current distance from the robot's position to the goal.

19.5.3 Modifying the Package Configuration

Once we have defined the `.action` file, we need to update the package configuration to include it. This requires modifying the `CMakeLists.txt` and `package.xml` files.

Modifying `CMakeLists.txt`

In the `CMakeLists.txt` file, we need to:

- Add the `actionlib_msgs` dependency to ensure that ROS can recognize and process action messages.
- Use the `add_action_files()` macro to point to the location of the `.action` file.
- Update the `generate_messages()` macro to include the necessary message dependencies.

Here's how to modify `CMakeLists.txt`:

CMakeLists.txt Modifications

```
find_package(catkin REQUIRED COMPONENTS
        rospy
        actionlib
        actionlib_msgs
        geometry_msgs
)

add_action_files(
        DIRECTORY action
        FILES MoveToPoint.action
)

generate_messages(
        DEPENDENCIES actionlib_msgs geometry_msgs
)

catkin_package(
        CATKIN_DEPENDS rospy actionlib_msgs geometry_msgs
)
```

Explanation:

- `add_action_files()`: This specifies the directory and the action file that we want to compile.
- `generate_messages()`: This instructs ROS to generate the necessary message files for the action. We include the dependencies for `actionlib_msgs` and `geometry_msgs`.
- `catkin_package()`: Declares the dependencies on `actionlib_msgs` and `geometry_msgs`.

Modifying `package.xml`

In the `package.xml` file, we need to add dependencies for `actionlib_msgs` and `geometry_msgs`.

package.xml Modifications

```
<build_depend>actionlib_msgs</build_depend>
<build_depend>geometry_msgs</build_depend>
<exec_depend>actionlib_msgs</exec_depend>
<exec_depend>geometry_msgs</exec_depend>
```

Explanation:

- `build_depend`: This ensures that `actionlib_msgs` and `geometry_msgs` are available during the build process.
- `exec_depend`: These dependencies are also needed at runtime when the action is executed.

19.5.4 Things to Keep in Mind

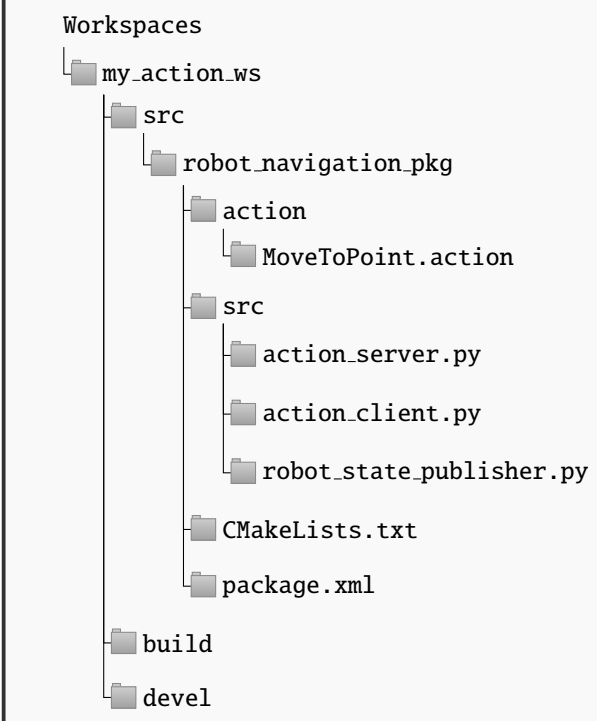
As we proceed with the project, make sure you follow these best practices:

- **Sourcing the Workspace:** Ensure that your workspace is sourced by running the `source devel/setup.bash` command or add it to your `.bashrc`. This was explained in Section [12.2].
- **Executable Files:** Remember to make all the Python scripts executable by using the `chmod +x` command. Refer to Section [12.4] for more details.
- **ROS Master:** Before running the nodes, make sure that `roscore` is running. Refer to Section [12.6] for more details.

19.5.5 File Structure

To clarify the organization of the files, here's what the workspace structure looks like after setting up the project:

File Structure



In this structure:

- **action/MoveToPoint.action**: Contains the definition of the action message.
- **src/server.py, src/client.py, src/robot_state_publisher.py**: The Python scripts for the action server, client, and robot state publisher, respectively.
- **CMakeLists.txt, package.xml**: The configuration files for the package.

Now that we've defined the action file and set up the package, we are ready to implement the action server in the next section.

19.6 Writing the Action Server Script

In this section, we will write the `action_server.py` script, which will be responsible for processing the goal sent by the client, providing feedback on the robot's progress, and returning the result when the goal is reached. The Action Server listens for requests from the Action Client and manages the robot's movement towards the goal.

Let's break down the `action_server.py` code into understandable parts.

19.6.1 Importing Required Libraries

We start by importing the necessary ROS libraries and messages.

Python Code

```
import math
import rospy
import actionlib
from robot_navigation_pkg.msg import MoveToPointAction,
     MoveToPointFeedback, MoveToPointResult
from geometry_msgs.msg import Point
```

Explanation:

- `math`: Provides mathematical functions, such as `dist()` to calculate the distance.
- `rospy`: The ROS client library for Python.
- `actionlib`: Provides the tools for creating ROS actions.
- `MoveToPointAction, MoveToPointFeedback, MoveToPointResult`: These are the custom messages defined in our `MoveToPoint.action` file that represent the goal, feedback, and result, respectively.
- `geometry_msgs/Point`: Represents the current and goal positions of the robot as `x`, `y`, and `z` coordinates.

19.6.2 Initializing the Action Server and Subscribers

Next, we create the Action Server and subscribe to the robot's current position.

Python Code

```
class Navigate2DClass:
                def __init__(self):
                        self.action_server = actionlib.SimpleActionServer("navigate_2D_action",
                        MoveToPointAction, self.navigate_cb)
                        self.robot_point_sub = rospy.Subscriber("robot/point", Point,
        self.update_robot_position)
                        self.robot_current_point = None
                        self.robot_goal_point = None
                        self.distance_threshold = 0.25
                        self.feedback_rate = rospy.Rate(1)
```

Explanation:

- `SimpleActionServer`: Creates a simple action server named `navigate_2D_action`. It listens for action goals and calls `navigate_cb` when a new goal is received.
- `Subscriber`: Subscribes to the `robot/point` topic, which provides the current position of the robot as a `Point` message.
- `robot_current_point` and `robot_goal_point`: Variables to store the current and goal positions of the robot.
- `distance_threshold`: The minimum distance at which the robot is considered to have reached the goal.
- `feedback_rate`: Sets the rate at which feedback is published, here it is 1 Hz (one message per second).

19.6.3 Defining the Callback Function for Action Goal

The callback function is triggered when the client sends a goal. This function calculates the distance to the goal and publishes feedback.

Python Code

```
def navigate_cb(self, goal):
        navigate_start_time = rospy.get_time()
        self.robot_goal_point = [goal.point.x, goal.point.y, goal.point.z]

        while self.robot_current_point == None:
                rospy.sleep(5)

        distance_to_goal = math.dist(self.robot_current_point, self.robot_goal_point)

        while distance_to_goal > self.distance_threshold:
                self.action_server.publish_feedback(MoveToPointFeedback(distance_to_point =
       distance_to_goal))
                self.feedback_rate.sleep()
                distance_to_goal = math.dist(self.robot_current_point, self.robot_goal_point)

        navigate_end_time = rospy.get_time()
        elapsed_time = navigate_end_time - navigate_start_time
        self.action_server.set_succeeded(MoveToPointResult(elapsed_time))
```

Explanation:

- `navigate_cb`: The callback function that processes the goal and provides feedback.
- `goal.point`: Retrieves the goal position from the client.
- `self.robot_current_point == None`: Waits for the robot's current position to be received from the `robot/point` topic.
- `math.dist`: Calculates the Euclidean distance between the robot's current position and the goal.
- `publish_feedback`: Sends feedback to the client with the distance to the goal.
- `set_succeeded`: Once the robot reaches the goal, it sets the result (elapsed time) and informs the client that the goal was successfully achieved.

19.6.4 Updating the Robot's Position

The robot's position is updated by subscribing to the `robot/point` topic, and this position is used to calculate the feedback.

Python Code

```
def update_robot_position(self, point):
        self.robot_current_point = [point.x, point.y, point.z]
```

Explanation:

- `update_robot_position`: This function is triggered whenever a new robot position is received on the `robot/point` topic. The current position is updated and used to calculate the distance to the goal.

19.6.5 Running the Action Server

Finally, we initialize the ROS node and run the Action Server.

Python Code

```
if __name__ == "__main__":
        rospy.init_node("navigate_2D_action_server_node")
        server = Navigate2DClass()
        rospy.spin()
```

Explanation:

- `rospy.init_node`: Initializes the ROS node with the name `navigate_2D_action_se`
- `rospy.spin`: Keeps the node running to handle incoming requests.

19.6.6 Complete Action Server Script

Here's the full `action_server.py` script:

Complete Python Code

```
#libraries...

class Navigate2DClass:
                def __init__(self):
                        ...

                def navigate_cb(self, goal):
                        ...

                def update_robot_position(self, point):
                        ...

if __name__ == "__main__":
                rospy.init_node("navigate_2D_action_server_node")
                server = Navigate2DClass()
                rospy.spin()
```

19.6.7 Summary of New Functions and Commands

Summary of New Functions

Function/Command	Description	Usage
`actionlib.Simple ActionServer`	Creates an action server to handle requests.	`Simple ActionServer(name, action_type, callback)`
`publish_feedback`	Publishes feedback to the action client about progress.	`self.action _server.publish _feedback(feedback)`
`set_succeeded`	Sends a success result back to the action client.	`self.action _server.set _succeeded(result)`
`rospy.Subscriber`	Subscribes to a topic to receive messages.	`rospy.Subscriber(topic, msg_type, callback)`
`math.dist`	Calculates the Euclidean distance between two points.	`math.dist(point1, point2)`

19.7 Writing the Python Action Client Script

Now that we have written the action server in the previous section, we will move on to writing the `action_client.py` script. This client script will allow us to send goals to the action server and receive feedback about the robot's progress toward reaching the goal. Let's break down the client code step by step.

19.7.1 Importing Required Libraries

We begin by importing the necessary libraries for ROS and action handling.

Python Code

```
import rospy
import actionlib

from robot_navigation_pkg.msg import MoveToPointAction,
     MoveToPointFeedback, MoveToPointResult, MoveToPointGoal
from geometry_msgs.msg import Point
```

Explanation:

- `rospy`: This imports the ROS Python client library.
- `actionlib`: Imports the actionlib library to manage the action client.
- `MoveToPointAction, MoveToPointFeedback, MoveToPointResult, MoveToPointGoal`: These are the message types generated from the `MoveToPoint.action` file. They represent the goal, feedback, and result message types for the action.
- `Point`: This is a standard ROS message type used to represent a 3D point with `x`, `y`, and `z` coordinates.

19.7.2 Defining the Feedback Callback Function

The feedback callback function is responsible for handling the feedback provided by the action server during the robot's movement toward the goal.

Python Code

```
def feedback_callback(feedback):
        print("Distance To Goal: " + str(feedback.distance_to_point))
```

Explanation:

- `feedback_callback(feedback)`: This function is triggered whenever the server sends feedback to the client. It simply prints the distance to the goal, which is contained in the feedback message.

19.7.3 Defining the Action Client Function

This is the core function of the client, which sends the goal to the action server, waits for feedback, and retrieves the result.

Python Code

```
def nav_client(user_coords):
        client = actionlib.SimpleActionClient("navigate_2D_action",
     MoveToPointAction)
        client.wait_for_server()

        point_msg = Point(x = user_coords[0], y = user_coords[1], z
     = user_coords[2])
        goal = MoveToPointGoal(point_msg)

        client.send_goal(goal, feedback_cb=feedback_callback)
        client.wait_for_result()

        return client.get_result()
```

Explanation:

- `client = actionlib.SimpleActionClient("navigate_2D_action", MoveToPointAction)`: Initializes the action client, connecting to the action server named `navigate_2D_action`.
- `client.wait_for_server()`: Waits for the action server to become available.
- `point_msg = Point(x = user_coords[0], y = user_coords[1], z = user_coords[2])`: Creates a point message using the user-provided coordinates.
- `goal = MoveToPointGoal(point_msg)`: Creates a goal message using the `MoveToPointGoal` message type, which contains the target coordinates.
- `client.send_goal(goal, feedback_cb=feedback_callback)`: Sends the goal to the action server and registers the feedback callback function.
- `client.wait_for_result()`: Waits for the action server to finish processing the goal and return a result.
- `return client.get_result()`: Retrieves and returns the result from the action server (in this case, the elapsed time to reach the goal).

19.7.4 Running the Client Script

Now we define the main part of the script, which interacts with the user and sends the goal to the action server.

Python Code

```
if __name__ == "__main__":
        try:
                rospy.init_node("navigate_2D_action_client_node")

                user_x = input("What is the desired x-coordinate: ")
                user_y = input("What is the desired y-coordinate: ")
                user_z = input("What is the desired z-coordinate: ")

                user_coords = [float(user_x), float(user_y),
     float(user_z)]

                result = nav_client(user_coords)
                print("Elapsed Time: " + str(result.elapsed_time) +
     " seconds")

          except rospy.ROSInterruptException:
                print("Program interrupted")
```

Explanation:

- `rospy.init_node("navigate_2D_action_client_node")`: Initializes the ROS node for the action client.
- `user_x, user_y, user_z`: Prompts the user to enter the desired `x`, `y`, and `z` coordinates for the robot to navigate to.
- `user_coords`: Stores the user-provided coordinates in a list and converts them to floats.
- `result = nav_client(user_coords)`: Sends the coordinates to the action server and stores the result (the elapsed time to reach the goal).
- `print("Elapsed Time: " + str(result.elapsed_time) + " seconds")`: Prints the elapsed time returned by the server.
- `except rospy.ROSInterruptException`: Handles any interruptions to the program (e.g., pressing `Ctrl+C`).

19.7.5 Complete Action Client Script

Here is the complete `action_client.py` script, which sends a goal to the action server and receives feedback and results.

Complete Python Code

```
import rospy
import actionlib
from robot_navigation_pkg.msg import MoveToPointAction,
     MoveToPointFeedback, MoveToPointResult, MoveToPointGoal
from geometry_msgs.msg import Point


def feedback_callback(feedback):
        print("Distance To Goal: " + str(feedback.distance_to_point))


def nav_client(user_coords):
        client = actionlib.SimpleActionClient("navigate_2D_action",
     MoveToPointAction)
        client.wait_for_server()
        point_msg = Point(x = user_coords[0], y = user_coords[1], z
     = user_coords[2])
        goal = MoveToPointGoal(point_msg)
        client.send_goal(goal, feedback_cb=feedback_callback)
        client.wait_for_result()
        return client.get_result()

if __name__ == "__main__":
        try:
                rospy.init_node("navigate_2D_action_client_node")

                user_x = input("What is the desired x-coordinate: ")
                user_y = input("What is the desired y-coordinate: ")
                user_z = input("What is the desired z-coordinate: ")

                user_coords = [float(user_x), float(user_y),
     float(user_z)]

                result = nav_client(user_coords)
                print("Elapsed Time: " + str(result.elapsed_time) +
     " seconds")

        except rospy.ROSInterruptException:
                print("Program interrupted")
```

19.7.6 Summary of New Functions and Commands

Summary of New Functions

Function/Command	Description	Usage
`actionlib.SimpleActionClient`	Creates an action client to send goals to the action server.	`SimpleActionClient(name, action_type)`
`send_goal`	Sends the goal to the action server.	`client.send_goal(goal, feedback_cb)`
`feedback_cb`	Callback function for receiving feedback from the action server.	`client.send_goal(goal, feedback_cb)`
`wait_for_result`	Waits for the action server to return the result.	`client.wait_for_result()`
`get_result`	Retrieves the result from the action server.	`client.get_result()`
`rospy.init_node`	Initializes a ROS node for the action client.	`rospy.init_node(name)`

19.8 Writing the Robot State Publisher Script

In this section, we will write the `robot_state_publisher.py` script, which will publish the current location of the robot to a ROS topic. This script will act as the robot's location broadcaster, sending the robot's position at regular intervals.

19.8.1 Importing Required Libraries

First, let's import the necessary libraries for ROS and message handling.

Python Code

```
import rospy
from geometry_msgs.msg import Point
```

Explanation:

- `rospy`: The ROS Python client library, used for interacting with ROS nodes.
- `Point`: A standard ROS message type representing a 3D point, consisting of `x`, `y`, and `z` coordinates.

19.8.2 Defining the Publisher Function

We now define the main function responsible for publishing the robot's current position to the `robot/point` topic. This function will continuously broadcast the robot's location at regular intervals.

Python Code

```
def robot_point_pub(user_coords):
        pub = rospy.Publisher("robot/point", Point, queue_size=10)
        print("Publishing...")

        rate = rospy.Rate(1)  # 1 Hz
        while not rospy.is_shutdown():
                pub.publish(Point(x = user_coords[0], y =
     user_coords[1], z = user_coords[2]))
                rate.sleep()
```

Explanation:

- `pub = rospy.Publisher("robot/point", Point, queue_size=10)`: Initializes a publisher that publishes messages of type `Point` on the `robot/point` topic.
- `rate = rospy.Rate(1)`: Sets the publishing rate to 1 Hz (i.e., once per second).
- `pub.publish(Point(x = user_coords[0], y = user_coords[1], z = user_coords[2]))`: Publishes the robot's current `x`, `y`, and `z` coordinates to the topic.
- `while not rospy.is_shutdown()`: Continuously loops and publishes the robot's position until the ROS node is shut down.

19.8.3 Running the Publisher Script

Now, we write the main part of the script, which prompts the user for the robot's current position and starts the publisher.

Python Code

```
if __name__ == "__main__":
        try:
                rospy.init_node("robot_point_pub_node")

                user_x = input("What is the current robot
    x-coordinate: ")
                user_y = input("What is the current robot
    y-coordinate: ")
                user_z = input("What is the current robot
    z-coordinate: ")

                user_coords = [float(user_x), float(user_y),
    float(user_z)]

                robot_point_pub(user_coords)

          except rospy.ROSInterruptException:
                print("Exception Occurred")
```

Explanation:

- `rospy.init_node("robot_point_pub_node")`: Initializes the ROS node for the publisher with the name `"robot_point_pub_node"`.
- `user_x, user_y, user_z`: Prompts the user to input the robot's current `x`, `y`, and `z` coordinates.
- `user_coords = [float(user_x), float(user_y), float(user_z)]`: Converts the user inputs to floats and stores them in the `user_coords` list.
- `robot_point_pub(user_coords)`: Calls the `robot_point_pub` function to start publishing the robot's position.

19.8.4 Complete Robot State Publisher Script

Here is the complete `robot_point_pub.py` script, which continuously publishes the robot's current position to the `robot/point` topic.

Complete Python Code

```
import rospy
from geometry_msgs.msg import Point


def robot_point_pub(user_coords):
        pub = rospy.Publisher("robot/point", Point, queue_size=10)
        print("Publishing...")

        rate = rospy.Rate(1)
        while not rospy.is_shutdown():
                pub.publish(Point(x = user_coords[0], y =
    user_coords[1], z = user_coords[2]))
                rate.sleep()


if __name__ == "__main__":
        try:
                rospy.init_node("robot_point_pub_node")

                user_x = input("What is the current robot
    x-coordinate: ")
                user_y = input("What is the current robot
    y-coordinate: ")
                user_z = input("What is the current robot
    z-coordinate: ")

                user_coords = [float(user_x), float(user_y),
    float(user_z)]

                robot_point_pub(user_coords)

        except rospy.ROSInterruptException:
                print("Exception Occurred")
```

19.8.5 Summary of New Functions and Commands

Summary of New Functions

Function/Command	Description	Usage
`rospy.Publisher`	Initializes a ROS publisher for a topic.	`rospy.Publisher(topic, msg_type, queue_size)`
`publish`	Publishes a message to the topic.	`pub.publish(message)`
`rospy.Rate`	Sets the rate at which the loop runs.	`rospy.Rate(hz)`
`rospy.init_node`	Initializes a ROS node.	`rospy.init_node(name)`

19.9 Running the Action Nodes and Testing the System

Now that we've created all the necessary Python scripts—`action_server.py`, `action_client.py`, and `robot_point_pub.py`—we can move on to testing our system.

19.9.1 Starting the Action Server

The first step is to start the action server. The action server will handle the goals sent by the client, process them, and provide feedback during execution. Here's how to run it:

Starting the Action Server

```
rosrun robot_navigation_pkg action_server.py
```

Make sure you replace `your_package_name` with the name of your package (e.g., `robot_navigation_pkg`). This command will launch the action server and start waiting for incoming action goals.

19.9.2 Starting the Robot State Publisher

Next, we need to start the `robot_state_publisher.py` script to simulate the robot's movement. This node will continually publish the current position of the robot.

Starting the Robot State Publisher

```
rosrun robot_navigation_pkg robot_state_publisher.py
```

After running this script, you will be prompted to enter the robot's current `x`, `y`, and `z` coordinates. Once entered, the node will start publishing the robot's position to the `robot/point` topic.

19.9.3 Running the Action Client

Finally, we start the `action_client.py` script to send a goal to the action server. The client will request the robot to navigate to a specified point in 3D space.

Running the Action Client

```
rosrun robot_navigation_pkg action_client.py
```

Once you run this command, you will be prompted to enter the target `x`, `y`, and `z` coordinates for the robot. After entering these values, the client will send the goal to the action server. The server will then navigate the robot towards the goal and provide feedback (distance to the goal) during execution.

19.9.4 Monitoring the Feedback and Result

While the system is running, you can observe the feedback being printed to the terminal by the action client. This feedback represents the distance between the robot's current position and the goal. Once the robot reaches

the goal, the client will print the final result, which is the time taken to reach the goal.

You can also use the following command to see all the topics, including those used for action communication:

Monitoring ROS Topics

```
rostopic list
```

This will list all the topics currently being published, including feedback, status, result, and goal-related topics for the action.

19.9.5 Shutting Down the Nodes

Once the test is complete, you can stop the nodes by pressing `Ctrl+C` in each terminal where they are running. This will terminate the action server, client, and robot state publisher nodes cleanly.

19.9.6 Things to Keep in Mind

To ensure your scripts run smoothly, make sure to follow these important steps:

1. **Source your workspace:** Don't forget to source your workspace before running the scripts. If you haven't set up auto-sourcing, run `source devel/setup.bash` in your workspace directory. Refer to the *Sourcing Your Workspace* section in [12.2] for more details.

2. **Make the scripts executable:** Use the `chmod +x` command to make your Python scripts executable. Refer to the *Making Python Scripts Executable* section [12.4 for a detailed explanation.

3. **Add the Shebang Line:** Ensure that the shebang line `#!/usr/bin/env python3` is included at the top of each Python script so that ROS knows to use Python 3 as the interpreter. This was explained in section [12.5].

4. **Run roscore:** Before launching any ROS nodes, make sure `roscore` is running. Refer to the *Running roscore* section [12.6].

19.9.7 Summary of New Commands and Functions

Summary of New Commands and Functions

Command/Function	Description	Usage
`actionlib.SimpleActionServer`	Creates an action server.	`SimpleActionServer("name", ActionType, callback)`
`actionlib.SimpleActionClient`	Creates an action client.	`SimpleActionClient("name", ActionType)`
`send_goal`	Sends a goal to the action server.	`client.send_goal(goal)`
`wait_for_result`	Waits for the server to return a result.	`client.wait_for_result()`
`get_result`	Retrieves the result from the server.	`client.get_result()`
`rospy.Publisher`	Initializes a ROS publisher for a topic.	`rospy.Publisher(topic, msg_type, queue_size)`
`rospy.Subscriber`	Initializes a ROS subscriber for a topic.	`rospy.Subscriber(topic, msg_type, callback)`
`publish_feedback`	Sends feedback to the action client.	`self.publish_feedback(feedback_msg)`

19.10 Conclusion

In this chapter, we delved into the concept of ROS Actions, exploring how they extend the capabilities of ROS services to handle more complex and long-running tasks. We compared ROS Actions with ROS Services and Topics and explained how Actions provide feedback and allow for goal cancellation, making them highly useful in real-time robotic applications.

We then walked through a detailed project example, implementing a navigation task where the robot moves to a goal position while giving feedback on the distance and returning the total time it took to complete the task. This involved creating an action server to handle the goals, a client to send the goals, and a separate node to publish the robot's current position.

Finally, we demonstrated how to test the complete system by running the action server, client, and state publisher nodes. The provided code examples, explanations, and step-by-step testing instructions gave you

a comprehensive understanding of how to use Actions in ROS to solve real-world problems.

Actions in ROS offer a flexible and powerful mechanism for handling tasks that require continuous monitoring and feedback, making them a valuable tool for any robotics developer. We hope you found this chapter informative and useful for your ROS learning journey.

ROS Functions & Commands

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Consolidated Summary of ROS Functions and Commands

Function/Command	Description	Input	Output
`rospy.init_node(name)`	Initializes a ROS node	`name`: string	Initializes the node
`rospy.Publisher(topic, type, queue_size)`	Creates a publisher for a topic	`topic`: string, `type`: message, `queue_size`: int	Publishes data on the topic
`rospy.Rate(hz)`	Controls the message publishing rate	`hz`: int	Sets the publish rate
`rospy.is_shutdown()`	Checks if the node is shutting down	None	Returns True if the node is shutting down
`pub.publish(data)`	Publishes data on the topic	`data`: string	Sends data to the ROS topic
`rate.sleep()`	Pauses the loop to maintain the publish rate	None	Delays the loop
`rospy.Subscriber(topic, type, callback)`	Creates a subscriber for a topic	`topic`: string, `type`: message, `callback`: function	Subscribes to messages on the topic
`rospy.spin()`	Keeps the subscriber node running	None	Prevents the script from closing
`process_hello_world_message(data)`	Callback function to process received messages	`data`: message	Prints the message content

Consolidated Summary of ROS Functions and Commands

Function/Command	Description	Input	Output
`rosnode list`	Lists all active ROS nodes	None	Displays node names including `/hello_world_pub_node`
`rostopic list`	Lists all active ROS topics	None	Shows available topics including `/hello_world`
`rostopic echo /hello_world`	Displays messages published to the topic	None	Prints "Hello World" messages with counter
`rostopic info /hello_world`	Provides information about the topic	None	Details on publisher, message type, and subscribers
`rostopic hz /hello_world`	Monitors the publishing rate of the topic	None	Shows frequency (Hz) of messages
`Ctrl+C`	Stops the ROS node	None	Shuts down the publisher
`rospy.get_param(param, default)`	Retrieves a parameter from the server	`param`: string, `default`: value	Parameter value
`rosparam set`	Sets a parameter on the server	`name`: string, `value`: value	Sets the parameter
`rosparam get`	Retrieves a parameter from the server	`name`: string	Parameter value
`rosparam dump`	Saves parameters to a YAML file	`filename`: string	Saves the file
`rosparam load`	Loads parameters from a YAML file	`filename`: string	Loads the parameters
`LaserScan()`	Creates a LaserScan message	None	Data structure for laser range data
`Vector3(x, y, z)`	Creates a Vector3 message	`x, y, z`: floats	Vector in 3D space

Summary of ROS Python Functions

Function/Command	Description	Input	Output
`rospy.init_node(name)`	Initializes a ROS node	`name`: string	Initializes the node
`rospy.Publisher(topic, type, queue_size)`	Creates a publisher for a topic	`topic`: string, `type`: message, `queue_size`: int	Publishes data on the topic
`rospy.Rate(hz)`	Controls the message publishing rate	`hz`: int	Sets the publish rate
`rospy.is_shutdown()`	Checks if the node is shutting down	None	Returns True if the node is shutting down
`pub.publish(data)`	Publishes data on the topic	`data`: string	Sends data to the ROS topic
`rate.sleep()`	Pauses the loop to maintain the publish rate	None	Delays the loop
`rospy.Subscriber(topic, type, callback)`	Creates a subscriber for a topic	`topic`: string, `type`: message, `callback`: function	Subscribes to messages on the topic
`rospy.spin()`	Keeps the subscriber node running	None	Prevents the script from closing
`process_hello_world_message(data)`	Callback function to process received messages	`data`: message	Prints the message content
`rospy.get_time()`	Returns the current ROS time	None	Current time (float)
`rospy.loginfo(msg)`	Logs information to the ROS console	`msg`: string	None
`rospy.logwarn(msg)`	Logs a warning to the ROS console	`msg`: string	None
`rospy.logerr(msg)`	Logs an error to the ROS console	`msg`: string	None
`rospy.get_param(param)`	Retrieves a parameter from the ROS Parameter Server	`param`: string	Value of the parameter
`rospy.set_param(param, value)`	Sets a parameter on the ROS Parameter Server	`param`: string, `value`: any	None

Summary of ROS Commands

Command/Function	Description	Input	Output
`rosnode list`	Lists all active ROS nodes	None	Displays node names including `/hello_world_pub_node`
`rosnode info (node_name)`	Provides information about a specific node	`node_name`: string	Displays the status and connections of the node
`rosnode kill (node_name)`	Terminates a specific ROS node	`node_name`: string	Shuts down the node
`rosnode ping (node_name)`	Pings a ROS node to check if it's running	`node_name`: string	Success message if the node is reachable
`rostopic list`	Lists all active ROS topics	None	Shows available topics including `/hello_world`
`rostopic echo (topic)`	Displays messages published to a specific topic	`topic`: string	Prints the messages to the terminal
`rostopic info (topic)`	Provides information about a specific topic	`topic`: string	Details on publishers, message type, and subscribers
`rostopic hz (topic)`	Monitors the publishing rate of a specific topic	`topic`: string	Shows the frequency (Hz) of the messages
`rosparam get (param)`	Retrieves a parameter from the ROS Parameter Server	`param`: string	Parameter value
`rosparam set (param, value)`	Sets a parameter on the ROS Parameter Server	`param`: string, `value`: any	None
`rosparam delete (param)`	Deletes a parameter from the ROS Parameter Server	`param`: string	None
`roslaunch (package, launch_file)`	Launches a launch file in a ROS package	`package`: string, `launch_file`: string	Starts the nodes and parameters defined in the launch file
`rosrun (package, node)`	Runs a specific node from a package	`package`: string, `node`: string	Starts the node
`roscore`	Starts the ROS master	None	Initializes the ROS system
`Ctrl+C`	Stops a running ROS node or process	None	Shuts down the node/process

Summary of General Python Functions

Function/Command	Description	Input	Output
`print()`	Prints the given message to the console	`msg`: any	None
`len(obj)`	Returns the length (number of items) of an object	`obj`: sequence	Length of the object (int)
`type(obj)`	Returns the type of an object	`obj`: any	Object's type
`range(start, stop, step)`	Generates a sequence of numbers	`start`: int, `stop`: int, `step`: int	Sequence of numbers
`input(prompt)`	Takes input from the user	`prompt`: string	User input as a string
`sum(iterable)`	Returns the sum of the elements in an iterable	`iterable`: list or tuple	Sum of the elements (int or float)
`open(file, mode)`	Opens a file for reading, writing, or appending	`file`: string, `mode`: string	File object
`with open(file, mode) as f:`	Opens a file and ensures it's closed automatically	`file`: string, `mode`: string	File object

Summary of General Python Commands

Command/Function	Description	Input	Output
`os.system (command)`	Executes a shell command in Python	`command`: string	Command output
`subprocess.call (command)`	Runs a shell command from Python	`command`: list or string	Return code of the command
`time.sleep (seconds)`	Pauses the program for a given number of seconds	`seconds`: int or float	None
`sys.exit()`	Exits the Python program	None	Exits the program with an optional status code
`sys.argv`	List of command-line arguments passed to the script	None	List of arguments
`argparse. ArgumentParser()`	Parses command-line arguments	None	Argument parser object
`argparse.add _argument()`	Adds a command-line argument to the parser	`arg_name`: string	Argument definition
`argparse.parse _args()`	Parses all arguments provided by the user	None	Parsed arguments object
`import module`	Imports a Python module	`module`: string	None
`from module import function`	Imports a specific function from a module	`module`: string, `function`: string	None
`def function():`	Defines a Python function	`args`: list of arguments	None
`class ClassName:`	Defines a Python class	None	Class definition

Reference

Reference

1.1 :: For further reading on the history of ROS, including its evolution and impact on robotics development, refer to [93].

1.1.1 :: For more details about the Stanford period and the early development of ROS, including Keenan Wyrobek's work, refer to [113].

1.2 :: For further reading on the challenges in robotics development, particularly the complexities of low-level programming and the advent of frameworks like ROS, refer to [6] and [75].

1.3 :: For further reading on the origins and development of ROS, including its initial creation at Stanford University and its impact on modern robotics, refer to [75] and [1].

1.4 :: For further reading on the architecture and role of ROS as middleware, and a detailed explanation of what ROS is and isn't, refer to [75] and [94].

1.5 :: For further reading on the benefits of learning ROS, especially its open-source nature and modular design, refer to [50].

1.5.3 :: For more information on development tools like Rviz and Gazebo, refer to [7].

1.6 :: For an overview of the languages supported by ROS, including both officially supported and community-driven languages, refer to [105].

2.1 :: For further reading on setting up ROS and Ubuntu, including step-by-step guidance on environment setup, refer to [110].

2.2 :: For more detailed instructions on installing Ubuntu, especially through virtual machines or dual booting on Windows or macOS, refer to [4].

2.2.2 :: If you're working with Apple Silicon and need more detailed steps on installing Ubuntu using UTM, refer to [2].

2.3 :: For information on using Raspberry Pi as a platform for ROS, refer to [39].

2.4 :: For more details on installing various code editors for ROS development, including Visual Studio Code, Atom, and Sublime Text, refer to [49].

3.1 :: For further reading on ROS installation and official step-by-step instructions, refer to [3].

3.2 :: For more detailed guidance on the commands and steps involved in installing ROS Noetic on Ubuntu, refer to [73].

4.1 :: For further reading on the core components of the ROS framework, including the ROS Master, Nodes, Topics, and other essential features, refer to [80].

4.2 :: For more detailed information on the role and functioning of the ROS Master, refer to [8].

4.3 :: To learn more about how nodes work in ROS and their role in modular robotics development, refer to [101].

4.3.1 :: For further reading on how nodes communicate in ROS using topics, services, and actions, refer to [111].

4.3.2 :: To learn more about the node lifecycle in ROS, including the processes of initialization, running, and shutdown, refer to [51].

4.4.1 :: For further reading on how topics work in ROS, including the publisher/subscriber model, refer to [25].

4.4.2 :: To explore more examples of how topics are used in real-world ROS applications, refer to [55].

4.5 :: For further reading on ROS Services and the request/response model, refer to [15].

4.6 :: For more details about how ROS Actions work and when to use them, refer to [112].

4.7 :: For further reading on the ROS Parameter Server, its usage, and real-world applications, refer to [29].

4.8 :: To explore more details about Bag Files in ROS, including how to record and play back data, refer to [61].

4.9 :: For more information on the structure and usage of ROS Packages, refer to [79].

5.1 :: For further reading on how to set up and manage a ROS workspace, refer to [97].

5.2 :: To understand more about the ROS workspace structure and its components, refer to [70].

5.3 :: For more examples of ROS workspace visualization and organization, refer to [82].

5.4 :: For further reading on how to create a ROS workspace in Ubuntu, refer to [67].

5.4.1 :: To learn more about organizing your workspace directory and creating workspace folders, refer to [96].

5.4.2 :: For detailed guidance on creating a ROS package with dependencies, refer to [18].

5.5 :: For more information on compiling ROS workspaces using the catkin_make command, refer to [95].

6.1 :: For further reading on how to create ROS publishers in Python, refer to [27].

6.2.1 :: To learn more about ROS libraries and their functionalities in Python, refer to [53].

6.2.2 :: For more details on the structure of a ROS Python script, including the main function, refer to [17].

6.2.3 :: To understand the process of initializing a ROS node in Python, refer to [103].

6.2.4 :: For further reading on how to create a ROS publisher and publish messages to a topic, refer to [16].

6.2.5 :: To learn more about controlling the message publish rate in ROS, refer to [106].

6.2.6 :: For more details on publishing messages in a loop with proper rate control in ROS, refer to [85].

6.2.7 :: For more information on importing and using different ROS message types, refer to [20].

6.4.1 :: For further reading on how to list active nodes in ROS, refer to [60].

6.4.2 :: To learn more about listing topics and verifying topic availability, refer to [77].

6.4.3 :: For more information on using `rostopic echo` to inspect messages in ROS, refer to [100].

6.4.4 :: To explore how to get detailed topic information in ROS, refer to [58].

6.4.5 :: For further details on monitoring topic publish rates with `rostopic hz`, refer to [12].

6.4.6 :: For more guidance on stopping a ROS publisher and managing node shutdown, refer to [83].

7.1 :: For further reading on how to create a ROS subscriber in Python, refer to [66].

7.2.1 :: To learn more about the ROS libraries used in Python subscribers, refer to [24].

7.2.2 :: For detailed guidance on structuring the main function in ROS Python scripts, refer to [71].

7.2.3 :: For more information on initializing a ROS node for subscribers, refer to [98].

7.2.4 :: To learn more about creating and handling ROS subscribers, refer to [19].

7.2.5 :: For more details on defining and processing callback functions in ROS, refer to [84].

8.1 :: For further reading on the various ROS message types available for communication between nodes, refer to [31].

8.2.1 :: To explore more standard message types in ROS and how they are used, refer to [56].

8.2.2 :: For guidance on creating custom ROS message types, refer to [104].

8.3 :: For more detailed information on sensor message types, including `LaserScan`, refer to [34].

8.3.1 :: To learn more about publishing and using `LaserScan` data in ROS, refer to [57].

8.4 :: For further reading on how to use geometry messages in ROS, including the `Vector3` message type, refer to [107].

8.4.1 :: To learn more about how to publish and use `Vector3` messages in ROS, refer to [78].

9.2.1 :: For further reading on the transformation matrix used in differential drive robots, refer to [5].

11.1 :: For further reading on the ROS parameter server and its benefits, refer to [65].

11.3.1 :: To learn more about listing parameters in ROS, refer to [22].

11.3.2 :: For more details on setting and getting parameters via the terminal in ROS, refer to [108].

11.4 :: For more detailed information on saving and loading ROS parameters using YAML files, refer to [32].

11.5.1 :: To learn more about integrating the ROS parameter server into Python scripts using `rospy.get_param`, refer to [52].

12.1 :: For further reading on the essential ROS concepts like sourcing workspaces and running ROS commands, refer to [64].

12.2.1 :: To understand more about why sourcing is necessary for your ROS workspace, refer to [28].

12.2.2 :: For a detailed guide on automating the sourcing process by modifying the `.bashrc` file, refer to [81].

12.3 :: For more details on using the `rosrun` command to execute ROS nodes, refer to [26].

12.3.1 :: If you are experiencing issues with tab completion not working when using `rosrun`, refer to [69].

12.4 :: To learn more about making Python scripts executable in ROS, refer to [88].

12.4.1 :: For further details on resolving Python version errors when running ROS scripts, refer to [109].

12.5 :: For more information on how to manage Python version errors in ROS and using the shebang, refer to [72].

12.6 :: For further guidance on starting `roscore` and managing ROS master nodes, refer to [21].

13.1 :: For further reading on how to simplify running ROS nodes using launch files, refer to [62].

13.4.1 :: To learn more about the various tags used in ROS launch files, refer to [87].

13.7 :: For more detailed information on running launch files in ROS and managing multiple nodes, refer to [14].

16.1 :: For further details on ROS bag files and their usage, refer to [59].

16.2 :: To explore more about the different purposes of ROS bag files, refer to [23].

16.7.2 :: For detailed information on playing back ROS bag files and inspecting their contents, refer to [102].

17.1 :: For further reading on integrating existing ROS packages like `usb_cam`, refer to [33].

17.2 :: To explore more about the benefits of using ROS packages, refer to [48].

17.5 :: For more detailed information on running the `usb_cam` node and troubleshooting issues, refer to [99].

17.6 :: For further reading on how to visualize camera data in ROS, refer to [43].

17.6.1 :: To explore more about ROS topics and their use, refer to [10].

17.6.2 :: For detailed information on using `rostopic echo` to inspect camera data, refer to [44].

17.7.1 :: For further guidance on using RViz to visualize sensor data in ROS, refer to [11].

17.8 :: To learn more about using launch files in ROS, refer to [47].

17.8.1 :: For detailed steps on using launch files to automate node execution, see [40].

17.9 :: For more on troubleshooting USB camera issues in ROS, refer to [38].

18.1 :: For further reading on services in ROS, refer to [15].

18.2 :: To better understand the client-server model in ROS services, see [45].

18.3 :: For a detailed comparison between ROS services and topics, refer to [9].

18.4 :: For more examples of ROS services in action, refer to [90].

18.5 :: For a deeper understanding of how ROS services differ from traditional APIs, see [74].

18.6 :: To learn more about the client-server architecture in ROS services, refer to [35].

18.7.2 :: For additional examples on how to structure service definitions, see [91].

18.7.3 :: For an in-depth guide on setting up ROS packages, refer to [41].

18.7.5 :: For more information on updating CMakeLists.txt and package.xml for custom services, consult [89].

18.7.6 :: To learn about building ROS packages with catkin, see [36].

18.9.2 :: For more information on starting ROS service servers, see [92].

18.9.3 :: For a complete guide on how to verify ROS services, refer to [42].

18.9.6 :: To learn more about manually calling ROS services, check [37].

18.9.7 :: For additional insights into ROS client-server communication, refer to [45].

19.1 :: For further details on Actions in ROS and how they compare to other communication mechanisms like Topics and Services, refer to

[63].

19.2 :: To learn more about the asynchronous communication model provided by Actions in ROS, refer to [86].

19.2.1 :: For a deeper understanding of the basic flow and lifecycle of Actions in ROS, refer to [13].

19.4 :: For further reading on the importance of Actions in complex robotic applications like navigation and arm control, refer to [68].

19.5.1 :: For a deeper dive into conceptual approaches for designing Action Servers and Clients in ROS, refer to [30].

19.5.2 :: For more information on defining action files in ROS, refer to [54].

19.5.3 :: To understand how to correctly modify `CMakeLists.txt` to integrate actions, refer to [46].

19.5.3 :: For guidance on adding dependencies in `package.xml` for action messages, refer to [76].

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