ROS 2: Callbacks Handling, Control & Behavior Modeling

Course: Robotic Programming Environments

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Content

1. ROS 2: Callback Groups
2. ROS 2: Managed Nodes
3. ros2_control
4. Behavior modeling: FSM, BT

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ROS 2: Callback Groups

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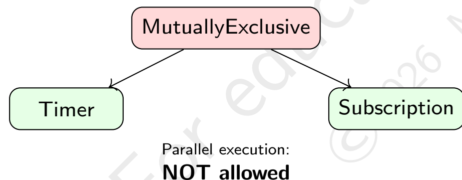
Callback Groups

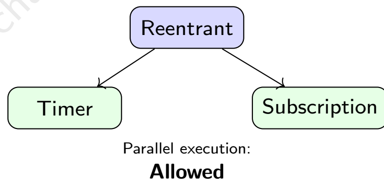
Definition

Callback groups organize callbacks (subscriptions, timers, services) to control their parallel execution within a node.

Mutually Exclusive Group
Only one callback at a time



Reentrant Group
Multiple callbacks in parallel



This mechanism is relevant when using a `MultiThreadedExecutor`.

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Problem Overview

In ROS 2:

- Every node has a **default callback group**.
- Default type: `MutuallyExclusive`.
- Even with `MultiThreadedExecutor` callbacks in the same group do not run concurrently.

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Example: Default Callback Group

```python
class MyNode(Node):
    def __init__(self):
        super().__init__("my_node")

        self.sub1 = self.create_subscription(
            String, "topic1", self.cb1, 10)

        self.sub2 = self.create_subscription(
            String, "topic2", self.cb2, 10)

    def cb1(self, msg):
        self.get_logger().info("Callback 1")

    def cb2(self, msg):
        self.get_logger().info("Callback 2")
```

Result

Both subscriptions use the default `MutuallyExclusive` callback group.

MultiThreadedExecutor

```
executor = MultiThreadedExecutor()

node = MyNode()
executor.add_node(node)
executor.spin()
```

Even with multiple executor threads:

- `cb1()` and `cb2()` are serialized
- They cannot execute at the same time

Callback Group rules > Executor threads

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Execution Visualization

Default Callback Group

Time	Thread 1	Thread 2	Result
t1	cb1()	idle	serialized
t2	cb1()	idle	serialized
t3	cb2()	idle	serialized

Second thread is unused because the callback group prevents parallel execution.

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Creating Reentrant Callback Groups

```python
from rclpy.subscription import SubscriptionOptions
from rclpy.callback_groups import ReentrantCallbackGroup

group1 = ReentrantCallbackGroup()

options = SubscriptionOptions()
options.callback_group = group1

self.sub1 = self.create_subscription(
    String, "topic1", self.cb1, 10, callback_group=group1)
```

- Reentrant groups allow concurrent execution
- Now the same callback can be executed simultaneously in multiple instances.

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Parallel Execution Example

Reentrant Callback Groups

Time	Thread 1	Thread 2	Result
t1	cb1()	cb1()	parallel
t2	cb1()	cb1()	parallel

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Creating Mixed Callback Groups

```
from rclpy.callback_groups import ReentrantCallbackGroup,
    MutuallyExclusiveCallbackGroup

# cb1: must NOT run in parallel with itself
cb1_group = MutuallyExclusiveCallbackGroup()

# cb2: can run in parallel
cb2_group = ReentrantCallbackGroup()

self.sub1 = self.create_subscription(
    String, "topic1", self.cb1, 10, callback_group=cb1_group
)

self.sub2 = self.create_subscription(
    String, "topic2", self.cb2, 10, callback_group=cb2_group
)
```

- cb1 is serialized (safe for shared state)
- cb2 runs concurrently (independent work)

Mixed Execution Example (MultiThreadedExecutor)

Time	Thread 1	Thread 2	Result
t1	cb1()	cb2()	parallel
t2	cb2()	cb2()	parallel
t3	cb1()	cb2()	parallel

cb1 never overlaps with itself, but can run alongside cb2.

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Fully Controlled Parallel Execution

Goal

We want to control callback execution such that:

- `cb1` must NOT run in parallel with itself
- `cb2` must NOT run in parallel with itself
- `cb1` and `cb2` can run in parallel

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Solution: Callback Group Separation

Use **two separate MutuallyExclusive callback groups** to enforce per-callback serialization while allowing cross-callback parallelism.

- `cb1` → MutuallyExclusive group A (no self-parallelism)
- `cb2` → MutuallyExclusive group B (no self-parallelism)
- Different groups → can execute in parallel (MultiThreadedExecutor)

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Fully Controlled Parallel Execution

```
from rclpy.callback_groups import
    MutuallyExclusiveCallbackGroup

# cb1 must not overlap with cb1
cb1_group = MutuallyExclusiveCallbackGroup()

# cb2 must not overlap with cb2
cb2_group = MutuallyExclusiveCallbackGroup()

self.sub1 = self.create_subscription(
    String, "topic1", self.cb1, 10,
    callback_group=cb1_group
)

self.sub2 = self.create_subscription(
    String, "topic2", self.cb2, 10,
    callback_group=cb2_group
)
```

Callback Groups: Summary

- ROS 2 nodes use a default `MutuallyExclusive` callback group
- MultiThreadedExecutor alone does not provide concurrency
- Callback groups determine whether callbacks may execute in parallel
- Use:
    - `Reentrant`
    - or separate callback groups

  for true multithreaded execution

Executor threads + proper callback groups = parallel execution

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ROS 2: Managed Nodes

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ROS 2 Lifecycle Nodes

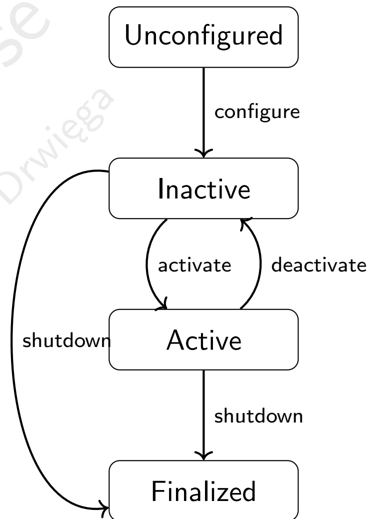
Lifecycle nodes provide a managed execution model that enables controlled startup, shutdown, and recovery of system components.

Main states:

- **Unconfigured** – node not initialized
- **Inactive** – configured, no processing
- **Active** – normal operation
- **Finalized** – node shutdown state

Advantages:

- Controlled system startup
- Improved fault handling
- Deterministic initialization sequence



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ROS 2 Lifecycle Node – Python Example

```python
import rclpy
from rclpy.lifecycle import LifecycleNode,
    TransitionCallbackReturn


class CameraNode(LifecycleNode):
    def __init__(self):
        super().__init__('camera_node')

    def on_configure(self, state):
        self.get_logger().info('Configuring node')
        return TransitionCallbackReturn.SUCCESS

    def on_activate(self, state):
        self.get_logger().info('Activating node')
        return TransitionCallbackReturn.SUCCESS

    ...

```

ROS 2 Lifecycle Commands

```
# List available lifecycle nodes
ros2 lifecycle nodes

# Show current node state
ros2 lifecycle get /camera_node

# Configure node
ros2 lifecycle set /camera_node configure

# Activate node
ros2 lifecycle set /camera_node activate

# Deactivate node
ros2 lifecycle set /camera_node deactivate

# Shutdown node
ros2 lifecycle set /camera_node shutdown
```

ros2_control

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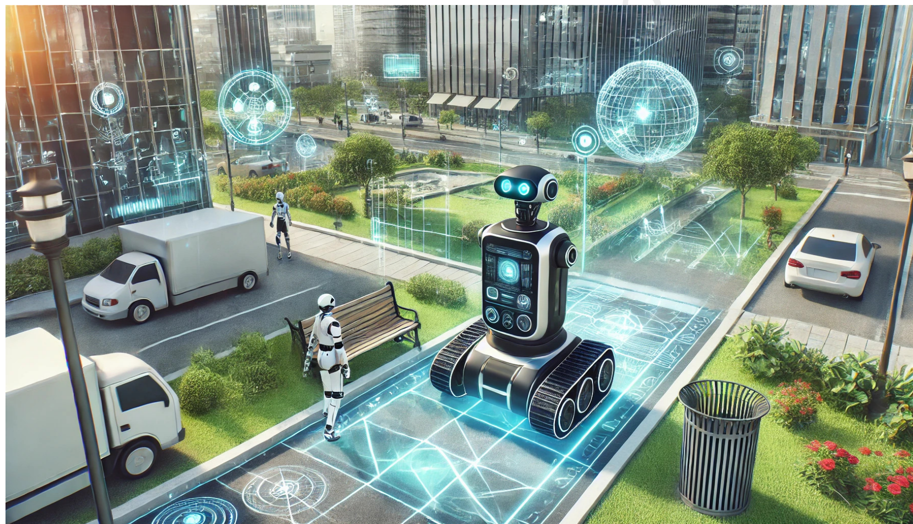
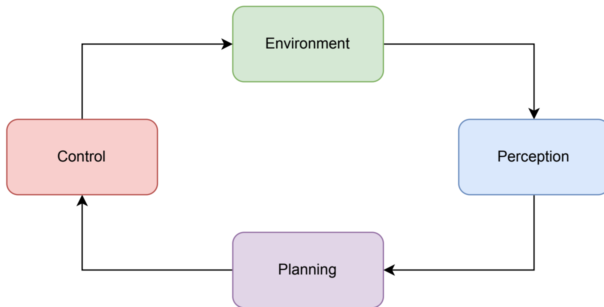
What is Autonomous Robot?



Autonomous Robot: Perception, Planning, and Control



Introduction to ROS 2 Control (ros2_control)

- ROS 2 Control is a framework for real-time control of robotic hardware.
- Provides interfaces for controlling joints, actuators, and sensors in ROS 2.
- Built to address limitations of the ROS 1 Control framework with a more modular and efficient design.
- Ideal for robotics applications requiring precise control over hardware in real-time.

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ROS 2 Control: Key Components

- **Controller Manager** - Manages and loads controllers dynamically.
- **Resource Manager** - Abstracts physical hardware and its drivers (called hardware components) for the ros2_control framework.
- **Controllers** - Specific modules for joint position, velocity, and effort control.
- **Hardware Interface** - Defines communication with robot hardware (motors, sensors).

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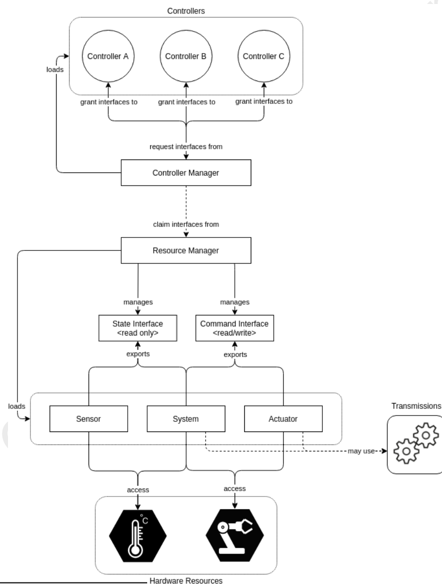
ROS 2 Control: Architecture



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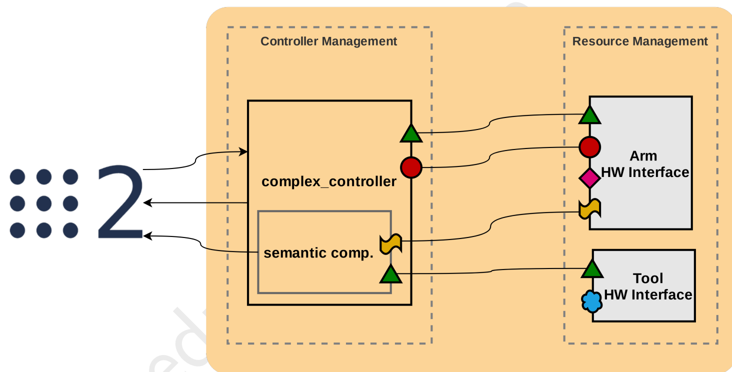
[1] https://control.ros.org/rolling/doc/getting_started/getting_started.html

ROS 2 Control: Architecture



CC-BY: Denis Stogl, Bence Magyar (ros2_control) [2]

[2] https://control.ros.org/rolling/doc/getting_started/getting_started.html

ROS 2 Control: Controller Manager

- **Lifecycle Management**: Load, configure, start, and stop controllers dynamically.
- **Real-time Safe Execution**: Ensures controllers update in a deterministic, efficient loop.
- Improves flexibility by managing controller states without disrupting other parts of the system.

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ROS 2 Control: Types of Controllers

- **Effort Controllers**: Control force/torque output for joints.
- **Velocity Controllers**: Control the speed of joints or wheels.
- **Position Controllers**: Set the position of joints.
- **Gripper Controllers**: Control the gripper (e.g. vacuum gripper).
- **Joint Trajectory Controllers**: Allows control over multiple joints for smooth trajectory execution.
- **PID Controller**
- **Custom Controllers**: Users can implement custom controllers for specific hardware needs.

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ROS 2 Control: Broadcasters

Broadcasters are used to publish sensor data from hardware components to ROS topics.

Types of Broadcasters:

- **Force Torque Sensor Broadcaster**: Publishes data from force and torque sensors.
- **IMU Sensor Broadcaster**: Transmits data from IMU, providing information on orientation, angular velocity, and acceleration.
- **Joint State Broadcaster**: Publishes the states of each joint (position, velocity, effort).
- **Range Sensor Broadcaster**: Sends data from range sensors like LIDAR or ultrasonic sensors.
- **Pose Broadcaster**: Provides the pose of a component.

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ROS 2 Control: Hardware Interface

- **Hardware Abstraction Layer**: Interfaces between robot hardware and ROS 2.
- **Components**: Includes *actuators* (motors, etc.) and *sensors* (encoders, etc.).
- Standardized data flow for easy integration of various hardware types.

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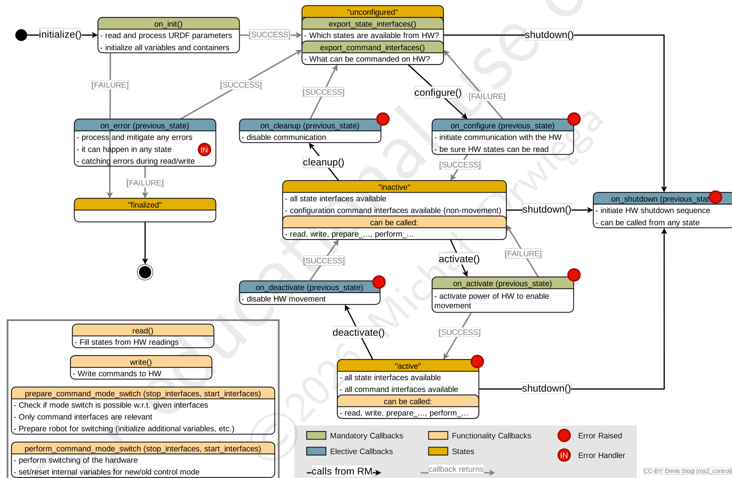
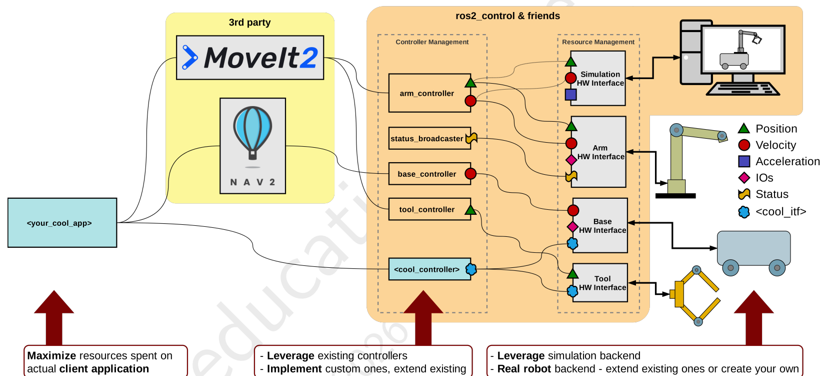
Hardware Interface Life Cycle



[3]

[3] https://control.ros.org/rolling/doc/getting_started/getting_started.html

ROS 2 Control: Example



[4] https://control.ros.org/rolling/doc/resources/resources.html

Behavior modeling: FSM, BT

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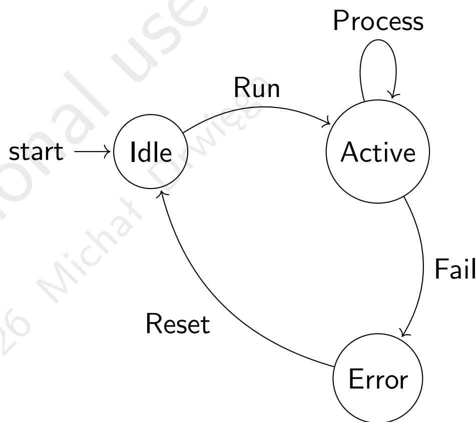
Finite State Machine (FSM)

- A Finite State Machine consists of:
  - A set of states.
  - A starting state.
  - Input events causing transitions between states.



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FSM - example in Python

```python
state = "IDLE"

def handle_event(event):
    global state

    if state == "IDLE":
        if event == "start":
            state = "RUNNING"
    elif state == "RUNNING":
        if event == "stop":
            state = "IDLE"

if __name__ == "__main__":
    while True:
        event = input("Enter event (start/stop): ")
        handle_event(event)
```

Behavioral Trees in ROS 2

- **What are Behavioral Trees?**
  - A hierarchical model for robot behavior management.
  - Combines logic and control for task execution.
  - Nodes represent actions, conditions, or control flow elements.
- **Advantages over Finite State Machines (FSMs)**
  - Modularity: Individual behaviors are isolated and reusable.
  - Flexibility: Easy to add or modify behaviors.
  - Robustness: Handles failure and retries naturally.
- **Behavioral Trees in ROS**
  - Popular libraries: `BehaviorTree.CPP`, `py_trees`.
  - Integration with ROS actions and services.
  - Useful for autonomous navigation, manipulation, and task planning.

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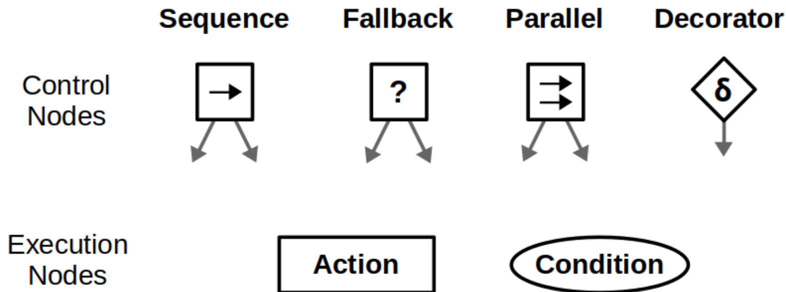
Behavioral Trees: Types of Nodes



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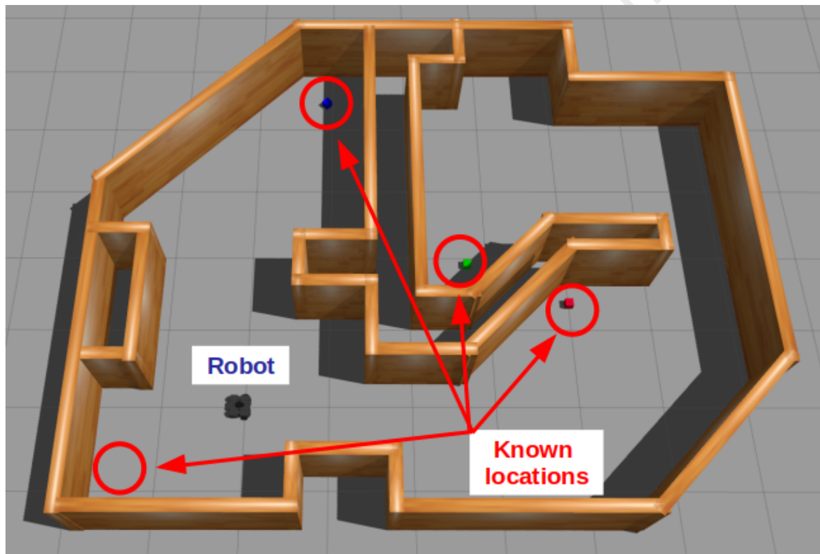
[5] https://robohub.org/introduction-to-behavior-trees/

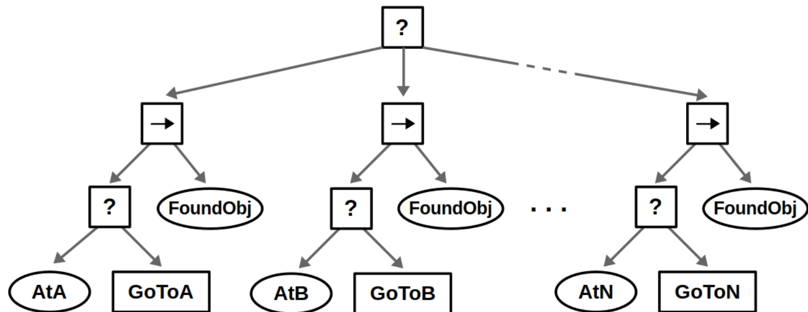
Behavioral Trees: Example



[6]

[6] https://robohub.org/introduction-to-behavior-trees/

Behavioral Trees: Example



[7]

[7] https://robohub.org/introduction-to-behavior-trees/

Summary

1. ROS 2: Callback Groups
2. ROS 2: Managed Nodes
3. ros2_control
4. Behavior modeling: FSM, BT

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The end

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