Software Lecture 6:

State Machines with ROS

Jacques Cloete

Contents

In this lecture, we shall cover:

- Overview for finite state machines and SMACH
- Creating a simple SMACH state machine in Python
- Passing data between states
- Calling ROS Services/Actions from SMACH state machines

Before We Begin

- Again, I strongly suggest bookmarking the following link: https://github.com/OxRAMSociety/RobotArm

- All example code can be found in:

Tutorials/Software Tutorials (2022)/Example Scripts

Of course, code for this lecture will be in the Lecture 6 folder, and so on for future lectures

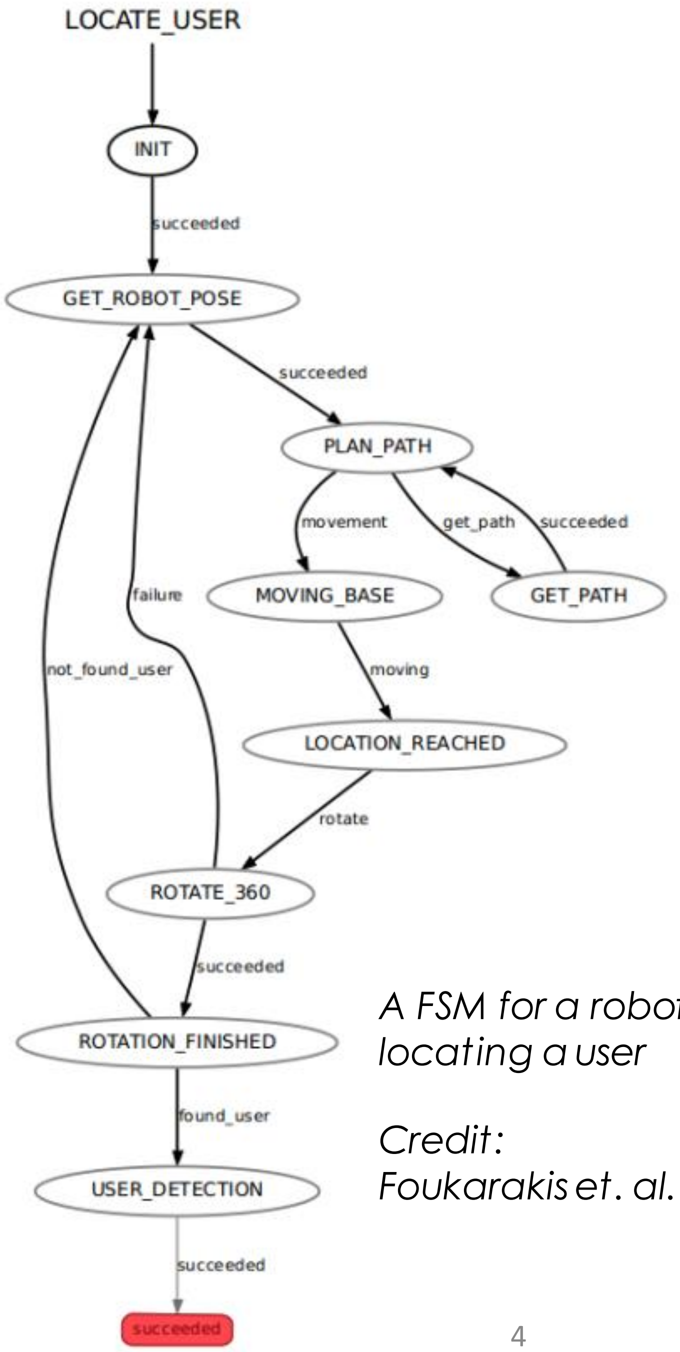
- I will highlight some code in these presentations, but you should refer to the Example Scripts for the entire code

State Machines – Overview (1)

- Finite state machines (FSMs) are abstract machines that can be in exactly one of a finite set of states at a given time

- FSMs can transition between states depending on the outcomes from the current state

- When they are initialised, they start in the start state, and eventually finish in one of the possible end states



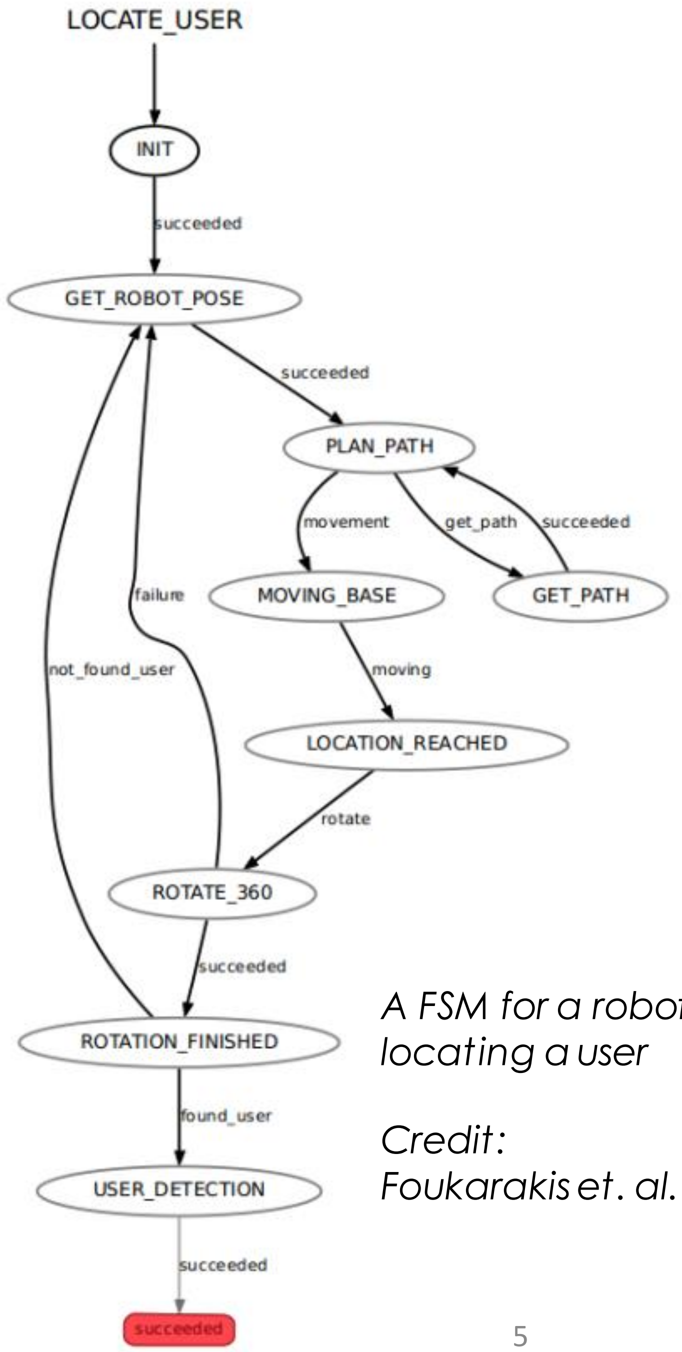
A FSM for a robot locating a user

Credit: Foukarakis et. al.

State Machines – Overview (2)

- The FSM algorithm works as follows:

  1. With the inputs provided to the current state, carry out the behaviour defined for that state (e.g. move the arm to a target position)
  2. Observe the results from the behaviour (did the arm reach the target?)
  3. Use these results to choose the outcome of the state (from a discrete set of outcomes)
  4. Transition to the next state according to the outcome (each outcome has a corresponding transition)



A FSM for a robot locating a user

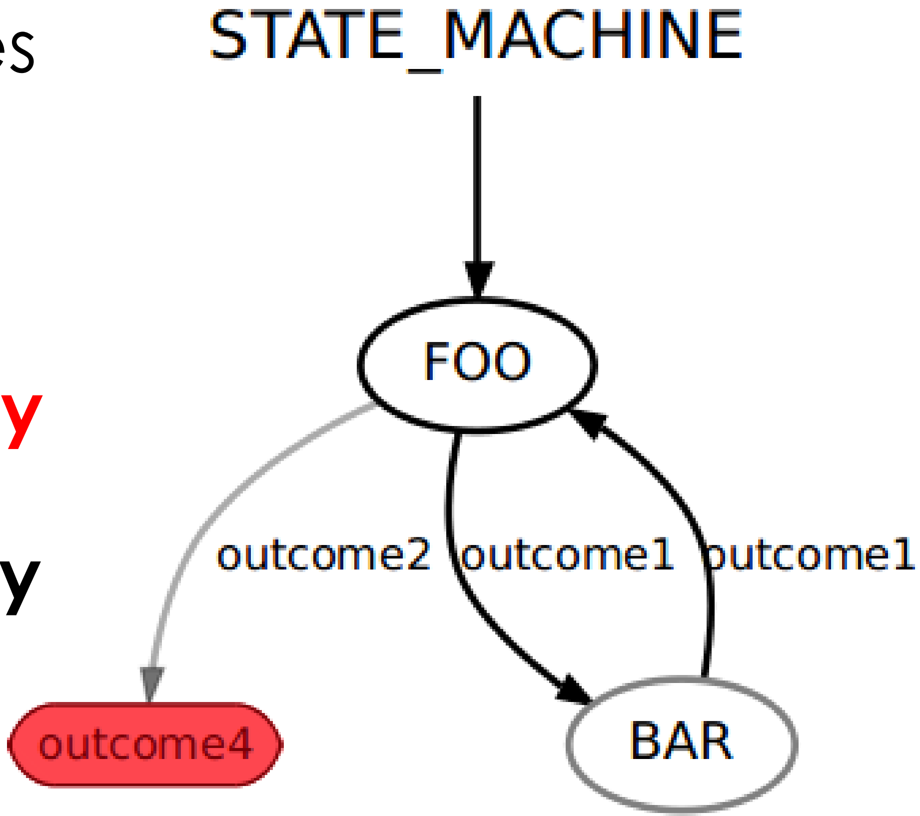
Credit: Foukarakis et. al.

SMACH

- SMACH is a Python library used to create FSMs
- Very useful for rapidly creating complex robot behaviour
- While being ROS-independent at its core, SMACH has a package for ROS that allows its FSMs to integrate seamlessly into a ROS network
- We will be using this library to create behaviours for our robot arm

Creating a Simple FSM (1)

- Our first FSM shall transition between two states, FOO and BAR, a few times before finishing on an end state
- **In tutorial_script's scripts folder, create the file Example_SM_Simple.py**
- **Find the script in our GitHub and copy it into your file**
- Let's have a look at the code…



A very similar example FSM
Credit: ROS Wiki

Creating a Simple FSM (2)

```python
# Define a class for state Foo
class Foo(smach.State):
    def __init__(self): # This method runs when the state is first initialised
        # Initialise the state and define its possible outcomes:
        smach.State.__init__(self, outcomes=['outcome1','outcome2'])
        self.counter = 0

    def execute(self, userdata): # This method runs when the state machine transitions to this state
        rospy.loginfo('Executing state FOO')
        if self.counter < 3:
            self.counter += 1
            return 'outcome1' # The outcome returned by the method will determine the next state
        else:
            return 'outcome2'
```

- Here we define a class for the FOO state type, with an initialisation method as well as the method execute that runs when the FSM transitions to the state

    - In the code, we also define a class for BAR

Creating a Simple FSM (3)

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

    # Create a SMACH state machine, defining the possible outcomes
    sm = smach.StateMachine(outcomes=['end'])

    # Open the container
    with sm:
        # Add states to the container
        # Provide the name of the state, the class from which it is derived,
        # and the next state for each possible outcome
        smach.StateMachine.add('FOO', Foo(),
                               transitions={'outcome1':'BAR', 'outcome2':'end'})
        smach.StateMachine.add('BAR', Bar(),
                               transitions={'outcome1':'FOO'})

    # Execute SMACH plan
    outcome = sm.execute()
```

- Here we initialise the FSM, add some states to it and define the transitions for the outcomes, and finally execute the FSM

Creating a Simple FSM (4)

- As always, **give your script permissions, then run roscore in one terminal and your script in another.** You should see this:

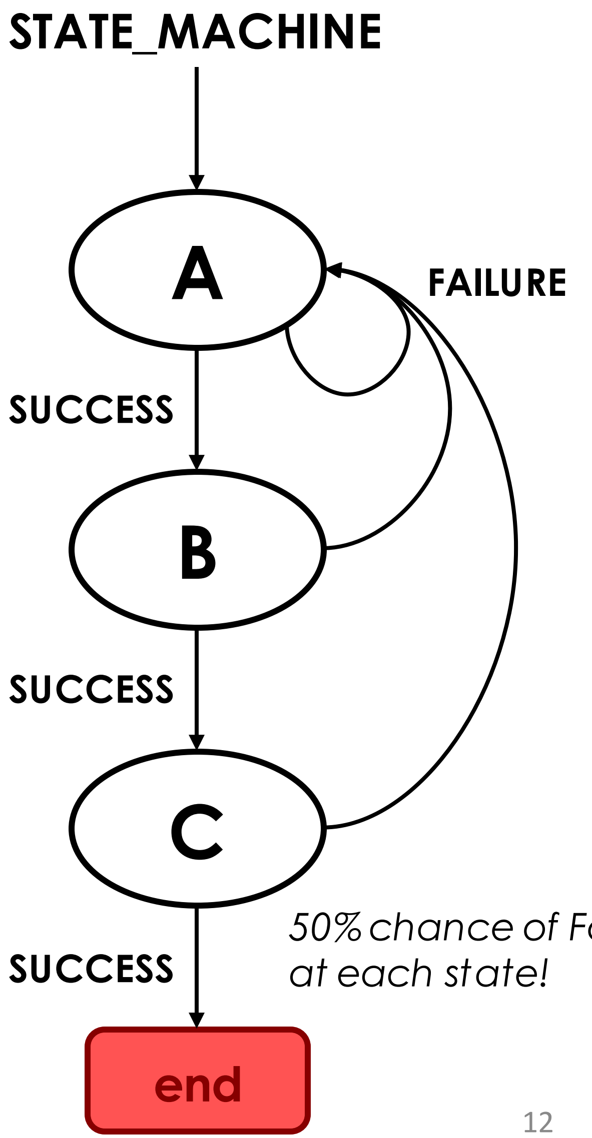
```
jacques@jacques-VirtualBox:~$ rosrun tutorial_scripts Example_SM_Simple.py
[INFO] [1669550311.148662]: State machine starting in initial state 'FOO' with userdata:
        []
[INFO] [1669550311.149684]: Executing state FOO
[INFO] [1669550311.150522]: State machine transitioning 'FOO':'outcome1'-->'BAR'
[INFO] [1669550311.151384]: Executing state BAR
[INFO] [1669550311.152321]: State machine transitioning 'BAR':'outcome1'-->'FOO'
[INFO] [1669550311.153429]: Executing state FOO
[INFO] [1669550311.156788]: State machine transitioning 'FOO':'outcome1'-->'BAR'
[INFO] [1669550311.157808]: Executing state BAR
[INFO] [1669550311.161178]: State machine transitioning 'BAR':'outcome1'-->'FOO'
[INFO] [1669550311.161796]: Executing state FOO
[INFO] [1669550311.162506]: State machine transitioning 'FOO':'outcome1'-->'BAR'
[INFO] [1669550311.163123]: Executing state BAR
[INFO] [1669550311.163787]: State machine transitioning 'BAR':'outcome1'-->'FOO'
[INFO] [1669550311.165545]: Executing state FOO
[INFO] [1669550311.166535]: State machine terminating 'FOO':'outcome2':'end'
jacques@jacques-VirtualBox:~$
```

Passing Data Between States (1)

- In SMACH, the FSM can be given userdata, a set of variables global to the FSM and used to pass data between states
- You can even access the final userdata directly from the FSM once execution is complete
- For a state to read and write to a variable in userdata, it must have it defined as an input key and output key respectively

Passing Data Between States (2)

- We shall demonstrate this by implementing the FSM shown and logging the number of times it transitions to each state
- **In tutorial_script's scripts folder, create the file Example_SM_Advanced.py**
- **Find the script in our GitHub and copy it into your file**
- Let's have a look at the code…



50% chance of Failure at each state!

Passing Data between States (3)

```
class stateA(smach.State):
    def __init__(self):
        smach.State.__init__(self, outcomes=['SUCCESS','FAILURE'], output_keys=['A_count'])
        # This state can output data to our custom 'A_count' field for the state machine's global userdata
        # To let the state receive input data from a field, use 'input_keys=['...']'

        self.counter = 0    # This variable is stored internally within the state,
                            # and will be remembered when the state is executed again

    def execute(self, userdata):
        rospy.loginfo("Executing State A...")
        r.sleep() # Sleep for one second

        self.counter += 1   # Increment the counter
        userdata.A_count = self.counter # This demonstrates how to acess the global userdata

        # Determine next state (here, random with 50% chance of success)
        result = random.choice(['SUCCESS','FAILURE'])

        return result
```

- Here is our class definition for state A; note how we defined the variable A_count in the list of output keys
  - We update this variable every time the FSM transitions to state A

Creating a Simple FSM (4)

```python
if __name__ == '__main__':
    rospy.init_node('example_sm_advanced')

    r = rospy.Rate(2)

    sm = smach.StateMachine(outcomes=['end'])

    with sm:
        smach.StateMachine.add('A', stateA(), transitions={'FAILURE':'A','SUCCESS':'B'})

        smach.StateMachine.add('B', stateB(), transitions={'FAILURE':'A','SUCCESS':'C'})

        smach.StateMachine.add('C', stateC(), transitions={'FAILURE':'A','SUCCESS':'end'})

    # To exit the State Machine, Tasks A, B, and C must each be successfully completed in order
    # Each Task has a 50 percent chance of success
    # If any Task fails, re-start from Task A

    # initialise our userdata
    sm.userdata.A_count = 0
    sm.userdata.B_count = 0
    sm.userdata.C_count = 0

    outcome = sm.execute()

    # We can access these
    rospy.loginfo("State A Attempted %d Times", sm.userdata.A_count)
    rospy.loginfo("State B Attempted %d Times", sm.userdata.B_count)
    rospy.loginfo("State C Attempted %d Times", sm.userdata.C_count)
```

Here we set up and execute the FSM as before, but also initialise our userdata before execution and read the logged data values after execution

Passing Data Between States (5)

- **Give your script permissions, then run roscore in one terminal and your script in another.** You should see something like this:

```
jacques@jacques-VirtualBox:~$ rosrun tutorial_scripts Example_SM_Advanced.py
[INFO] [1669550357.617107]: State machine starting in initial state 'A' with userdata:
        ['A_count', 'B_count', 'C_count']
[INFO] [1669550357.618414]: Executing State A...
[INFO] [1669550358.118699]: State machine transitioning 'A':'FAILURE'-->'A'
[INFO] [1669550358.122125]: Executing State A...
[INFO] [1669550358.618136]: State machine transitioning 'A':'FAILURE'-->'A'
[INFO] [1669550358.620118]: Executing State A...
[INFO] [1669550359.118857]: State machine transitioning 'A':'SUCCESS'-->'B'
[INFO] [1669550359.120489]: Executing State B...
[INFO] [1669550359.619824]: State machine transitioning 'B':'SUCCESS'-->'C'
[INFO] [1669550359.623382]: Executing State C...
[INFO] [1669550360.118600]: State machine terminating 'C':'SUCCESS':'end'
[INFO] [1669550360.120230]: State A Attempted 3 Times
[INFO] [1669550360.122563]: State B Attempted 1 Times
[INFO] [1669550360.123611]: State C Attempted 1 Times
jacques@jacques-VirtualBox:~$
```

Since each success is random, you will likely get different results each time you run the script!

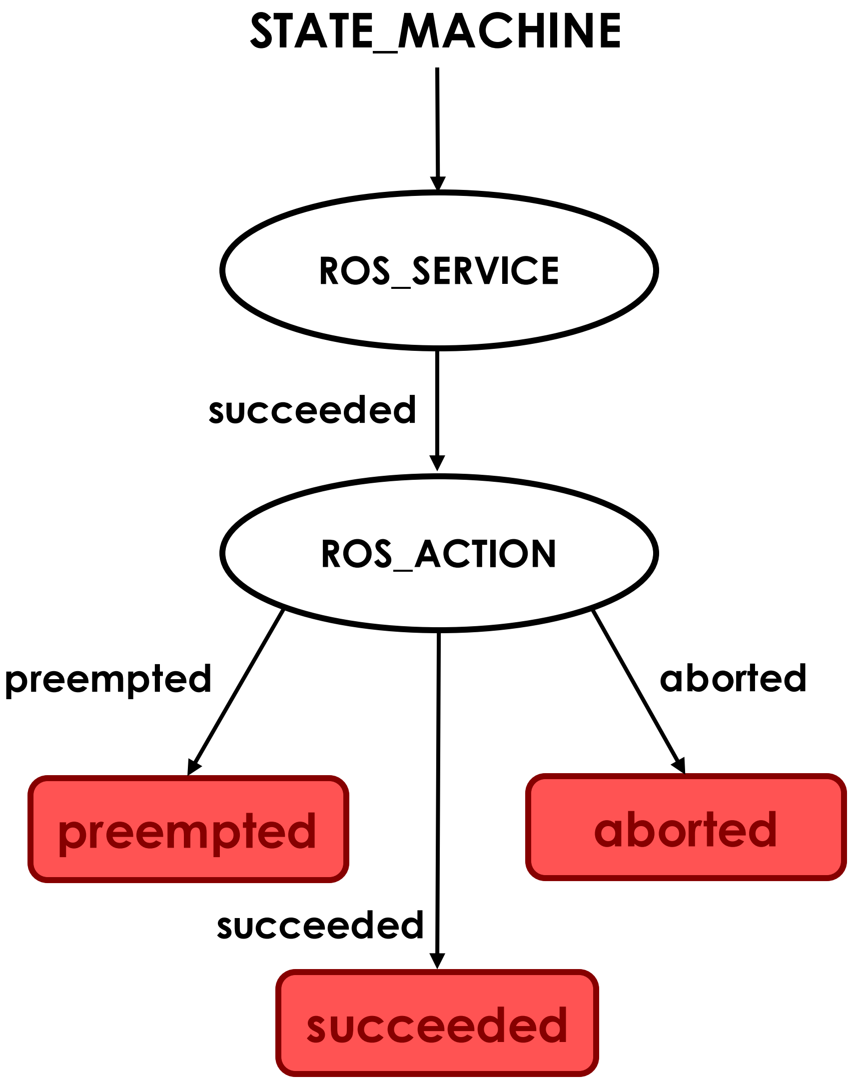
```
[INFO] [1669550536.849852]: State A Attempted 9 Times
[INFO] [1669550536.853074]: State B Attempted 3 Times
[INFO] [1669550536.855435]: State C Attempted 2 Times
```

SMACH and ROS (1)

- As mentioned previously, SMACH has an extension for ROS that allows us to integrate our FSMs into the rest of the ROS network, e.g. for calling Services and Actions
- We could take the naïve approach of setting up Service and Action Clients in the same way as Lectures 4/5 within the execute_cb method…
- …but SMACH_ROS provides a more sophisticated approach, with specialised Service and Action Client states

SMACH and ROS (2)

- We shall demonstrate this by implementing a FSM that calls our ExampleService and uses the response as a goal for ExampleAction
- **In tutorial_script's scripts folder, create the file Example_SM_ROS.py**
- **Find the script in our GitHub and copy it into your file**
- Let's have a look at the code…



SMACH and ROS (3)

```python
#  Example ROS Service Client State:
def request_cb(userdata, request):  # This is called upon transitioning to the service client state
    request = ExampleServiceRequest()
    request.input_number = random.randint(1,3)
    return request  # This is used as the service request

def response_cb(userdata, response):    # This is called upon receiving a response from the server
    userdata.service_response = response.output_number
    return 'succeeded'  # This is used as the state outcome

# Initialise the state
smach.StateMachine.add('ROS_SERVICE',
                        smach_ros.ServiceState('ExampleService',
                        ExampleService,
                        request_cb=request_cb,
                        response_cb=response_cb,
                        output_keys=['service_response']),
                        transitions={'succeeded' : 'ROS_ACTION'})
```

- Here is our implementation for the Service Client; note how we only need to define callbacks for the request and response

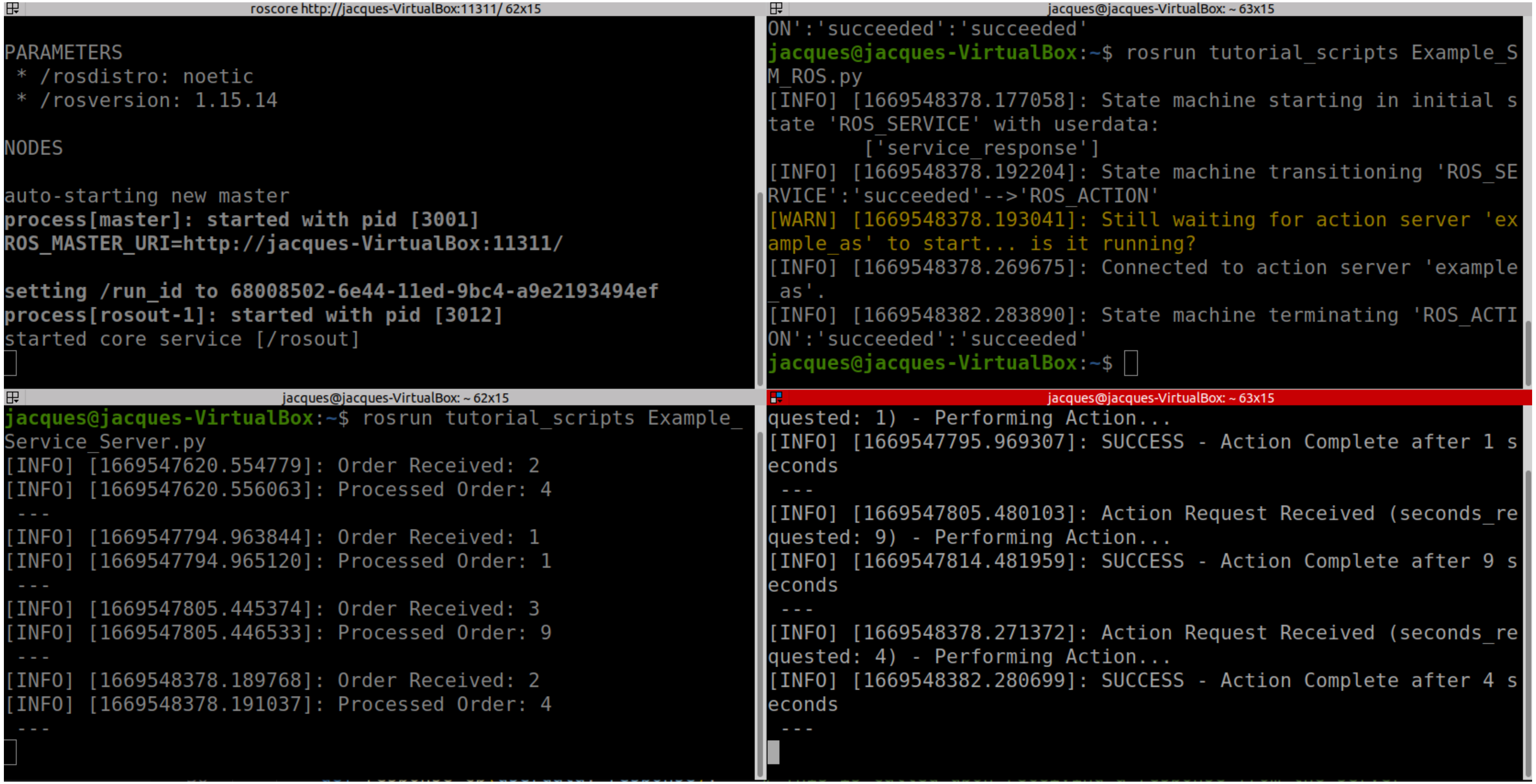
SMACH and ROS (4)

```python
#  Example ROS Action Client State:
def goal_cb(userdata, goal): # This is called upon transitioning to the action client state
    goal = ExampleGoal()
    goal.seconds_requested = userdata.service_response
    return goal # This is used as the action goal

def result_cb(userdata, status, result): # This is called upon receiving a result from the server
    if status == actionlib.GoalStatus.SUCCEEDED: # Check goal status
        return 'succeeded' # This is used as the state outcome
    elif status == actionlib.GoalStatus.PREEMPTED:
        return 'preempted'
    else:
        return 'aborted'

# Initialise the state
smach.StateMachine.add('ROS_ACTION',
                        smach_ros.SimpleActionState('example_as',
                        ExampleAction,
                        goal_cb=goal_cb,
                        result_cb=result_cb,
                        input_keys=['service_response']),
                        transitions={'succeeded' : 'succeeded',
                        'preempted' : 'preempted',
                        'aborted' : 'aborted'})
```

- Here is our implementation for the Action Client; again, we only need to define callbacks for the goal and result

Passing Data Between States (5)

- **Give your script permissions, then run roscore in one terminal, run the Example Service and Action Servers, and finally your script:**

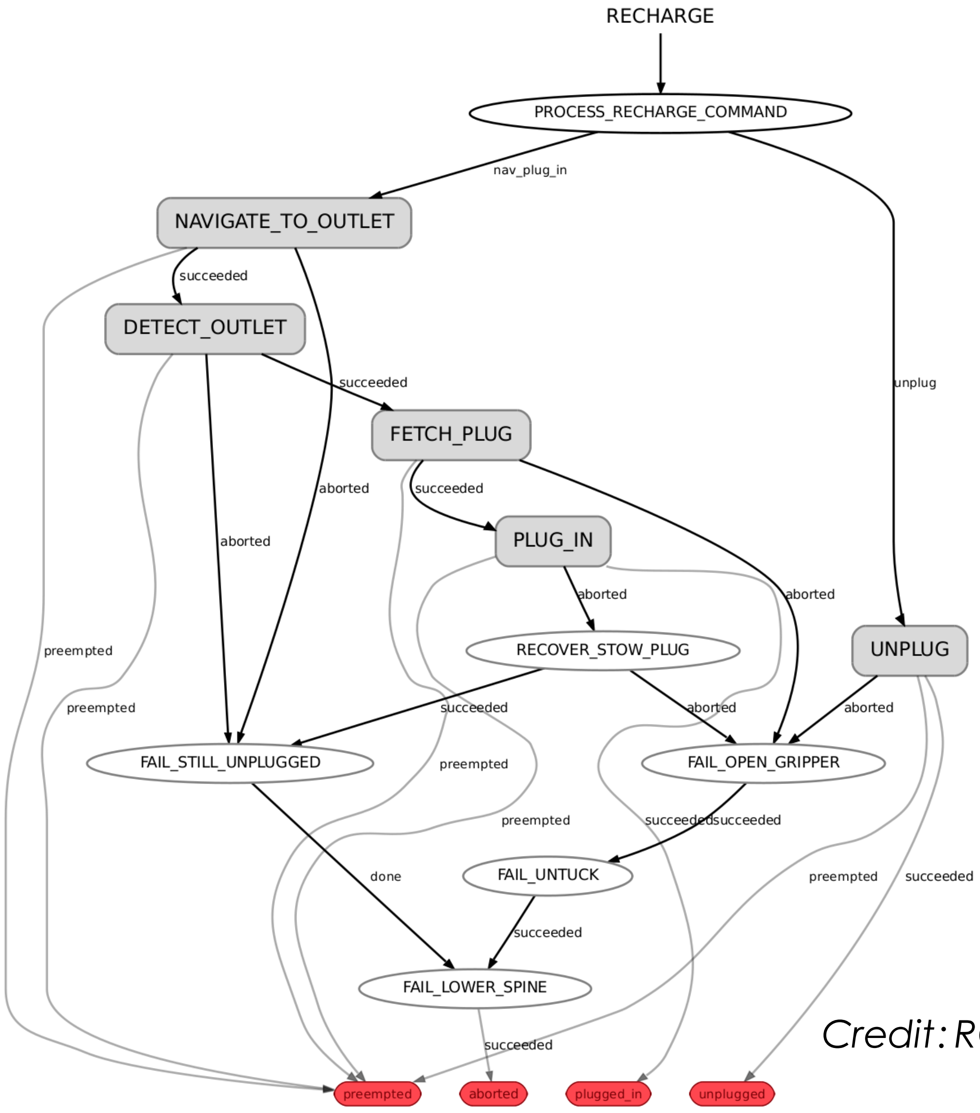


Closing Thoughts: Fault-Tolerant FSMs (1)

- When you're creating a FSM for your robot, you need to make sure you've covered every possible outcome, even the undesirable ones
  - What if your robot fails to move to a target?
  - What if your object detection software can't find the object you're looking for?
- Your FSM must have fallbacks in place for when things inevitably don't go to plan – this is fault-tolerant FSM design
  - This process will likely take up the most time when you design FSMs!

Closing Thoughts: Fault-Tolerant FSMs (2)

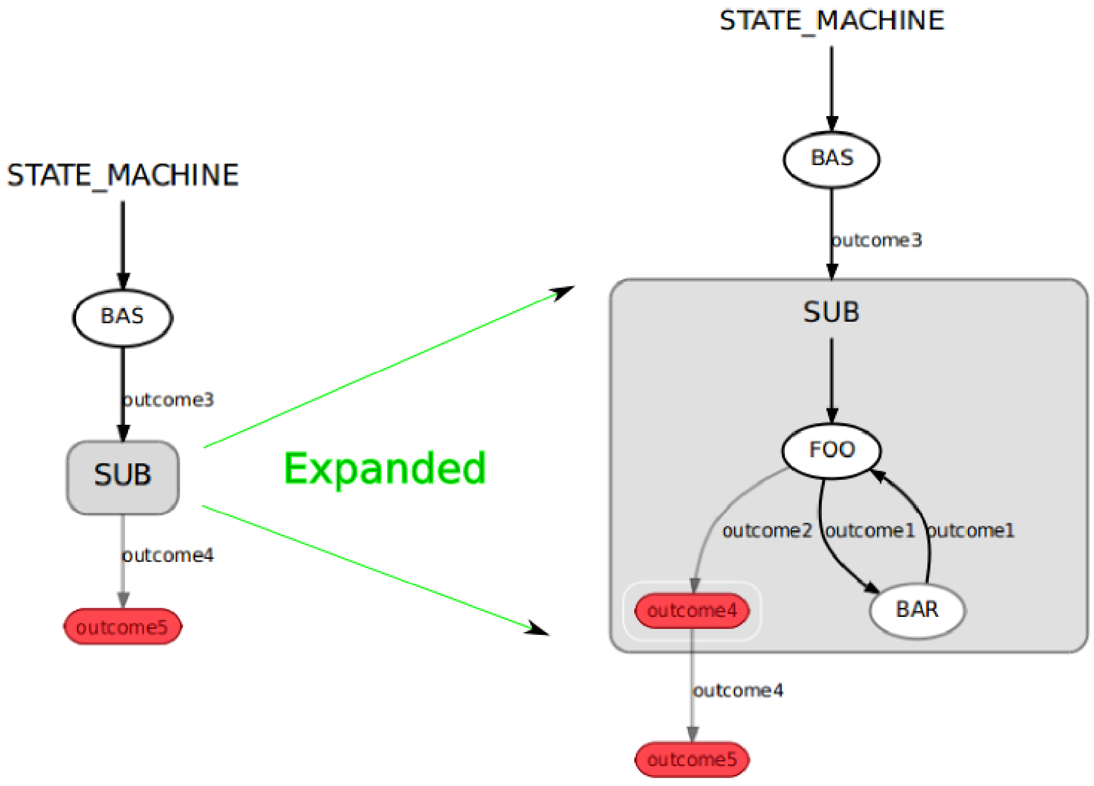
- This is an example FSM used as the behaviour for a robot charging itself at a standard outlet
- The states each call a ROS Action, and their outcomes depend on the result
- Observe how the FSM is built to handle task failure robustly



Credit: ROS Wiki

Closing Thoughts: Hierarchical FSMs

- You can nest a FSM within another FSM; the result is called a Hierarchical FSM
- The nested FSM essentially acts as a state within the parent FSM
- This allows you to develop FSMs for simple behaviours and use these as building blocks for more complex ones
- SMACH provides full functionality for this!



An example Hierarchical FSM
Credit: ROS Wiki

Closing Thoughts: SMACH Tutorials

- SMACH and SMACH_ROS have extensive documentation and plenty of tutorials on the ROS Wiki; I suggest checking this out if you want to learn more about using FSMs!
- Link: http://wiki.ros.org/smach/Tutorials

Summary

We covered:

- Overview for finite state machines and SMACH
- Creating a simple SMACH state machine in Python
- Passing data between states
- Calling ROS Services/Actions from SMACH state machines

Homework: Revise the contents of the lecture, go over the code and make sure you can follow what's going on

Thank You!

This was the final lecture, I really hope you enjoyed this course!

Any Questions? Contact jacques.cloete@stx.ox.ac.uk