

A VERY INFORMAL JOURNEY THROUGH ROS 2

PATTERNS, ANTI-PATTERNS, FRAMEWORKS AND BEST PRACTICES

Marco Matteo Bassa

A very informal journey through ROS 2

patterns, anti-patterns, frameworks and best practices

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Robotics is the art of bringing some piece of your own brain to work on a machine.

I hope you aren't a psychopath.

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Colophon

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Introduction

1.1 ROS 2

The Robot Operating System, widely known as ROS, was for the first time released in 2007, and has since then revolutionized the way developers create, and most importantly share, software for modern robots around the world. Roboticists tend to have mixed feelings about this framework: while it allows for the fast development of code for robotic platforms, reusing existing modules that are common between different use-cases, it is often criticized for not being an “industry ready solution”, good only for prototyping and for research purposes. In the past few years, many companies have been fighting against this idea, bringing on the market solutions based on ROS capable of running with good reliability over an extended period of time. However, over time, the ROS community has developed an awareness of the limitations of the original architecture, and realized that it would not be possible to overcome all of them through incremental upgrades.

As a result, in 2017, a new version of the operating system appeared in the robotics world: ROS 2. Along the book more insights will be given about why this transition happened / is happening, for now the reader should know that support for the last release of "ROS1"¹, 'Noetic Ninjemis', is set to end in May 2025. As a consequence, the whole community was invited to continue the development of new features using the new version of ROS. Another important aspect of the transition is that, while the architecture of ROS 2 resembles in many aspects that of the original ROS, the two are not compatible. Even though some ROS packages can be converted to/from the new version of ROS with relatively little effort, a successful transition often involves significant architectural changes across the entire system.

1: I will sometimes use this notation instead of "ROS" to make the distinction between the old and the new version clearer.

1.2 Why this book?

The ROS community made significant efforts to provide users with [tutorials](#) [1], [documentation](#) [2] and open discussion forums like [discourse.ros.org](#)[3] or [answers.ros.org](#)[4] in order to make the learning and the troubleshooting of ROS 2 as smooth as possible. Chances are that, before reading this, you already went through most of it. If not, please do it. This book is not a programming guide that teaches ROS 2 from the basics, as the previously mentioned resources already do that exceptionally well. There is plenty of free, dynamic and entertaining material for beginners that will enable you to create your first ROS 2 nodes in no time. However, while the ROS documentation is really good at explaining how to perform “single operations”, if you’ll be dealing with the development of a large system, you will likely soon be asking yourself questions like: “is this the proper way of doing stuff?”, “How does the rest of the world usually tackle this problem using ROS?”. These questions almost inevitably arise because ROS often provides the

developers with multiple ways to achieve the same objective. Oftentimes, the answer to these dilemmas will not be unique and universal, but will depend from the requirements and the constraints of the specific system. However, it is also true that some patterns can be identified that generally make the architecture more reusable, modular and less error-prone. At the same time, anti-patterns exist that, if introduced in your code, will most likely make you struggle and lose time / performance as the system expands.

1.3 How and when to read this book

Given the big amount of quality material about ROS 2 already existing on the web, this book will strive to avoid repeating basic examples and concepts, and will instead make extensive use of references and links to direct you to the most current information available. As this is a book about programming, the author assumes that you have access to some form of digital device that will facilitate your ability to follow the references and try out examples (so please don't print this and save some tree).

Each chapter ends with a short homework assignment. While you may be tempted to (and most likely will) skip it and quickly move on with the book, it's important to note that "The biggest drop in retention happens soon after learning. Without reviewing or reinforcing our learning, our ability to retain information plummets"^[5]. In the context of programming tools, I believe it's crucial to put what you've learned into practice by writing your own code. With time, I will provide the solution to some of the exercises on [this github repository](#) and in the last chapter. If you don't find what you are looking for, feel free to contact me to discuss any solution.

Regardless of whether you are an expert robotic engineer used to work with the "old ROS", a developer used to work with other kinds of frameworks, or someone venturing for the first time into the magic world of robotics, this book will hopefully provide you with some good tips on how to choose and properly use the correct tools in the ROS 2 world.

Many robots have been cursed, hit, smashed into walls and boxes and (partially) burned while gaining the material on which this book was based. I hope I can help to make your journey less troubled, but just as fun as mine.



2 The Node

In ROS 2, just like in the dear old ROS, the basic unit of execution for each program is called a Node. While it would look like there's not much to say about it¹[6], the way you'll create your Nodes deeply affects the way your application can be managed, integrated into the rest of the system, and the functionalities it will be able to provide.

1: A description of the core Node concept can be found [here](#)

2.1 How to (properly) instantiate it

As you probably already figured out, there are two main ways to create a Node. The most immediate one, if you are using rclcpp, will look something like:²

```
1 #include "rclcpp/rclcpp.hpp"
2 int main(int argc, char **argv)
3 {
4     rclcpp::init(argc, argv);
5     auto node = std::make_shared<rclcpp::Node>("best_node_name");
6     rclcpp::spin(node);
7     rclcpp::shutdown();
8     return 0;
9 }
```

2: Most of the code samples provided through this book are written in C++. The described concepts, however, almost always generalize to the other languages that can be used with ROS 2. Later in the book we will see how ROS 2 facilitates the support of most of its functionalities across different programming languages.

The node is created as a shared pointer to a rclcpp::Node class instantiated with your favourite name. This pointer can now be used to read parameters, create publishers, subscribers, and all the other fancy features[7] that a good node should provide. You can also share this little guy (that somewhat resembles the retired nodehandle[8]) with other functions or classes, who can optionally store a copy of it. After all, it's a shared pointer, why not? We'll soon see how, in many cases, this solution can prove to be problematic.

Another way to instantiate a node, is through a class deriving from rclcpp::Node:

```
1 #include "rclcpp/rclcpp.hpp"
2
```

```

3 class OurClass : public rclcpp::Node {
4     public:
5         OurClass() : Node("best_node_name") {
6             // Some constructor
7         }
8     }
9
10 int main(int argc, char **argv)
11 {
12     rclcpp::init(argc, argv);
13     auto node = std::make_shared<OurClass>();
14     rclcpp::spin(node->get_node_base_interface());
15     rclcpp::shutdown();
16     return 0;
17 }
```

The first thing that you'll notice is that we now have to write more code, so why bother to do this? The key answer to this is reusability. Once you created your own Node class, it is easy to isolate it into a library that is independent from the execution of a process. This allows us to easily replicate and share whatever logic we decided to implement in our Node, at least at compile-time. ROS 2 actually allows us to do something even better than that: the execution of a node can be controlled at runtime. In order to achieve that, another couple of steps are required.

2.1.1 Components and when to use them

Components are **the recommended way to create nodes in ROS 2**. Once a Node is created as a component, its execution can (optionally) be controlled by an executor³, who can run multiple components at the same time. Let's take a look at how to make our class a component.

3: In Chapter 3 you will find a detailed description of executors.

```

1 #include "rclcpp/rclcpp.hpp"
2
3 namespace our_namespace
4 {
5
6 class OurClass : public rclcpp::Node {
7     public:
8         OurClass(const rclcpp::NodeOptions & options) : Node("best_node_name", options) {
9             // Some constructor
10        }
11    }
12 }
13
14 #include "rclcpp_components/register_node_macro.hpp"
15 RCLCPP_COMPONENTS_REGISTER_NODE(our_namespace::OurClass)
```

In addition to this, some trick needs to be applied in the CMakeLists.txt file of our package:

```

1 add_library(our_component SHARED
2     src/our_file.cpp)
3
4 # For Windows compatibility
5 target_compile_definitions(our_component
6     PRIVATE "COMPOSITION_BUILDING_DLL")
7
8 ament_target_dependencies(our_lib
9     "rclcpp"
10    "rclcpp_components")
```

```
12 | rclcpp_components_register_nodes(our_component "our_namespace::OurClass")
```

What we did here is creating a way to allow the component to be discoverable when its library is being loaded into a running process (for example the executor). A component can be loaded into an executor at runtime using command line commands (see [here](#)[9] for the details), through a launchfile (see this [example](#)[10]), or can be manually integrated into your program at compile time, just like we did with our class above. Since it is compiled as a shared library, you can easily export it and [link other packages against it](#)[11]. If you are compiling for Windows, you might want to check [these tips](#) [12].

While it is common for components to derive from `rclcpp::Node`, this is not mandatory. The requirements for a class to be exported as a component are:

- ▶ Have a constructor that takes a single argument that is a `rclcpp::NodeOptions` instance
- ▶ Have a method of the signature:

```
1 | rclcpp::node_interfaces::NodeBaseInterface::SharedPtr  
     get_node_base_interface(void)
```

When should we implement our nodes as components? The short answer is: always.⁴

You might think that it's not worth the overhead of doing all these declarations if, at the end of the day, you don't plan to put your node in an executor at runtime. However, you should not assume that the way you are using your code today is the way it will be used tomorrow. One day, your grandchildren might stumble upon your old component and decide that it should run in an executor. Since there is no relevant drawback (at least that I know) from implementing it as a component, you shouldn't be too lazy and adopt from the beginning a structure that will make the life of your grandchildren easier.

Now that we've structured our node as a component, you might be asking yourself: "Why would my grandchildren want to run multiple components within a single executor?"; there are three possible motivations I can think about (but let me know if you come up with more):

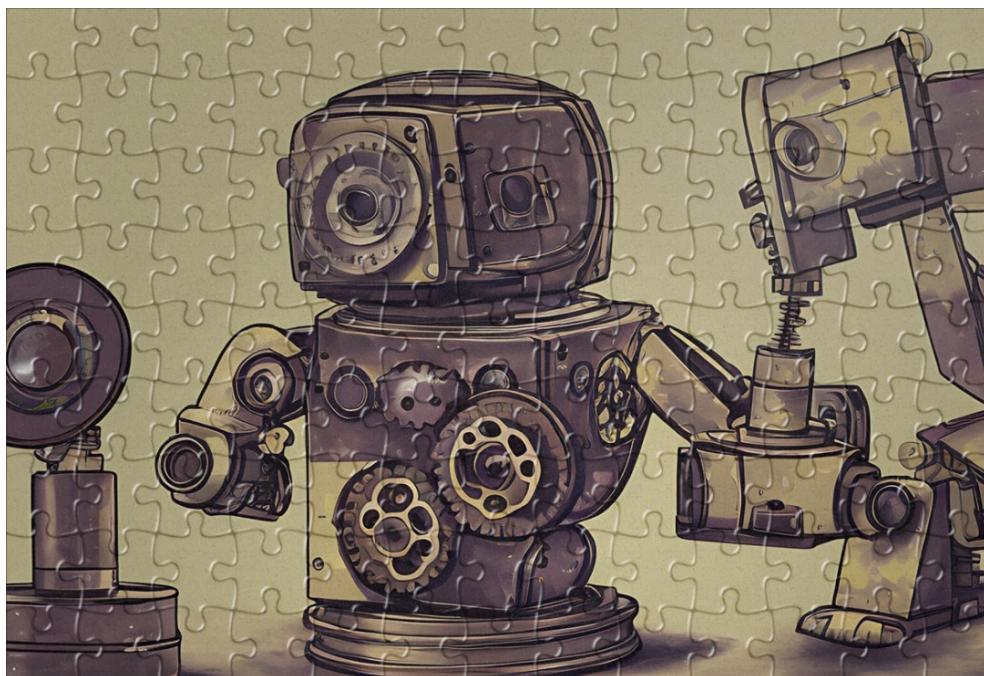
- ▶ While an executor can spawn as many threads as it likes, all the managed components will be running in the same process. This reduces a little bit the effort made by your operating system when performing context switching, since switching between threads of the same process is [slightly faster](#)[13]. Some [experiments](#)[14] have shown how the communication latency between two nodes is significantly lower if these are running within the same process.
- ▶ When two components are running within the same process, they will be sharing the same memory space, and hence cool features like the [zero copy publish and subscribe mechanism](#)[15] can be used⁵. This is especially useful when dealing with devices producing a big amount of data, like for example cameras: if both the drivers and the consumer are implemented as components and run in the same executor, they will be able to transfer data using smart pointers. If they are executed in different processes, ROS will instead perform data serialization without any need for modifications in your code.

4: Ok, you can actually skip this for small scripts and tests, but it's a good idea to use it for your core components.

5: In case you are wondering, yes, this is the ROS 2 equivalent of the old [nodelet](#)[16], however in ROS 2 their role is much more important

- ▶ Putting many components with a limited workload into an executor that is using a small number of threads (or only one), can reduce the total number of threads running on the system, which results, especially on low-end platforms, in a happier scheduler and increased overall performance.

There is anyway an implicit danger when putting multiple components on the same process. Sharing the same memory space implies that errors like a segmentation fault will no longer crash only the affected component, but the entire executor with his family. Consequently, when "merging" two components in the same executor, you should ask yourself: "Should one of them run into trouble, is it important for the other to continue normal operation?". Let's consider for example a component implementing a camera driver and a component using the data from the camera to detect people in a room. If the camera driver dies, the other component probably becomes useless, and it's ok for it to stop working. However, if the camera is additionally used for something else, you'll have to choose if you want to keep those functionalities active in the case of a people-detector malfunction. You probably shouldn't put your camera driver together with the driver of your mobile base. If the camera driver crashes, you still want to be able to drive and maybe charge your robot while waiting for help. Another consequence of using the components structure, is that it forces the programmer to give-up the control over the spinning of the callbacks. Components are meant to be paired with an executor; calling functions like `spin_some`, `spin_once`, and `spin_until_future` on an already paired node results in an exception. In Chapter 3, I will explain how to properly manage this inconvenience.



2.2 The Node types

After taking a look at the ROS 2 tutorials and at some examples[17], you might be tricked into thinking that, in order to write a ROS node, your class will have to derive from rclcpp::Node, or rclpy.node. There's nothing wrong in deriving from these classes, and this is indeed the most convenient way to create your node; however, you should not assume that any node you'll be dealing with will be using them. Other classes exist, that allow you to create a node with special functionalities. You could also choose to create your own customized version.

2.2.1 Managed Nodes

The most common kind of "special node" you'll likely encounter while strolling around the ROS 2 world is the lifecycle node[18]⁶. When using this as base for your class, the resulting node will become a "managed node", whose internal state can be controlled through a set of service calls. A description of all the states and transitions that such a node implements, can be found on the corresponding design article[20].

⁶: A python based implementation is available [here](#)[19]

The transitions of a set of managed nodes are usually handled by a dedicated manager, which can implement any kind of customized logic to choose the order in which the nodes are configured, activated, and eventually deactivated. A complete example can be found in the Nav 2 lifecycle manager[21], that, in addition to handle the initialization of its components, keeps track of their status using a heartbeat strategy.

Starting from ROS 2 Iron, it is possible to trigger these transitions directly from a launchfile using a dedicated ros-launch action: LifecycleTransition. Here is an example of launcher using this functionality to configure and activate two nodes:

```

1 from launch import LaunchDescription
2 from launch_ros.actions import LifecycleNode
3 from launch_ros.actions import LifecycleTransition
4 from lifecycle_msgs.msg import Transition
5
6 def generate_launch_description():
7     return LaunchDescription([
8         LifecycleNode(package='package_name', executable='
9             a_managed_node', name='node1'),
10        LifecycleNode(package='package_name', executable='
11            a_managed_node', name='node2'),
12        LifecycleTransition(
13            lifecycle_node_names=['node1', 'node2'],
14            transitions_ids=[
15                Transition.TRANSITION_CONFIGURE,
16                Transition.TRANSITION_ACTIVATE]
17        )
18    ])

```

This strategy, however, should be used only for test purposes, since it can't perform proper error management.

Lifecycle-managed nodes are very handy when the program is dealing with components implementing a long initialization routine. If other components in the system need to wait for the initialization of the previous ones, a waiting strategy needs to be implemented. The managed

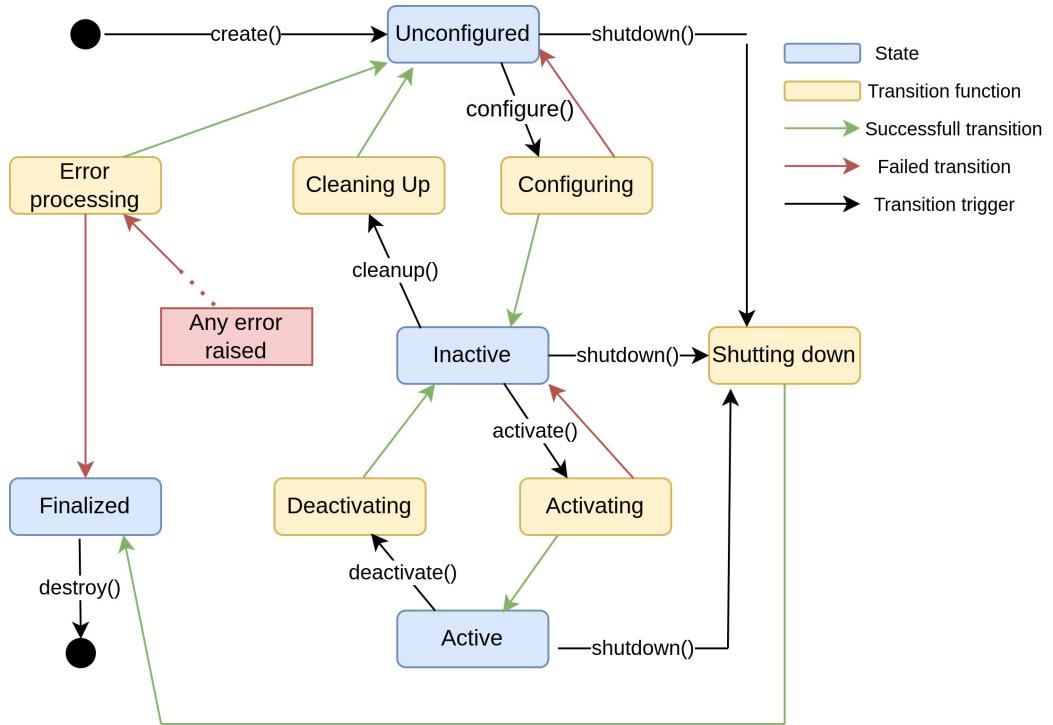


Figure 2.1: Diagram of the state machine implemented by lifecycle managed nodes.
Based on https://design.ros2.org/articles/node_lifecycle.html

nodes provide in this case a clean, standardized way to control their ordered initialization or their deactivation.

If you take a closer look at the [implementation of the lifecycle node](#), you'll notice that this doesn't inherit from `rclcpp::Node`, but only uses some of its components, while providing a new set of interfaces to access them. We'll see why in the coming section.

2.2.2 Custom base nodes

If you are not satisfied with the current implementation or `rclcpp::Node`, and you want to create a new class that provides additional or modified functionalities, you have multiple options:

The first thing that could come to your mind, is to simply inherit from `rclcpp::Node` and extend its public interface with additional functionalities. This works perfectly fine until the moment your application needs to provide some of these functionalities to a nested class or library.⁷ In this scenario, [you won't be able](#) to share your custom node using smart pointers, since a call to `shared_from_this` will resolve the base `rclcpp::Node`. This partially explains why the [implementation of the lifecycle node](#) doesn't inherit from `Node`, but verbosely reproduces its interfaces. The process is a bit longer, but the resulting node is much more versatile.

To provide a node with the functionalities necessary to interface with ROS 2 without deriving from `rclcpp::Node`, a possible way is to instantiate the required [node interfaces](#)[23]. Most of these classes require to first instantiate a `NodeBaseInterface` object, which can be seen as the "core" of the node, and then use it to provide the different functionalities that you

7: It is a common practice to implement libraries / classes that, even if interacting with the ros apis, are not intended to be used as a stand-alone node, but within the context of an existing one. If you need to be able to load these classes at runtime, [plugins](#)[22] might help you.

would usually access using a node pointer. For example, the `NodeTopics` class will allow you to create publishers and subscriptions to topics, the `NodeParameters` to interact with parameters and so on. Once these classes are instantiated, you can wrap and combine them to create your own custom interface. If you respect the rules described in the components section, and declare your class using `enable_shared_from_this`[24], your node will be ready to be run as base for your applications.

Is there a downside in doing all this? Of course, building your system around a custom node implementation drastically reduces your capability of sharing it: whenever you will want to distribute a component based on it, the node implementation will have to follow. Custom nodes also create a very strong "dependency point": having many components depending on it implies that modifying its functionalities while ensuring to not break the existing behaviour of the system is going to be more and more difficult as your system expands. Moral of the story: unless you have a very good reason, stick with the existing default node-classes.

2.3 Using nodes in the interfaces

As we've just seen, even if the `rclcpp::Node` is the most used and convenient base class when creating a node, it is not the only one you might encounter during your ROS 2 adventure. As a consequence, whenever you implement a library or a class that requires ros functionalities, providing them through a pointer to `rclcpp::Node` will reduce its re-usability, since different kind of nodes won't be able to use it⁸. Using a pointer to your own custom node will make it even less re-usable, and re-usability is one of the things that make ROS great in the first place.

So what can we do to generalize our solution? Here are some alternatives:

- ▶ Use the aforementioned node interfaces classes: if your library, for example, only requires to access parameters, provide a `NodeParameters` object instead of a full node. These interface classes will most likely be instantiated and exposed by any kind of node, so you should be safe (for example[25] executors were designed to take the node base interface as input).
- ▶ Rethink your design to use multiple small-nodes instead of integrating small libraries or plug-ins within the same program. Using ROS interfaces (topics, services, actions) makes it easier for other components to access the shared information without having to perform any change on the code of the data-producers. This doesn't apply if you need very deterministic low latency interfaces between the components, since `real time ROS interfaces`[26] are still only experimental.
- ▶ Try to make your component ROS-agnostic. If the ROS specific functionalities used by your code are limited and easy to replace, keeping it ROS-agnostic might not only force you to minimize its interface, but also make it more resilient to updates in the ROS libraries. This should make your packages (or at least a piece of them) easier to maintain, especially while transitioning to a new ROS version like `ROS3`.

⁸: An example of component suffering from this issue can be found [here](#).

Since sometimes none of these approaches leads to a clean implementation, a new strategy was recently developed for dealing with different kinds of nodes in a generic way: the "Generic node interfaces".

2.3.1 Generic node interfaces

Starting from ROS 2 Iron, it is possible to wrap different node interfaces into a unified object: the [NodeInterfaces class](#)[27]. Using this object, it is possible to provide to a function or a class multiple node-functionalities using only one parameter.

To better explain this, I'll report an example from [here](#). Suppose that we have a function and that we want to use some of the functionalities provided by a node within it. Using the classic node interfaces, you would write a function definition like:

```
1 void fn(NodeBaseInterface::SharedPtr base_interface,
2         NodeClockInterface::SharedPtr clock_interfaces);
```

You would later call fn like this:

```
1 rclcpp::Node node("some_node");
2 fn(node->get_node_base_interface(),
3     node->get_node_clock_interface());
```

Using the NodeInterfaces class we can instead define:

```
1 void fn(NodeInterfaces<NodeBaseInterface,
2         NodeClockInterface> interfaces);
```

The function fn can now be called in two different ways:

```
1 // explicitly
2 auto ni = NodeInterfaces<NodeBaseInterface,
3       NodeClockInterface>(node);
4 fn(ni);
5
6 // implicitly
7 fn(node);
```

The implicit form is probably the one you will want to use: the function call is now much more compact and elegant, resembling what in ROS1 was done with a node-handle. If you need it, it is additionally possible to subset a node interface, to build it from aggregation or to extract its internal interfaces:

```
1 // subsetting
2 auto ni_base = NodeInterfaces<NodeBaseInterface>(ni);
3 auto ni_aggregated = NodeInterfaces<NodeBaseInterface,
4       NodeClockInterface>(
5     node->get_node_base_interface(),
6     node->get_node_clock_interface()
7 )
8
9 auto base = ni.get<NodeBaseInterface>();
10 auto clock = ni.get_clock_interface();
```

Homework

Create two managed nodes as components, and a third node that, upon getting a request through a service, will initialize and start them sequentially. Put all these components within the same executor using a launchfile. You can find hints in the linked documentation.

The solution to the homework can be found [here](#)



3 Callbacks and Executors

When taking a look at a ROS 2 application, it is important to distinguish between what part of the code is running within a *callback*, and what part isn't. If you are following the components design pattern, as we suggested in the previous chapter, and you are not manually spawning your own threads, it is likely that most of your code is already running within a callback.

3.1 The callback

What is exactly a callback? Technically speaking, it is that part of the code that can be executed only by an executor, or by an invocation of one of the spinning functions (*spin*, *spin once*, and *spin until future complete*). This includes the following:

- ▶ Subscription callbacks ([example\[28\]](#))
- ▶ Timer callbacks ([example\[29\]](#))
- ▶ Service calls, including parameters callbacks ([example\[30\]](#))
- ▶ Received client responses ([example\[31\]](#))

You are in charge of defining what the callbacks do, but you can not strictly enforce the moment in which they will be executed.

At a first glance, callbacks look pretty harmless and easy to implement; however the bad management of callbacks execution is probably the most common source of issues for novice ROS 2 programmers. On the other hand, a good management can simplify your code reducing the need for thread-synchronization mechanisms like mutexes and condition variables.

To understand why callback management is so critical, we need to take a look at the tools that allow us to control their execution.

3.2 The executors

Simply put, the job of an executor[32] is to check for available work and to execute it. More specifically, an executor controls the threading model used to process callbacks.

You can interface with an executor to let it know that you would like it to wake up and do some stuff using a set of spin functions[33]. In the most classic scenario, like we showed in the node chapter, you will assign one or more nodes to an executor, and then call the blocking spin function on it; this will delegate to the executor the task of executing any callback associated with the nodes whenever it thinks it's best to.

It is also possible to interface with it using non blocking functions, like spin once / spin node once or spin some / spin node some; while the first two will only execute one available callback, the former two will execute all the available work before exiting.

One important thing to note is that **nodes can not be associated simultaneously with multiple executors**. Consequently, if you already associated a node with an executor, calling functions like spin_some or spin_until_future_complete from within the node will generate a runtime error.

There are three types of executors: the SingleThreadedExecutor[34], the StaticSingleThreadedExecutor and the MultiThreadedExecutor[35]. As it is easy to guess, under the hood, the SingleThreadedExecutor will use only one thread of your operating system, while the MultiThreadedExecutor will use more than one¹.

The "static single threaded executor", contrary to what happens for the other two executors, only scans for new subscriptions (anything associated to a callback) right after a node was added to it. This means that if new associations (like for ex subscriptions or timers) are performed after starting the node, they will be ignored. This reduces the runtime overhead of the executor, but needs to be used very carefully: only do this if you are absolutely sure that nobody will ever ever try to create new subscriptions dynamically. Other developers might be unaware of the constrictions imposed by this executor and might lose a lot of time trying to understand why their code isn't executed as expected. At the moment of writing, this functionality is only available for rclcpp.

When I started the chapter, I tried to scare you saying that callbacks are evil beasts who can easily generate issues in your application. Let's see an example where this happens.²

We'll create an application with two nodes: the first one will start a timer and, twice per second, will ask the second node if it's alive using a service. The second node will simply host the *is alive* service. The complete program can be found on my examples folder on Github[36]. Our simple service server class looks like:

```

1 // service_server.hpp
2 #include "rclcpp/rclcpp.hpp"
3 #include "std_srvs/srv/empty.hpp"
4
5 class ServiceServer : public rclcpp::Node {
6 public:
7     ServiceServer(const rclcpp::NodeOptions& options);

```

1: By default a MultiThreadedExecutor will use as many threads as the number of processors on the running machine, but you can (and you should) specify a different amount at instantiation time.

2: This is going to be easy for me: years and years of experience as a ROS programmer have given me a great deal of ability to write code that doesn't work.

```

8 private:
9   /// Executed when a request is received
10  void serviceCallback(std::shared_ptr<std::srvs::srv::Empty>::Request:::
11    SharedPtr srv_request,
12    std::shared_ptr<std::srvs::srv::Empty>::Response::SharedPtr
13    srv_response);
14  /// Service to get callbacks
15  rclcpp::Service<std::srvs::srv::Empty>::SharedPtr service_>;
16 };
```

And is implemented as:

```

1 // service_server.cpp
2 #include "service_test_pkg/service_server.hpp"
3 using namespace std::chrono_literals;
4
5 ServiceServer::ServiceServer(const rclcpp::NodeOptions&
6   options)
7   : rclcpp::Node("service_server", options) {
8     service_ = create_service<std::srvs::srv::Empty>(
9       "is_alive", std::bind(&ServiceServer::serviceCallback
10      , this,
11      std::placeholders::_1, std::placeholders::_2));
12     RCLCPP_INFO(get_logger(), "Service started");
13 }
14
15 void ServiceServer::serviceCallback(std::shared_ptr<std::srvs::srv::Empty>::Request:::
16   SharedPtr srv_request,
17   std::shared_ptr<std::srvs::srv::Empty>::Response::SharedPtr srv_response)
18   {
19     RCLCPP_INFO(get_logger(), "Got a request");
20 }
```

The client class is:

```

1 // service_client.hpp
2 #include "rclcpp/rclcpp.hpp"
3 #include "std_srvs/srv/empty.hpp"
4
5 class ServiceClient : public rclcpp::Node {
6   public:
7     ServiceClient(const rclcpp::NodeOptions& options);
8   private:
9     /// Executed periodically by the timer
10    void timerCallback();
11    /// Timer to run periodic tasks
12    rclcpp::TimerBase::SharedPtr timer_;
13    /// Client to call the service server
14    rclcpp::Client<std::srvs::srv::Empty>::SharedPtr client_;
15 };
```

And is implemented as

```

1 // service_client.cpp
2 #include "service_test_pkg/service_client.hpp"
3
4 using namespace std::chrono_literals;
5
6 ServiceClient::ServiceClient(const rclcpp::NodeOptions&
7   options)
8   : rclcpp::Node("service_client", options) {
9     client_ = create_client<std::srvs::srv::Empty>("is_alive")
10    ;
11    client_->wait_for_service();
12    timer_ = create_wall_timer(500ms, std::bind(&
13      ServiceClient::timerCallback, this));
14    RCLCPP_INFO(get_logger(), "Client started");
```

```

12 }
13
14 void ServiceClient::timerCallback() {
15     RCLCPP_INFO(get_logger(), "Sending request");
16     auto request = std::make_shared<std::srv::Empty::Request>();
17     auto future_result = client_->async_send_request(request)
18     ;
19     future_result.wait();
20     RCLCPP_INFO(get_logger(), "Got result");
}

```

If we associate each of these nodes to a separate single threaded executor and launch them, we'll get the following output:

```

1 [INFO] [1669578059.747553782] [service_server]: Service
2     started
3 [INFO] [1669578059.747617040] [service_client]: Client
4     started
5 [INFO] [1669578060.248018749] [service_client]: Sending
6     request
7 [INFO] [1669578060.248209118] [service_server]: Got a
8     request

```

As you probably already guessed, the code gets stuck waiting for the response of the service. This is happening because the service is called from within a callback (which is executing the timer): in order for the answer to be processed, another callback needs to be executed, but since the executor is not yet done with the previous one, it will not process it. We got our self into a [deadlock](#)[37]: no matter how long we wait, we'll never get that answer.

A tentative solution could be replacing the SingleThreadedExecutor with a MultiThreadedExecutor: intuitively, if one thread is stuck on a callback, a different thread could take over the execution of another. However, this won't solve the problem (try it yourself using the code in my repo). To understand what's going wrong we need to introduce a new concept: the *callback groups*.

3.3 The callback groups

[Callback groups](#)[38] are, together with the executors, the second way the execution of callbacks can be controlled. The groups give you the ability of managing some of your callbacks together in order to control when the executor's threads are going to run them.

There are two possible kind of callbacks:

- ▶ *MutuallyExclusive*: the callbacks added to this group can not be executed simultaneously. These give you the ability of avoiding data-races when accessing shared data without the need of using mutexes. For example, you could put the callback of the topic getting the data from a sensor in the same *MutuallyExclusive* group as the callback that is processing that data to do something.
- ▶ *Reentrant*: callbacks in this kind of group can be executed concurrently by different threads. This can give you the ability of solving deadlock situations like the one described before, and bring with themselves [all the advantages and disadvantages of multithreaded applications](#)[39].

Unless otherwise specified, a ROS 2 application uses by default only one **MutuallyExclusive** callback, even if associated to a multithreaded executor. This explains why, in the previous example, our code got into a deadlock: the periodic timer's callback executes in the default callback group, and, when a service call is executed, a new callback to get the answer is created, which is also put in the default group³. Since the code performs a "synchronous call", meaning that it will wait for the result to be returned before continuing, the timer's callback is never exited, and since the default group is **MutuallyExclusive**, the callback thread can't be executed.

How can we get out of this trap? There are two possible approaches:

- ▶ Avoid blocking operations within callbacks. If the code is written in a way that guarantees that each callback is executed quickly without ever waiting for other callbacks to occur, deadlocks simply can't occur. If you manage to, this is the recommended way to go: only one callback group, no additional threads, no concurrency issues. You should also note that functions like *wait for service* don't require a callback, and hence can be safely used as long as you specify a relatively short time-out.
- ▶ Create additional callback groups and use a Multithreaded spinner. If the callbacks that need to be executed concurrently or with parallelism[40] are stored in separated groups, or into a group of type "Reentrant", the spinner will be able to allocate different threads for each of them. While this seems very convenient, since it allows the programmer to almost forget the callback-deadlock issue, the previous solution should be preferred to avoid the "costs"
⁴ and the dangers deriving from multi-threading programming.

Now let's take a look at how to use an additional callback group to avoid the callback deadlock in the previous example. If we assign the timer to a dedicated callback group, the default callback group of the node will be free to process the service response:⁵

```

1 // in service_client.hpp
2 rclcpp::CallbackGroup::SharedPtr cb_group_;
3
4 // in service_client.cpp
5 cb_group_ = create_callback_group(rclcpp::CallbackGroupType
6   ::MutuallyExclusive);
    timer_ = create_wall_timer(500ms, std::bind(&
      ServiceClient::timerCallback, this), cb_group_);

```

If we keep associating the client to a single threaded executor, this won't do the trick, because no thread is available to pick up the new job. If instead we associate the client with a multi threaded executor⁶, we get the following output:

```

1 [INFO] [1669578073.154820240] [service_server]: Service
  started
2 [INFO] [1669578073.154899273] [service_client]: Client
  started
3 [INFO] [1669578073.655154472] [service_client]: Sending
  request
4 [INFO] [1669578073.655417424] [service_server]: Got a
  request
5 [INFO] [1669578073.655641974] [service_client]: Got result
6 [INFO] [1669578074.155132710] [service_client]: Sending
  request

```

3: This is automatically created by ROS, even if you don't explicitly instantiate the callback, and associated with the returned future

4: Instantiating too many threads might hurt the performance of your system[41]. When instantiating a Multithreaded spinner, specify only the amount of threads you need. Often two threads are enough to avoid callback deadlocks.

5: For this scenario, using a **MutuallyExclusive** callback group or a Reentrant one won't make any difference: only the timer is associated to it. If, instead, we had chosen to add the service client to the same callback group, a Reentrant group would have been necessary to avoid deadlocks.

6: Two threads are sufficient for this scenario.

```

7 [INFO] [1669578074.155607484] [service_server]: Got a
     request
8 [INFO] [1669578074.155951888] [service_client]: Got result
9 ...

```

Which is the expected behavior.

3.4 Deterministic execution

Do you remember when you were told that ROS 2 is capable of real-time operations and hence a framework that can be used to develop industry-ready solutions? Well, this isn't exactly true for ROS 2 applications using the "default" ROS 2 libraries. Most of these objects make an ample usage of dynamic memory allocations, blocking publish-calls and in general were not thought to run deterministically.

A real-time system should provide a way to establish a hierarchy of priorities between the executing processes and threads. This should allow to make sure that high priority tasks get executed within their deadlines. The default ROS 2 executors don't allow fine-grade control over what is executed at what point in time, and are not capable of dealing with the "priority inversion problem": a thread with low priority might prevent the execution of another thread with higher priority⁷.

Is all of this bad? Not really. Many robot-applications don't require a deterministic execution, and are better off with a "relaxed" task scheduling that tries to optimize the global utilization of the robot's resources. Furthermore, programming deterministic applications restricts a lot the kinds of resources that a programmer can use (libraries, programming languages, operative system...).

There are however cases where deterministic execution is necessary for the correct robot's behavior. You will find some examples in chapter 6. In these cases, if the information provided by some callbacks needs to be processed with a defined order, you can use one of the following solutions:

3.4.1 WaitSet

The `WaitSet` object, available in `rclcpp`⁸, allows the programmer to specify which callbacks are executed under a specified set of conditions, called `GuardConditions`. When using a `WaitSet`, the execution flow looks more or less like this:

- ▶ One or more subscriptions (or timers, clients, ...) are created using the normal ROS 2 APIs.
- ▶ One or more `GuardConditions` objects are instantiated. These will later be used to signal the moment in which the callbacks will become processable.
- ▶ A `WaitSet` object is constructed. The subscriptions and the guard conditions are assigned to it. Multiple types of `WaitSet` objects exist, some of them will require all the associations to be performed at construction times, while others allow for dynamic additions / removals.

7: Here the [sad story](#) of an old Mars robot suffering from priority inversion.

8: If you are trying to perform deterministic operations using `rclpy`, you are on the [wrong path](#).

- ▶ When the code is ready to process new callbacks, the "wait" method of the WaitSet object is called; a wait-timeout can be specified to avoid blocking indefinitely.
- ▶ One or more guard conditions are signalled asynchronously using their "trigger" method, unlocking in this way the waiting thread.
- ▶ The awakened thread verifies if new data is available on any of the callbacks using the "get_rcl_wait_set" method of the WaitSet. If new data is available it can be retrieved from the subscribers using their "take" method.

In this way, the programmer can control which information is processed in each moment. This would not have been possible using methods like "spin_once" that would execute all the available "work" in an undefined order.

Using this feature can be, for example, useful for synchronizing part of the execution flow with the feedback provided by sensors in a control system.

Multiple examples of programs using the WaitSet, very useful for understanding all its capabilities, can be found [here](#).

It must be noted that using a WaitSet doesn't exclude the usage of a normal executor in the same node, but can be complementary to it. The programmer must take care of creating the subscriptions to be associated with the WaitSet without adding them automatically to the executor⁹. The Wait Set must later be handled as explained above by a dedicated thread.

⁹: This can be usually done through a dedicated flag in their constructor.

3.4.2 Micro-ROS and the rclc Executor

Traditionally, ROS is not executed on micro-controllers, but on embedded industrial PCs with "good" computational capabilities and a "big" amount of memory. Microcontrollers are, however, often executing part of the robot's functionalities alongside a "main controller". This can be done in order to aggregate data coming from multiple devices using compact hardware, to minimize latencies, for the sake of separating responsibilities, or for many other reasons.

Usually, the communication between the device running ROS and the micro controllers needs to happen using customized protocols, since the micro-controller can't execute ROS nodes. [Microros\[42\]](#) was born to change this.

Using this framework, which is based on ROS 2 and optimized for the execution on micro-controllers, it is possible to run ROS 2 nodes directly on "edge devices" simplifying in this way the communication interface. The devices can run different kinds of real time operative systems designed for embedded devices, like FreeRTOS, Zephyr and others.

The stack is designed to allow the creation of deterministic applications that interact with ROS using the C client library: [rclc](#). Contrary to what happens for other client libraries (we will take a look at them in chapter 4) this doesn't constitute an additional layer on top of rcl, but is rather a set

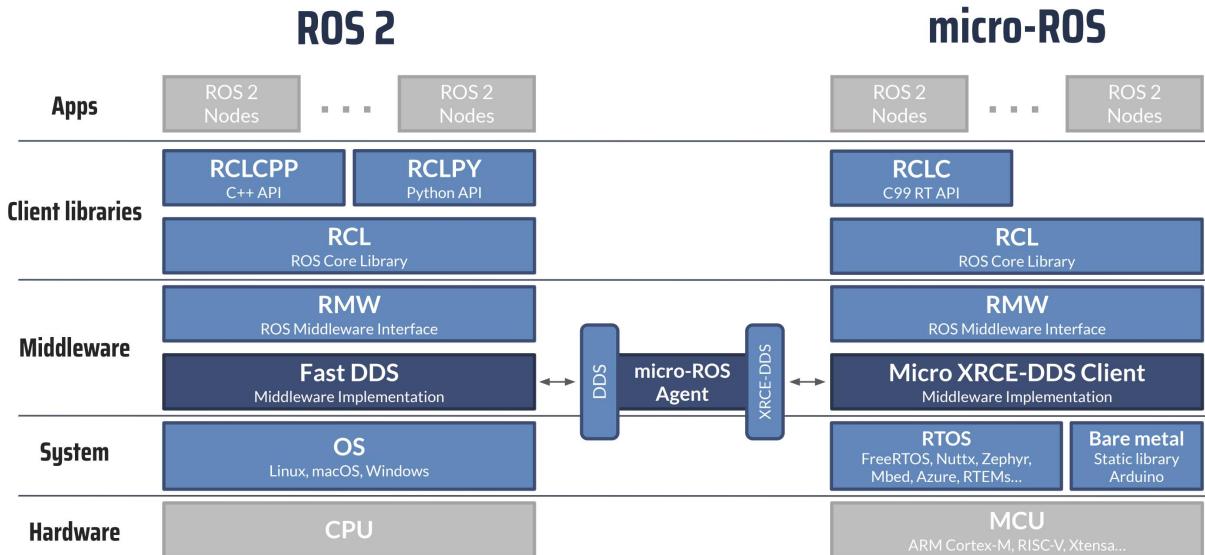


Figure 3.1: Architecture of micro-ROS

From <https://micro.ros.org>

of convenience functions that make building an application on top of the rcl layer easier.

An important component in this architecture is the **executor**. "The goal of the Executor in micro-ROS is to support roboticists with practical and easy-to-use real-time mechanisms which provide solutions for" [43]:

- ▶ Deterministic execution
- ▶ Integration of real-time and non real-time functionalities on one platform
- ▶ Specific support for RTOS and microcontrollers

This executor is capable of leveraging the real-time characteristics of the underlying operating-system scheduler to have finer control on the order of executions. Embedded systems are typically based on the time-triggered paradigm, which implies that processes are executed periodically. Processes with high priority can preempt processes with lower priority. In addition to this, it is often desirable for the time spent between reading values (for example from a sensor) and producing output that depends on those values, to be constant. In chapter 6, we will explain in detail why this is important. For now you should know that the rclc executor is capable of leveraging the **logical-execution time paradigm**[44] to make this possible. Time-critical callbacks are executed without the risk of priority inversion, making it easier to determine the average and the worst case execution latencies.

It must be noted that, even if this framework was designed to work on micro-controllers it can execute on Linux too.

If you are not afraid of C, and would like to have more information about the ins and outs of the rclc executor, or about the limitations of the rclcpp executors, you can find plenty of useful information [here](#).

Should your robot require to provide real-time ROS compatible functionalities on one or more embedded micro-controllers, microROS is definitely something you should take into consideration.

Homework

- ▶ Can you change the previous example to make it work using only a single-threaded executor?
- ▶ Verify that a static single threaded executor won't run callbacks registered after the corresponding node was added to it.
- ▶ Which risk do you face if you manually call "rclcpp::spin_once()" in the constructor of a lifecycle-managed node?



4 Interfaces

In the first chapters we have gone through some tips that can help us build the blocks of our application in a generalized and scalable way. It is now time to make these blocks talk with each-other.

One question that comes up many many times while implementing a ROS 2 application is: what kind of interface should I use to pass information between two nodes? ROS 2 provides a pool of options you can choose from, and figuring out which one is best suited for your use-case is not as trivial as one might think.

Before discussing the main interfaces provided by ROS 2, to come up with a selection criteria, we'll take a quick look at how the "internal interfaces" are organized in the ROS 2 stack.

4.1 Internal interfaces

In order to allow for the easy integration of [APIs](#) for new programming languages and different [DDS](#)[45] implementations, while keeping the system behavior coherent and the amount of maintained code limited, ROS 2 adopts a layered architecture model, which is displayed in figure 4.1.

On the top layer, the user application only interacts with a set of APIs specific for the used programming language, called the [client libraries](#). These APIs provide the "high level functionalities" that we will be mostly talking about (access to topics, services, ...) in a way that completely abstracts from the underlying implementation.

The ROS Client Library Interface (rcl) was introduced in order to limit the code replication during the implementation of the client libraries and consequently reduce the effort necessary to maintain them. If you are familiar with ROS1, you'll know how [roscpp](#)[47] and [rospy](#)[48] differ in terms of functionalities offered to the user. Just as an example: it is possible to create UDP based connections using roscpp, but not using rosdp. ROS

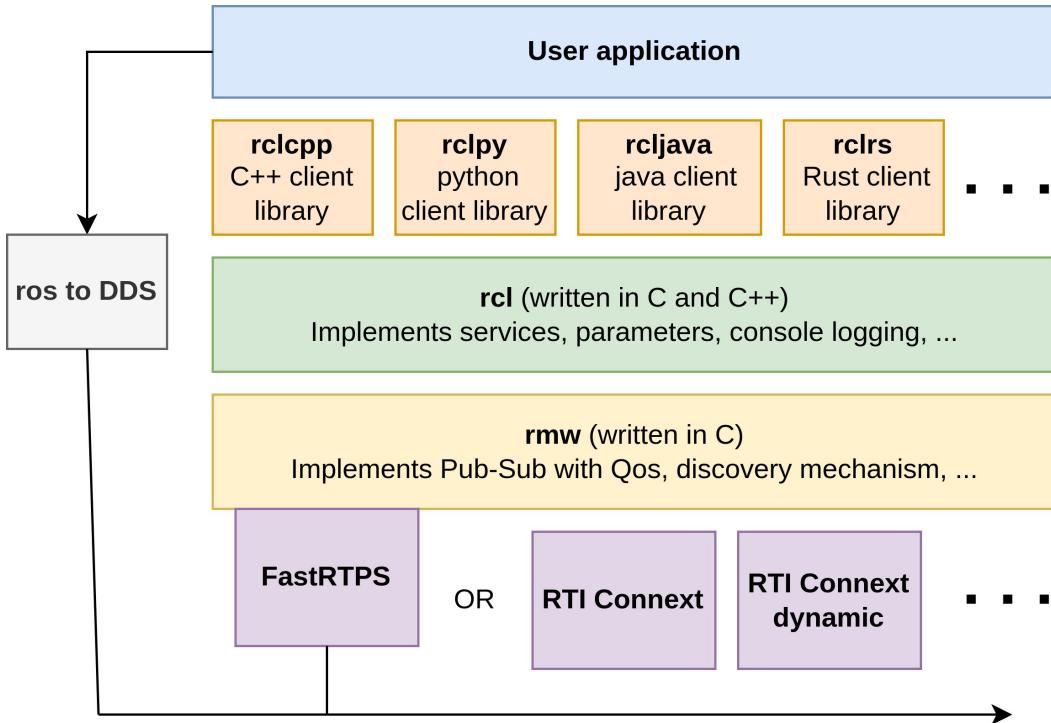


Figure 4.1: Diagram of the internal ROS 2 interfaces structure
 Based on <https://docs.ros.org/en/humble/Concepts/About-Internal-Interfaces.html>[46]

2 avoids these issues providing a common underlying implementation mainly written using C APIs.

The ROS Middleware Interface (rmw) allows the rcl to abstract from the specific middleware (in the specific DDS) implementation used at the bottom layer. It is actually possible to execute the same ROS application [using different pairs](#)[49] of rmw implementation and DDS. When installing ROS 2, the default rmw implementation you will be using will depend from the distribution; for example [ROS 2 Galactic](#)[50] will by default use [rmw_cyclonedds](#)[51] while [ROS 2 Humble](#)[52] will use [rmw_fastrtps](#)[53]. This choice is usually performed by the ROS community based on stability and performance criteria, but it is often a good idea to test which of the available options performs better for your specific application.

At the moment of writing, the DDS implementations supported by ROS 2 are:

- ▶ [eProsim Fast DDS](#)[54], supported through `rmw_fastrtps_cpp`
- ▶ [Eclipse Cyclone DDS](#)[55], supported through `rmw_cyclonedds_cpp`
- ▶ [RTI Connex DDS](#)[56], supported through `rmw_connexdds`
- ▶ [GurumNetworks GurumDDS](#)[57], supported through `rmw_gurumdds_cpp`

Switching between them is [fairly easy](#), but, when doing it, keep in mind that you might have to first install the desired rmw implementation, and then recompile your code from scratch. This is often necessary because some packages will enable "rmw specific features" at compilation time.

Now that we have a rough idea of what's going on under the hood, let's take a look at how some of the DDS features were wrapped by the ROS 2 APIs to provide intra and inter-process communication mechanisms.

4.2 Policies

Contrary to what happens in ROS1, when creating a topic in ROS 2, the user doesn't have direct control over the used transport mechanism, meaning that it can not specify at the user application level if a [TCP\[58\]](#) socket, a [UDP\[59\]](#) socket or memory sharing mechanisms will be used to transfer the data. These details are delegated to the underlying middleware implementation (the [DDS](#) we were talking about before), while the programmer is required to specify "the desired properties of the communication channel".¹

When publishing or subscribing to an interface, you are asked to choose between different "policies", which will influence the probability of messages being lost, the latency of the communication, the criteria used to choose when to publish new messages and how many messages can be buffered into a queue before being discarded. As specified in the [docs\[60\]](#), the choices currently available are:

- ▶ History, can assume the following values:
 - Keep last: only store up to N samples, configurable via the queue depth option (see below).
 - Keep all: store all samples, subject to the configured resource limits of the underlying middleware.

Using "Keep all" is somewhat discouraged (why would you do that without knowing what the real middleware limit actually is?).

- ▶ Depth
 - Queue size: only honored if the "history" policy was set to "keep last". As a rule of thumb, if you only care about your subscribers getting the most recent information (as is often the case with sensor data), you should keep this small (1 or 2), while if all the published information needs to be processed, this should be large.
- ▶ Reliability
 - Best effort: attempt to deliver samples, but may lose them if the network is not robust. This is similar to using a pure UDP transmission channel in ROS1.
 - Reliable: guarantee that samples are delivered, may retry multiple times. This is similar to a reliable TCP transmission channel in ROS1.
- ▶ Durability
 - Transient local: the publisher becomes responsible for persisting samples for "late-joining" subscriptions. This is for example required if you want to recreate something similar to the old ROS1 [latching mechanism\[61\]](#)².
 - Volatile: no attempt is made to persist samples.
- ▶ Deadline

1: Most of the DDS implementations will use by default communication mechanisms based on the UDP protocol, even for reliable communication channels. In some cases it is however possible to force the DDS to use the TCP protocol or, if running within the same machine, shared memory

2: But better! Multiple publishers can now publish to the same "latched" topic and new subscribers will get the last published information from all of them.

- Duration: the expected maximum amount of time between subsequent messages being published to a topic. This can be used to create a sort of "contract" between publishers and subscribers: a subscriber might reject data if the publisher doesn't commit to publish it at a given frequency, and can be notified through a callback in the case of missed deadlines.
- For details on the implementation, checkout this [example\[62\]](#).

► Lifespan

- Duration: the maximum amount of time between the publishing and the reception of a message without the message being considered stale or expired (expired messages are silently dropped and are effectively never received). This is very useful when publishing control commands: reacting on a very old message could lead to unexpected behaviours of the robot.
- [Here\[63\]](#) you can find a usage example.

► Liveliness

- Automatic: the system will consider all of the node's publishers to be alive for another "lease duration" when any one of its publishers has published a message.
- Manual by topic: the system will consider the publisher to be alive for another "lease duration" if it manually asserts that it is still alive (via a call to the publisher API).

[Here\[64\]](#) you can find an example on how to get notifications about changes on the liveliness of a topic.

► Lease Duration

- Duration: the maximum period of time a publisher has to indicate that it is alive before the system considers it to have lost liveliness (losing liveliness could be an indication of a failure).

As you can imagine, specifying all of these parameters each time you want to create a new publisher would be quite a bit of work; to make your life easier, ROS 2 provides a set of preconfigured profiles.

4.2.1 Profiles

It is likely that the requirements for your interface will fall within a set of categories that are common in Robotics. For some of these, [profiles\[65\]](#) were created, that will set the [communication policies\[66\]](#) in order to help you satisfying the requirements of the corresponding use-case. Let's take a look at some of them:

- **Sensor data:** This profile will use the "best effort" communication strategy, meaning that some data might not be correctly delivered, since errors will not result in re-transmissions. Under the hood, this will result in "smaller packages" transmitted with a lower latency, resulting in less network traffic. This profile could be your choice if you want to get the latest available information, without caring about losing some message now and then. This is often the case when listening to sensor data, hence the profile name³.

3: It must be noted that using an unreliable connection to transmit big messages (like point cloud data) might be counterproductive: these messages need to be fragmented into many packets to be transmitted, and losing any of these could result in the whole message being discarded. Using a mechanism that contemplates the re-transmission of lost packages (a reliable connection) might be necessary in order to achieve the desired transmission frequency.

- ▶ **Parameters / Parameters events:** since, frequently, parameters are used to configure a node only at the beginning of its execution, it is important that when this happens a reliable communication mechanism is used. This profile adds a very big queue to a reliable communication strategy to make sure that no information is lost.⁴
- ▶ **Services default:** by default, ROS 2 will assume that you don't want to lose messages, and will hence use a reliable communication strategy. Note that it also assumes that producers and consumers will be able to process the data at a similar frequency, since the communication queue is kept relatively small.
- ▶ **System default:** this profile will use the default settings of the underlying middleware (DDS). Since different DDS implementations use different configurations, and figuring out which configuration is actually used a priori is not trivial, **you should never use this setting**. Use more specific ones to avoid making the behavior of your system dependent on the used DDS implementation.

4: When interacting with parameters, this profile is used automatically without you needing to specify any configuration.

4.2.2 Compatibility of policies

As we just discussed, in a ROS 2 interface, the data producer and the data consumer can specify which communication policy to use independently. The obvious question you might be asking yourself is, what happens if these differ?

As you can check in more detail with these [compatibility tables](#)[67], it can actually happen that no data is transmitted between them if the policies are not compatible. This characteristic can easily trick you into thinking that a publisher is not working, just because your subscriber is using an incompatible policy. To make it even more tricky, older version of the CLI tools like "`ros2 topic echo`" are not able to figure out automatically which quality of service to use to receive and display the data. An example: should you have a robot at hand that is publishing its description on the standard "/tf" and "/tf_static" topics, executing

```
1 | ros2 topic echo /tf_static
```

will not display any result on ROS 2 versions older than Humble. This happens because "/tf_static" is published with durability "transient_local" in order to let new subscribers get the last published message upon subscription. If you want to make the "echo" command on the command line interface work, you'll probably have to execute:

```
1 | ros2 topic echo --qos-durability transient_local --qos-reliability reliable /tf_static
```

Policies incompatibilities can be annoying, but there are a couple of tricks that can help you to remember how to handle the compatibility constraints. If you take a look at the [tables](#) we were just talking about, you will notice that the logic behind them can be simplified to two points:

- ▶ For a connection to work, the quality of service provided by the publisher has to be \geq than the quality of service(Qos) provided by the subscriber.
- ▶ If compatible, the Qos specified by the subscriber will be used.

A consequence of this is that data producers defined with a high quality of service will be compatible with any kind of data consumer. To take advantage of this, **it is a good practice to use reliable Qos settings on the publishing side**, and delegate the choice of the kind of connection to be used to the subscriber. For example, in order to get the information as quickly as possible, a node checking for collisions between the robot and its environment could subscribe to the data produced by a lidar using the "Sensor data" profile. A different node performing a less time-sensitive operation, like a calibration routine, could choose to subscribe to the information provided by same publisher using a reliable connection. If the publisher was instantiated using a reliable Qos, both will work.

In the case it is important to always limit the amount of data-traffic on a given interface, or to enforce a desired Qos across all its users, specifying an "unreliable" Qos on the publisher might be more effective.

If you want to introspect the Qos used on an existing topic, you can use the "verbose" option of "ros2 topic info". Here is an example of output:⁵

5: When trying to visualize a topic with a Qos different from the default one in **Rviz**[68], you can configure the policies to be used to achieve compatibility directly from the user interface.

4.3 Topics

Topics[69] are the most common communication system used to transfer data between ROS 2 nodes. They constitute a one-to-many mechanism, in which the publishing node specifies a name for the communication channel (the topic) and the type of data (the message) to be transferred. Any other node in the system knowing the name of the topic and the structure of the transmitted message can subscribe to this information.

4.3.1 Specifying the desired Qos profiles

If you got here, you probably already know [how to create a simple publisher and a subscriber](#)[70]. Specifying what profile you would like to use on a publisher or a subscriber just requires a couple of additional parameters. To make an example, let's see how we can setup a "string" publisher so that whoever subscribes to its topic will receive the last published message without having to wait for a new one to be published:

```

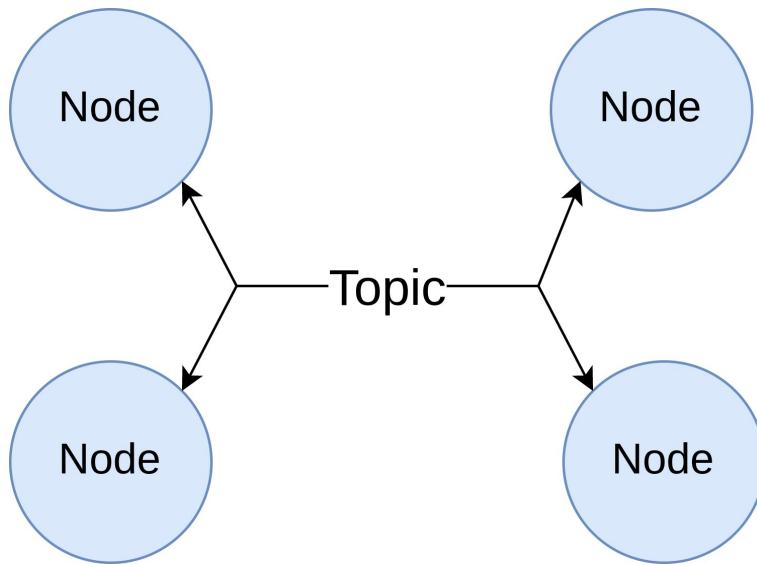
1 awesome_publisher = this->create_publisher<std_msgs::msg
2   ::String>(
  "topic_name", rclcpp::QoS(1).transient_local());

```

Easy, right? After specifying the topic name, you need to add a new argument and do the following:

- ▶ Build a **QoS object**, passing as only parameter the depth of the history the publisher should keep. Since we want to transmit only the last published message to any new subscriber, we specify 1.
- ▶ Set the durability setting to transient local. This makes the publisher responsible for persisting samples for “late-joining” subscriptions. As we already commented before, this is similar to what happens with the ROS1 latched topics.

If no other profile setting is specified, the default ones will be used. This implies, for example, that the reliability will be set to "reliable".



4.3.2 When should you use a Topic interface?

This question can be briefly answered with "Whenever your node produces data without requiring any input from the listener and doesn't care if and when anyone will receive it". This includes a lot of typical use-cases:

- ▶ **Data produced by sensors.** Sensors are a prerequisite for a robot to be called robot, so this case is quite common. Sensors will typically produce data at a specified frequency, without caring about who is listening to them, so a topic is usually the perfect match. When dealing with sensors producing a lot of data that is not consumed regularly (like when reading 3D point-clouds for object detection), it might make more sense to switch to a "produce on request" mechanism to reduce the overall computational effort of the system.
- ▶ **Robot-state information.** It is quite common for robots to parse the information produced by some of their sensors into messages that describe the robot state in a human-readable way. These could,

for example, contain the `battery state`, or the `transformations`[71] between the joints of the robot. Since this is usually a one-to-many transmission that doesn't require any input from the listeners, topics are a good match.

- ▶ **Diagnostic information.** If your nodes are producing data that, in order to assess the correct behaviour or the performance of the system, needs to be examined in "real-time"⁶, topics are again the way to go. Anyone can subscribe to their information without needing to synchronize with the publisher. Once your data is on a topic, it can also be recorded to disk using `rosbag`[72], and replayed at a later moment in time.

If the published information assumes discrete values and doesn't change frequently, it is a good practice to use the "transient local" policy and publish the information only when a change is detected. This can drastically reduce the amount of data transmitted on the network, making everybody happier.

⁶: Here real-time needs to be read as "simultaneous" and not in the deterministic sense of the word.

4.3.3 Naming your topic

Now that you've finally decided that your interface should be a topic, it's time to give it a name. Just as it happens for babies, there are a `couple of rules`[73] to look out when assigning a name to an interface.

- ▶ It must not be empty. Might sound obvious, but sooner or later you'll have a node crashing because you forgot to assign a name.
- ▶ Must only contain alphanumeric symbols and underscores '_' or the forward slash '/'; the latter two should never be repeated and never be at the end of the name.
- ▶ Can start with the prefix "~/", the private namespace substitution character (but, as we'll see later, you don't really need it).
- ▶ Can use curly brackets '{}' for name substitutions.
- ▶ Should not be named Adolf.

Some topic names are by convention bounded to specific message types and usages. This is not an enforced rule, but to avoid confusion it's good rule to respect it. These include:

- ▶ 'initialpose', associated to a `pose stamped` message, is used to provide the localization systems of mobile robots with an initial guess of the robot position in a map.
- ▶ 'joint_states', associated to the `homonym message`, is used to describe the position, velocity and effort of the joints of the robot.
- ▶ 'map', is used to transmit the `occupancy grid` describing the map of the robot's environment.
- ▶ 'rosout', used as standard interface for logging messages with different `verbosity levels`[74].
- ▶ 'odom', used to publish the computed `odometry` in mobile platforms.
- ▶ 'tf' and 'tf_static', are used by `tf2` to distribute the transformations between joints and other elements in the environment to any node requiring them.

Since, under the hood, topic names are mapped to DDS names, and DDS names are limited to 256 characters, topic names are limited to 256 characters too. I/would/recommend/to/stay/below/50/for/readability. At the same time, try to avoid abbreviations and use instead descriptive names that properly represent the content of the channel.

4.3.4 Namespaces

Just as it happens with different programming languages, namespaces can be used to "scope" the names of nodes and topics, avoiding conflicts in large projects and providing logical separation.

The most common way to add namespaces to a node, is using a launch-file: namespaces can be either specified for each single node, or for a group of nodes / nested launch files using the "push" mechanism. A complete implementation example can be found [here\[75\]](#).

When creating or subscribing to a topic, you can choose to use a "fully qualified name", meaning the combination of the namespace and the topic name, or a "private name", that will later get the namespace of the executing node as prefix. Fully qualified names always begin with a forward slash (/) and should never contain tildes. Private names are the other option and can optionally begin with the prefix "~/".

As your ROS project grows, using namespaces will become increasingly important. Since all the interfaces functioning within the same namespace can interact with each-other using private names, it is a good practice to **group under a namespace those nodes that need to tightly cooperate together** to provide a certain functionality. These nodes can still access the information provided by nodes in other namespaces using fully qualified names, but are otherwise "isolated" from them and are not at risk of conflict.

Let's make a simple example: imagine that your robot is composed of a mobile base on which a movable laser beamer is mounted that can kill mosquitoes. To move the base, two nodes need to cooperate: one that reads the map of the environment and chooses a random target pose for the base, while the other will actually drive the robot toward that pose. To kill the mosquitoes, the system uses two other nodes: one that uses the data provided by a camera to detect the pose of the mosquito, and another one that points the laser beam toward the mosquito to kill it.⁷ Since these functionalities were developed by different teams who didn't talk to each-other, both the navigation node and the laser beam controller happen to be listening for their target on the topic called "target_pose", that is published by the respective detector. If no namespace is used, you might end up with your laser beam pointing toward random points in the map, and your base trying to drive over the mosquitoes (which might actually still work to kill them). To solve the issue, the first two nodes could be launched in the "navigation" namespace, while the other two could run in the "mosquito_killer" namespace. If both the mosquito detector and the navigation controller need to access a common interface, for example the odometry of the robot, they can still do it using a fully qualified name like "/odom".

⁷: Yes, even if I despise the usage of robots for violent tasks, many mosquitoes were hurt during the realization of this book.



If the developers had created their subscription on "/target_pose" instead, using in this way a fully qualified name, pushing a namespace would not make the robot any smarter. In this case one or both the channels would require a [remapping](#)[76] to be applied in their launch files. You can find a remapping example in the [how-to guides](#).

The moral of the story is: by default **use private names whenever possible**. Fully qualified names should only be used to publish information that is shared across multiple "node groups", or to access the interfaces of resources defined in a different namespace.

An additional practice that I like to use when namespacing interfaces, is to use the "debug" namespace for all those topics that are only meant to be used to introspect the system (so for debugging or performance analysis purposes). This simplifies the process of distinguishing the real "outputs" of the nodes, which need to be consumed by other nodes, from the channels that have no impact on the robot's behavior.

4.3.5 Lazy publishers and subscribers

Our imaginary robot contains a node, called `data_filter`, that subscribes to the data provided by a sensor, applies a bunch of filters on it, and republishes it to a different topic. If nobody is listening on its output topic, receiving the data and applying the filters on it is just a waste of CPU time. In this scenario, you might want the node to subscribe to the input data only when somebody shows up asking for its output. To

achieve this, we need a mechanism that can let us know when a new connection is established with a publisher or a subscriber.

Until ROS 2 Iron, the only way for knowing if any other node was listening to the data provided by a publisher was monitoring the output of the methods "get_subscription_count" and "get_intra_process_subscription_count". This solution resembles a **busy wait mechanism** and is consequently not very efficient, especially if you need to create a dedicated routine (a timer or a dedicated thread) for it.

Luckily, starting from ROS 2 Iron, it is possible to receive an event notification as soon as a new connection is created on a publisher or a subscriber. To execute a callback as soon as a "matching"⁸ event is detected, you can write something like this:

```

1 rclcpp::PublisherOptions options;
2 options.event_callbacks.matched_callback =
3 [](rmw_matched_status_t & status) {
4     RCLCPP_INFO_STREAM(get_logger(), "Tot Matching
5         connections: "<<status.total_count);
6     RCLCPP_INFO_STREAM(get_logger(), "Tot Count change: "<<
7         status.total_count_change);
8     RCLCPP_INFO_STREAM(get_logger(), "Current connections:
9         "<<status.current_count);
10    RCLCPP_INFO_STREAM(get_logger(), "Current change: "<<
11        status.current_count_change);
12};
13
14 auto publisher = create_publisher<YourMsgType>(topic_name,
15     10, options);

```

⁸: A matching event is created only if the QoS of the subscriber is compatible with that of the publisher.

Using such a callback you could, for example, create a subscription to the input data as soon as a subscription to the output data is detected, and disable it when no active subscriber is available (when `status.current_count` is 0).

For a complete example, check the solution to the homework of this chapter (but try to solve it before!). Additional examples of usage can be found in the corresponding [tests](#).

4.4 Services

The second most common mechanism to communicate information between two nodes in ROS are [services](#)[[77](#)]. As you should already know, services implement a client-server mechanism, where multiple clients can send "requests" to a server that will respond to each of them individually.

4.4.1 Services in ROS1

In [ROS1](#)[[78](#)], services have a huge drawback: whenever a client wants to contact a server, he has to perform a blocking call. This has two major implications:

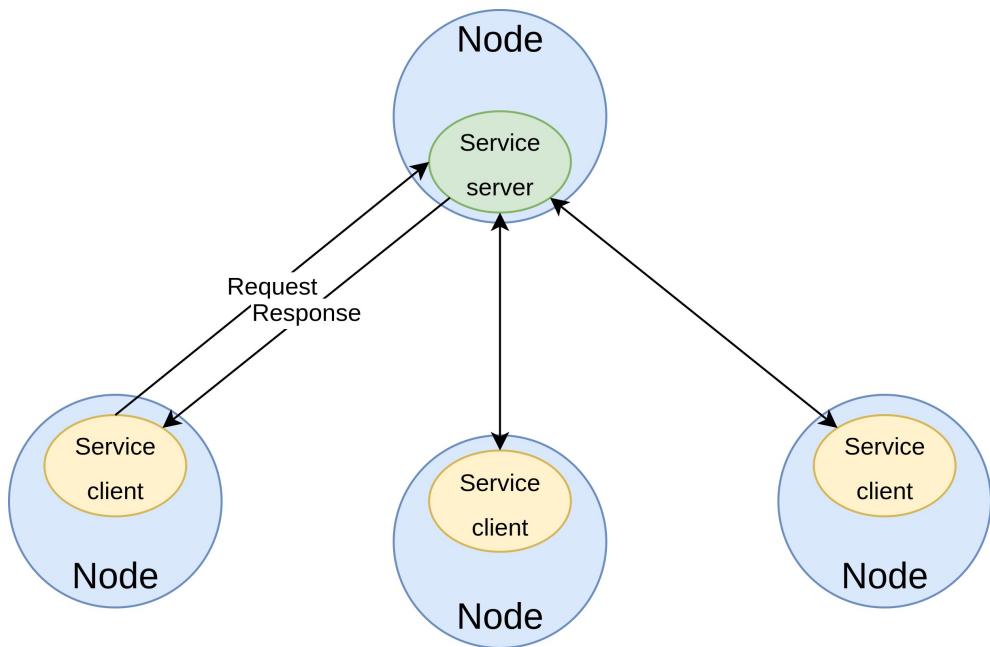
- ▶ If the server, for any reason, doesn't send a response, the client will hang forever and ever. There's no option to set a time-out.

- ▶ Since the client is blocked and waiting, the server should return an answer as soon as possible. This implies that services should only be used for those scenarios where an answer can be computed almost immediately.

The first point is particularly critical, and for many considered bad enough to completely ban services in favour of action servers (which we will discuss later).

4.4.2 Services in ROS 2

Luckily, in ROS 2, services can be called in an asynchronous way and are consequently more versatile. When a client performs a call to communicate with a service server, the result is returned through a "future object", meaning that the client can continue its execution and check for the result whenever he prefers.



Unfortunately, the [basic example](#)[30] proposed in the ROS tutorials doesn't reflect the best practice to call a service in production code, and could instead be considered an anti-pattern because of two reasons:

- ▶ It uses the "spin_until_future_complete" function, that, as we have previously seen in subsection 2.1.1, can not be used if the node is added as a component to an executor. Since components are the default way of writing nodes, spin_until_future_complete should only be used in scripts that will never ever be associated to an executor.
- ▶ It doesn't handle timeouts, and doesn't allow the caller to perform other operations while waiting for the response.

Both these issues can be solved using the `wait for` method of the returned future. The exact code to write will depend on the version of ros 2 that you are using (and on the programming language), but a pseudo-code could look something like this:

```

1 auto result = client->async_send_request(request);
2 auto start_time = get_clock()->now();
3 using namespace std::chrono_literals;
4 const auto timeout = 10s;
5 while(result.wait_for(1s) != rclcpp::FutureReturnCode::
6     SUCCESS && rclcpp::ok())
7 {
8     // Any other code to execute while waiting
9     if(get_clock()->now() - start_time > timeout) {
10         RCLCPP_ERROR(get_logger(), "Timeout elapsed waiting
11         for service");
12         break;
13     }
14     if(get_clock()->now() - start_time < timeout)
15         auto my_result = result.get();
16     else
17         // handle failure

```

Even if there is no special action that you want to perform while waiting (like for example logging), setting and managing meaningful time-outs is often a better choice than waiting forever.

When writing a client, you should remember that, in order for its result to be received, an executor needs to be available to pick-up the processing job.⁹ At the same time, while processing the request on the server side, you should remember that an executor will be busy during the callback. Consequently, other callbacks might not be able to execute concurrently depending on the type of executor you are using and on how you configured your callback groups.

⁹: This was previously presented with an [example](#) in chapter 3

4.4.3 Services introspection

Whenever one or more nodes in your system are not working as expected, it is natural that you will want to know what information is contained in their inputs or outputs in order to understand what's going on. Topics can be easily introspected without the need of any modification to the source code: the content of the transmitted data can be monitored using the "ros2 topic echo" CLI command, or visualization tools like [RQt](#) or [PlotJuggler](#). Services, however, don't provide similar functionalities by default.

Luckily, starting with ROS 2 Iron, it is possible to configure clients and servers of services to publish additional information on an hidden topic, that can later be introspected. The topic has a name in the format "<service_name>/_service_event" and contains three fields:

- ▶ `service_msgs/msg/ServiceEventInfo` info, can contain four different kinds of event: REQUEST_SENT, REQUEST RECEIVED, RESPONSE_SENT and RESPONSE RECEIVED, together with a timestamp, client identifier, and sequence number.
- ▶ `YourService_Request[<=1]` request, which optionally contains the request content.
- ▶ `YourService_Response[<=1]` response, which optionally contains the response content.

As already mentioned, in order to reduce network traffic, this functionality needs to be explicitly enabled for each service client-server. Both the

client and the server provide a function, `configure_introspection`, that can be called in this way:

```
1 client->configure_introspection(get_clock(), rclcpp::  
    SystemDefaultsQoS(), introspection_state);
```

The programmer has the option of enabling only the transmission of the metadata (`service_msgs/msg/ServiceEventInfo`) by setting `introspection_state` to `RCL_SERVICE_INTROSPECTION_METADATA`, or also of the request-response content by setting it to `RCL_SERVICE_INTROSPECTION_CONTENTS`.

Executing `ros2 topic echo "<service_name>/_service_event"` will produce an output of the form:

```
1 -----  
2 request_type: REQUEST_SENT  
3 stamp: 0.0  
4 client_id: 1  
5 sequence_number: 1  
6 request:  
7 ...  
8 -----  
9 request_type: REQUEST RECEIVED  
10 stamp: 0.01  
11 client_id: 2  
12 sequence_number: 1  
13 request:  
14 ...  
15 -----  
16 request_type: RESPONSE_SENT  
17 stamp: 0.02  
18 client_id: 2  
19 sequence_number: 2  
20 response:  
21 ...  
22 -----  
23 request_type: RESPONSE RECEIVED  
24 stamp: 0.03  
25 client_id: 1  
26 sequence_number: 2  
27 response:  
28 ...  
29 -----
```

The introspection can be enabled/disabled at runtime, but you need to provide your own mechanism: you could for example associate it with a parameter change, like it is proposed in [this example](#), but this approach requires adding quite a lot of code, and you probably don't want to do it for all your services. I consider a good practice to enable the full introspection whenever the provided service is expected to be called with low frequency and to convey a small amount of information. Under these assumptions, the overhead introduced by the additional topic is probably negligible for your system. If you don't want to call the `configure_introspection` function all the times you are declaring a new service, consider wrapping the client/server declaration into a function that does that automatically for you.

4.4.4 When should you use a service?

You should consider using a service if one or more of the following conditions apply:

- ▶ A client expects a server to produce and send back some data that depends on the content of the request.
- ▶ A client needs to receive a confirmation that the data was processed correctly by the server. A missed communication between sender and receiver is treated as an error.
- ▶ A client needs to verify that the receiver of the data (the server) is ready to process the message before sending it.

At the same time, you should avoid using services if:

- ▶ The server needs "a lot of time" to process the data and generate a response. How much "a lot" is, depends on the requirements of your system. If you foresee that during this time you might need to stop the service server, for example to react to an unrelated event, you should probably use a different kind of interface.
- ▶ The client needs to receive information from the server during the server execution (before getting a final response).

If your use-case includes any of these points, you should consider using actions instead of services.

4.5 Actions

Actions^[79] are the communication strategy of choice whenever you want a different node to execute long tasks asynchronously. On top of the functionality already offered by services, actions optionally allow to:

- ▶ Cancel a task during its execution.
- ▶ Provide feedback while executing.

Under the hood, actions are implemented using services (for sending the goal and receiving the result) and one topic for the feedback.¹⁰

Any time an action server receives a goal from a client, it can decide if accepting or rejecting it. If accepting it, the server creates a new state machine for the goal, that will initialize in the "accepted" state. From here the server will internally transition to the "executing" state, where it will stay until one of the following conditions occurs:

- ▶ The task is completed and the state machine transitions to the "succeeded" state.
- ▶ The task fails and the state machine transitions to the "aborted" state
- ▶ The client requires to cancel the goal and the state machine transitions to the "canceled" state.

In order for the action execution to happen asynchronously, actions servers usually spawn a thread to handle the goals without blocking the node executor. Consequently, the amount of code required to host a server or to create a client^[81], is significantly bigger than that required for a service or a topic.¹¹ At the same time, since the spawned threads are

10: Contrary to what happens in ROS1, feedback topics are "hidden" by default and can be listed using the option "include_hidden_topics" of "ros2 topic list".

11: It must be noted that not all the functions implemented in the basic example are mandatory, in many cases their default implementation will be sufficient for your purposes. For example, the "goal response callback" and the "feedback callback" can be omitted on the client side if you are not planning to use them for something specific.

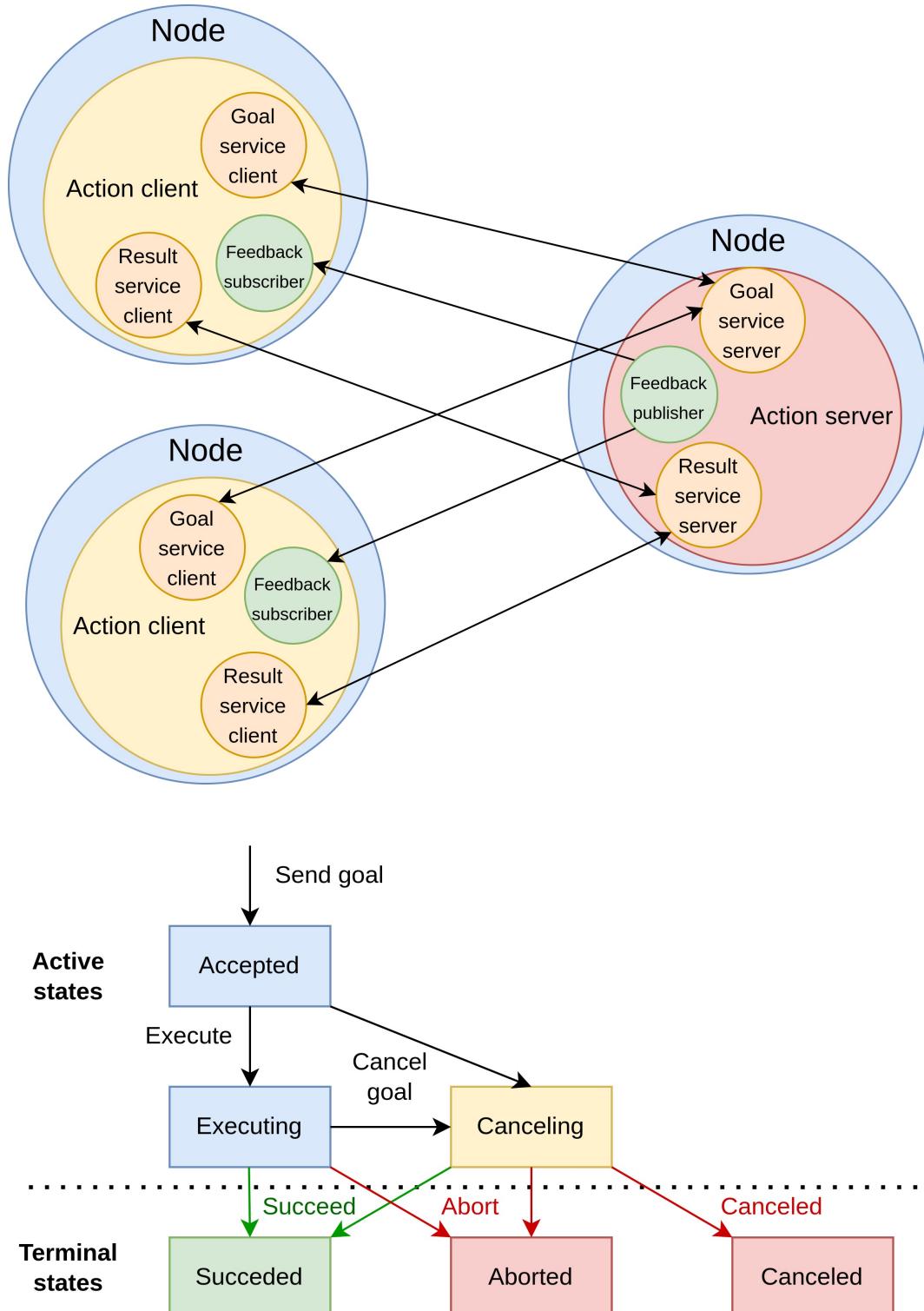


Figure 4.2: State machine implemented by the action server
Based on <https://design.ros2.org/articles/actions.html>[80]

not blocking the executor, it is less likely to fall into the "callback groups deadlocks" we were talking about before.

Even if at first look actions don't bring much new to the table with respect to an asynchronous service call, the capability of canceling running tasks is particularly important in modern robotics algorithms. A proper

robotic brain should in-fact be able to react to unexpected changes in the environment or in its internal state. Imagine for example that, while executing an action that is driving your robot around the world, your system detects that one of its motors disconnected and is no more reporting updated information. It is important to have an organized mechanism to stop the execution of the navigation action, otherwise, instead of turning around the world, your robot will just spin around one of its wheels.

Complementary to this, feedback can be used by the client or a dedicated monitor to figure out if the action is not progressing in the expected way, or to trigger additional behaviours under specific circumstances. You could for example program your robot to play a [celebration song](#) when the feedback reports that the target is almost reached.

If you would like to see some examples of usage of action servers, and check how to control their execution using [behavior trees](#)[82], take a look at the [Nav2 project](#)[83].

4.6 Standard and custom interfaces

For communication to take place between two nodes, both must know the structure of the messages being sent. Topics require the definition of a "msg file", specifying the data types of the sent data fields, services require "srv files", where the types of the response need to be specified too. Actions require the definition of an "action file", where, in addition to the goal and result structure, the structure of the optional feedback message is specified.

These files, which we will refer to as "interface files", can be defined and exported using normal packages.

ROS 2 provides a definition for the most commonly used messages and services in the [common_interfaces](#)[84] repository, which contains multiple interface packages. Alternatively, it is possible to define customized messages following the procedure that you can find [here](#)[85].

Whenever the information that you want to communicate fits into one of the messages defined in the "standard" packages, you should prefer using them instead of creating your own custom files. This brings the following advantages:

- ▶ Your software will be easier to integrate and distribute: should your nodes need to cooperate with nodes programmed by someone else, you won't need to distribute the interface files alongside your code.
- ▶ The number of dependencies used by your packages will be minimized.
- ▶ You will save coding and compilation time.

You should instead avoid using the messages defined in the common interfaces if:

- ▶ The information that you want to send doesn't semantically match the already existing messages. If, for example, one of your nodes is producing four float values representing voltages, you shouldn't

put them into a `geometry_msgs/Quaternion` message just because it fits: this would result in a confusing interface.

- ▶ You can't fill all the mandatory fields in the message: the receiver of the message has no way to know if the values in these fields are valid, or if the default values were assigned.

If you decide to create a custom interface, you should also try to stick to the following best practices:

- ▶ Interface files should be defined inside interface packages. This packages will contain **only** interface files. This allows to avoid cyclical dependencies between packages, and makes it easier to distribute your software: you might not want to distribute your source code, but the user of your nodes will at least need the messages definitions to be able to communicate with them.
- ▶ The name of interface packages should end with either the `_msgs` or `_interfaces` suffix. It will be easier for other programmers to locate the interfaces definition, and systems like the `ros1 bridge`^[86] will be able to find them automatically.
- ▶ Optional values should be assigned to "vector fields". Using this practice allows the receiver to know if the value was filled or not by checking if the corresponding vector is empty. The size of the vector can be constrained to a maximum of one using the following syntax:

```
1 | float64 [<=1] optional_value_name
```

Homeworks

You have been tasked with programming a robot that must make and deliver a coffee upon hearing a vocal command. The robot also needs to open the door and welcome visitors with a sentence upon hearing the door's bell. Welcoming visitors has precedence on making coffee. The components of the robot's system are:

- ▶ A node that, using a microphone, monitors the environment for new commands.
- ▶ A node that takes care of preparing the coffee.
- ▶ A node that provides the information generated by a camera used to monitor the environment.
- ▶ A node that uses the information provided by the camera to move the robot to its destinations without colliding with other objects.
- ▶ A node that converts text to speech to welcome the visitors.
- ▶ A node implementing the brain of the robot, in charge of orchestrating the execution of the other nodes.

What kind of interfaces would you use to make the robot's components communicate with each other¹²?

You can find an example of solution in the last chapter.

Modify the examples provided by the tutorials about `writing a single service and client` to enable the introspection of the communicated data. Use the available CLI tools to visualize the exchanged messages.

12: Should you ever really build such a robot, please let me know because I want one.

Solution available [here](#).

Consider the Tutorial example about [writing a simple publisher and subscriber](#). Modify the example by inserting a node, between the publisher and the subscriber, that will republish the string after making it uppercase. This node should subscribe to the topic provided by the publisher only when the listener activates its subscription to the "uppercase topic", and should disable the subscription as soon as the listener stops listening.

Solution available [here](#)



5 Tasks organization

Now that we have a clear idea about what kind of nodes we can implement, and what kind of interfaces we can use to make them communicate with each other, the time has come to glue things together.

Just like organs in the human body, the nodes in a ROS-based architecture need synchronization in order to carry out complex tasks. While some components will be capable of operating on their own, without requiring any input from the rest of the system (like for example the sensor's interface of the robot), many of them will need some information, probably generated by other nodes, in order to carry out their tasks.

Ideally, the flow of information between the different entities should be organized in a way that allows for:

- ▶ Easy introspection: figuring out what the robot is going to do given its state and inputs shouldn't be too complicated.
- ▶ Maintainability: the system should be easily modifiable.
- ▶ Resilience: the system should be capable of dealing with unexpected circumstances in the environment.
- ▶ Modularity and scalability: the components, and those actions composed by the interaction of multiple components, should be reusable not only within one system, but also in heterogeneous systems (for example in different robots).
- ▶ Efficiency: the organization should happen without significant computational overhead.
- ▶ A cool name: your marketing department should be capable of selling this as something extremely smart. Given the general lack of fantasy between roboticists, this will probably happen to be "Brain" or something mentioning AI.

One of the main design principles behind ROS-based architectures is the separation of concerns^[87]. According to this practice, each one of the building blocks of the system needs to have its own limited "concern", meaning that its behavior (its outputs) will depend on a limited amount of inputs, and not on the entire state of the system. We have already seen how ROS, providing a mechanism to define clear interfaces between its

components, supports this practice. There is another implication to the “separation of concerns” approach: the logic controlling the execution flow of the machine needs to be separated from the actions implementation.

To better explain this concept, let’s consider a classic application where a robot needs to detect something before grasping it. We can expect the software to be made of a module to detect the object, one to find a graspable pose on its surface, and one to control the robot to the configuration required for grasping. We could program the detection module to call the “find pick pose” module as soon as the detection is over, then the “find pick pose” node to call the robot controller. This way of programming introduces a chain of dependencies between clients and servers: the detection module becomes dependent on the nodes it calls, or at least on the interfaces required to communicate with them. It is no more possible to use the detection node in a context where no manipulation is available. If, instead, we introduce a new module whose only responsibility is to call in an organized way the other modules, we can get rid of the dependency chain. To reuse the modules in a different application, we’ll only need to change the “managing node”.

Programmers around the world came up with three main ways of organizing the components of a robotic system in order to carry out complex tasks. We’ll briefly go through them and describe how these can integrate with ROS 2.

5.1 Sequential code

Most of the robots out there in the wild are carrying out repetitive tasks. Even if more and more often the executed movements are guided by sensors (cameras, force-torque sensors, range sensors...), the sequence of operations to be executed is typically the same over and over again, with only minor variations required to handle errors or missing inputs.

The easiest and most common way to deal with this kind of scenarios, is organizing the code as a sequence of operations to be executed in a loop.

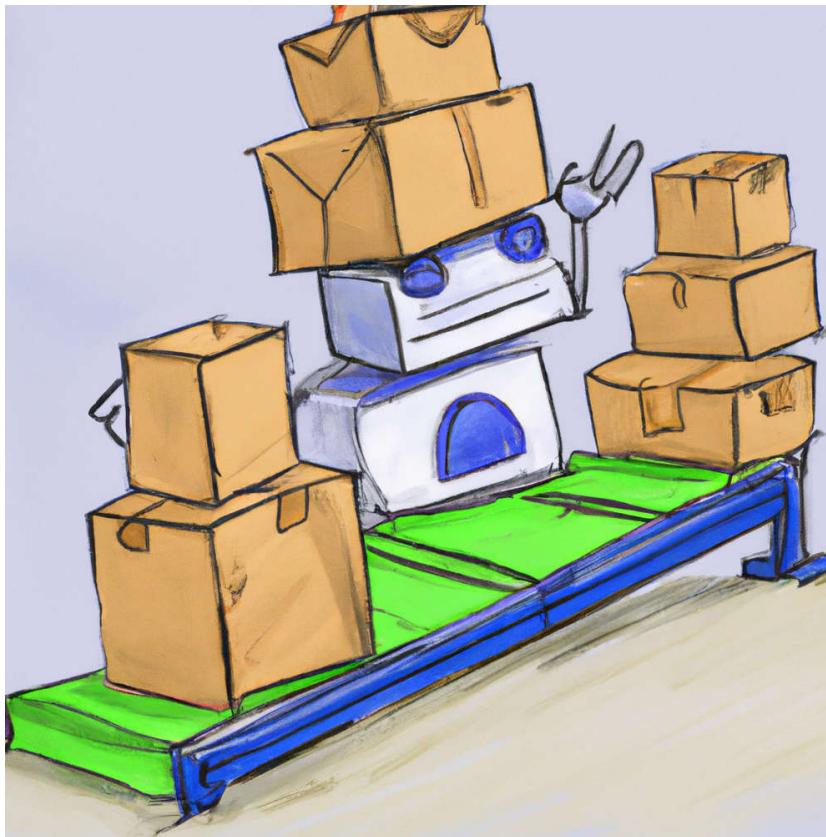
Let’s take a look at the case of an industrial robot, which needs to pick a box from the pose detected by a camera and move it to a target location. The pseudo-code to control the execution flow could look something like this:

```

1 open_gripper_service()
2 while (robot_active) {
3     if (!detect_item_pose_action(item_pose))
4         continue;
5     if (!move_to_pose_action(item_pose))
6         handle_error_and_exit()
7     close_gripper()
8     if (!move_to_pose_action(target_pose))
9         handle_error_and_exit()
10    open_gripper()
11 }
```

As you can see, the code required to organize the execution flow is quite simple¹. It is easy to understand how the robot will behave, and it would be easy to find a bug or make a small change in its logic. If this is all what

¹: The real code would be slightly more complex, including approach poses and probably other checks



the robot has to do, you are actually unlikely to program it using ROS, and more likely to use an industrial [PLC\[88\]](#) with the corresponding programming language and tools. This kind of programming, however, does not scale well with the complexity of the system. To understand why, let's add a couple of requirements to the previous example.

- ▶ The movements need to follow a plan computed in real-time taking into account the obstacles currently present in the environment.
- ▶ The target pose is not fixed: the robot needs to detect an area with free space. If no free space is available, the robot needs to wait.
- ▶ In order to save time, planning, motion and detection need to execute concurrently whenever possible.
- ▶ After placing an object, the robot should move to a homing configuration. The final object position needs to be verified with a camera and eventually corrected by picking and placing the object again.

Here a possible pseudo-implementation using sequential programming:

```

1 open_gripper_service()
2 start_detection_thread(item_pose)
3 start_detection_thread(target_pose)
4 while (robot_active) {
5     wait_detection_thread(item_pose)
6     if(object_not_found(item_pose))
7         start_detection_thread(item_pose)
8     continue;
9     if(!plan_between_poses(current_pose, item_pose,
10                           first_motion_plan))
11        handle_error_and_exit()
11     free_space_found = false

```

```

12  while(!free_space_found)
13      wait_detection_thread(target_pose)
14      if (free_space_detection_failed(target_pose))
15          start_detection_thread(target_pose)
16          continue
17      else
18          free_space_found = true
19      start_planning_thread(item_pose, target_pose,
20          second_motion_plan)
21      if (!execute_motion_plan(first_motion_plan))
22          handle_error_and_exit()
23      close_gripper()
24      wait_planning_thread()
25      if (planning_error)
26          open_gripper_service()
27          handle_error_and_exit()
28      start_planning_tread(target_pose, home_pose, homing_plan)
29      if (!execute_motion_plan(second_motion_plan))
30          handle_error_and_exit()
31      start_detection_thread(item_pose)
32      open_gripper_service()
33      wait_planning_thread()
34      if (planning_error)
35          handle_error_and_exit()
36      if (!execute_motion_plan(homing_plan))
37          handle_error_and_exit()
38      placed_sucsesfully = false
39      while (!placed_sucsesfully)
40          if (!detect_placed_object(placed_object_pose))
41              handle_error_and_exit()
42          if(delta_between_poses(placed_object_pose, target_pose)
43              < threshold)
44              placed_sucsesfully = true
45          else
46              if (!plan_between_poses(current_pose,
47                  placed_object_pose, re_pick_motion_plan))
48                  handle_error_and_exit()
49              start_planning_thread(placed_object_pose, target_pose
50                  , re_place_motion_plan)
51              if (!execute_motion_plan(re_pick_motion_plan))
52                  handle_error_and_exit()
53              close_gripper()
54              wait_planning_thread()
55              if (planning_failed())
56                  handle_error_and_exit()
57              if (!execute_motion_plan(re_place_motion_plan))
58                  handle_error_and_exit()
59              open_gripper_service()
60              execute_motion_plan(homing_plan)
61              start_detection_thread(target_pose)
62      }
63
64 planning_thread(start_pose, end_pose, plan)
65     if (!plan_between_poses(start_pose, end_pose, plan))
66         signal_planning_error()
67     else
68         signal_planning_completed()
69
70 detection_thread(pose)
71     if (!detect_item_pose_action(pose))
72         signal_opject_not_found()
73     signal_object_found()

```

Now, I have to admit, it is possible to write much nicer sequential code, but my goal here was scaring you. The pseudo-code I wrote is not complete, since it lacks the proper handling of the multiple errors that can happen along the way, but is already difficult to follow. It also contains a bunch

of bugs / inefficiencies, but good luck finding all of them.

The code controlling modern robots, capable of dealing with uncertainty and mutable environments, is usually much more complex than the reported example. While it is always possible to organize the flow using sequential programming, as the system becomes more complex it is probably wiser to organize your code using frameworks that are more comprehensible and easier-to-read.

5.2 State machines

A common way to make the execution flow easier to introspect and control, is defining a finite number of states in which the system is allowed to be. At each moment in time, the system is allowed to be only in one of these states. The transition between two different states is only allowed if a defined condition is verified. The control logic performs different actions depending on the current state or the performed transition.

Given a state in which the system is initialized, it is easy to verify if any other state is reachable, and to determine which sequence of actions is required for the transition. This form of organization is commonly called a [Finite state machine \(FSM\)](#)[89].

It is possible to design a state machine, and hence to model the execution flow of a system, on paper, without writing a single line of code. The most common representation uses geometrical forms (ex circles or rectangles) to represent the states, and arrows to represent transitions. This kind of visualization is much closer to what the human brain is accustomed to process than a simple list of commands, it consequently drastically reduces the amount of coffee required to design and debug complex systems. Even if you don't like coffee, there's a good chance that some colleague of yours, who will have to understand what you wrote two years from now, does. Given how much [tropical forests are being damaged](#)[90] to plant coffee, writing readable code ultimately helps saving the world, so take it seriously.

If implemented properly, state machines are usually computationally efficient and, due to their deterministic nature, suitable for real-time applications. FSMs allow for the organization of complex systems without adding significant memory or computational overhead. As the number of states that need to be handled grows, however, finite state machines tend to run into a couple of issues:

- An increasing amount of states implies an even greater amount of transitions that need to be specified, especially to handle errors and unexpected behaviors. Building and modifying this net of nodes and transitions can become extremely challenging.
- Even if state machines are way more readable than sequential code, representing all the possible states and transitions of the system in a compact way is not an easy task.
- Reusing parts of the logic defined in a state machine is not straightforward, since transitions tend to be bound to local state-variables.

A variation of the classic FSMs, [Hierarchical Finite State Machines](#)(HFSMs)[91], was developed in order to deal with some of these issues. In HFSMs, states are allowed to contain other states in themselves, forming a

sub-state machine. Transitions can be defined between sub-states and macro-states, grouping in this way task-related logic and increasing the modularity of the system.

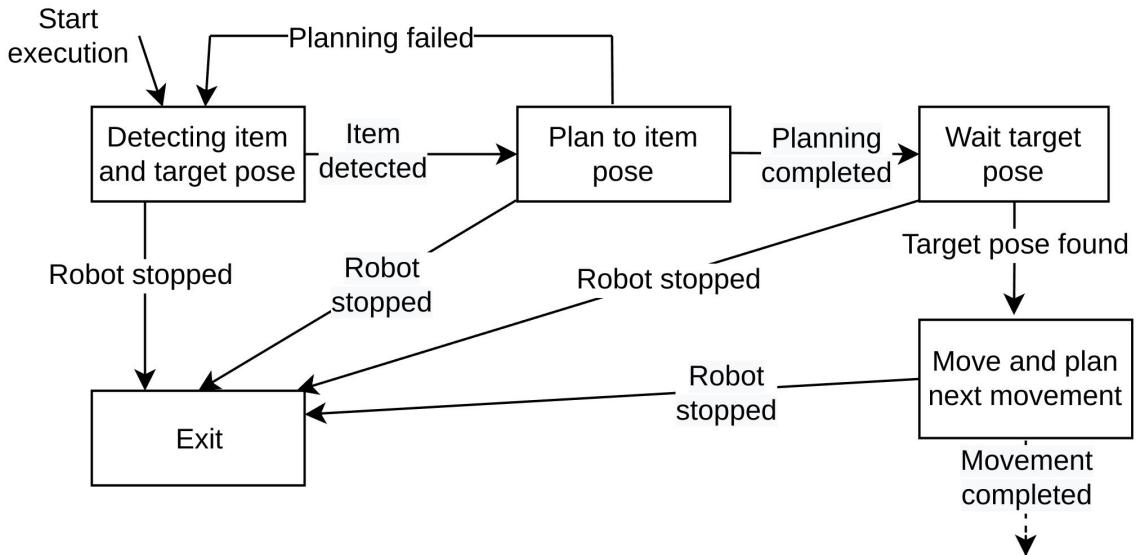


Figure 5.1: Example of FSM implementation for the beginning of the picking problem

In figure 5.1 you can see how, a piece of the picking problem described in the previous section, could be modeled using a FSM.

In order for our robot to actually follow the designed logic, we now need to translate the diagram into executable code. It is not very difficult^[92] to encapsulate the states of the system into programmable objects, the transition conditions into boolean functions, and to model external events affecting the system. However, since we are good developers², we should try to base our code on existing frameworks. This usually reduces the amount of code that needs to be written and maintained, while allowing the user to benefit from new features and improvements as the framework evolves.

2: lazy people

It is possible to find libraries that help the development using FSMs in practically all programming languages, this is because FSMs are a powerful, generic tool that can be used within a vast amount of applications that transcend robotics. Some examples include [Tinyfsm](#)^[93], [Boost](#)^[94], [python-statemachine](#)^[95], [pytransitions](#)^[96] and so on.

Open source frameworks have been developed that specifically target the development using ROS 2, some of them being [SMACC2](#)^[97] and [Yasmin](#)^[98]. These facilitate the integration of the communication interfaces used by ROS (mainly Actions and Services) in a generic way, and provide additional functionalities like the integration of [hyerarchical states](#)^[99], [Orthogonals](#)^[100], compile time validation, run-time visualization, recovery mechanisms and so on.

Despite the many functionalities integrated into modern FSMs frameworks, organizing large, maintainable systems using state machines remains an architectural challenge. In the past few years, a different kind of plan-execution model, which partially solves some of the limits of FSMs, has gained momentum in the robotic community: Behavior trees.

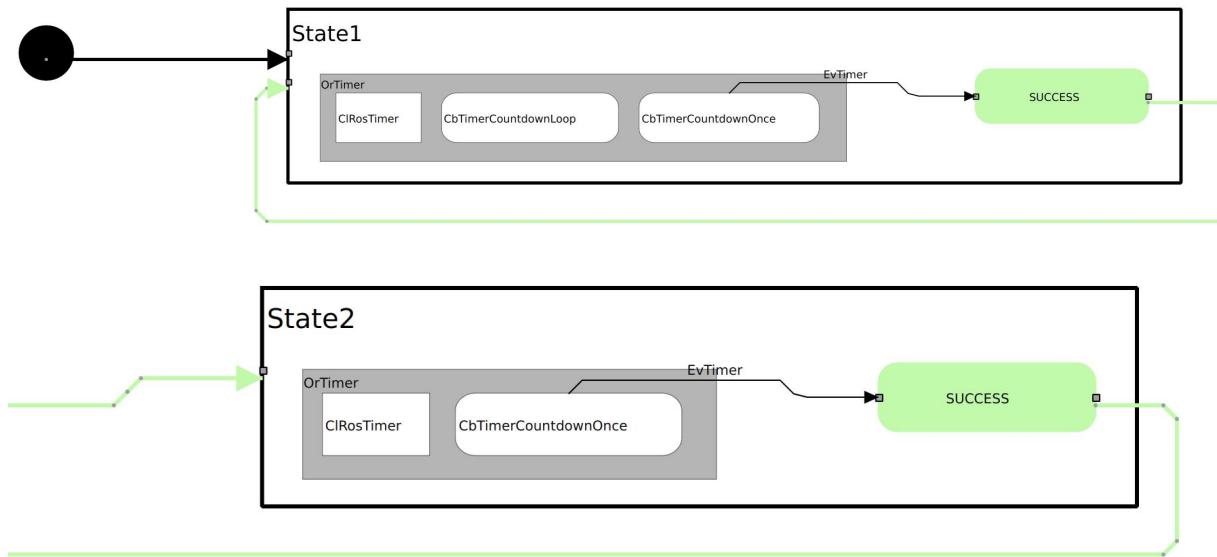


Figure 5.2: Simple example of FSM implemented using SMACC2
https://github.com/robosoft-ai/SMACC2/tree/rolling/smacc2_sm_reference_library/sm_atomic

5.3 Behavior trees



We have seen how, to split a problem into smaller parts, state machines make use of states and transitions. A different way to describe complex behaviors involves the usage of tasks and conditions. We'll define tasks as atomic actions (in the broad sense) that can be performed by our machine, and that are easily comprehensible by themselves without the need of

further division. Some examples are: generating a trajectory, moving a joint, emitting a sound. Conditions are instead predicates that can be either true or false, and that can be used to choose which tasks need to be executed. Behaviors are composed of multiple tasks that, depending upon a bunch of conditions, our machine might or might not execute in order to achieve a specific result. Some examples could be “put an object in a box”, “bake a pizza”, “conquer the world” and so on.

5.3.1 How do BTs work?

Behavior trees (BTs) provide a structured way to organize tasks and conditions in order to model behaviors. As you might have guessed, their structure involves a tree that is traversed from its root to its leaves. Each leaf represents either a task or a condition. In between them, control nodes are used to monitor their outputs and decide what should be executed in which order. While conditions can only reply with “success” or “failure” to a call from their parent, tasks can additionally reply with “running”, meaning that the task is still ongoing. Depending on the specific behavior tree implementation, different kind of control nodes might be available, but the most common ones are the “sequence node”, that calls all its “children leaves” sequentially, and the “selector (or fallback) node” that calls its leaves one-by-one until one of them succeeds. A “sequence node” will succeed only if all its children leaves succeeded, while a “selector node” will only fail if all the controlled leaves failed.

Behavior trees are executed (or ticked) periodically or upon detecting an event. At each “tick”, one branch of the tree will be traversed, and the resulting status (success, failure or running) will be propagated to the root of the tree. Additional variables are usually shared between all the “leaves” of a tree using a **blackboard model**[101].

Going into the implementation details of behavior trees, and trying to make them look like cool AI, is out of the scope of this book, but you can find more details [here](#)[102] or [here \(PDF\)](#).

Some of the reasons because of which behavior trees became very popular in the robotic world are:

- ▶ **Reactivity:** the tasks and the conditions composing the leaves of a BT should never block the execution of the tree, but always quickly return one of the three possible results listed before.³ This characteristic allows for quick reaction on changes of the conditions monitored by the tree (ex errors).
- ▶ **Modularity:** whenever the branch of a tree is itself modeling a specific sub-behavior, it can be transformed in a smaller tree (a sub-tree). Trees can include other trees as one of their leaves, allowing for easy reusability. Modifying a tree is also relatively simple: leaves can be added or removed without the need to specify any relationship with the other leaves in the tree, as it instead happens with states and transitions in state machines.
- ▶ **Readability:** Bts can be represented, and oftentimes edited, using graphical representations. While it is true that non-technical people might struggle to understand the behavior of a robot by reading its tree, once a user gets accustomed with the symbols used to model

3: This does not mean that long-running tasks can not be modeled, or that multiple tasks can not run in parallel, but these should execute asynchronously from the tree, and it should always be possible to verify if they failed, succeeded, or are still executing.

the different components, the resulting representation looks at the same time compact and organized.

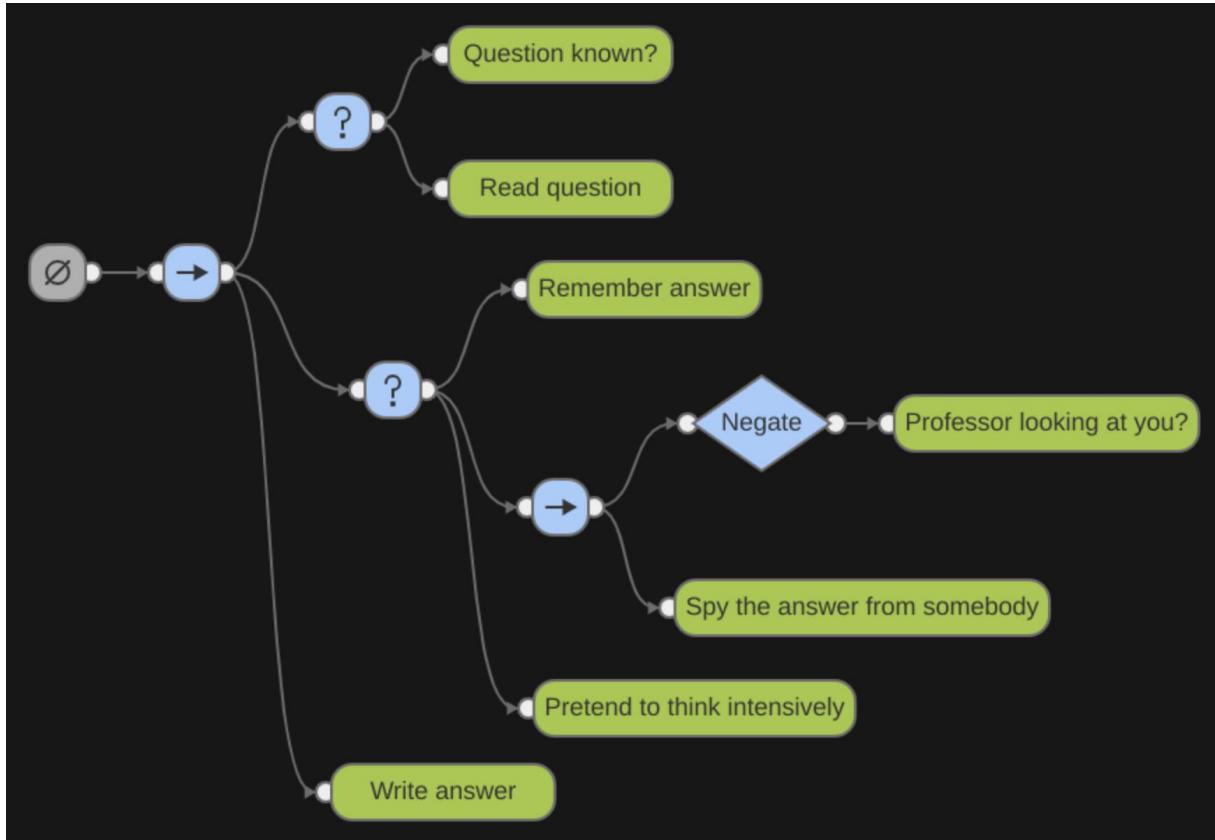


Figure 5.3: How to answer a question during an exam using a behavior tree.
The root of the tree is typically represented by a barred circle, sequence nodes by an arrow, selectors by a question mark, decorators by diamonds. In this representation the tree is traversed left to right and top to bottom.

5.3.2 Behavior trees in ROS 2

Just as it happens for state machines, you can find a couple of open-source frameworks out there that will help you organizing ROS 2 projects using behavior trees with reduced effort. The most used libraries are [behavior tree cpp](#)[103] for C++ and [Py trees](#)[104] for Python. Both libraries provide all the basic and some advanced component to implement the trees, plus a graphical user interface to speed up editing and introspection. Python based trees will give you more editing freedom and speed, while the C++ version will allow for compile-time checks and optimized performance. In both cases, organizing your tasks into asynchronous services and actions is crucial to achieve the abstraction and reactivity required by the framework.

An example of open-source project where behavior trees are being extensively used is [Nav2](#). In “nav2 behavior tree”, you will find some [class templates](#)[105] using which you can create your own ROS 2 tasks in no time. Similarly, [py trees ros](#), provides modules to speed up the integration of ROS 2 components in py-trees⁴.

4: Unfortunately, at the moment of writing, this project is not as active and updated as the C++ counterpart.

5.4 Higher levels of tasks organization and task planning

As the tasks that the robots need to carry out grow in complexity, even frameworks like hierarchical state machines and behavior trees can become difficult to manage. In some cases, it might even be helpful for the robots to figure out the tasks that they need to perform by themselves, without the need of a statically programmed decision schema; this is usually referred to as **task planning**[106]). To solve these issues, other frameworks were developed that provide a further level of abstraction on top of state machines or BTs. For some of these it is possible to find open source libraries that provide direct support for ROS 2; following is a brief description of some of the most popular.

5.4.1 FlexBE

In **FlexBE**, behaviors are modeled as hierarchical state machines where states correspond to active actions and transitions describe the reaction to outcomes[107].

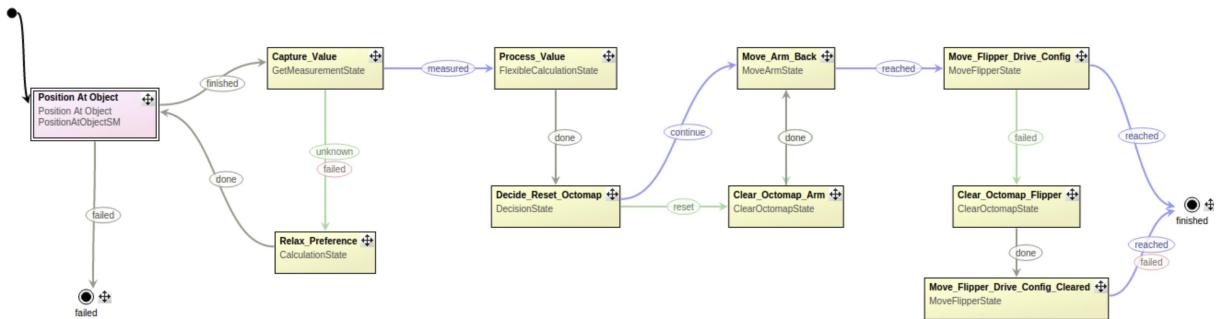


Figure 5.4: An example of state machine implemented using FlexBE.
From <http://philserver.bplaced.net/fbe/>

While its core is based on the state machine framework SMACH[97], the concepts have been extended and adapted to support a built-in mixed-initiative robot-operator interaction. This means, when executing a behavior, both the robot and the operator can initiate requests to ask the other party for help, e.g., by approving a decision or taking a specific transition. This can happen at any time during execution and does not need to be explicitly modeled in any state machine. The framework provides a GUI to interact and edit the behaviors.

If you need a dynamic interaction during the decision process and an interface that can be used by not-programmers, this framework might be of help.

5.4.2 Skiros2

Skiros2[108] implements an extension of the Behavior trees framework called **extended behavior tree model**[109]. These trees link BT procedures to a set of parameters (which are used to pass information to and from the tree) and conditions (which need to be valid before, during or after

the execution) to form what is locally called a **Skill**. Primitive skills are, for example, ROS 2 actions, while "compound skills" correspond to a tree modeling a specific task.

Skills are used together with a database where users can store semantic information about the environment, called the world model. The world model is a graph where nodes are elements and edges are relations between them. It is used for the semantic definition of concepts, data structures and relations of objects in the domain (Ontology) and to model the current world state for reasoning, planning and execution (Scene graph). This information can be used, for example, as input or output parameters for the skills. Skills allow for the transition from one world state to another.

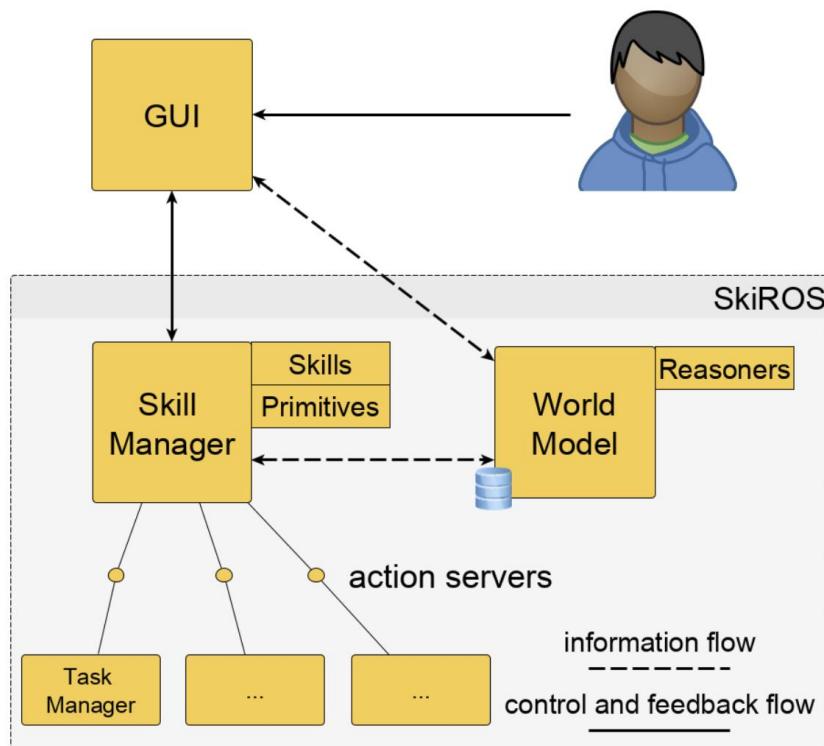


Figure 5.5: Skiros2 architecture
From <https://github.com/RVMI/skiros2/wiki>

A Skill manager node loads the skills related to a specific robotic system and offers services to start and stop them and monitor their execution. A Task manager node offers an action server to request a task planning. It automatically uses the world model instance as starting state and the available skills to setup the planning domain. This works as an integration point for **PDDL**[110] (Planning Domain Definition Language) task planning.

SkiROS can be used in partially structured environments, where the robot has a good initial understanding of the environment, but it is also expected to find discrepancies, fail using initial plans and react accordingly[108].

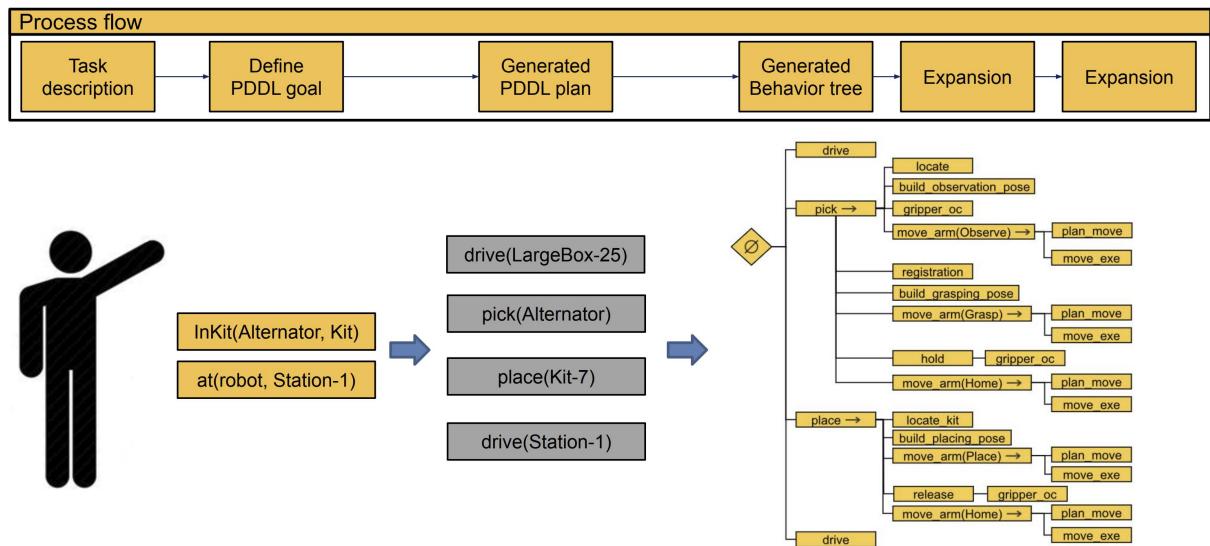


Figure 5.6: Example of task planning action workflow

From <https://static1.squarespace.com/static/51df34b1e4b08840dcfd2841/t/5dadac81ca3a6955cc2ba1fb/1571662994469/ROS+Industrial+-+SkiROS+workshop.pdf>

5.4.3 Task planning: Plansys2

Plansys2[111], the successor of ROSPlan[112], is a PDDL(Planning Domain Definition Language)-based task planning system.

As we already mentioned, given a task and an environment description(model), **task planning** allows robots to figure out autonomously the sequence of actions to be performed to accomplish the desired result. This can be very useful when you can not foresee all the possible scenarios that your robot might need to face and design ahead a state machine or a behavior tree to handle them.

In Plansys2, the plans generated by the planning algorithms are transformed into Behavior Trees using an algorithm for plan analysis and parallel execution of action flows [113]. Under the hood, the library uses the same **behavior tree cpp**[103] framework that we introduced previously.

Plansys2 is composed of 4 nodes:

- ▶ **Domain Expert:** Contains the PDDL model information (types, predicates, functions, and actions). It is capable of accepting several different domains that we can mix to get a single one. This capacity allows for modular applications where each package contributes its part of the domain and the implementation of the actions it requires.
- ▶ **Problem Expert:** Contains the current instances, predicates, functions, and goals that compose the model.
- ▶ **Planner:** Generates plans (sequence of actions) using the information contained in the Domain and Problem Experts. It is designed to be able to use different plan solvers through the use of plugins.
- ▶ **Executor:** Takes a plan and executes it by activating the action performers (the ROS 2 nodes that implement each action).

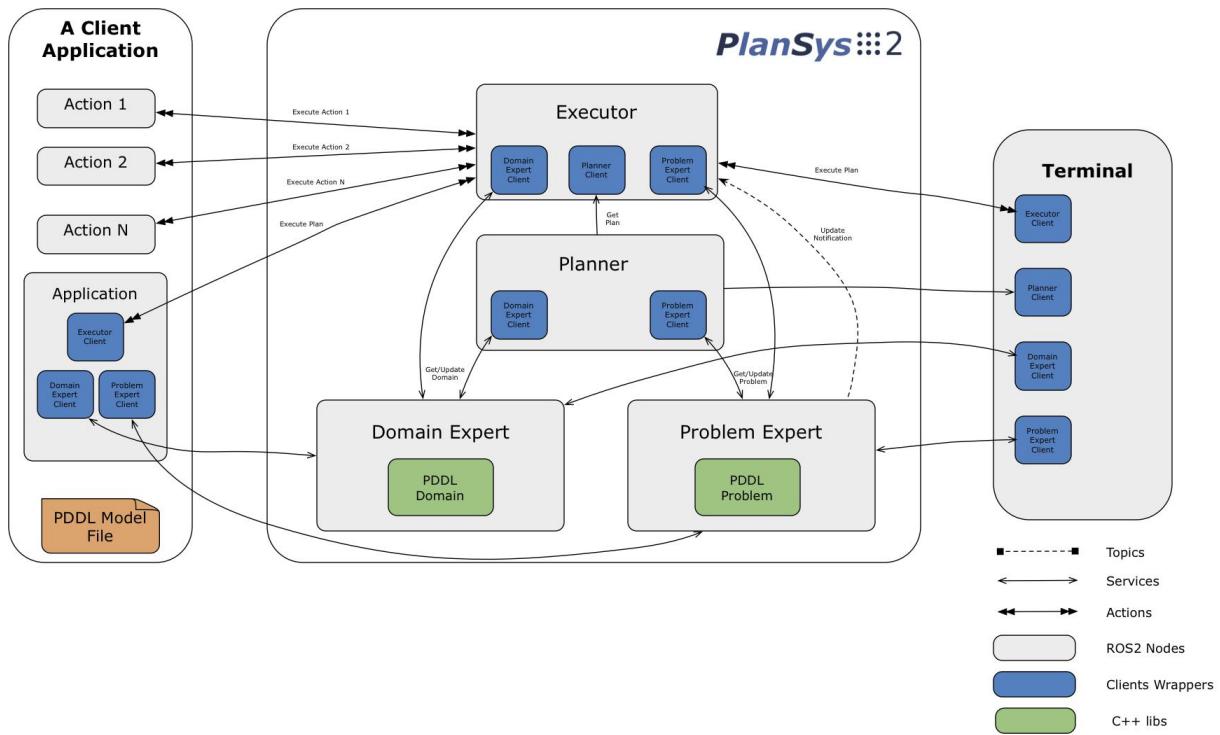


Figure 5.7: Plansys2 architecture
From <https://plansys2.github.io/design/index.html>

In very very simplified words: the planner uses the domain information provided by the domain expert and the problem information provided by the problem expert to generate a plan. This plan is translated into a behavior tree by the Executor that can then be used to generate commands for the robot. Going into the details of the implementation is out of the scope of this book, but more information can be found in the framework's [website](#) or in [this article](#)[113].

5.5 Which framework is the right one for my project?

To answer this question, you first need to ask yourself another couple of questions:

- ▶ What's the complexity level that needs to be handled? If your application is small, mainly linear and its components can communicate with little synchronization logic, chances are that sequential instructions are the best choice for you. Introducing a framework for this kind of tasks brings in more overhead than advantages. If, instead, these conditions are not verified, using either a state machine or a behavior tree is likely to help you on the long run.
- ▶ How many people are going to work on the project? With a big amount of contributors, the readability of the used framework has a big impact on the development times. When you need to modify code written by someone else, it is likely that most of the invested time is spent in carefully understanding the existing logic in order to avoid messing it up. We have seen how state machines

help structuring the code in a human-readable way; if your task management looks tidy once it is written as a state machine, you are likely on the right path. If, instead, you feel that your state machine is becoming a “spaghetti state machine”, behavior trees might help you to make things understandable again.

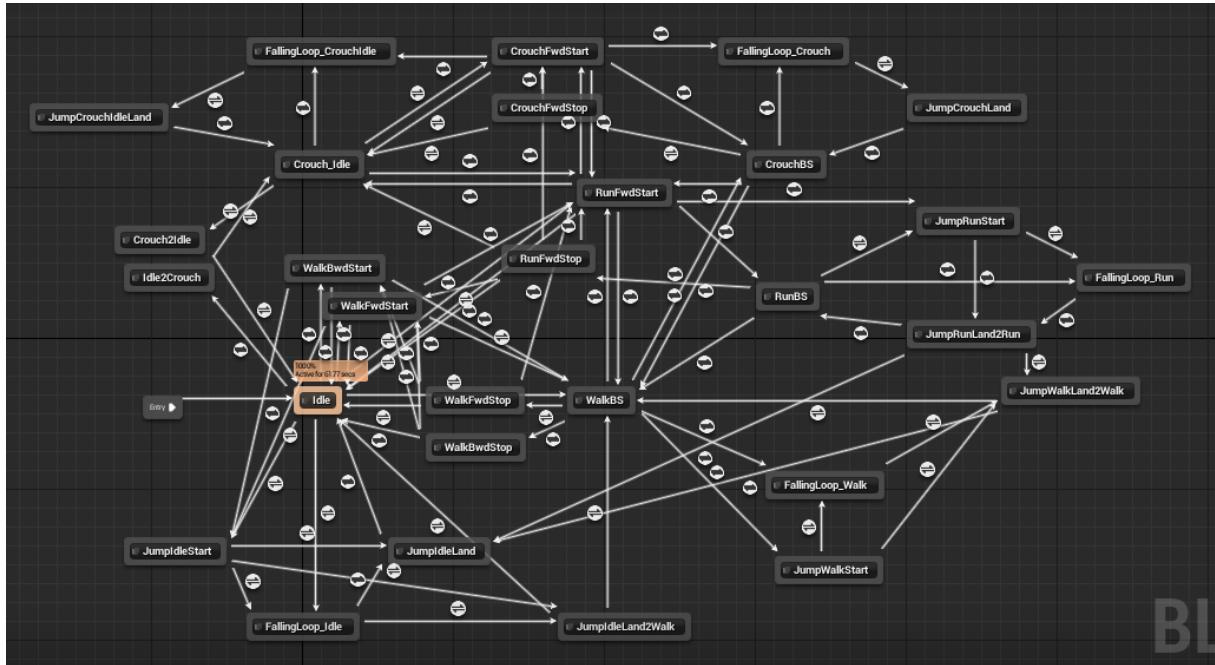


Figure 5.8: A spaghetti state machine,
<https://forums.unrealengine.com/t/cleaning-up-state-machine-spaghetti/300647>

- Are there parts of the management logic that are often repeated? If you can describe your task as the composition of multiple, reusable, sub-tasks, it is likely that behavior trees will save you from repeating code, which, as we know, is one of the capital sins for a programmer.
- Can you delegate concurrent tasks to processes / threads that are not managed by the tree? While behavior trees can, theoretically, spawn new threads to execute tasks in parallel, this tends to introduce concurrency issues in the access to the shared data, and makes the debugging of logical issues much more difficult. A proper behavior tree implementation should execute on a single thread and delegate long running tasks needing to run concurrently to other entities, for example through actions or services.
- Hierarchical state machines, on the other hand, can use orthogonal regions to model separate flows within the same “macro state”.
- What's the performance level that needs to be achieved? Frameworks like Bts and State machines inevitably bring in additional computational overhead respect to simple if / else statements. For the vast majority of applications, the additional time spent is negligible, but if you are trying to perform extreme optimizations, you might want to take it into account. A rough list of the frameworks by decreasing computational efficiency is: sequential code, compiled state machines, compiled Bts (C++), interpreted Bts (Python).
- Is the problem description too large or unpredictable for it to be modeled by a static set of Instructions? Then using a framework supporting task planning might be useful.

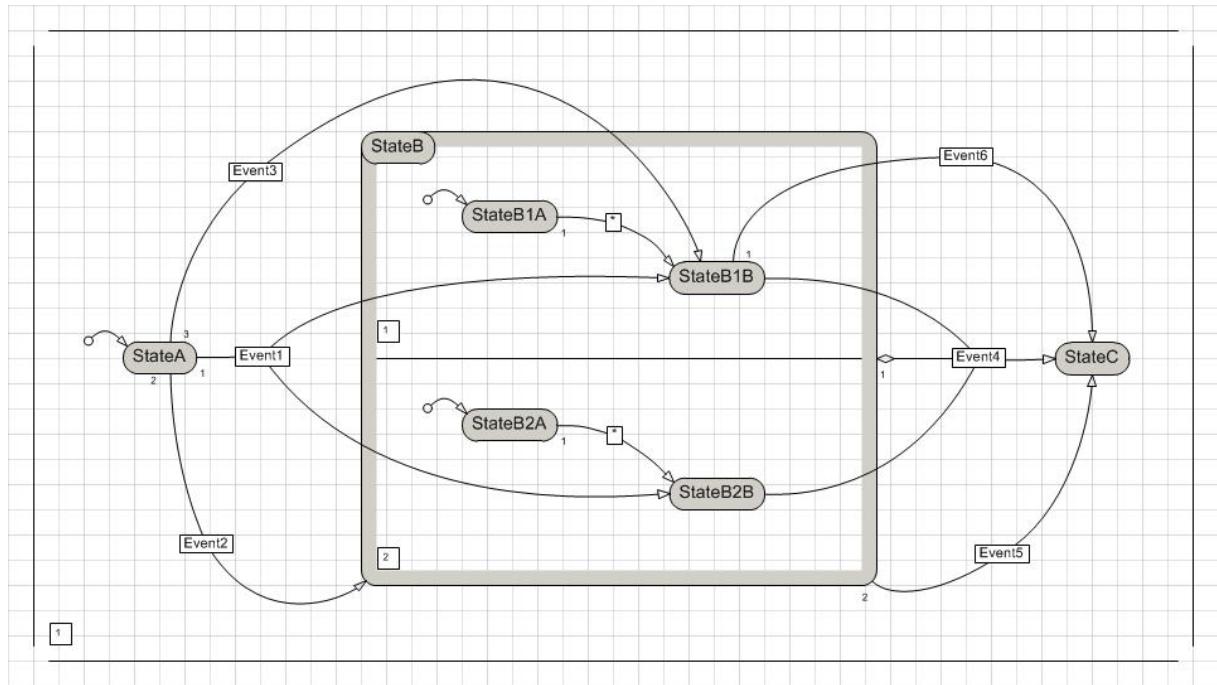


Figure 5.9: State machine diagram with orthogonal regions, fork transitions and join transitions.

<https://stama-statemachine.github.io/StaMa/html/7e6981a4-284a-4027-9e21-50d195fe0169.htm>

If you ask someone who has been mainly using FSMs to organize robot code, whether BTs are a good instrument, you'll likely be told that **BTs are unsuitable for complex robotic applications.**[114]. Similarly, BTs advocates might tell you that **state machines are a thing of the past.** I've been working with both and I don't like either of them. In fact, I'm waiting for some super AI to self-design itself and take over my job.⁵ Until then, I would recommend any developer to stay open-minded and play a bit with both: the more items you have in your toolbox, and the more likely you are to come up with a good system architecture.

5: Apparently this is already happening pretty quickly.

Homework

A fancy chain of hotels tasked you with programming a robot that will prepare the beds for their customers. The robot needs to:

- ▶ Check if there are pillows on the bed. If there are at least 2, the robot needs to replace their cover with a clean one. If there are less than 2, it needs to retrieve new pillows from the storage.
- ▶ Check if there are sheets on the bed. If any, it needs to remove them and put them with the dirty laundry.
- ▶ Clean the bed from any stain.
- ▶ If any stain is still visible, the previous step needs to be repeated for a maximum of three times.
- ▶ Place new sheets and the pillows on the bed.
- ▶ During winter, it needs to lay warm blankets on the beds, otherwise use lighter blankets.

Organize this task using the functionalities provided by a state machine (ex SMACC2) and using Behavior trees (ex Behavior Tree Cpp or Pytrees).



6 Integrating controllers in ROS 2

Any robot, to be called a robot, needs to perform some sort of movement. Just like humans use their muscles to interact with the world and their senses to guide them, robots use their actuators (typically electric motors) and their sensors to perform movements. The logic relating the sensed information with the actuation commands is governed by [control systems](#)[115]. If you don't plan to ever write a control system using ROS 2, you can completely skip this chapter¹.

Most control systems work as schematized in figure 6.1. A reference is specified by the user of the controller and compared with the current status of the system². The difference between these two is the input of the "controller", which contains the logic necessary to compute the desired "control command". The command is sent to an actuator, which will modify the status of the physical system. The status of the system is measured by a sensor and used for the original comparison, providing in this way "control feedback".

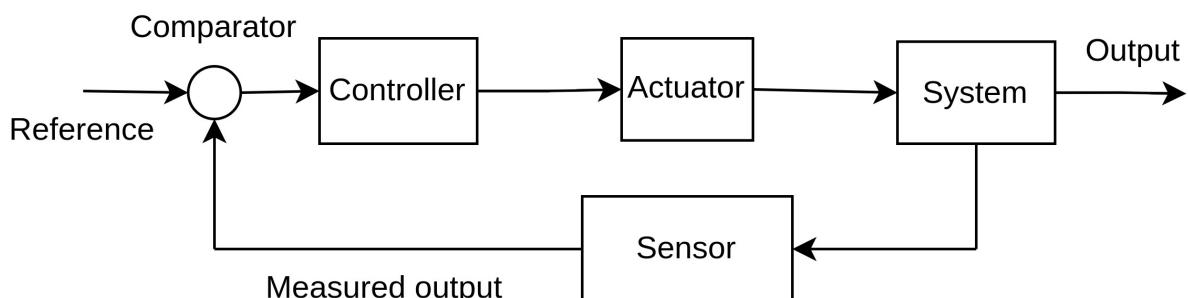


Figure 6.1: Diagram of a closed loop control system

Control systems are not exclusively used in robotics, but can be found practically everywhere in the modern world. A simple example is the thermostat controlling the heating system in a room: it uses a sensor to measure the temperature, and actuates the heaters to guide it toward a specified target.

1: This, however, would make me sad.

2: In this chapter I will not strictly follow the lexicon generally used to describe control theory. After all, this book has "very informal" in its title.

The logic implemented by the controller influences the relation between the reference and the output of the system. A "good controller" will allow the output to quickly follow the reference without oscillation or overshooting. A "bad controller" could result in an "unstable system", which is a system where a constant reference results in an oscillating output.

Designing a control system is a fascinating but relatively complex task. In this chapter I will not give an introduction to control theory³, but I will try to point out those aspects that need to be considered when implementing a digital controller running as a node in a ROS 2 ecosystem. We will later take a quick look at some control frameworks that were designed specifically for ROS.

3: This would require a couple of dedicated books. A good introduction can be found on *Modern Control Systems* by Richard C. Dorf and Robert H. Bishop.

6.1 The biggest enemy of a controller: delays

In every control application, the state describing the controlled system evolves in time according to the laws of physics. Motors need time to accelerate between different speeds because of inertias, temperatures need time to change because of thermal capacities and so on. These dynamics can usually be easily modeled and taken into account when designing the "control law" implemented by the controller. There are other dynamics, however, that are not introduced by the nature of the controlled system, but are instead a consequence of how the information is transmitted, digitalized or processed. Time-delays are inevitably introduced in any control system. If the control architecture is poorly designed, such delays can become too big or unpredictable and heavily damage the stability and the performance of the application. On top of this, if we are dealing with a digital controller (which is almost always the case in robotics), commands are not sent continuously to the actuators, but at a specified "control frequency". Similarly, sensors will likely not produce new data continuously, but with a certain "reading frequency".

To better understand why delays are bad for the health of your machine, let's analyze a simple example where we want to command a motor to move a robot-joint to a specified position. We will use the position reference to generate a velocity command for the motor, which will then translate into target torques and currents inside another internal controller⁴. The position of the joint will be read by an encoder and provided as feedback to our controller. The inner controller will use velocity and current measurements to regulate the torque delivered by the motor. A schematic of the resulting architecture is displayed in figure 6.2.

4: The practice of "nesting" controllers is very common in the control world. This isn't the only way to solve this particular control problem.

To simplify the problem, we will focus on the implementation of the position controller and assume that the inner control loop allows for the joint velocity to evolve linearly (according to an acceleration limit)⁵.

One of the simplest and most intuitive forms of control is the [proportional control](#)[116]. According to this control principle, the actuation command (in our case the target velocity for the motor) is proportional to the

5: Many motor vendors provide integrated solutions capable of efficiently solving part of the control problem.

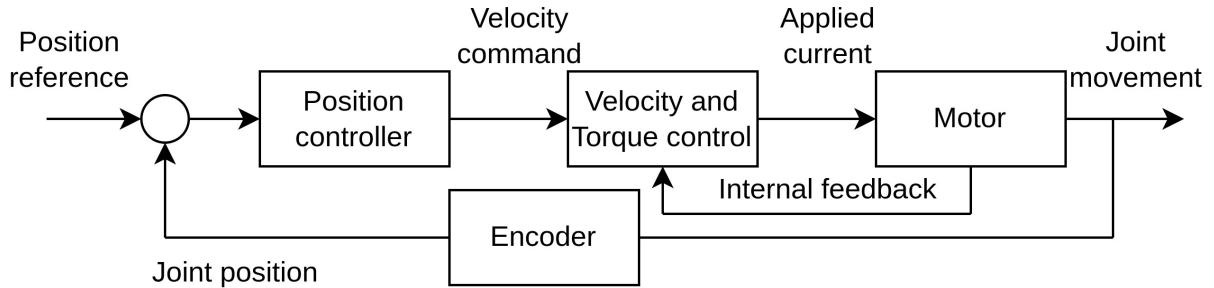


Figure 6.2: Diagram of a closed loop position control system for a robot-joint.

computed error (in our case the distance from the target). The amplitude of the output is moduled by a constant, usually written as K_p .

$$\text{Command} = K_p * \text{error} \quad (6.1)$$

The proposed control strategy is not the optimal one (the relation between position and velocity is not linear in an acceleration-limited system), but as long as K_p is "small enough", the joint will approach its target with decreasing speed, to then stop when reaching the set-point. This, at least, in theory. In practice, as we anticipated, the system will be affected by multiple delays which can be grouped in two categories:

- ▶ Some time ($D_{actuation}$) will be required from the moment our controller computes the command, until the moment the actuator will start to follow it. This is due to computation times, the dynamics of the inner control loop, transmission times along the fieldbus and mechanical non-idealities in the used components.
- ▶ The encoder will need time to make a measurement. Digitalizing and transmitting the measurement to the controller will take another bit of time($D_{feedback}$).

To show you the effects of these delays on the system, I've written a simple simulation that you can find on [my github account](#). We will run a first simulation assuming no delays and the following parameters:

- ▶ $K_p = 5.0$
- ▶ $D_{actuation} = 0\text{ms}$
- ▶ $D_{feedback} = 0\text{ms}$
- ▶ System acceleration = deceleration = 0.5rads^2
- ▶ Control period = 50ms (20Hz)

Now let's assume that our joint is stopped in its origin and is commanded to move to the position 0.05 rad . The following sequence of commands will be generated:

- ▶ t_0 : our controller will produce a command of $0.05 * 5 = 0.25\text{ rad/s}$, send it to the motor, then go to sleep for the control period.
- ▶ t_1 : when the controller wakes up, the motor will be just about to start its movement because of the actuation delay: both from the controller perspective and from the encoder perspective, its position is still 0, so our controller will keep sending the same command as before, then go to sleep.

- ▶ t_2 : the motor will have reached the velocity of acceleration * control-period = 0.025 rad/s, and have travelled a distance $x = 0.5 * \text{acceleration} * t^2 = 0.000625 \text{ rad}$.

If we continue with the iterations, we will get the behavior described in figure 6.3:

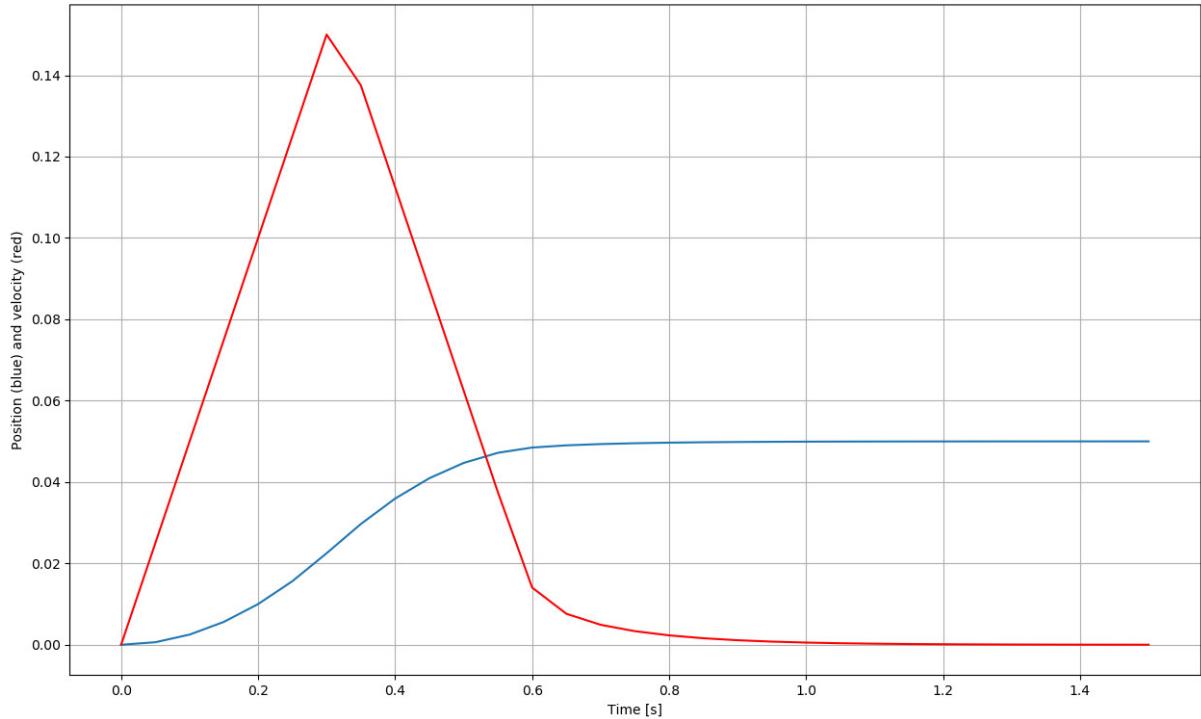


Figure 6.3: Position control of the joint without delays. Blue: position of the joint in radians. Red: velocity of the motor in rad/s.

The position of the joint is quickly converging to its target, there are no over-shoots, your robot is happy, your boss is happy, you are happy. Then the delays come. We will now change our simulation to use the following parameters:

- ▶ $D_{\text{actuation}} = 50\text{ms}$
- ▶ $D_{\text{feedback}} = 50\text{ms}$

The behavior of the system changes as described in figure 6.4:

Suddenly our joint is overshooting its target and oscillating for a while around it before being able to stop. Your robot is not that happy any more, so isn't your boss that asks you to improve the controller. You can't really get rid of all the delays, but you can try to reduce those introduced by the control period. You decide to change the control frequency from 20 to 100Hz, corresponding to a control period of 10ms instead of 50ms. The results are displayed in figure 6.5.

This is slightly improving the situation: the overshoot is reduced and the position stabilizes to 0 in a shorter time. However, your boss is not quite happy yet. You could try to reduce the K_p parameter, but this would result in a slower response of your system.

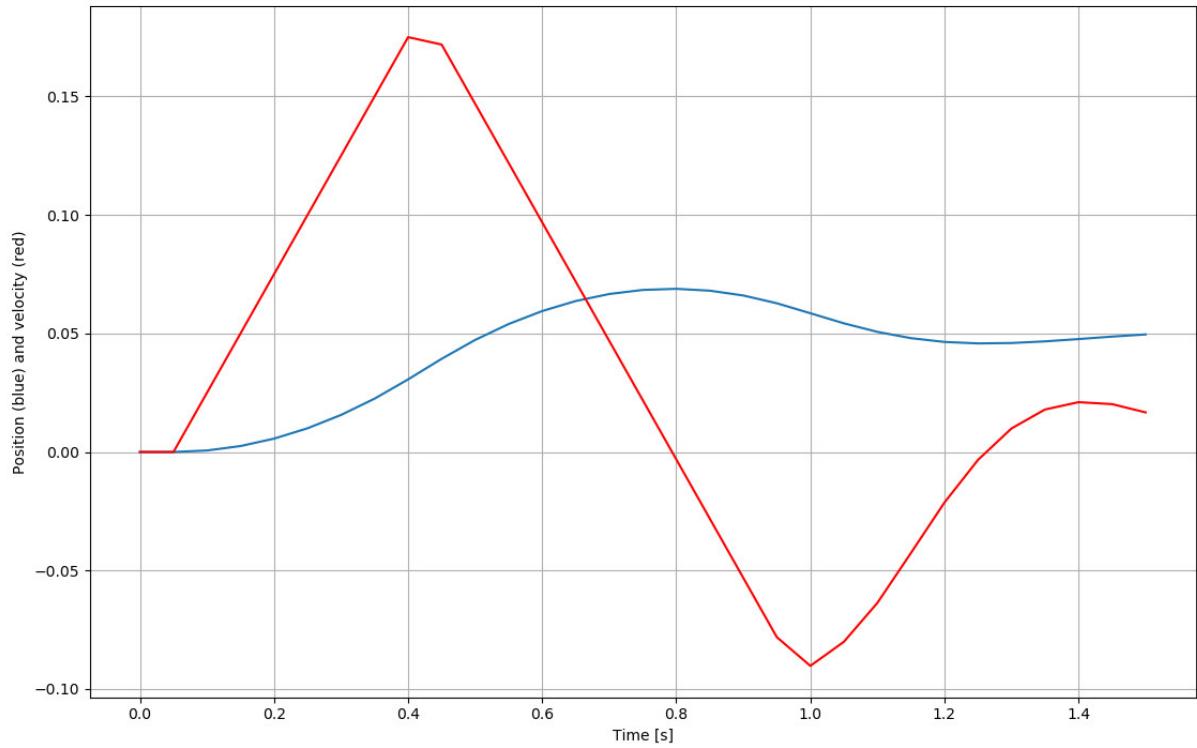


Figure 6.4: Position control of the joint with delays.

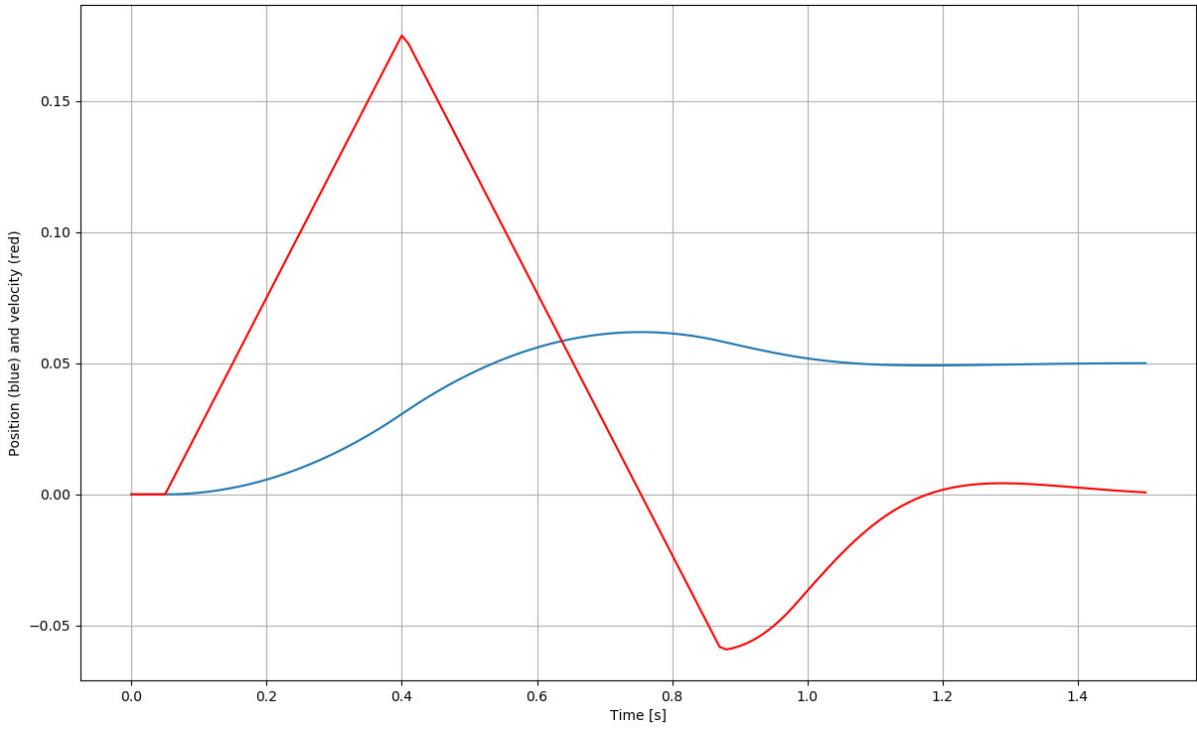


Figure 6.5: Position control of the joint with delays and a control frequency of 100Hz.

Compensating delays

We need something smarter. What if, instead of using the last read position as value for our comparison, we use the position that we predict

our robot will have at the moment in which the command will actually be applied? This requires us to know some additional values: the current velocity of our joint, and the expected delays⁶. We then change our error computation as following:

$$\text{error} = \text{error} - \text{velocity} * D\text{t}_{\text{actuation}} - D\text{t}_{\text{feedback}} \quad (6.2)$$

As a consequence, the system response will change as displayed in figure 6.6.

6: If the encoder can't provide the velocity as feedback, we can estimate it by calculating the derivative of the position.

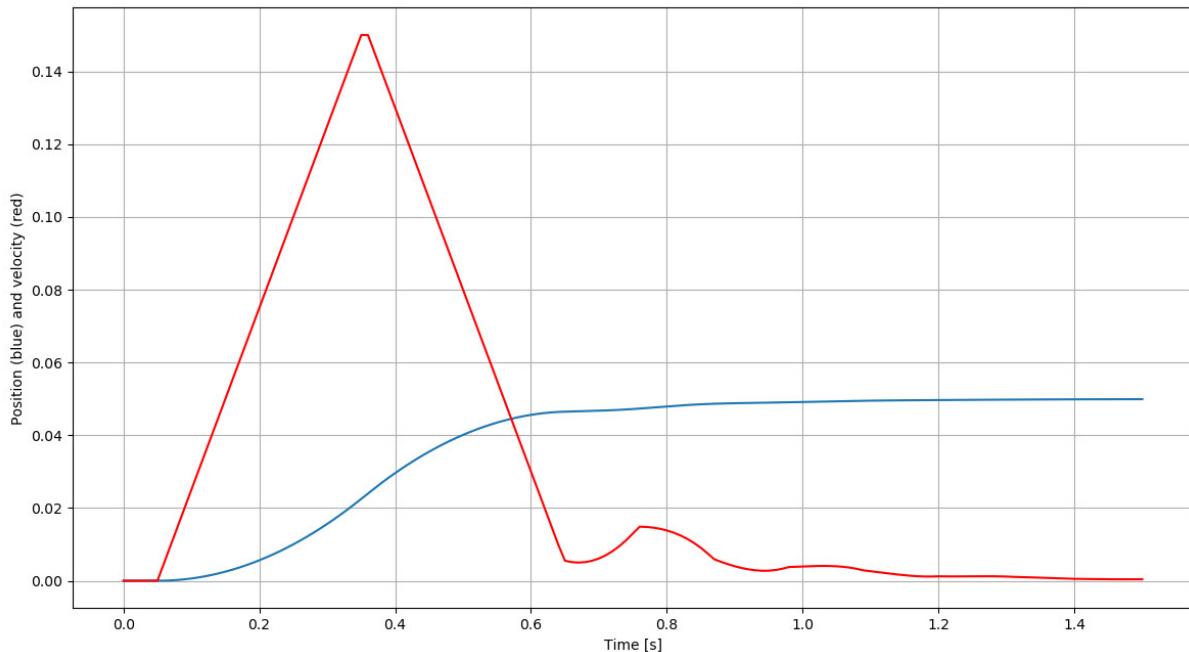


Figure 6.6: Position control of the joint with delays and delays compensation.

Much better, right? This could still be improved if, instead of predicting the position using the delayed velocity reading, we would use a prediction of the real velocity, to then use a value averaged during the delay-period. Since I'm a lazy guy, I will leave that to you as an exercise.

If we can compensate for delays, why am I bothering to tell you all this? After all, this is a book about ROS 2, not about control theory. Well, when we made the last correction, a very strong and important assumption was made: **delays are known and constant**.

We can't get rid of delays, but as long as this assumption is true, and you know how to write a decent controller, your robot will be fine. If, instead, the delays affecting your system are not constant and unpredictable, even the smartest controller will struggle to provide a decent output.

Now comes the most important question of this chapter: *Which elements of a robot architecture can introduce non-constant delays?*

6.1.1 Sources of delays

To answer this question, let's first imagine to implement a generic controller on an embedded computer running ROS 2. The controller will be

sending commands and listening for sensor data on a fieldbus.

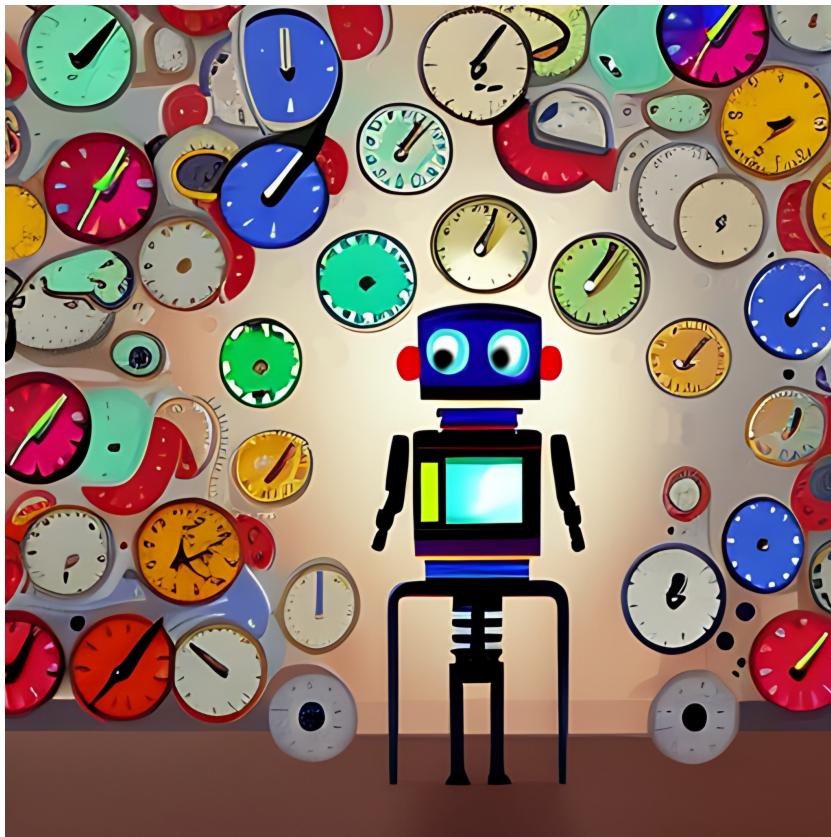
The ROS 2 graph will consist of:

- ▶ A node implementing the controller and producing commands at a specified frequency.
- ▶ A node listening to the commands and sending them to a fieldbus.
- ▶ A node listening on a fieldbus (could be the same used to write, or a different one) to monitor the state of the joint and communicate it to the controller.

We will now follow the chain of delays along the control loop, starting from the controller, and discuss which of them are deterministically limited and which aren't.

- ▶ The controller produces its command at a specified frequency. If the controller is executing [real time](#)^[117] capable code on a real-time capable machine, the delay introduced by the time-discretization can vary between something close to 0 (if the controller runs right after getting the position feedback) to a maximum of a control period⁷. If, instead, the controller runs on a classic, non-real-time scheduler, the introduced delay will depend on the capability of the scheduler to allocate time for its process and may vary significantly.
- ▶ The control command is transmitted on a topic from the controller to the node communicating with the fieldbus. If this communication is performed using a real-time capable topic, the introduced delay will be small and limited to a deterministic amount. If, instead, a normal topic is used, the delay will again become non-deterministic.
- ▶ The communication node will receive the command and send it to the fieldbus. If this operation is again done at a specified frequency, the same considerations made for the control node will be valid.
- ▶ The message is transmitted on the fieldbus to the motor. The delays introduced in this operation may vary deeply depending on the kind of fieldbus used and on its load. Interfaces specialized for the transmission of control data like [EtherCAT](#)^[118] will be capable of running at high frequencies and small [jitter](#), while interfaces not designed for this purpose might result in data being re-transmitted multiple times on the network, resulting in unpredictable delays.
- ▶ The actuator picks-up the command and begins its execution. The introduced delay will of course depend on the kind of actuator used, but is typically deterministic for industrial actuators.
- ▶ The sensor performs a measurement and sends it on the fieldbus. Different sensors produce data at different, sometimes inconstant frequencies. Industrial sensors will typically guarantee a specified frequency with a maximum jitter, but depending on the measurement principle and on the internally applied filters, this data might already be delayed. For example, measuring speed using a standard encoder requires at least two ticks to be received in order to perform the mathematical derivative of the position.
- ▶ The message containing the sensor information is sent on the fieldbus. The communication node will receive the message and send it to the controller using a topic. For these the same considerations as for the command message are valid.

⁷: It is common practice to approximate this delay to half control period. Specific scheduling techniques, like the "Logical Execution Time Paradigm" can make this kind of delays almost constant.



6.1.2 Making your system deterministic

It is now clear that any step in a control loop can potentially become a source of delays, and hence of problems. Since we don't want problems, we should try to follow some practices that help making a control system more deterministic:

- ▶ Use hardware designed for control purposes. The only way to influence the delays introduced by the fieldbus communication, the actuators and the sensors, is to use devices that were designed to work deterministically.
- ▶ Use a real-time capable OS and make your program real-time capable.⁸. This will ensure that, as long as your computation times are reasonable, your scheduler will give execution permission to your program whenever it needs it. Remember that a real-time system is not necessarily fast, but guarantees to perform defined operations within a defined amount of time. You can find useful tips for creating a real-time setup on the [real-time programming demos\[119\]](#) or on the [real-time work group\[120\]](#).
- ▶ Synchronize the data flow whenever possible. If you manage to compute and send the control command as soon as new feedback is made available⁹, you will reduce the delay introduced in the loop¹⁰. Ideally, the computation should also be synchronized with the data flow of the used fieldbus. Could you, for example, run your controller as a plugin of a program that is capable of direct communication with the network instead of using multiple nodes?
- ▶ If part of the used information needs to flow through multiple nodes, choose minimalistic interfaces with low latency. If you need

⁸: A common practice is to patch the Linux kernel with the [PreemptRT patch](#).

⁹: If you can't get feedback at the desired frequency, consider interpolating it with predictions.

¹⁰: If the execution time of your controller is relevant and subject to variability, it might be a better idea to use the already mentioned Logical Execution Time Paradigm.

to publish data from within a real-time loop, consider using the real-time publisher provided by the [real-time tools package](#)^[121]: normal ROS publishers are not real-time compatible, and could compromise the determinism of any thread using them. Note that, even if they won't block the publishing thread, real-time publishers will still publish the data using a separate non real-time thread. Despite ROS 2 being branded as real-time capable, there is currently no easy way to transfer data between nodes deterministically. The overall latency will anyway be much better when performing shared memory operations between nodes running in the same process.

- ▶ As we already explained in section 3.4, avoid relying on the default ROS-executors for getting time-critical callbacks executed. Use some of the mentioned alternatives instead.

6.1.3 Do you need determinism?

As we have just observed, a deterministic system is much easier to control than a non deterministic one. At the same time, writing real-time capable software is more difficult than writing normal software: any library using dynamic memory allocations won't be available, including most of the std libraries.

It is then natural to ask yourself: "Is it worth the effort?". This will depend on how fast the dynamics of the controlled system evolve.

If your control system is adjusting the temperature in a room, introducing a bunch of delays here and there is not likely to make any difference: it will anyway take multiple minutes for the heating system to change the temperature of the environment. This kind of controllers could even run on a Windows machine.

If the controller is instead trying to adjust how much force the tool mounted on a robotic arm is applying on a surface, even a millisecond could make a big difference: the currents and the forces applied by electric motors can change very quickly.

Many robots find themselves somewhere in between these two scenarios, like for example autonomous mobile robots (AMRs). While some of their functionalities require good determinism, like the capability to brake in front of obstacles, other functionalities might be tolerant to a certain degree of variability (like for example path-planning). In these cases, it is a common practice to delegate those functionalities requiring a deterministic behavior to dedicated components, while leaving other modules capable of nondeterministic operations^{[\[11\]](#)}. As a rule of thumb, controllers requiring reliable update frequencies above the 100Hz should be handled by deterministic components, while those exceeding the 10000Hz are usually delegated to specialized devices. Components that need to undergo a safety certification need for obvious reasons to be fully deterministic even if executing at relatively low frequencies^{[\[12\]](#)}.

¹¹: Even for this case, a parallelism can be made with the human body: while many of its functionalities work deterministically, like the control of the pulses in our heart, our brain is free to take as much time as it takes to contemplate cats videos on YouTube.

¹²: Some useful resources for profiling your application and monitoring the used resources can be found [here](#).

6.2 ROS 2 control

Integrating robot controllers in a real-time friendly way is a very common challenge between ROS2 users. Because of this, a framework was developed, that is both hardware agnostic and allows for the integration of custom controllers: [Ros2-control\[122\]](#).

ROS 2 control defines three categories of hardware systems: Sensor, Actuator, and System (a mix of the previous 2, used when there is only one logical communication channel to the hardware). These can be instantiated and integrated into the framework as [plugins](#). Plugins allow to avoid the latency introduced when components communicate using normal ROS 2 interfaces, while keeping the interfaces agnostic from the integration framework.

Sensors expose a set of state interfaces, which provide the information that can be used by the controllers to introspect the system. Actuators expose command interfaces, which can be used by the controllers to interact with the system.

The sensors and actuators available for each of the robot's joints are described using specific URDF tags. You can find a simple example [here](#).

In the case of a differential drive, the base motors could for [example\[123\]](#) implement the following interfaces:

```

1 command interfaces
2     left_wheel_joint/velocity
3     right_wheel_joint/velocity
4 state interfaces
5     left_wheel_joint/position
6     left_wheel_joint/velocity
7     right_wheel_joint/position
8     right_wheel_joint/velocity

```

Controllers are implemented deriving from a common [ControllerInterface](#) class and are as well integrated as plugins. They are implemented as lifecycle-managed nodes, which makes it easier to start and stop them using a standard interface. Some commonly used controllers, like the [PID controller\[124\]](#) are available out of the box, but customized controllers can be created.

Finally, two components manage the communication between the hardware interfaces, the controllers and the user: the "controller manager" and the "resource manager".

The controller manager is in charge of loading / unloading controllers, request the hardware interfaces that they need in order to function and of providing services that can be used to interact with the framework by the user.

The resource manager is in charge of loading the hardware devices in an abstract way, while making sure that there are no conflicts between different controllers trying to interact with the hardware.

For each execution of a control loop, the "update()" function of the manager is called, which will:

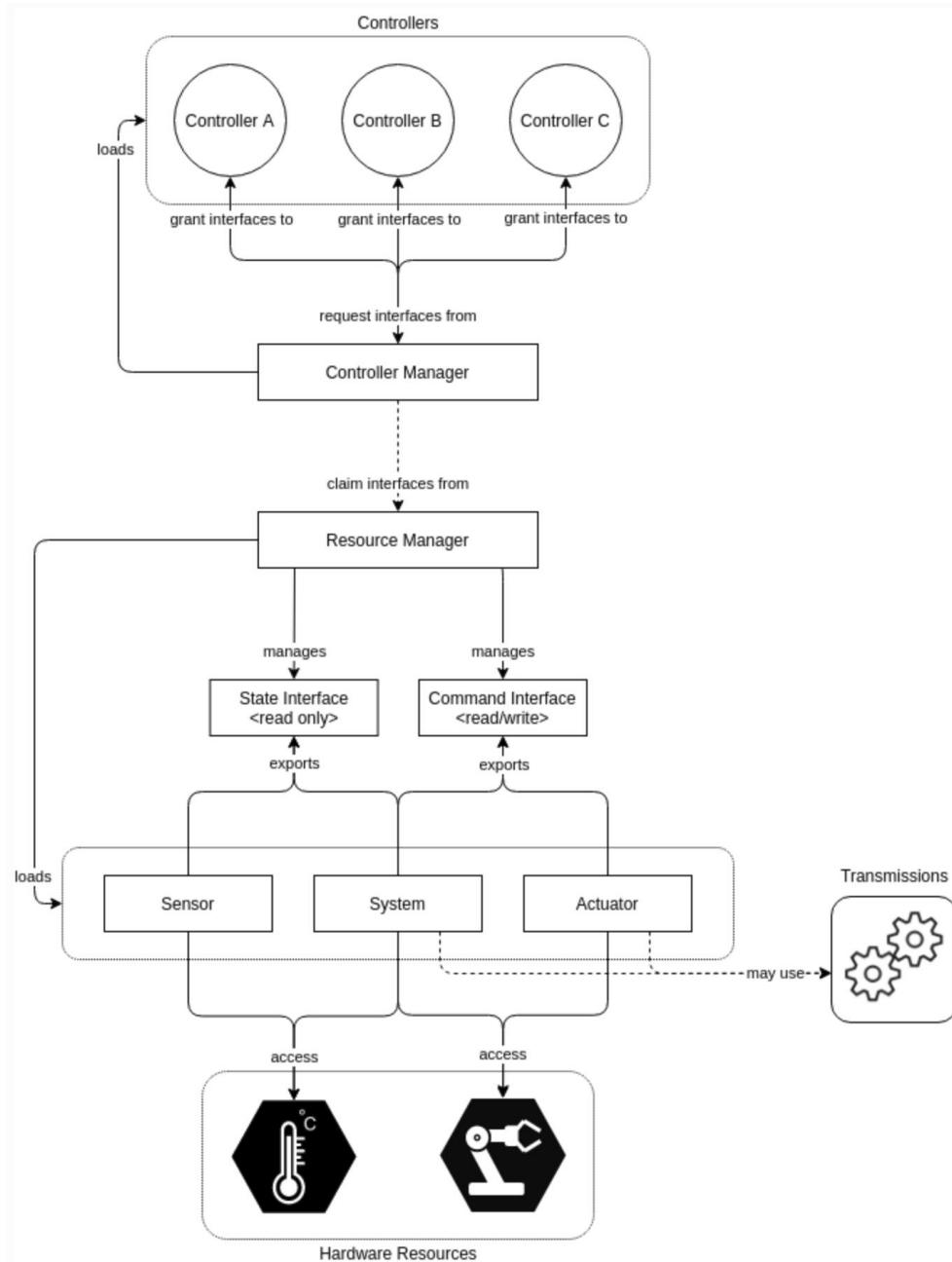


Figure 6.7: ROS 2 control architecture.

From https://control.ros.org/master/doc/getting_started/getting_started.html

- ▶ Read the data from the interfaces that were declared by the enabled controllers (through the resource manager).
- ▶ Execute the control logic of the activated controllers.
- ▶ Write the outputs to the hardware devices according to what was specified by the control interfaces (through the resource manager).

On the corresponding [Github repository](#) you can find plenty of examples and more detailed documentation to help you getting started with this framework.

ROS 2 control is particularly indicated for robots using multiple degrees of freedom together with different control strategies that need to be switched at runtime.

6.3 Domain-specific control frameworks

ROS 2 control provides the tools required to integrate a generic controller with its inputs and outputs in a modular way. In many cases, controllers need to work together with additional components in order to obtain the desired robot behaviors. A moving robot, for example, usually only follows commands that don't bring it in collision with its environment. At the same time, as the control architecture grows more and more complex, developers need additional tools in order to be able to introspect and debug the system.

Because of this, frameworks were developed that provide multiple additional components required to control robots of a specific domain. We will take a quick look at the most popular ones: Nav2 and MoveIt.¹³

6.3.1 Nav2

Nav2[83], successor of the "ROS Navigation Stack", provides tools that allow a mobile robot to navigate between two poses in its environment. The required components usually are:

- ▶ One or more dynamic maps of the robot's environment, where obstacles can be continuously added or removed.
- ▶ A localization system, capable of understanding the current position of the robot in a map, or to generate a new map using the robot's sensor information.
- ▶ A global planner, capable of generating trajectories connecting the robot origin to its target while avoiding the obstacles modeled by the map¹³.
- ▶ A local planner, capable of generating commands for the robot's actuators based on the target trajectory and the obstacles in the map¹³.
- ▶ Actions that are functional to the navigation: tracking moving obstacles, resetting the maps state, etc.

13: This dual-planning strategy is often referred to as "Hybrid Planning".

In Nav2 all these components are orchestrated by Behavior trees(BT). In particular, the same behavior tree library that we described in Chapter 4.6 is used: "Behavior trees cpp".

In a typical execution flow, the navigation BTs will update the maps with the current obstacles, generate a trajectory to the target, then repeatedly call the local planner and update the map until the target is reached. This sequence, however, is not guaranteed to always work: the robot might encounter unexpected obstacles that prevent it from planning a trajectory or following an existing one, the local planner might get stuck in a local-minima and so on. Because of this, the navigation BTs additionally need to integrate mechanisms to handle these scenarios.

Different kinds of robots operating in different environments with different requirements, will almost certainly have different planning needs. Because of this, allowing for the customization of the order of execution of different tasks is essential to any modern robotic framework.

Similarly to what happened for ROS 2 control, in Nav2 components are integrated within a single framework using plugins. This not only allows

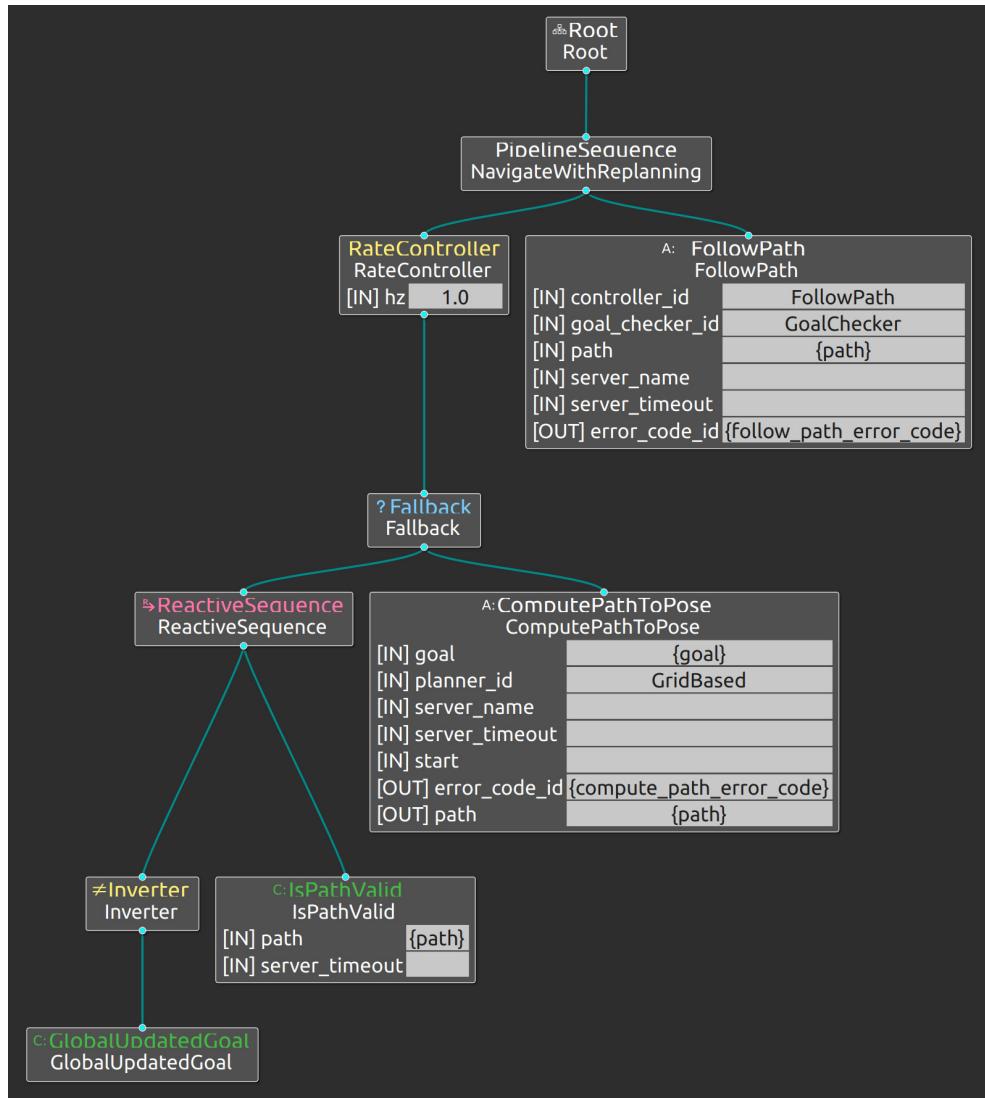


Figure 6.8: Example of simplified BT that generates a trajectory, follows it, and continuously checks for its validity.

to reduce the communication latency between them, but most importantly to share resources like the maps tracking the state of the obstacles in the environment (costmaps). The execution of all the components is synchronized using lifecycle-managed nodes.

For each of the required plugins, Nav2 provides a basic implementation to help you getting started with your project¹⁴. A complete list of the plugins implemented by the community can be found [here](#)[125].

If you are planning to integrate navigation functionalities within your robotic platform, using Nav2 will provide you a large set of tools ready to execute out of the box, while still allowing you to fully customize the system components and execution logic.

Since this is one of the largest open-source projects based on ROS 2, you should take a look at its architecture even if you are not planning to use it.

14: Many of these aren't industry-ready solutions, but can easily be replaced with custom implementations.

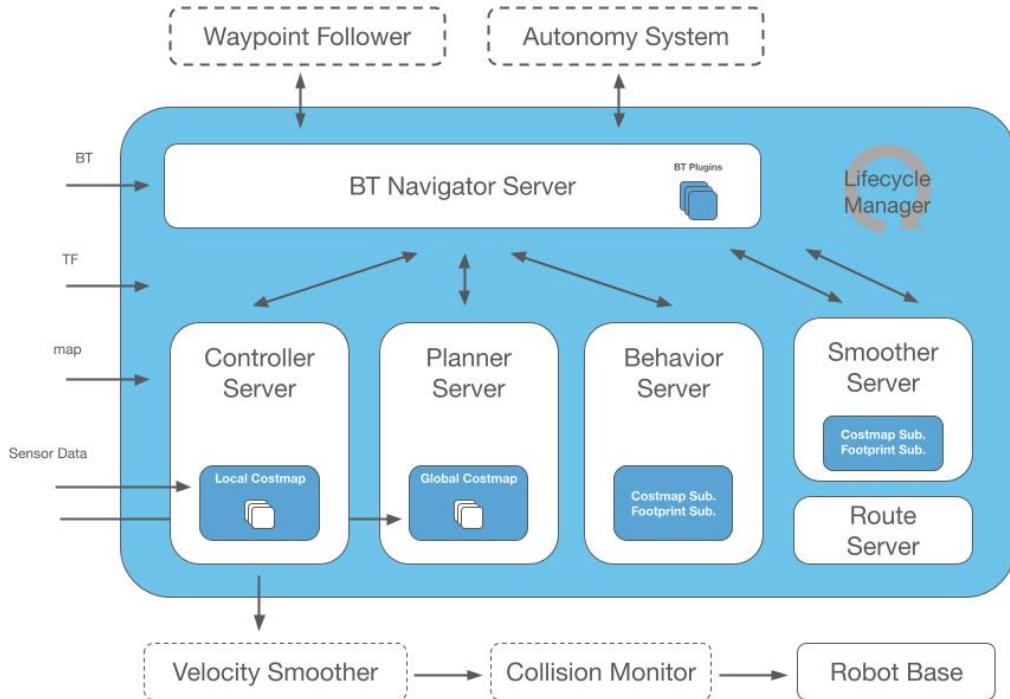


Figure 6.9: Nav2 architecture overview.
From: <https://navigation.ros.org/>

6.3.2 MoveIt2

The MoveIt2[126] can be seen as the brother of Nav2 that primarily targets robotic manipulators. It provides a set of tools to move a generic robot between multiple configurations while taking into account not only its description, but also the characteristics of the environment where it operates. These include:

- ▶ A planning scene, where the framework stores all the information about the environment in which the robot operates. This can simultaneously include static information in the form of preconfigured polygons / meshes and information coming from sensors like lidars or cameras.
- ▶ A planning pipeline, using the description of the robot and the planning scene to generate collision-free trajectories for the manipulator. Similarly to what happens with Nav2, this uses hybrid planning and divides the problem between global and local planning¹⁵.
- ▶ A move-group that, after receiving a command from the user, collects the information required for planning, communicates it to the planning pipeline, and forwards the output to the trajectory execution manager. A single robot can incorporate multiple move groups.
- ▶ The trajectory execution manager communicates the trajectory to be executed to the robot's controller using an action interface. The system can react to changes in the environment communicating updated trajectories to a running action.
- ▶ A dedicated Rviz plugin and a command line interface provide the user with additional functionalities to introspect the generated trajectories and to manually send commands to the robot.

15: Since the problems to be solved are, however, usually involving a bigger number of degrees of freedom, sampling-based planning algorithms are the default choice.

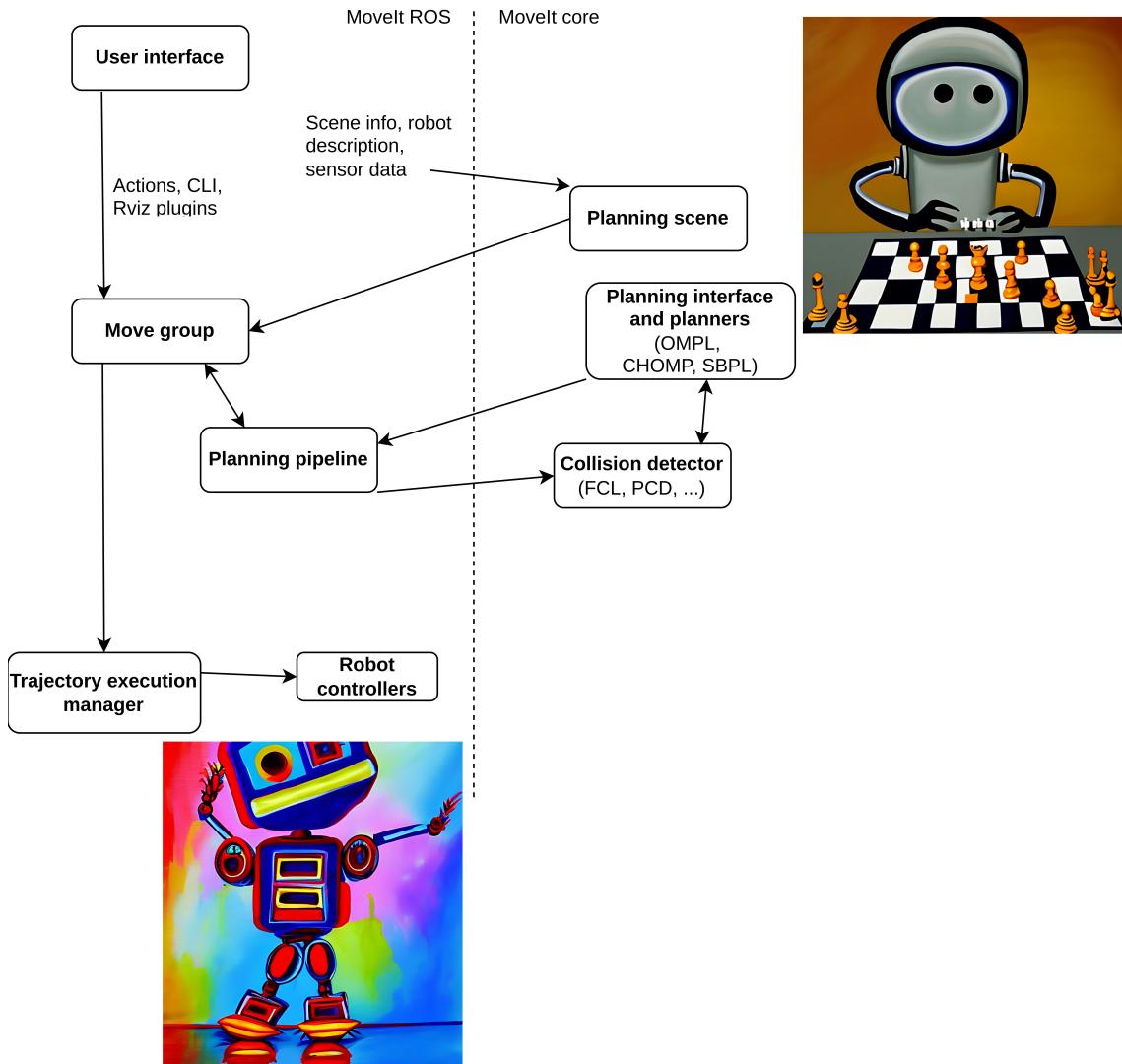


Figure 6.10: MoveIt2 architecture overview.

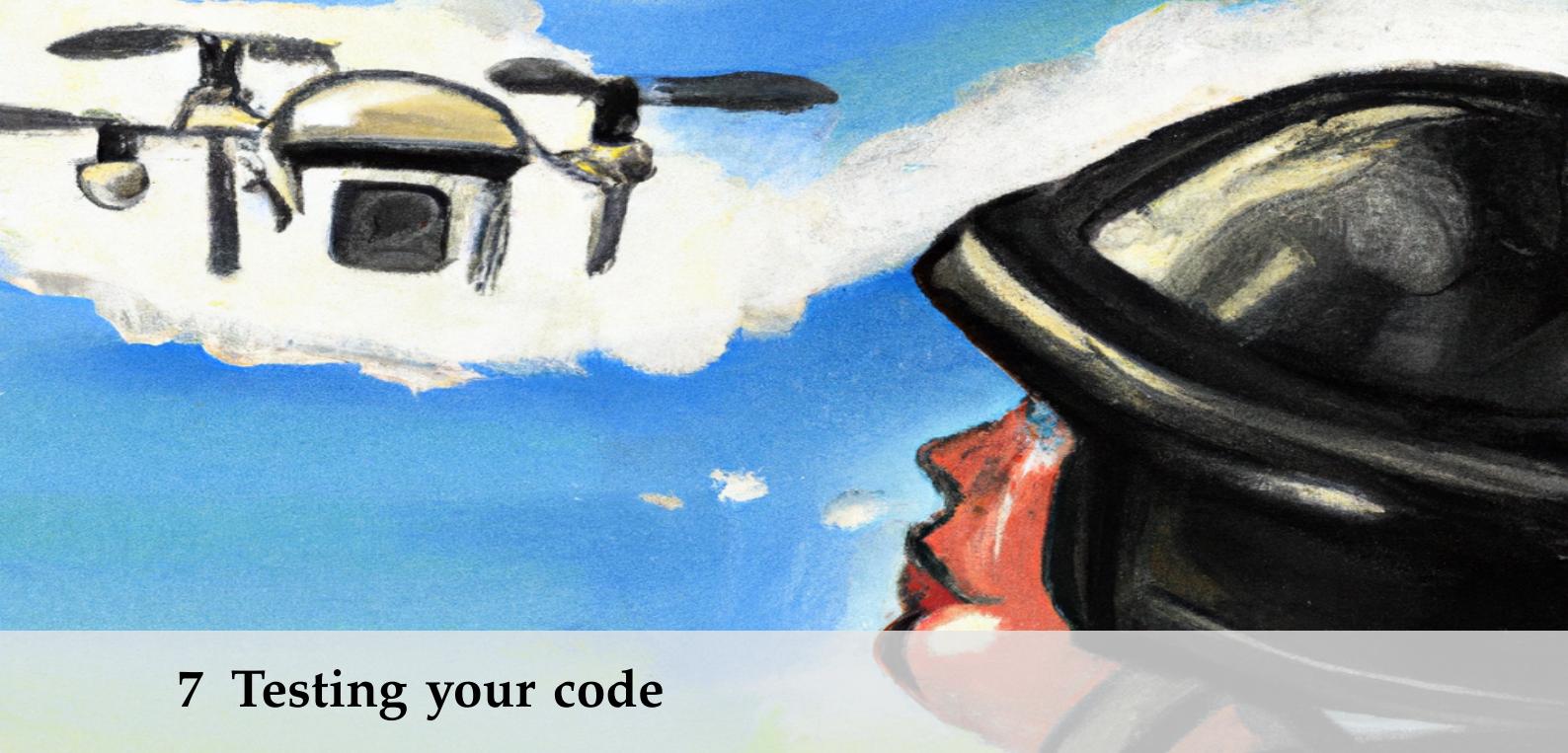
Based on: <https://moveit.picknik.ai/humble/doc/concepts/concepts.html>

Similarly to what happens in Nav2, most components are integrated as plugins and can be replaced or customized.

Due to its flexibility, moveit can be used in both academic and industrial projects, with classic or collaborative manipulators. If you are planning to integrate a manipulator in your ROS 2 based platform, it's definitively worth taking a look at it.

Homework

- ▶ Under what conditions does the **joint-control algorithm** proposed in this chapter become unstable (not converge to a steady-state)? Can you think about better implementations?
- ▶ Modify the algorithm to use the prediction of the current velocity instead of the current velocity as feedback.
- ▶ Integrate the created controller as a plugin for ros2-control.



7 Testing your code

One of the phases I love the most in the development process of robotic software, is testing the code on the robot's hardware. In this magical moment, all the effort, the ideas, the algorithms that were developed in the abstract world of the code, turn into something concretely happening in the real world: the robot moves. Unfortunately, this is also the part of the development where we are more likely to crash into something, to burn the robot, or to step on someone's feet¹. Even if all this might sound like fun, it is a fact that testing on the robot's hardware is a quite costly operation: robots tend to be expensive tools, that you might have to share with other developers, often in a dedicated environment.

Cost is not the only concern in on-hardware testing. Repeatability can be difficult to achieve in real-world conditions. For example, testing a feature that allows a robot to extricate itself from an obstacle-filled configuration requires resetting the environment and positioning the robot and obstacles precisely. This can be time-consuming and challenging, especially if one of your colleagues stole one of the tables you were using as obstacles to install his new monitor. Debugging the software in case of a test failure can also be time-consuming and challenging, making it difficult to reproduce errors.

Testing on the robot is, at the same time, an essential part of the development process. At the end of the day, that's where the action is going to happen, and the resilience to the unpredictability of the environment is one of the most important characteristics of a good robotic stack. However, before coming to this step, you should put a brake to your adventurer's spirit, and perform other kinds of test that don't involve the hardware. These tests will likely not be as much fun, but will allow you to catch a lot of issues early in the development process, saving time and resources. An important advantage of "pure software tests", is that they not only catch bugs currently existing on the robot, but also prevent future ones. A well done testing layer should give you the confidence that, as long as the tests are passing, your new features didn't break the existing code's logic. Once the tests are integrated into the build

1: It is statistically proven that your boss' feet are the most endangered.

pipeline and automated, it becomes more difficult for any contributors to unintentionally change the system's behavior.

In "recent" times, software developers around the world have realized the power of testing, and developed a paradigm called "Test driven development (TDD)". This software development process starts with the translation of the requirements of the developed system into tests **before** the actual development of the code. After verifying the test's failure, the developer should implement the required features until all tests are succeeding. The main advantage of this practice is that the code is developed with good testability from the beginning, instead of adapting the tests to an existing software stack. The *World Wide Web* is full of information about TDD, so I won't repeat what you can already find [out there](#), but you should know that, if the requirements of your system are clear from the beginning, it is a good idea to start your development from the tests.

ROS 2 facilitates the creation of tests using a modular and layered model. The modularity implies that it should be possible to test, or at least partially test, each one of the "building blocks" of the application independently from the others. This is a common practice when building complex systems: it is easier to ensure that the final application will work properly if you can trust that all the components it is built upon are behaving as expected. A layered architecture allows to gradually increase the scope of the tests , passing from single libraries, to nodes, to group of nodes until testing the entire application. We will now take a look at how these principles can be implemented using ROS 2.

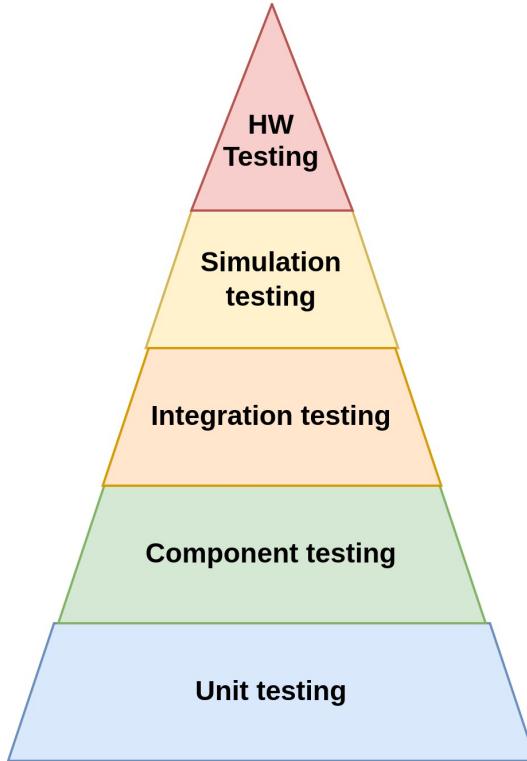


Figure 7.1: The sacred pyramid of robot testing.

7.1 Unit testing

The tests targeting the smallest units of code are called "[unit tests](#)[127]". Using these tests, a programmer can verify that a function or an object, given a specified set of inputs, produces the expected outputs. Testing small parts of code has a couple of advantages with respect to tests that target bigger chunks of the system:

- ▶ Debugging failing tests is easier. When a test running a complex action fails, it is often not immediate to figure out which of the components building the functionality was responsible. If, instead, a test covering a small piece of code fails, you know who to blame.
- ▶ Increased readability. One of the easiest way to figure out how some piece of code written by the guy that was working on your project eight years ago is supposed to work, is to take a look at its tests². Small tests implies more tests, which implies more material to help you. Some people like to say that tests are "executable documentation".

2: I know, this is quite unrealistic, that guy probably didn't write any test.

A fine granularity of testing can, however, bring some disadvantages. Most relevantly, modifications in the execution flow of the code might imply the modification of a large amount of tests, making the development slower. It is hence important to find a balance in the portion of code covered by each of your tests, increasing the granularity on those functions that are less likely to be modified as your code evolves.

Since unit testing is a widely diffused software development practice, multiple frameworks have been developed to structure and speed up the definition of tests. For those functions and classes that don't require any interaction with ROS, these frameworks can be directly used in your project without any adaptation; the ROS tools will simply make it easier for you to install and execute them. The main frameworks of choice are [GTests](#)[128] for code developed with C++, and [pytest](#)[129] for Python based implementations, but you are free to use different ones if you like.

7.1.1 GTests in ROS 2

GTests, developed years ago by a tiny company called [Google](#), is one of the most used testing frameworks for the C and C++ languages. It's usually the default choice when your code needs to interact with hardware, because it supports [mocking](#)[130] out of the box. Without going too much into the details, let's take a quick look at how these guys look like.

To write a basic unit test, capable of executing ROS 2 code, you can create an executable in the form:

```

1 #include <rclcpp/rclcpp.hpp>
2 #include <gtest/gtest.h>
3
4
5 int main(int argc, char** argv) {
6     rclcpp::init(argc, argv);
7     ::testing::InitGoogleTest(&argc, argv);
8     int res = RUN_ALL_TESTS();
9     rclcpp::shutdown();
10    return res;

```

11 | }

This will initialize ROS 2, look for tests, execute them, then shutdown the ros context. To define one or more tests, Gtests provides a set of macros that are automatically discovered at initialization time. The simplest form of test looks something like:

```
1 TEST(TestSuiteName, TestName) {
2     ... Run some stuff
3     ... Make some assertions
4 }
```

Where the `assertions` are another set of macros that allow you to verify that the outputs of the algorithm you are testing are within the expected ones. There is no constraint on the type of code you can run during a test: you can create nodes, add parameters and test their public interface. You can also test free functions, or code that doesn't require the ros context.

It is very likely that, while defining multiple tests for the same object / node or library, you'll find yourself repeating a part of the code in each of them. In this case, it is a good idea to use the `TEST_F` macro, which allows you to define a fixture class, deriving from `testing::Test`, which will be instantiated before executing any of the tests using it. The tests will later execute as member functions of this class and will hence be capable of accessing its members and methods. Here a basic example:

```
1 #include <rclcpp/rclcpp.hpp>
2 #include <gtest/gtest.h>
3
4
5 #include "a_class_using_ros.hpp"
6
7 classTestFixtureName : public testing::Test {
8 public:
9     TestFixtureName()
10    : node_(std::make_shared<rclcpp::Node>("test_with_node")){}
11
12    void SetUp() override {
13        // Any code that should execute before the test starts
14        node_->declare_parameter("param_name", std::string{"param_default_value"});
15    }
16
17    void TearDown() override {
18        // Any code that should execute after the test run
19    }
20
21 protected:
22     rclcpp::Node::SharedPtr node_;
23 };
24
25 TEST_F(TestFixtureName, TestMethodTrue) {
26     AClassUsingRos class_ = AClassUsingRos(node_);
27     EXPECT_TRUE(class_.aClassMethodThatShouldReturnTrue());
28 }
29
30 TEST_F(TestFixtureName, AnotherTestName) {
31     EXPECT_EQ(aFunctionThatShouldReturnOne(node_), 1);
32 }
```

In other cases, you might find yourself running the same code with different parameters. For this case, the `TEST_P` macro is the way to go: it allows you to define a vector with different parameters against which

your test will be executed. To define the values that you want to use in your test, you can use the INSTANTIATE_TEST_CASE_P macro, then you can retrieve one of these calling the GetParam() function in your test. If you want to pass multiple parameters, [Tuples](#) are there to help you:

```

1 class ParamTestFixtureName : public ::testing::TestWithParam<std::tuple<int, int, bool>> { ... }

3 TEST_P(ParamTestFixtureName, TestSmaller) {
4     auto first_element = std::get<0>(GetParam());
5     auto second_element = std::get<1>(GetParam());
6     auto expected_result = std::get<2>(GetParam());
7     EXPECT_EQ(IsSmaller(first_element, second_element),
8               expected_result);
9 }
10
11 INSTANTIATE_TEST_SUITE_P(
12     BoringSmallerTests,
13     ParamTestFixtureName,
14     ::testing::Values(
15         std::make_tuple(0, 1, true),
16         std::make_tuple(1, 0, false),
17         std::make_tuple(-5, -4, true));

```

Mocks

While writing code for a robot, it is very likely that, at some point, you will have to interact with some hardware device. A part of your code might, for example, be sending commands to a motor, or reading the state of an I/O device. Unfortunately, attaching a motor or an I/O module to your PC any time you want to run a test involving them, is not very convenient, so you need to structure your code in a way that allows it to abstract from the layer performing the communication with the hardware. The most common way to achieve this, is using the [Dependency injection design pattern](#)[131]. If you choose this technique, your code won't be interfacing directly with a Motor or IOModule class, but with abstract interface classes, ex MotorInterface and IOModuleInterface. The code actually managing the hardware, located for ex. in the Motor class, will inherit from these interface classes and override their Methods. Note that the usage of the dependency injection pattern is not only limited to code interacting with hardware, but can in general be used whenever you don't want to be tightly coupled with a dependency.

Now that we have things a bit sorted out, how do we proceed to write our tests? We have 2 options:

- ▶ We can create new classes, still derived from the interface ones, that will emulate the behavior of the real device, then use these classes for our tests.³ Unfortunately, creating and maintaining these emulators requires a lot of resources.
- ▶ We can create mock classes for the objects, then use these to set expectations for the calls performed by our tests.

³: Emulating the behavior of the entire robot, is similar to creating a simulator.

Since there's no generic approach for the first option, we'll take a quick look at how to write mocks. As we mentioned in the beginning of the chapter, GTests provides a dedicated framework for creating mocks, called [GMock](#)[132]. This framework tries to minimize the amount of work

you need to do to set-up mocks, and provides a generalized way to set expectations on them.



It is easier to understand how this tool works by looking at an example. Imagine that somewhere in your robot's code you defined a class that manages the interaction with an integrated umbrella used by the robot to protect itself from the rain. Since you knew the day would come when you would have had to write a test involving the umbrella, you based your implementation on an interface class that could look something like this:

```

1 class UmbrellaInterface {
2     virtual ~UmbrellaInterface() {};
3     virtual void openUmbrella() = 0;
4     virtual void closeUmbrella() = 0;
5     virtual bool isOpen() const = 0;
6 };
7 
```

Now you are tasked to write a test for a function that will open the umbrella when it's raining and close it when it's not:

```

1 class Umbrella : public UmbrellaInterface {
2     public:
3         void openUmbrella() override {
4             ... Advanced science stuff that interacts with real
5                 umbrellas
6         }
7         void closeUmbrella() override { ... }
8         bool isOpen() const override { ... }
9     };
10 
```

```

11 void manageUmbrella(bool its_raining, std::shared_ptr<
12   UmbrellaInterface> umbrella) {
13   if(its_raining && !umbrella->isOpen())
14     umbrella->openUmbrella();
15   if(!its_raining && umbrella->isOpen())
16     umbrella->closeUmbrella();
}

```

Since we can't create an instance of the Umbrella class in our test, we need to create a mock for it:

```

1 #include "gmock/gmock.h"
2
3 class MockUmbrella : public UmbrellaInterface {
4 public:
5   MOCK_METHOD(void, openUmbrella, (), (override));
6   MOCK_METHOD(void, closeUmbrella, (), (override));
7   MOCK_METHOD(bool, isOpen, (), (const, override));
8 };
9

```

All you need to do is fill in the macro MOCK_METHOD for each function using the signature "MOCK_METHOD(ReturnType, MethodName, (Args))"⁴. Assuming that we stored this in a dedicated header file, we can write our test:

```

1 #include "mock_umbrella.hpp"
2 #include "headers/with/functions/we/want/to/test.hpp"
3 #include "gmock/gmock.h"
4 #include "gtest/gtest.h"
5
6
7 using ::testing::AtLeast;
8 using ::testing::Return;
9
10 TEST(UmbrellaTest, willOpenUmbrella) {
11   auto umbrella = std::make_shared<MockUmbrella>();
12   EXPECT_CALL(*umbrella, isOpen())
13     .WillOnce(Return(false));
14   EXPECT_CALL(*umbrella, openUmbrella())
15     .Times(AtLeast(1));
16   const bool its_raining{true};
17   manageUmbrella(its_raining, umbrella);
18 }

```

⁴: Old versions of GTests require a different signature: "MOCK_METHODn(MethodName, ReturnType(Args))" where n equals the number of arguments

The test verifies that, if it rains and the umbrella is not open, the function openUmbrella is called.

There is of course much more to say about mocks; before you choose to implement any, I would recommend you to take a look at the [official documentation](#). If you are already a veteran Gmocker, I suggest you to refresh them anyway, since recent versions of the library introduced some tricks and simplifications.

Compilation

As with any other C or C++ program out there, you will need to compile your tests to be able to execute them; the simplest way involves using Cmake. Before doing this, it is good practice to separate the source files of your tests from the source files of the tested code by putting them in a "tests" folder. In this folder, you should create a new "CMakeLists.txt" that will contain only the logic required to compile the tests.

The compilation of the tests should be optional: while you want to build and run your tests on your CI/CD pipeline, when releasing your code on the robot, you don't need the tests. To achieve this, on the main CMakeLists.txt file of the package, we will conditionally include the testing CMakeLists file:

```
1 | if(BUILD_TESTING)
2 |   include_directories(tests)
3 | endif()
```

In the testing CMakeLists, we can easily include the GTests library without the need to manually install them in our project; you simply need to find this package:

```
1 | find_package(ament_cmake_gtest REQUIRED)
```

If you want to enforce the code to be formatted following the [ROS 2 guidelines](#)[133], you can additionally add the following:

```
1 | find_package(ament_lint_auto REQUIRED)
2 | ament_lint_auto_find_test_dependencies()
```

and in the package.xml:

```
1 | <test_depend>ament_lint_auto</test_depend>
2 | <test_depend>ament_lint_common</test_depend>
```

This will automatically add tests that will make your CI pipeline fail if your files were not formatted using "ament_uncrustify -reformat" or "ament_clang_format" before pushing them.

It is now possible to add a test, that will automatically link against the GTests libraries, adding a single line in the CMakeLists.txt:

```
1 | ament_add_gtest(test_name test_file.cpp)
```

If you are using GMocks in your test, you will need a slight modification:

```
1 | find_package(ament_gmock REQUIRED)
2 | ament_add_gmock(test_name test_file.cpp)
```

By default, tests added in this way will be automatically built when executing "colcon build"; if you want to skip their compilation, you can execute:

```
1 | colcon build --cmake-args -DBUILD_TESTING=OFF
```

Once the compilation is complete, you will find the binaries of your tests in "build/package_name/tests". You can then run all the tests in your workspace executing the command "colcon test", and the tests of a specific package with:

```
1 | colcon test --packages-select package_name
```

The logs with the results will be stored in "build/package_name/tests_results". You can find additional testing options in the [official colcon documentation](#)[134].

The above parameter file can be passed to any node regardless of namespace or name and the parameters will populate those of the node if the declared parameters match those in the file. from [here](#)[135] the

7.1.2 Unittest and Pytest in ROS 2

Unittest[136] and Pytest[129] are both very popular frameworks that allows to create tests for python programs in a simplified way. There is already a lot of nice documentation about how to exploit their features, so we'll just go through the core functionalities and how to integrate them in a ROS 2 package.

Unittest

The Unittest framework is heavily object-oriented and supports all the main features that you would like a test framework to have⁵.

The first step to write a test, is creating a fixture class subclassing unittest.TestCase. The "setUpClass" and "setUp" methods can be implemented in order to prepare the tests defined in the class. While the first will run only once before executing any test, the second will run right before any test. Similarly, the "tearDownClass" and "tearDown" methods can be used to clean-up their execution.

Tests are defined as methods of this class, and can use any of the assertion methods to verify the expected behavior of the code. Let's take a look at how this can be used, for example, to test the ROS 2 service functionality:

```

1  from example_interfaces.srv import AddTwoInts
2
3  import rclpy
4  import time
5
6
7  class ATestClass(unittest.TestCase):
8
9      @classmethod
10     def setUpClass(cls):
11         cls.context = rclpy.context.Context()
12         rclpy.init(context=cls.context)
13         cls.node = rclpy.create_node('testSum', context=cls
14         .context)
15         cls.srv = cls.create_service(AddTwoInts,
16             'sum_service', cls.srv_callback)
17
18     @classmethod
19     def tearDownClass(cls):
20         cls.node.destroy_node()
21         rclpy.shutdown(context=cls.context)
22
23     def srv_callback(self, request, response):
24         response.sum = request.a + request.b
25         return response
26
27     def test_call_service(self):
28         client = self.node.create_client(AddTwoInts,
29             'sum_service')
30         self.assertTrue(client.wait_for_service(timeout_sec
31             =5.0))
32         req = AddTwoInts.Request()
33         req.a = 2
34         req.b = 3
35         future = client.call_async(req)
36         while rclpy.ok():
37             rclpy.spin_once()

```

⁵: Actually, I would love the framework to write the tests by itself, but that's probably asking too much.

```

34     if future.done():
35         response = future.result()
36         assertEquals(response.sum, 5)
37         break
38     time.sleep(0.1)
39
40 if __name__ == '__main__':
41     unittest.main()

```

This test instantiates a node while setting up the test fixture class. Any test added to this class can now access the ROS functionalities provided through the node. You can find plenty of additional examples in the [rclpy tests on github](#)[137].

Pytest

Compared to Unittest, the Pytest framework allows to write tests with fewer lines of code. In particular, the tester is no more forced to create a fixture class, but can directly assert the output of function calls.

To create a test, you should create a file in the form `test_some_name.py` (to discover tests, Pytest always looks for the prefix "test_" or suffix "_test" in files, functions and classes). Within this file, for each test that you want to execute, you'll add a function with the signature

```
1 def test_any_name():
```

Within this, you need to define at least one "assert" statement to verify the outcome of the tested function.

```

1
2 def cube_of(n):
3     return n * n * n
4
5 def test_cube_of_n():
6     assert cube_of(2) == 8
7     assert cube_of(-3) == -27

```

Easy, right? Pytest and Unittest don't exclude each other, they are often used together to create compact and modular tests. We will see some example in the coming section.

7.2 Component tests

While unit tests can be used to verify the functioning of methods or objects, component tests verify the correct behavior of a module, which, in the case of ROS, is a node. I've already stressed out how important modularity is in ROS: in order to build complex applications, it is important to break down actions into sub-actions that are carried out by independent nodes. A prerogative for the resulting application to function properly, is that each one of the blocks building it behaves as expected.

When executing a component test, the node to be tested is launched together with the environment needed for its execution (for example its parameters). The test will verify the correct behaviour of the node by calling its interfaces, without caring about the details of the internal implementation. If the node requires the interaction with other nodes in order to function properly, these can be replaced by mocked interfaces. In

order to achieve realistic behaviors, the data normally produced by the robot's sensors can optionally be provided by [rosbags](#)[138] previously recorded on the real robot.

7.2.1 Python component tests

A convenient way to perform component tests in python is using [Launch testing](#)[139], a tool that allows the execution of a launch-file in parallel to the tests to be executed. The tests can interact with the processes started by the launch file and can evaluate their output once they have been terminated.

To write a test of this kind, we need to implement the method "generate_test_description", which should return a launch.LaunchDescription object used to launch the node to be tested together with its environment. In addition to this, the function can return a dictionary (the test_context) to be passed to any of the executed tests.

```

1 import ament_index_python
2 import launch_testing
3 import launch_testing.actions
4 import pytest
5 import unittest
6
7
8 from launch import LaunchDescription
9 from launch_ros.actions import Node
10
11 @pytest.mark.launch_test
12 def generate_test_description():
13
14     ld = launch.LaunchDescription([
15         Node(
16             package='package_name',
17             namespace='a_namespace',
18             executable='an_executable',
19             name='tested_node'
20         )])
21
22     test_context = {
23         'a_test_input': "some string",
24         'another_test_input': 10
25     }
26
27     return ld, test_context

```

In the launch description, you can provide any environment condition that the node requires for its normal execution; for example you can start the execution of a rosbag with pre-recorded topics, run other nodes implementing a fake interface, you can add parameters and so on.

After the launch description, you should add the tests that need to execute concurrently to the launch file. To do this, we can use the text fixtures from unittest that we introduced in the previous section:

```

1 class ATestFixtureClass(unittest.TestCase):
2
3     def test_to_be_executed(self, proc_output, a_test_input,
4                           another_test_input):
5         # Publish to topics, call services, whatever you need
6         # to do...
7         self.assertEqual(a_test_input, "some string")
8         self.assertEqual(another_test_input, 10)

```

The argument 'proc_output' is an object added automatically by the launch_testing framework which captures the outputs of the processes launched in generate_test_description(). It can be handy, but I personally try to avoid using it, since the console output is a node to human interface that shouldn't affect the behavior of the system. If possible, during a component test, you should try to verify the correctness of the information provided by the interfaces of the tested node.

A different set of tests can be run at the end of the execution, after shutting down the "launch file". For these, we need to provide a dedicated decorator to the test fixture. Here is an example to verify the exit codes of the launched processes:

```
1 @launch_testing.post_shutdown_test()
2 class TestOutcome(unittest.TestCase):
3     def test_exit_codes(self, proc_info):
4         launch_testing.asserts.assertExitCodes(proc_info)
```

The tests can be executed with the command:

```
1 | launch_test test_name.py
```

In alternative to launch testing, if you are using a release >= Humble, the [launch_pytest](#)[140] framework leverages pytest fixtures to provide additional features and a richer output. At the moment of writing this is, however, not as widely used as launch_testing.

7.2.2 C++ component tests

Similarly to what is done in Python, component tests can be written in C++ using the GTests framework introduced in the unit tests section. Before doing this, it must be noted that, the language used to write a component test for a Node, doesn't need to match the language used to write the node itself. Since these tests communicate to the node using its ROS-interfaces, there's nothing stopping you from writing Python tests for a C++ node.

The first step for creating a C++ component test, is writing a launch file that starts the node together with its environment. Since launch files are written in python, and our test will be written in C++, they will reside in different files. Here an example where, alongside the node to be tested, we start another launchfile to publish the robot description, and a bagfile containing data previously recorded from the real robot:

```
1 #! /usr/bin/env python3
2
3 import os
4 import sys
5 from ament_index_python import get_package_share_directory
6 from launch import LaunchDescription
7 from launch import LaunchService
8 from launch.actions import ExecuteProcess,
9     IncludeLaunchDescription
10 from launch.launch_description_sources import
11     AnyLaunchDescriptionSource
12 from launch_ros.actions import Node
13 from launch_testing.legacy import LaunchTestService
14
15 def generate_launch_description():
16     ld = LaunchDescription([
17         Node(
18             package='my_robot',
19             executable='my_node',
20             parameters=[{'param': 'value'}],
21             output='screen'),
22         Node(
23             package='tf2_ros',
24             executable='static_transform_publisher',
25             parameters=[{'x': 1.0, 'y': 0.0, 'z': 0.0, 'yaw': 0.0}]]))
```

```

15 # Assuming the bagfile to be installed in the shared
16 folder
17 bagfile = get_package_share_directory('a_package') + '/'
18 bags/" + "my_bag"
19 return LaunchDescription([
20     IncludeLaunchDescription(
21         AnyLaunchDescriptionSource(
22             os.path.join(
23                 robot_description_pkg,
24                 'launch/robot_description.launch.py'))
25     ),
26     Node(
27         package='a_package',
28         executable='name_of_the_exe_to_be_tested',
29         name='test_node_name',
30         output='screen'
31     ),
32     ExecuteProcess(
33         cmd=['ros2', 'bag', 'play', bagfile,
34               '-l', '--clock'
35     )
36 ])
37
38 def main(argv=sys.argv[1:]):
39     ld = generate_launch_description()
40
41     testExecutable = os.getenv('TEST_EXECUTABLE')
42
43     first_test_action = ExecuteProcess(
44         cmd=[testExecutable],
45         name='your_test_name',
46         output='screen')
47
48     lts = LaunchTestService()
49     lts.add_test_action(ld, first_test_action)
50     ls = LaunchService(argv=argv)
51     ls.include_launch_description(ld)
52     return lts.run(ls)
53
54 if __name__ == '__main__':
55     sys.exit(main())

```

Playing a bagfile alongside the test is a great alternative to run a simulation: it's much easier to setup and assures that the code works properly with real data. The flag -l allows to play the bag in a loop: in this way even a short bag can produce data for an infinite amount of time. It must be noted that this could result in undesired side-effects deriving from jumps in the time-stamps contained in the published data. Since bags can potentially contain a lot of data, it is a good idea to store them separately from the repository containing the source code, and to download and install them at compilation time. The exact procedure for doing this will depend on what storage system you choose.

To interact with this node, the tests will initialize a ROS context and create the interfaces required for the communication. The content of the interchanged data can be compared to the expected one using the usual assertions provided by GTests. Following is an example where an action server residing on the tested node is called by an action client created in the test.

```

1 #include <gtest/gtest.h>
2 #include <chrono>
3 #include <memory>

```

```

4 #include "my_msgs/action/my_action.hpp"
5 #include "rclcpp/rclcpp.hpp"
6 #include "rclcpp_action/rclcpp_action.hpp"
7
8 using namespace testing;
9 class MyTestFixture : public ::testing::Test {
10 public:
11     static void SetUpTestCase() { rclcpp::init(0, nullptr); }
12
13     void SetUp() override {
14         node_ = rclcpp::Node::make_shared("test_node");
15         client_ptr_ = rclcpp_action::create_client<MyAction>(
16             test_node_, "my_action");
17     }
18
19     void sendGoalToNode(const my_msgs::action::MyAction::Goal
20         & goal, rclcpp_action::ClientGoalHandle<MyTestFixture::
21         MyAction>::WrappedResult& result) {
22         auto fut_response = client_ptr_->async_send_goal(
23             goal_msg);
24         ASSERT_TRUE(rclcpp::spin_until_future_complete(
25             test_node_, fut_response) ==
26             rclcpp::FutureReturnCode::SUCCESS);
27         auto goal_handle = fut_response.get();
28         auto fut_result = client_ptr_->async_get_result(
29             goal_handle);
30         ASSERT_TRUE(rclcpp::spin_until_future_complete(
31             test_node_, fut_result) ==
32             rclcpp::FutureReturnCode::SUCCESS);
33         result = fut_result.get();
34     }
35
36     std::shared_ptr<rclcpp::Node> test_node_;
37     rclcpp_action::Client<my_msgs::action::MyAction>::
38         SharedPtr client_ptr_;
39 };
40
41 TEST_F(MyTestFixture, TestMyAction) {
42     ASSERT_TRUE(client_ptr_->wait_for_action_server(5s));
43     auto goal = my_msgs::action::MyAction::Goal();
44     rclcpp_action::ClientGoalHandle<MyTestFixture::MyAction
45         >::WrappedResult goal_result;
46     sendGoalToNode(goal_msg, goal_result);
47     EXPECT_TRUE(result->success);
48 }
49
50 int main(int argc, char** argv) {
51     ::testing::InitGoogleTest(&argc, argv);
52     return RUN_ALL_TESTS();
53 }
```

Like in the previous examples, the same fixture class can of course be used to define multiple tests. These tests will then behave as unit tests, with the only difference that a node, executed by the previously defined launchfile, will be running in parallel to them. To achieve this, we need to add a couple of entries to our CMakeLists.txt:

```

1
2 find_packageament_cmake_gtest REQUIRED
3 include(GoogleTest)
4 SET (TEST_NAME "name_of_your_test")
5
6 ament_add_gtest_executable(${TEST_NAME}
7     test_file.cpp
8 )
9
10 target_link_libraries(${TEST_NAME})
```

```

11     gtest_main
12 )
13
14 ament_target_dependencies(${TEST_NAME}
15   rclcpp
16 )
17
18 ament_add_test(${TEST_NAME}
19   GENERATE_RESULT_FOR_RETURN_CODE_ZERO
20   COMMAND "${CMAKE_CURRENT_SOURCE_DIR}/launchfile_name.py"
21   WORKING_DIRECTORY "${CMAKE_CURRENT_BINARY_DIR}"
22   ENV
23     TEST_DIR=${TEST_DIR}
24     TEST_LAUNCH_DIR=${TEST_LAUNCH_DIR}
25     TEST_EXECUTABLE=<TARGET_FILE>:${TEST_NAME}>
26 )

```

In case you need the gmock features, you might have to additionally add the following before ament_add_test:

```

1 find_package(ament_cmake_gmock REQUIRED)
2 _ament_cmake_gmock_find_gmock()
3
4 target_include_directories(${TEST_NAME} PUBLIC ${GMOCK_INCLUDE_DIRS})
5 target_link_libraries(${TEST_NAME}
6   gtest_main
7   gmock
8 )
9

```

Running tests in parallel

A very important thing to keep in mind while writing tests of this kind is that, contrary to what happened for rostests in "ROS1", ROS 2 tests are not isolated by default. This means that all the tests using the ROS interfaces can potentially interfere with each other when executing in parallel. This can easily bring to unexpected test results and make you curse your CI pipeline in innovative ways. There are three possible solutions to this issue:

- ▶ Run your tests sequentially. To do this, simply add "-executor sequential" after the "colcon test" command. Since time is precious, you should choose this solution only if you feel extremely lazy.
- ▶ Namespace your tests. Launching each test in a different namespace avoids interference. This, however, will only work for those interfaces that are not using absolute names to resolve their partners.
- ▶ Use a different [Domain-ID\[141\]](#) for each test. Nodes executed with different Domain IDs work on different logical networks and can not talk to each-other. To automatically assign these IDs uniquely for each test, you can use the cmake functions provided by [ament_cmake_ros\[142\]](#). In particular, executing:

```

1 set(RUNNER "RUNNER" "${ament_cmake_ros_DIR}/
  run_test_isolated.py")

```

right before your test, will assign a dedicated Domain ID. This should be your preferred way of defining component and integration tests.

7.3 Integration tests

In the previous section we have seen how to test a single module using its ROS interfaces. While making sure that a single module is capable to operate as expected is extremely important, it is also important to evaluate if multiple nodes, composing a subsystem of your robot, are capable of cooperating to achieve the desired behavior. Luckily, the steps to achieve this are very similar to those needed to run a component test:

- ▶ Create a launch-file containing the nodes that need to be tested together with their environment.
- ▶ Create one or more tests that interact with one or more of these nodes to reproduce the desired scenario.
- ▶ Verify that the outputs produced by the nodes match the expectations.

Since launchfiles can contain as many nodes as we desire, the same tools that were used for the component tests can be used for integration tests too. Since they could test the interaction between nodes defined in different packages, integration tests might not belong to the package containing the tested code, and often require a dedicated package.

An important note: integration tests can not substitute lower layers of testing. You might be tempted to prefer this layer because it directly relates to the functionalities of your robot, however, when failing, these tests are also harder to debug. Integration tests also fail to provide the confidence that each of the modules building your application is working as expected and can consequently be safely used in different applications.

7.4 Simulation based tests

As the number of nodes to be tested in an integration test increases, you will need more and more effort to set up the environment required to execute the tests. While bagfiles and fake objects are often a reasonable solution to provide information to a small subset of nodes, doing so for tests that involve big parts or the totality of your system is usually very time expensive and results in "brittle" tests that need a lot of maintenance work.

A common solution to this issue is running the tests alongside a [Simulator](#)[143]. Simulators can create a virtual reconstruction of the robot's work environment alongside a model of the robot itself with its sensors.⁶ Simulators range from simple programs to very complex systems capable of photorealistic reproductions of the environment's aspect and of its physics.

Testing using a simulator provides a lot of advantages:

- ▶ The behavior of the robot can be predicted with good accuracy without requiring hardware and dedicated testing environments.
- ▶ A lot of different test environments can be created (optionally using randomization) with little effort.
- ▶ Encountered issues are easily reproducible

⁶: Tests of this kind are often referred to as "Software in the loop".

- ▶ Tests using simulations are "easy" to integrate with CI/CD pipelines.
- ▶ The time required to test features on the robot's hardware is reduced, and consequently the related costs.
- ▶ Developers get to have a safe playground even when working remotely.

On top of these test-related scenarios, simulated environments can be used to train neural networks, to plan deployment layouts, to create video games with your robot as the protagonist... the limit is in your fantasy.

7.4.1 Simulators in ROS 2

The amount of work needed to set up a simulation is of course related to the fidelity level that you want to achieve. If you went through the ROS 2 tutorials, you are probably already familiar with the [Turtlesim simulator](#)[144]. Setting up a simulation of this kind, and in general 2D simulations, is quite straightforward and doesn't require a lot of time or computational power. If, instead, you need an accurate 3-Dimensional simulation of a big environment, maybe with photorealistic surfaces, things get a bit more complex. Adapting the complexity of the simulation with the requirements of the task that you want to test is very important to save time and resources.

Luckily, there are already multiple simulators out there that can be easily integrated with ROS 2; some of these are free to use and open-source, while others require a paid subscription:

- ▶ [Gazebo](#)[145] / [Ignition Gazebo](#)[146] is historically the default simulation choice for ROS. It is open source and distributed with a permissive license (Apache 2.0). It provides a set of libraries for simulation and sensors modelling on top of which it is possible to integrate physics and rendering engines through a generic interface. [Here](#) you can get an idea of the features and plug-ins supported by its different versions.
- ▶ [Webots](#)[147], like Gazebo, is open source and released under the Apache 2.0 License. Customer support is available in exchange for a yearly fee.
- ▶ [Coppelia Sim](#)[148] is available in a free version with limited capabilities, a version that can be used for educational purposes, and a professional version.
- ▶ [Unity](#)[149] is a game engine that can also be used to build simulated environments and integrated with ROS 2 using [dedicated interfaces](#)[150]. Unity is rich of features and is capable of achieving good 3D fidelity, but is less immediate to learn for robotics purposes. It is distributed as a limited free version that can be used by small companies, and as a professional version that can be used by bigger companies. An example of unity based simulator specialized for autonomous vehicles is the [SVL simulator](#)[151], whose support was, unfortunately, discontinued.
- ▶ [Nvidia Omniverse](#)[152] is capable of photorealistic simulations and is distributed together with a [ROS bridge](#)[153]. It is free only for individuals and has very demanding [system requirements](#)[154].

Other smaller projects including lightweight 2D simulators for robots moving on a plane are [Flatland](#)[155] and [map simulator](#)[156].

The exact steps required to run any of these simulations together with the tests will depend on the chosen simulator. In most of the cases, the simulator can be started in a launchfile in the same way as we did for normal integration tests.

7.5 Testing on the hardware

After months of careful planning and programming, tons of unit tests, integration tests, simulations... finally comes the time to test your features on a real robot. Even if the previous steps were performed scrupulously, when running your code on the hardware it is quite common for new issues to pop up like mushrooms in a forest. To understand why this happens, it is important to take into account the unavoidable differences between the abstract world of software and the harsh world of hardware:

- ▶ Hardware can break. This doesn't need much explanation: even brand new hardware can contain defects that interfere with its functionalities. When one of your robots fails a mission, it can be hard to tell hardware anomalies apart from software bugs. To track this kind of issues as quickly as possible, it is important to test your hardware before testing software on top of it. There's a lot of stuff that can go wrong with hardware: broken circuits, mechanical backlash in the joints, scratched laser scanners, faulty bumpers, damaged cameras... It's up to you to identify all of them and come up with ways to verify their existence in a systematic way.
- ▶ The communication of data between different devices always introduces latency. The data produced by a sensor, a motor, or whatever you built into your robot, needs to be serialized and sent over a communication bus to the unit in charge of processing it. This process always requires a certain amount of time that, if the communication is not performed using real-time constraints, can be difficult to predict. Latency is the enemy of any control system and, if not taken into account, can drastically impact the performance of your robot.
- ▶ Hardware changes with time. The computer science professor at my university used to say that, even if you don't touch it, software will self-destroy with time. This is even more true with hardware: after months of operation, the position of the sensors might drift due to loose coupling, the gears connecting the motors might deteriorate, dirt and dust might affect multiple components etc.
- ▶ Real sensors are affected by noise and artefacts. Laser scanners will often produce shadows when their beams hit the corners of objects, stereo cameras might behave differently if exposed to sunlight, GPS sensors might lose accuracy between tall buildings and so on.
- ▶ The properties of the environment where the robot needs to operate might be changeable and difficult to predict. The wheels of your platform might operate well on a certain kind of surface and slip on a different one; the gripper of your manipulator might not work with different variations of the same object and so on.



When writing tests for the hardware, or that are supposed to run on the hardware, it is consequently important to focus on what could go wrong:

- ▶ Can we detect broken components automatically and generate detailed reports?
- ▶ Is the performance of the robot affected by the communication latencies?
- ▶ Is it possible to diagnose and report deteriorated hardware? How much does this affect the robot's behavior?
- ▶ Can we reproduce faulty sensors readings and verify that our system is resilient to them?
- ▶ Are all the environments that the robot needs to interact with properly represented by the created tests?

Use your fantasy!

Another good practice is to create new tests for each of the issues detected in the deployed robots. Whenever you fix something, make sure that, if the problem occurs again, you won't lose time debugging it, but will be able to detect it as soon as possible (ideally before shipping your robot).

Building a cool robot capable of doing fancy things is a difficult task, but making many of them work reliably is extremely challenging. Tests are an essential tool along this transition.

Homework

Many industrial robot producers provide gazebo based simulations for some of their robots. Some examples are the [ROS 2 Gazebo simulation for the UR robots](#)[157] or the [iiwa ros2 package](#)[158]. Create a test that:

- ▶ Launches the simulation for one of these robots.
- ▶ Moves the robot's joints to three specified configurations.
- ▶ Verifies that the robot reaches and stops at each of the configurations.

Use whatever interface you prefer to move the manipulator.



8 Parameters management

ROS 2 Parameters[159] is a tool that allows to dynamically change the configuration of a node.

Parameters are used whenever a value defined in the code varies depending from the context in which the node is executed. These parameters could represent characteristics of the robot, of its environment, the behavior to be executed... basically anything. They are an essential instrument to make a node reusable, since the values associated to parameters are not integrated in the program, but can be installed anywhere on the deployed system.

8.1 Where are parameters loaded?

Contrary to what happened in the first version of ROS, where parameters were stored in a shared dictionary accessible through network calls (the Parameter Server[160]), in ROS 2 a parameter is always assigned to the node declaring it. This implies that, whenever a node is reading one of its own parameters, it can do it without the overhead coming from accessing the networking layer: under the hood it will simply lock a mutex and access a local dictionary. At the same time, nodes can access the parameters of other nodes and subscribe to their changes using services and topics. This kind of operation is of course much more “expensive” and should be limited to the cases where a local declaration would not be appropriate¹.

By creating a node with the sole purpose of storing and sharing parameters, it is possible to emulate the old behavior of the parameter server, but, to avoid unnecessary overhead and to stay coherent with the ROS 2 architecture guidelines, you should try to avoid this path. If you anyway want to give this approach a try, the package “demo_nodes_cpp” provides an example of implementation. You can try it by simply running:

¹ | `ros2 run demo_nodes_cpp parameter_blackboard`

1: This is a frequent source of issues when using the old ROS: if novice developers are not aware of the overhead introduced when reading parameters, they could try to fetch them with high frequency. Because the parameter server is shared throughout the entire system, it can quickly become overwhelmed with requests.

8.1.1 How are parameters accessed from the code?

As we just mentioned, each node needs to declare the parameters it wants to use. The easiest way to do this using the C++ API is with a call in the form:

```
1 | value = declare_parameter(param_name, default_value);
```

where the default value can be omitted. ROS 2 supports parameters with the following types: double, integer, string, and lists of these types (translated to vectors in C++). Each parameter must be declared once and only once. When a declaration call is performed, the function will look for “parameters overrides”, which could come from yaml files / manual values specified in the launch file of the node or from arguments provided through the Command Line Interface (CLI). If an override is found, it will be stored in the local parameter dictionary, otherwise the default value will be used. From this moment on, it will be possible to access the parameter value locally using the “get_parameter” function:

```
1 | value = get_parameter(param_name);
```

or to set it using set_parameter:

```
1 | set_parameter(param_name, param_value);
```

From other nodes similar operations can be performed using, for example, the [AsynchParametersClient](#)[161]: in addition to the parameter name, the name of the hosting node needs to be provided.

8.1.2 Parameters description

Each parameter, in ROS 2, has at least three properties: its name, defined as a string, its type, defined using this [enum](#), and its value, stored using this [message structure](#).

When declaring a parameter, you can optionally specify additional constraints using the [Parameter Descriptor](#). This object can be instantiated and passed to the "declare_parameter" method as an additional value. The available fields are:

- ▶ *read_only*: defaulted to false, will forbid any change of the parameter if enabled. It is a good idea to set this to true for all the parameters not requiring dynamic updates. In this way, you'll let the user of your node know what is configurable at runtime and what isn't.
- ▶ *dynamic_typing*: defaulted to false, will allow the parameter to change type if enabled. It is preferable to leave this feature disabled unless you have a very specific need for it: parameters tend to keep the same type and static typing is less error-prone.
- ▶ *FloatingPointRange* / *IntegerRange*: If one of these values is provided, and the parameter is of compatible type, its value will be limited to the specified range. This is very useful when you expect that someone will try to assign to the parameter values that could compromise the correct behavior of the node , or that are not compatible with the robot's hardware. The maximum velocity of a joint could, for example, be limited to the maximum value reachable by a specific motor-gear combination.

- *additional_constraints*: this value can be used to specify constraints that can not be described by the previous fields. If, for example, your parameter is a string that can assume only specific values, these could be listed here in a comma separated list. It is up to the programmer to decode and use this field when receiving parameters updates.

8.2 Dynamic parameters updates

It must be noted that the declare_parameter function returns the value of the parameter updated with the overrides; consequently, if you are only interested in getting the parameter once and don't care about future updates, you don't need to call "get_parameter" at all. If, instead, you would like the behavior of the robot to change dynamically together with a parameter update, you can either repeatedly call the get_parameter function, which as we have seen doesn't bring much overhead, or subscribe to parameter changes². The latter can be done with both "internal" parameters and with parameters of other nodes using the ParameterEventHandler class; an example of usage can be found in the [tutorials](#)[162].

Continuous parameter updates are, for example, useful while tuning a mechanical system. Imagine a robot operating underwater to recollect trash from the bottom of the ocean.

2: When subscribing to parameter changes, custom logic can be implemented to accept or reject the required update. This is for example very useful when only a specific range of values is considered acceptable.



This robot is equipped with a fingered gripper capable of applying a specified amount of force to retain the picked object. While programming the robot, you don't know how much force will be needed to grasp objects

without breaking them, so you parametrize the value used to specify the force and, to be on the safe side, you use a small default guess. At a later stage, you will perform some tests with your robot to figure out a reasonable amount of force to be applied: you will run a series of service calls to increase the parameter until the robot is capable of grasping. This is way more convenient than updating the code or restarting the program each time you want to run a test.

On the old ROS1, a similar feature was provided by [dynamic_reconfigure package](#)[163], but this required a dedicated configuration file to specify which values were allowed for reconfiguration. In ROS 2 any parameter can potentially be dynamically reconfigurable. However, when declaring a parameter that is expected to change at runtime, it is good practice to specify the allowed range of values using the additional [ParameterDescriptor](#) field. This would for example save you from accidentally setting a very high force value that could damage your robot. The parameter descriptor field additionally allows to specify parameters as “read only”; this can be useful to let anyone trying to set them know that their value is not supposed to change at runtime.

While dynamic parameter updates can be very handy, they should not replace other interfaces as the main source of information for a node at runtime: whenever creating a ROS node, it is important to define clear communication interfaces with it. If a node implements a topic subscriber, a service server or an action server, it explicitly declares what information is required for its function and what information is produced. If parameters are used to convey part of this information at runtime, understanding and debugging the flow of information between components becomes much more challenging.

Let’s make an example to better understand this concept. Our submarine robot implements a node providing the functionality of moving its arm to a specified pose. The node declares a set of parameters defining the maximum velocity, acceleration and jerk of the end effector during the movement. A different node needs to communicate to the previous the target pose to be reached and an approach pose to go through. If we choose to convey this information through parameters, we’ll need three of them: one for the target pose, one for the approach pose and a boolean parameter to start the execution. An external observer, in order to figure out why the robot is doing what it’s doing, would need to keep track of the complete history of parameter changes. Setting the parameters in a different order could result in a different robot behavior, and there’s no way to know if a third node has been changing them concurrently.

Since you have already read the interfaces chapter, you already know that this kind of information is better conveyed through an action: the required data is encapsulated in the same message, which can be easily inspected; a mechanism to signal the completion of the action is provided by default, and the server can choose how to handle concurrent requests.

8.2.1 Parameters without declaration

If you are coming from the world of ROS1, you might not like having to perform a parameter declaration any time you want to get or set a parameter. After all, the old ROS didn’t have this constrain, so why does

the new one force you to do more work? How many programmers will stumble upon the issue of not being able of getting a parameter because they forgot to declare it?

ROS 2 doesn't actually force you to declare all the parameters: when creating a new node, the "*allow_undeclared_parameters*" flag of the NodeOptions object can be used to bypass this constrain and allow operations like setting or getting a parameter without the need for a declaration. You can additionally specify "*automatically_declare_parameters_from_overrides*" to automatically declare any parameter provided by the yaml file. The node declaration would look like the following:

```

1 OurNode() : rclcpp::Node(
2     "a_node_that_doesnt_want_to_declare_stuff",
3     rclcpp::NodeOptions().
4         allow_undeclared_parameters(true).
5         automatically_declare_parameters_from_overrides(true)
6 )

```

This can be convenient in some circumstances, but is **strongly discouraged**. Declaring parameters brings different advantages: optional static typing and additional constrains, control over multiple declarations, specification of default values... Skipping these makes your code much more prone to errors.

If your application doesn't know all the needed parameters at start-up, there's nothing stopping you from declaring them during the program's execution. Even if it is preferable to declare parameters early in order to immediately notice any error that the declaration may throw, there's no hard constrain about when you can do it.

Moral of the story: don't be lazy and declare your parameters.

8.3 Default parameters are evil

We have already seen how, at declaration time, parameters can be assigned to either a default value or to an override. It might be tempting to always assign a default value for the case in which the user doesn't provide an override, but this brings a notable side effect: there's no way to know if the parameter value loaded by the code is the default one, or the overridden one. It is unfortunately quite easy to make mistakes while writing overrides: any typo in the parameter name or mismatch in its namespace would result in the override to silently fail. If a default parameter was provided, the robot will likely still start and operate with degraded performance, which is often worse than not operating at all: the issue takes time to get noticed and it might be difficult to track it down to a bad parameter name. There are two possible approaches to solve this issue:

- ▶ Don't specify default parameters. This implies that, if no override is provided and the code tries to access one of the parameters, the application will throw an exception (and probably crash). This might sound like a draconian solution, but it ensures that overrides are always defined properly: if not, the user of the application will realize it right away. If this path is chosen, it is a good idea to try to

read all the parameters at least once right after startup, in order to make any error immediately visible.

- Warn the user whenever a parameter is not overridden. This is actually my favourite solution: it allows to prevent exceptions, while at the same time avoiding that a missing override remains unnoticed. It is easy to achieve this creating a modified version of the “declare_param” function, but I’ll leave that to you for exercise.

8.4 Defining parameter layers

If you have just built a single robot, the only of its kind, which is going to work its entire life in the same room, the default parameters management APIs provided by ROS are likely to cover all your needs. The values of all your parameters will be defined in multiple yaml files, stored together with the corresponding source code in a dedicated “config” folder. Parameters can in this way be released and tracked together with the rest of the application. Unfortunately, this is usually not enough to cover our needs. There’s a good chance that your company, laboratory, terrorist organization... is producing multiple robots of the same kind, or variations of it, and deploying them in different environments. While it could be reasonable to release different versions of your code for different versions of your robot, it is usually unwise to release new versions any time a new environment needs to be supported. If each single robot requires a dedicated configuration, like for example the calibrated position of its sensors, it is most likely not feasible to create a dedicated software release for each of them.

Fortunately, parameters are not bound to be stored together with their source code, but can be deployed anywhere on your system. Don’t get me wrong, if you expect a parameter to remain the same independently from the environment and the robot where it will be deployed, but you still feel that it shouldn’t be hardcoded in your program, storing and releasing it together with your application remains the best option. After all, different version of the same application might require different parameters.

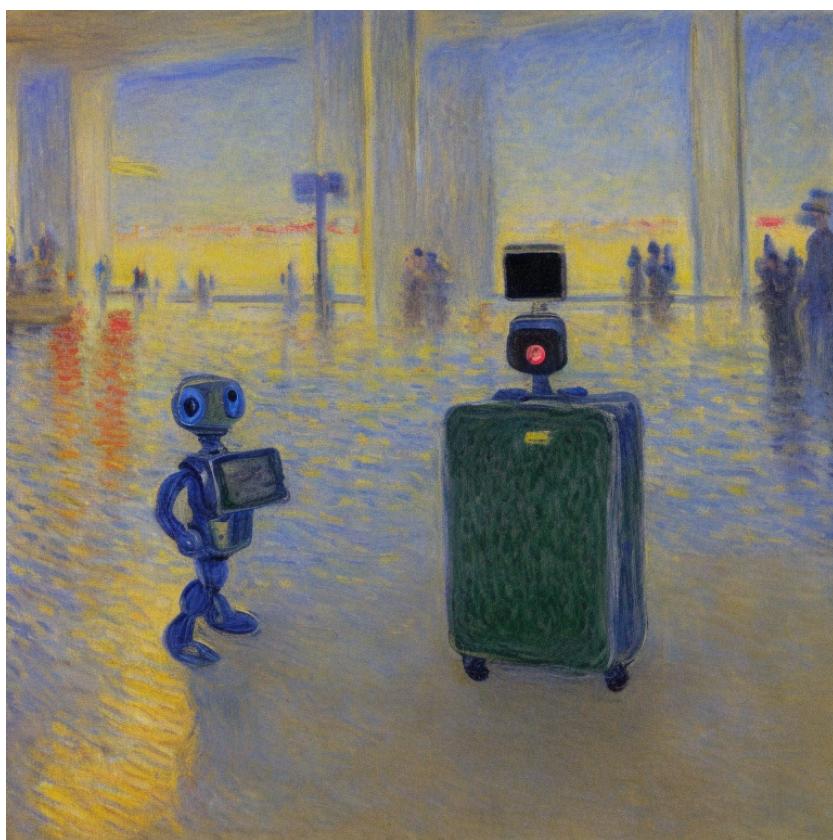
The rest of the parameters are better divided into hierarchical groups, typically separating those describing the environment where the robot operates from those describing the properties of the robot itself. Duplicating the definition of parameters is just as bad as duplicating code: it drastically increases the effort required to maintain the software. To avoid this, the higher levels of the parameters hierarchy (for example the environment) will contain values shared between a variety of robots (for example all those in the same environment), while the lower level will contain parameters specific to a single unit (for example the outputs of a camera’s calibration procedure). The amount of parameters stored at the lowest hierarchical level should be minimized in order to maximize the capability of releasing updates for multiple robots at once.

ROS 2 doesn’t ship with a mechanism capable of managing hierarchical parameters in a standardized way. However, it allows to customize launch files (where you can basically put any python code you like) and to load multiple yaml files to the same node. It is up to you to choose how to

exploit this freedom to achieve the desired management according to your specific requirements.

8.4.1 An example

To make all of this less abstract, let's imagine that our company is selling robots that help visitors navigate to their destination in an airport. These robot dispose of wheels controlled by motors, a laser scanner to detect obstacles in their environment and a speaker to communicate with people. If we are selling the same robot all over the world, the parameters used by the motors could be distributed together with the source code of the motor's controllers. The default language spoken by the robot would be shared by all the robots in the same airport or country, and would consequently be defined in the corresponding layer. Finally, the parameters storing the calibrated position of the scanners would be stored to each single robot and defaulted to a reasonable value.



Should your engineers figure out a smarter way to control the motors of the robot, they can easily release a software update valid for all of them at once. Should Icelanders get tired of their cold weather and decide to invade and conquer Cuba, you can easily switch the language used by your robots from Spanish to Icelandic in one place.

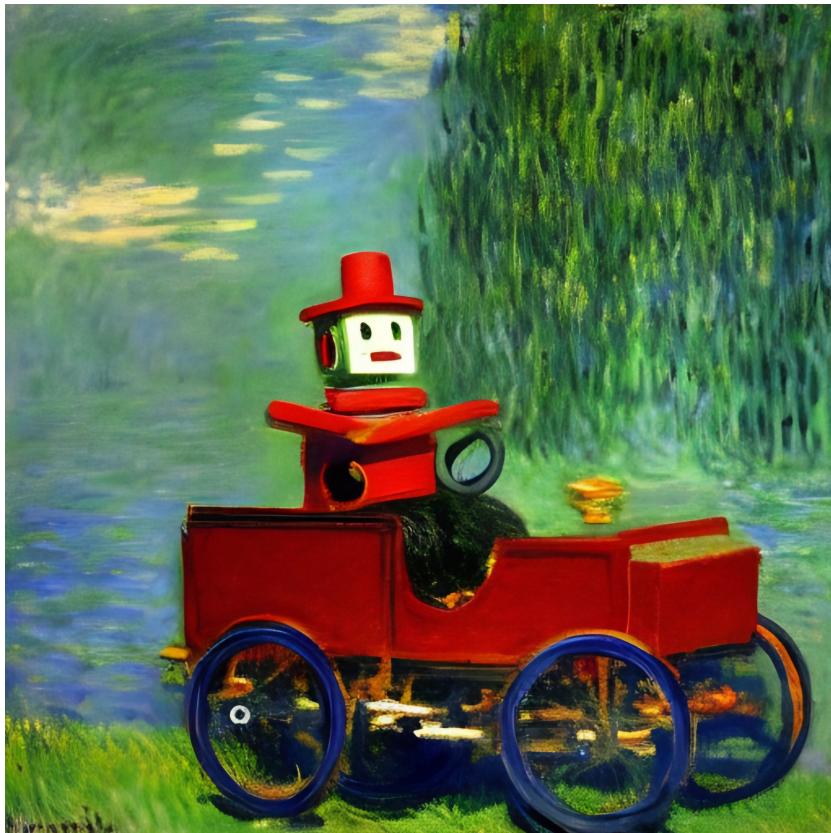
8.5 Too many parameters?

The earliest automobiles offered a minimalistic interface with the driver: a steering wheel, a set of pedals (gas, brake and clutch), a shift knob with three gears (two forward and one backwards) and a hand brake. As cars evolved, this interface gradually increased to include lights buttons, wipers, controls for the windows and the air flow control, more gears, mirrors adjustments, media systems (ex radios), more lights, more gears, air conditioning, navigators, seats heating, driving assistance functionalities, secret buttons to unlock compartments where you can hide refrigerated chocolate, a minibar with 4 varieties of beer, seat massage, another secret button to expel undesired passengers, and many buttons with symbols taken from an ancient scroll that apparently do nothing.

While learning to control the basic interfaces required a limited amount of time, taking full control of a modern car requires quite a bit of studying. Sure, after a while you get used to it, but when you rent a model you have never driven before, there is a good chance to confuse the chocolate button with the expel passenger button. There is also a chance that the car ends up being configured in an undesired way, making you jump on a German autobahn with your speed limiter fixed at 50 Km/h³.

As the software controlling your robot grows bigger and bigger, so will the parameters controlling it, and you risk ending up in a similar situation. Exposing a lot of parameters leads to a deteriorated human-robot communication experience, to an increased training effort for the users / robot "deployers", and to higher service costs.

3: Multiple lives were risked to collect the material required for this book.



But how can we push new features without making the parameters interface more complicated? There are two common ways of approaching this issue that apply not only to robots, but in general to any configurable product:

- ▶ Use a layered model: define who can access which parameter. In a car, most of the parameters controlling the engine and the internal components are usually only available for modification to the car developers. Some of these are made available to technicians for inspection and modifications, or can be tuned by enthusiasts to change the behavior of the car to their needs. The normal user of the car can only modify those configurations that do not compromise the functioning of the vehicle. In this way, no matter how many buttons you press, you hopefully won't break your car. The same principle can be applied in robotics.
- ▶ Figure out parameters automatically. In recent times, car producers realized that humans only have two hands and ten fingers, and decided to make part of the car's configuration automatic: Lights switch on and off autonomously, the temperature self-regulates, gears can shift without the need for a clutch pedal, rain sensors activate the wipers, seat integrated glucose monitoring systems figure out when you are hungry and open the secret chocolate compartment. Ultimately, cars are being made autonomous, becoming somehow a robot, so that you can just sleep. Similarly, if you can make your robot smart enough to figure out the best parameters by itself, you should do it. This usually implies extra development cost, but on the long run will make your product easier to use and maintain.

8.6 Storing parameters programmatically

There are cases where the result of an operation performed by the robot needs to be stored on permanent memory in order to be "remembered" after a reboot. This is almost always the case when a component of the platform needs to be calibrated. ROS 2 doesn't make any assumption on the kind of storage available for writing, and doesn't provide a generalized interface to perform this operation.

Since ROS parameters are, however, usually written as yaml files, it is not difficult to create these files using one of the readily available libraries like [yaml-cpp](#)[164] or [Pyyaml](#)[165] and store them to the local disk. A tricky point when performing this operations is to synchronize the access to the stored information. If multiple nodes try to read-write simultaneously to the same file, things can quickly become messy. To solve this issue, a common approach is to use a centralized server that has exclusive access to the stored information and provides interfaces to modify it.

An example of package implementing this approach is the [Persist parameters server](#)[166].

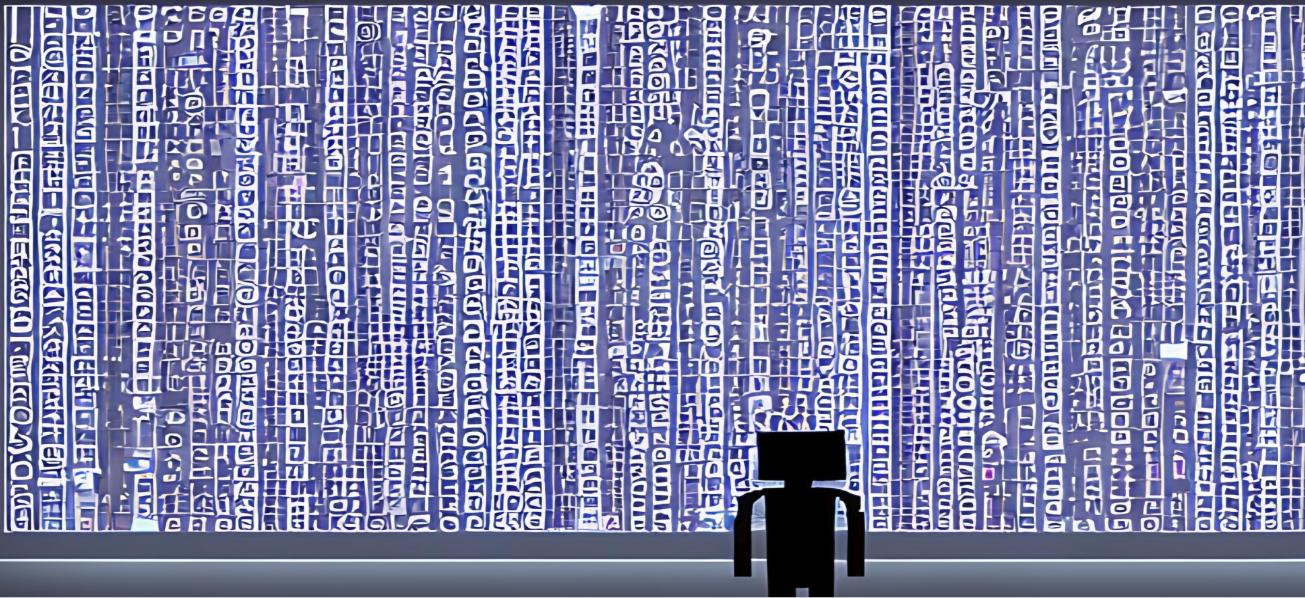
Alternatively, this kind of parameters can be stored to a remote server and requested / modified with a dedicated API. This is however only feasible if the connection with the remote server is guaranteed, or the parameters are optional.

Homework

Your evil company is producing swarms of flying drones to automatically monitor cars wrongly parked in the streets and fine them. There are different versions of these robots using different kinds of cameras to take pictures. The drones use a bunch of parameters:

- ▶ The weight of the robot.
- ▶ The flying control parameters.
- ▶ The map of the city.
- ▶ The criterias used to give a fine.
- ▶ The type of installed camera.
- ▶ The calibrated position of the camera on the drone.

How would you organize these parameters?



9 Logging messages

Your advanced robot, capable of cooking thousands of recipes, has been built, calibrated, parametrized, and sent off to a kitchen for its first job.

A couple of days later, you receive a call from a puzzled chef, reporting that when the robot was asked to prepare a pasta sauce, it started boiling apples. Something appears to be amiss, but what could it be? Did the robot interpret a different command? Did its visual algorithms mistake apples for tomatoes? Or perhaps the robot was attempting to create an innovative pasta sauce that actually called for apples?

To address these questions, robot operators must gather additional information about the sequence of events that led to the robot making a mistake. Logging is the most commonly employed mechanism to comprehend the inner workings of a robot and understand its behavior.

9.1 Logging a message

Logging is the process of writing programmatically a piece of information to a file, to the console, or to a remote system. You are probably already familiar with logging: when learning a new programming language, it is common practice to begin by writing a program that prints the "Hello world!" message. In a generic C++ program, it is common to use the "standard output stream" with the object `"std::cout"` for this purpose. While it is still possible to use the same object in a ROS application, a set of [utilities](#)[167] were created that provide additional functionalities to this mechanism.

The most common way of printing a message looks like this:

```
1 | RCLCPP_INFO(node->get_logger(), "Hello ROS!");
```

This is composed of three parts:

- ▶ A macro (RCLCPP_INFO in this case). We will see in a second how different kinds of macros can provide you with different logging capabilities.

- ▶ A logger object. For now just know that you always need to provide one.
- ▶ The message that you would like to print.

The macro produces an output in the form¹:

```
1 | [INFO] [{timestamp}] [{logger name}]: "Hello ROS!"
```

1: We'll see in a moment how this format can be modified.



9.1.1 Choosing the severity level

The most important property that you need to choose when logging a message, is its severity level. ROS provides the following possible choices:

- ▶ **DEBUG**. These are the messages that should allow you to achieve the finest grade of introspection for your system. The information conveyed by these messages shouldn't be necessary for understanding the generic behavior of your robot, but could be helpful for tracking an issue in a specific component. To avoid having too much information displayed, these are not forwarded to the console by default, but need to be enabled before starting the node, or at runtime through specific service calls.

In the case of our cooking robot, debug messages could for example display the list of all the objects that were detected on the scene. Debug messages are typically displayed in green, making them quite valuable when you want to give your non-IT colleagues the impression that you're delving into "The Matrix."

- ▶ **INFO.** This severity level should be used to log important information that is critical for understanding the behavior of the robot, but that is not unexpected.

The cook could for example log what command it received, or what kind of object it's about to grasp.

Info messages are generally displayed in white.

- ▶ **WARN.** Messages represented with this level are used to communicate unexpected events. Unexpected events might be the cause for deteriorated performance, and should consequently not be ignored.

The robot might for example produce a warning log if it is using the default configuration for a specific parameter because it doesn't find its override.

Warn messages are usually displayed in yellow.

- ▶ **ERROR.** Error messages are used to represent... errors. These are the first logs you should be looking for when trying to understand why a robot is not behaving as expected.

If an ingredient required for the recipe can't be found, an ERROR message should be logged. The robot needs to abort its current task, and eventually initiate a recovery sequence.

Error messages are usually displayed in red.

- ▶ **FATAL.** These messages should communicate errors that render the robot completely inoperable. In such scenarios, the robot's programmers may not have implemented a recovery mechanism.

Should the robot lose connection with the field-bus used to communicate with its motors, this kind of message could be logged.

Fatal messages are usually displayed in dark red.

Using different severity levels brings the following advantages with respect to the basic logging mechanisms:

- ▶ Spotting errors and identifying their source becomes more manageable with logging. When debugging a system, programmers typically start by examining the messages logged with the ERROR or FATAL levels to determine the type of error that occurred. They will then analyse the messages that directly precede the reported error to gain a clearer understanding of the sequence of events and its origin. If necessary, they may enable all the DEBUG information for the relevant components and attempt to reproduce the event².
- ▶ The amount of displayed information can be changed at runtime. Logging messages is a relatively expensive operation. This practice doesn't only consume disk space, but can deeply affect the runtime performance of the application, and should consequently be done with care. It is consequently often desirable to disable the lowest severity levels unless they are needed for debugging a specific error.

2: You might have to export the environment variable `RCUTILS_COLORIZED_OUTPUT=1` to enable colorized output.

9.1.2 Available macros

ROS 2 provides additional means to control when a message is logged, such as the possibility to add the following [suffixes](#) to the base log macro:

- ▶ **_STREAM**: C++ stream-style message. Ex:
`RCLCPP_INFO_STREAM(get_logger(), "Robot " «robot_name» " has " «n_cameras» " cameras.");`
- ▶ **_THROTTLE**: accepts a minimum log period in milliseconds, very useful for not spamming messages too frequently. Ex:
`RCLCPP_INFO_THROTTLE(get_logger(), *get_clock(), 1000, "Waiting for sensor data");`
- ▶ **_ONCE**: prints the specified message only the first time it's invoked. Repeated calls to the same macro have no effect.
- ▶ **_SKIPFIRST**: prints the specified message all but the first time it's invoked.
- ▶ **_EXPRESSION**: outputs the message only if the specified expression is true. It's meant to save you some if statements and make your code more compact.
- ▶ **_FUNCTION**: similar to expression, outputs the message only if the specified function is true.

Some of these suffixes can be combined together to form the macros SKIPFIRST_THROTTLE, STREAM_ONCE, STREAM_EXPRESSION, STREAM_FUNCTION, STREAM_SKIPFIRST, STREAM_THROTTLE, STREAM_SKIPFIRST_THROTTLE.

9.2 Enabling and disabling log functionalities

In order to make the execution of your system easier to introspect, you might need to add a lot of log messages. We have seen that, however, this can bring to a loss of readability and performance. To mitigate these downsides, ROS 2 provides different mechanisms to disable / enable subsets of the logged information.

9.2.1 Logging channels, options, and environment variables

In ROS 2, messages can be logged on three different channels:

- ▶ The console, where they can be visualized in real-time.
- ▶ A log file on the filesystem.
- ▶ The "/rosout" topic.

As I already mentioned, logging is a relatively "expensive" operation; if all the logging mechanisms are enabled at the same time, it becomes even more resource-consuming. Because of this, it is good practice to only enable the log channels that are of your interest. For example, if None of your nodes is subscribing to the "/rosout" topic, disabling it can considerably reduce your network traffic.

The logging channels, together with other properties of the logged messages, can be controlled setting specific [node options](#):

- ▶ `log_stdout_disabled`, associated to the ros argument `--disable-stdout-logs`, disables logging to the console.
- ▶ `log_ext_lib_disabled`, associated to the ros argument `--disable-external-lib-logs`, disables logging to disk.
- ▶ `log_rosout_disabled`, associated to the ros argument `--disable-rosout-logs`, disables logging to the `"/rosout"` topic.

Another option, "log_levels", can be used to control the minimum log severity of the messages print by a specific node. From the CLI, you could for example run:

```
1 | ros2 run package_name node_name --ros-args --log-level
   node_name:=WARN
```

To suppress all the messages with severity level DEBUG or INFO. Finally, enabling the option "enable_logger_service" (available from ROS 2 Iron onwards), starts a service that allows to configure the minumum log severity at runtime (see dedicated section below).

Other properties of the logging mechanism can be changed using [environment variables](#):

- ▶ **ROS_LOG_DIR**: can be used to change the directory where messages logged to file are stored. This is defaulted to "ROS_HOME/.log".
- ▶ **RCUTILS_LOGGING_USE_STDOUT**: if set to true, messages will be forwarded through the stdout stream, otherwise through stderr. By default, stderr is used to keep stdout available for use by the application.
- ▶ **RCUTILS_LOGGING_BUFFERED_STREAM**: can be used to force the stream to be buffered or unbuffered. You will usually want it to be unbuffered in order to see messages right away when debugging an application. The stream stderr is by default unbuffered.
- ▶ **RCUTILS_COLORIZED_OUTPUT**: colorizes the output if enabled. Colors help a lot when trying to spot errors in logs, so I recommend enabling it.
- ▶ **RCUTILS_CONSOLE_OUTPUT_FORMAT**: controls the fields that are output for each log message. See [here](#) for details.

9.2.2 Different types of loggers

In the previously reported examples, we have seen that the first argument in all the log macros is a "rclcpp::Logger". Whenever you create a node, this will always include a logger, that can be retrieved using the `"get_logger()"` method and includes the node's name and namespace in the logged messages.

To log messages, you are actually not forced to use the logger provided by a node, but can can create your own:

```
1 | rclcpp::get_logger("your_logger_name");
```

This practice, however, should only be used if you have a specific group of messages that you plan on enabling/disabling independently from the other messages logged by the node. Loggers created in this way have an additional hidden property: they are shared between all the nodes running within the same container. Because of this, unless you take care of providing them with node-specific names, you won't be able of changing their properties (like the logged severity level) only for a specific node.

9.2.3 Changing the log severity level at runtime

As already anticipated, the minimum severity logged by a specific logger can be changed in two ways:

- ▶ Through a node option provided when starting the application.
- ▶ Using a dedicated service at runtime.

In order to use the latter, available starting from ROS 2 Iron, a specific node option needs to be provided to the node: "enable_logger_service". Once this is done, the node will expose an additional service, called "/node_name/set_logger_levels", that can be called from the CLI with a command in the form:

```
1 Terminal 2: ros2 service call /node_name/set_logger_levels
   rcl_interfaces/srv/SetLoggerLevels "{levels:[name: '
   logger_name', level: CHOSEN_LEVEL]}"
```

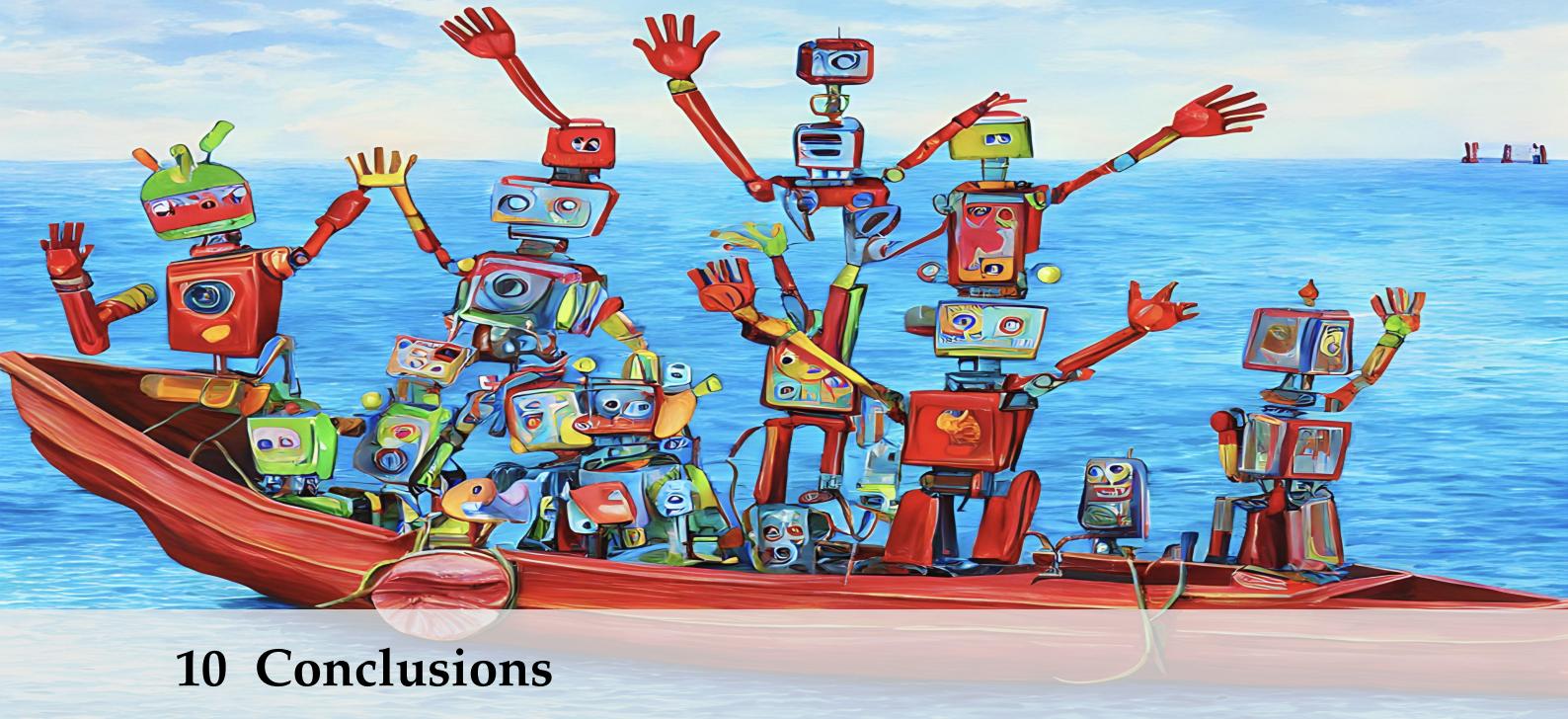
where CHOSEN_LEVEL can be any of:

```
1 uint8 LOG_LEVEL_UNKNOWN = 0
2 uint8 LOG_LEVEL_DEBUG = 10
3 uint8 LOG_LEVEL_INFO = 20
4 uint8 LOG_LEVEL_WARN = 30
5 uint8 LOG_LEVEL_ERROR = 40
6 uint8 LOG_LEVEL_FATAL = 50
```

If you are using the logger integrated in the node (and hence not a named logger), the name of the logger should be specified as an empty string (name: "").

Homework

Create a modified version of [the simple topic publisher](#) that prints a message to the screen with different logging levels each time a message is published. Modify the log level of the node's logger during runtime using the command line interface and verify that the printed messages changes accordingly. You can find the solution [here](#).



10 Conclusions

Along this book we have shown how to organize the software controlling a robot using modular reusable nodes, and how to make this nodes talk to each other using clear interfaces. We have discussed how to properly manage execution groups and how to organize complex tasks using different frameworks. Finally we have discussed how to treat large parameter configurations, how to test our software using a layered strategy and how to introspect it using the logging mechanism.

10.1 Feedback please

Since ROS 2 is a young framework still undergoing frequent changes, the recommendations that I gave along the way shouldn't be interpreted as absolute truths, but as guidelines that should be subject for discussion. I would be very glad to receive comments, corrections, critics and feedback about any of the points that were discussed in this book. If you think that I missed any important topic, feel free to make suggestions about stuff you would like to read about. I will do my best to keep this book updated with your feedback and the most recent framework-changes¹.

10.2 Final tips

Independently from the practices that you will try to follow, here are some final advices that not only apply when building a ROS application, but in general when developing complex software projects:

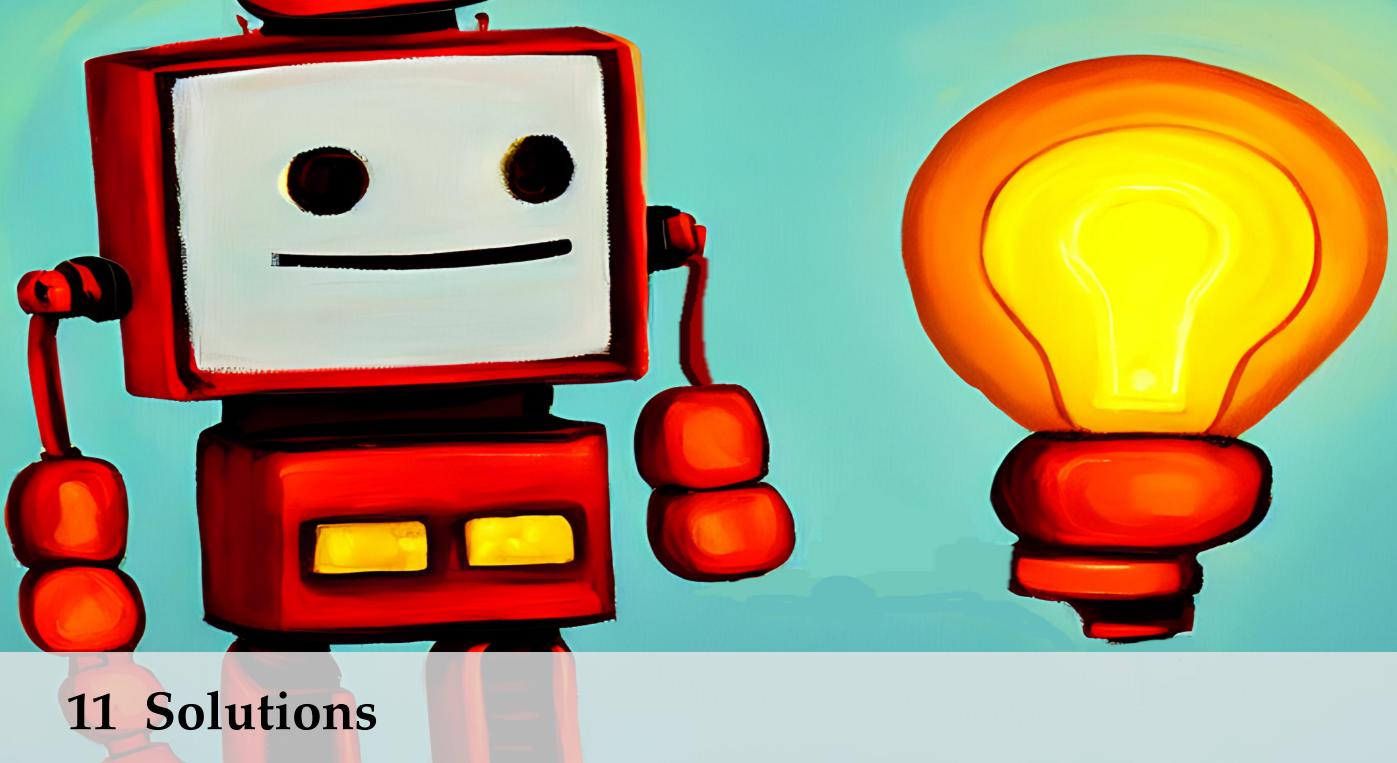
- ▶ Plan before coding. Before opening your favourite IDE for writing your software, grab a pen and a piece of paper, a whiteboard, or whatever you can use to sketch and try to come up with a simplified representation of your system. Which nodes do you need to implement? What information do they need to exchange? What kind of interface is better suited for each exchange? How

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will you synchronize the execution flow and how will you handle unexpected errors?

- ▶ Discuss your plans with someone else. It is relatively easy to come up with an initial sketch, but given the big amount of implementation possibilities, two developers with the same task almost never come up with the same solution. Merging multiple ideas and points of view almost always leads to better architectures. Teams tend to leave the cooperation and information-exchange part to the "code-review", but at this step the work is already done and making changes requires a significant amount of time. Coding stuff the first time is fun, but each iteration step becomes more and more boring. Discussing your solutions ahead of the implementation is easier (a sketch is usually more understandable than a piece of code), it will save resources and will make the following review tasks smoother.
- ▶ Do a lot of research and try to share your results. ROS is about collaboration, it was built with the task of reducing the amount of code that robotic developers need to implement from scratch. If you are building on top of ROS you should try to leverage this and make sure that you are not programming something that already exists out there. If what you find doesn't entirely suit your needs, don't be afraid of making adaptations and to propose your changes to the maintainers. If you implement something new and of general use, sharing it with the community might provide you with feedback, bug fixes and new features for free. Building software with the goal of sharing it usually leads to better, generic, architectures that are free of hacks tailoring a specific platform.

I hope you will consider some of the tips you found along this book to be helpful and we can meet up somewhere on our journey through ROS 2!



11 Solutions

This chapter provides the solution to some of the exercises proposed in the previous chapters. With time I will hopefully add more of them.

11.1 Chapter 2

The solution to this exercise can be found online at https://github.com/nirwester/ros2_journey_examples/tree/master/homeworks/chap2/lifecycle_examples.

11.2 Chapter 3

Which risk do you face if you manually call "rclcpp::spin_once()" in the constructor of a lifecycle-managed node?

Lifecycle managed nodes are usually ran in parallel with a "lifecycle manager" that controls their initialization. It is common for the manager to automatically request the configuration of the managed nodes at start-up.

When creating a lifecycle managed node inheriting from the corresponding base class, the service-servers required for the communication with the manager (the ones bounded to the `on_configure()`, `on_activate()`... callbacks) are started before the code in the constructor of the inheriting class (your node) is executed.

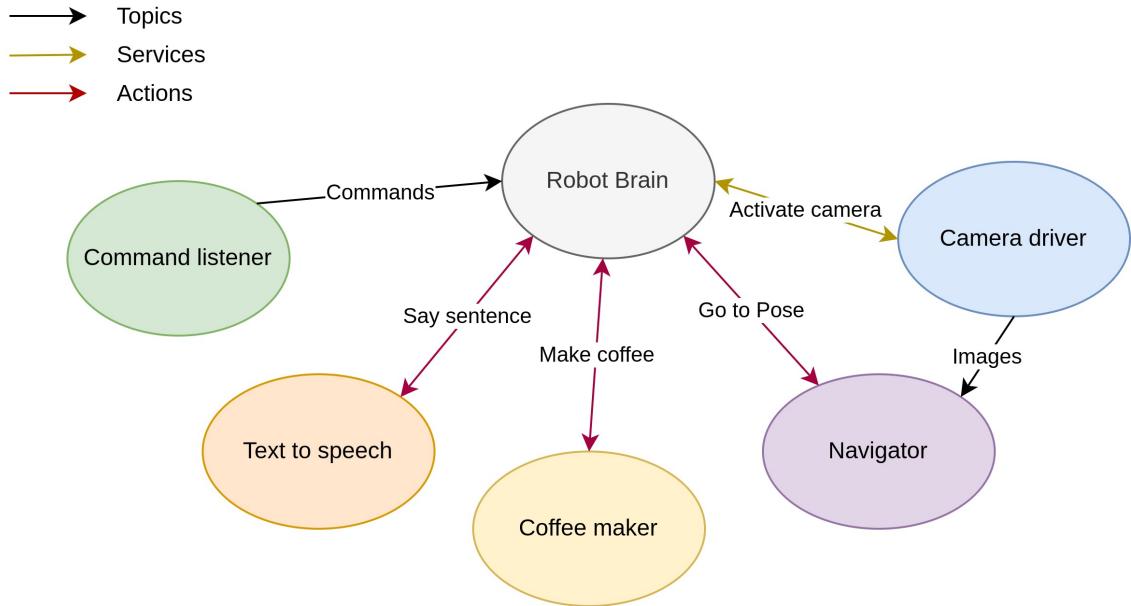
The manager can potentially start and requests the configuration of the nodes it's managing before these have actually completed the execution of their constructor.

If for any reason you call `spin_once()` during the construction of your node, this could consequently result in the node's configuration callback to be executed, even if the construction of the node is not yet completed.

You probably don't want to configure your class before it's fully constructed: this could result in any sort of issue, including black-holes and portals bringing you to another dimension where Nutella doesn't exist.

So as a rule of thumb: don't call any spin function in the constructor of a managed node!

11.3 Chapter 4



An example of implementation could involve the following interfaces:

- Commands topic: commands are generated asynchronously and hence can be forwarded to the brain at any time using a topic. The content of the topic could be either a string or an integer associated to an enumerator representing the possible commands for the robot.
- Say sentence: generating a sentence could take a considerable amount of time, and might need to be interrupted. For these reasons, an action server is better suited for the task. The exchanged data format could look something like this:

```

1 string sentence #(goal)
2 ---
3 bool success #(result)
4 ---
5 float32 progress #(feedback)
6
7
  
```

- Make coffee: as for the previous case, making a coffee might take a lot of time and might be interrupted, so we will use an action server. The action could be implemented as:

```

1 int32 ESPRESSO=1
2 int32 MACCHIATO=2
3 int32 DOPPIO=3
4 int32 CAPPUCCINO=4
  
```

```

6 int32 MOCACCINO=5
7 int32 CAFFELLATTE=6
8 int32 LUNGO=7
9 int32 AMERICANO=8
10 int32 CORRETTO=9
11 int32 DECAFFEINATO=10
12 int32 LATTE_MACCHIATO=11
13
14 int32 type_of_coffee 1
15 ---
16 bool success
17 ---
18 float32 progress
19

```

As you might have noticed, you are dealing with an Italian robot. If you don't specify what kind of coffee you want, you will get an espresso. Otherwise, to know the available kinds of coffee, you can look at the constants that are specified together with the action definition. We could also have used a string for this purpose, which would have been more readable, but slightly less efficient.

- ▶ Go to Pose: Moving from one pose in the house to a different one might take quite a bit of time (actually in my mini apartment it won't, but I assume this robot is owned by some rich guy with a villa). Since we said that answering the bell has precedence on other commands, the action could also be stopped and replaced with a different one. To satisfy these requirements, we will again use an action server. The action file could be implemented as:

```

1 geometry_msgs/PoseStamped target_pose
2 ---
3 geometry_msgs/PoseStamped reached_pose
4 bool success
5 ---
6 geometry_msgs/PoseStamped current_pose
7
8

```

In this case we are including a standard message (geometry_msgs/PoseStamped) into our own custom action definition.

- ▶ Activate camera: Starting the execution of a camera is usually a quick operation. The brain would probably also need to know if this operation fails (the robot shouldn't be allowed to drive blindly around the house). Because of this, a service could be an adequate interface. The SetBool service defined in std_srvs could work for our purpose:

```

1 bool data # e.g. for hardware enabling / disabling
2 ---
3 bool success # indicate successful run of triggered
4     service
5 string message # informational, e.g. for error
6     messages

```

Even if we don't need the "message" field, it is a good idea to stick to a standard interface when possible.

- ▶ Images: The camera produces data asynchronously, it is consequently a good idea to use a topic for this interface. Possible data types include sensor_msgs::msg::PointCloud2 or sensor_msgs::msg::Image depending on the camera type.

The solutions to the other exercises can be found on https://github.com/nirwester/ros2_journey_examples/tree/master/homeworks/chap4.

11.4 Chapter 9

You can find the solution to this exercise online at https://github.com/nirwester/ros2_journey_examples/tree/master/homeworks/chap9/change_logging_level.

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