Programming with Behavior Trees and ROS

Since a ready-made behavior tree library for ROS was not available at the time of this writing, a new ROS package called pi_trees was created for use with this book. In this section and those that follow, we will install the pi_trees package and learn how to use it to program our Patrol Bot and house cleaning robot using behavior trees.

*Installing the **pi_trees** library*

Before running the examples that follow, we need to install the pi_trees ROS package using the following commands:

```
$ sudo apt-get install graphviz-dev libgraphviz-dev \
  python-pygraph python-pygraphviz gv
$ cd ~/catkin_ws/src
$ git clone -b indigo-devel https://github.com/pirobot/pi_trees.git
$ cd ~/catkin_ws
$ catkin_make
$ rospack profile
```

*Basic components of the **pi_trees** library*

Behavior trees are fairly easy to implement in Python and while there are several different approaches one can take, the methods used in the pi_trees package lend themselves well to integrating with ROS topics, services and actions. In fact, the pi_trees package was modeled after SMACH so that some of the code might already seem familiar.

The core pi_trees library is contained in the file pi_trees_lib.py in the pi_trees/pi_trees_lib/src directory and the ROS classes can be found in the file pi_trees_ros.py under the pi_trees/pi_trees_ros/src directory. Let's start with pi_trees_lib.py.

Link to source: pi_trees_lib.py

```
class TaskStatus():
    FAILURE = 0
    SUCCESS = 1
    RUNNING = 2
```

First we define the possible task status values using the class TaskStatus as a kind of enum. One can include additional status values such as ERROR or UNKNOWN but these three seem to be sufficient for most applications.

```
class Task(object):
    """ The base Task class """
    def __init__(self, name, children=None, *args, **kwargs):
        self.name = name
        self.status = None

        if children is None:
            children = []

        self.children = children

    def run(self):
        pass

    def reset(self):
        for c in self.children:
            c.reset()

    def add_child(self, c):
        self.children.append(c)
```

```python
    def remove_child(self, c):
        self.children.remove(c)

    def prepend_child(self, c):
        self.children.insert(0, c)

    def insert_child(self, c, i):
        self.children.insert(i, c)

    def get_status(self):
        return self.status

    def set_status(self, s):
        self.status = s

    def announce(self):
        print("Executing task " + str(self.name))

    # These next two functions allow us to use the 'with' syntax
    def __enter__(self):
        return self.name

    def __exit__(self, exc_type, exc_val, exc_tb):
        if  exc_type is not None:
            return False
        return True
```

The base `Task` class defines the core object of the behavior tree. At a minimum it must have a name and a `run()` function that in general will not only perform some behavior but also return its status. The other key functions are `add_child()` and `remove_child()` that enable us to add or remove sub-tasks to composite tasks such as selectors and sequences (described below). You can also use the `prepend_child()` or `insert_child()` functions to add a sub-task with a specific priority relative to the other tasks already in the list.
When creating your own tasks, you will override the `run()` function with code that performs your task's actions. It will then return an appropriate task status depending on the outcome of the action. This will become clear when we look at the Patrol Bot example later on.

The `reset()` function is useful when we want to zero out any counters or other variables internal to a particular task and its children.

```python
class Selector(Task):
    """
        Run each subtask in sequence until one succeeds or we run out of tasks.
    """
    def __init__(self, name, *args, **kwargs):
        super(Selector, self).__init__(name, *args, **kwargs)

    def run(self):
        for c in self.children:

            c.status = c.run()

            if c.status != TaskStatus.FAILURE:
                return c.status

        return TaskStatus.FAILURE
```

A `Selector` runs each child task in list order until one succeeds or until it runs out of subtasks. Note that if a child task returns a status of `RUNNING`, the selector also returns `RUNNING` until the child either succeeds or fails.

```python
class Sequence(Task):
    """
        Run each subtask in sequence until one fails or we run out of tasks.
    """
```

```python
    def __init__(self, name, *args, **kwargs):
        super(Sequence, self).__init__(name, *args, **kwargs)

    def run(self):
        for c in self.children:

            c.status = c.run()

            if c.status != TaskStatus.SUCCESS:
                return c.status

        return TaskStatus.SUCCESS
```

A `Sequence` runs each child task in list order until one fails or until it runs out of subtasks. Note that if a child task returns a status of `RUNNING`, the sequence also returns `RUNNING` until the child either succeeds or fails.

```python
class Iterator(Task):
    """
        Iterate through all child tasks ignoring failure.
    """
    def __init__(self, name, *args, **kwargs):
        super(Iterator, self).__init__(name, *args, **kwargs)

    def run(self):
        for c in self.children:

            c.status = c.run()

            if c.status != TaskStatus.SUCCESS and c.status != TaskStatus.FAILURE:
                return c.status

        return TaskStatus.SUCCESS
```

An `Iterator` behaves like a `Sequence` but ignores failures.

```python
class ParallelOne(Task):
    """
        A parallel task runs each child task at (roughly) the same time.
        The ParallelOne task returns success as soon as any child succeeds.
    """
    def __init__(self, name, *args, **kwargs):
        super(ParallelOne, self).__init__(name, *args, **kwargs)

    def run(self):
        for c in self.children:
            c.status = c.run()

            if c.status == TaskStatus.SUCCESS:
                return TaskStatus.SUCCESS

        return TaskStatus.FAILURE
```

The key difference between the `ParallelOne` composite task and a `Selector` is that the `ParallelOne` task runs *all* of its tasks on every "tick" of the clock unless (or until) one subtask succeeds. A `Selector` continues running the *first* subtask until that task either succeeds or fails before moving on to the next subtask or returning altogether.

```python
class ParallelAll(Task):
    """
        A parallel task runs each child task at (roughly) the same time.
        The ParallelAll task requires all subtasks to succeed for it to succeed.
    """
    def __init__(self, name, *args, **kwargs):
        super(ParallelAll, self).__init__(name, *args, **kwargs)

    def run(self):
        n_success = 0
```

```python
        n_children = len(self.children)

        for c in self.children:
            c.status = c.run()
            if c.status == TaskStatus.SUCCESS:
                n_success += 1

            if c.status == TaskStatus.FAILURE:
                return TaskStatus.FAILURE

        if n_success == n_children:
            return TaskStatus.SUCCESS
        else:
            return TaskStatus.RUNNING
```

Similar to the `ParallelOne` task, the `ParallelAll` task runs each subtask on each tick of the clock but continues until all subtasks succeed or until one of them fails.

```python
class Loop(Task):
    """
        Loop over one or more subtasks for the given number of iterations
        Use the value -1 to indicate a continual loop.
    """
    def __init__(self, name, announce=True, *args, **kwargs):
        super(Loop, self).__init__(name, *args, **kwargs)

        self.iterations = kwargs['iterations']
        self.announce = announce
        self.loop_count = 0
        self.name = name
        print("Loop iterations: " + str(self.iterations))

    def run(self):

        while True:
            if self.iterations != -1 and self.loop_count >= self.iterations:
                return TaskStatus.SUCCESS

            for c in self.children:
                while True:
                    c.status = c.run()

                    if c.status == TaskStatus.SUCCESS:
                        break

                    return c.status

                c.reset()

            self.loop_count += 1

            if self.announce:
                print(self.name + " COMPLETED " + str(self.loop_count) + " LOOP(S)")
```

The `Loop` task simply executes its child task(s) for the given number of iterations. A value of `-1` for the `iterations` parameters means "loop forever". Note that a `Loop` task is still a task in its own right.

```python
class IgnoreFailure(Task):
    """
        Always return either RUNNING or SUCCESS.
    """
    def __init__(self, name, *args, **kwargs):
        super(IgnoreFailure, self).__init__(name, *args, **kwargs)

    def run(self):

        for c in self.children:

            c.status = c.run()
```

```
            if c.status != TaskStatus.RUNNING:
                return TaskStatus.SUCCESS
            else:
                return TaskStatus.RUNNING

        return TaskStatus.SUCCESS
```

The `IgnoreFailure` task simply turns a `FAILURE` into a `SUCCESS` for each of its child behaviors. If the status of a child task is `RUNNING`, the `IgnoreFailure` also takes on a status of `RUNNING`.

The `CallbackTask` turns any function into a task. The function name is passed to the constructor as the `cb` argument along with optional arguments. The only constraint on the callback function is that it must return `0` or `False` to represent a `TaskStatus` of `FAILURE` and `1` or `True` to represent `SUCCESS`. Any other return value is interpreted as `RUNNING`.

```
class CallbackTask(Task):
    """
        Turn any callback function (cb) into a task
    """
    def __init__(self, name, cb=None, cb_args=[], cb_kwargs={}, **kwargs):
        super(CallbackTask, self).__init__(name, cb=None, cb_args=[], cb_kwargs={}, **kwargs)

        self.name = name
        self.cb = cb
        self.cb_args = cb_args
        self.cb_kwargs = cb_kwargs

    def run(self):
        status = self.cb(*self.cb_args, **self.cb_kwargs)

        if status == 0 or status == False:
            return TaskStatus.FAILURE

        elif status == 1 or status == True:
            return TaskStatus.SUCCESS

        else:
            return TaskStatus.RUNNING
```

ROS-specific behavior tree classes

You can find the ROS-specific behavior tree classes in the file `pi_trees_ros.py` in the directory `pi_trees/pi_trees_ros/src`. This library contains three key ROS tasks: the `MonitorTask` for monitoring a ROS topic; the `ServiceTask` for connecting to a ROS service; and the `SimpleActionTask` for send goals to a ROS action server and receiving feedback. We will describe these tasks only briefly here as their use will become clear in the programming examples that follow.
Link to source: [pi_trees_ros.py]
Let's begin by looking at the `MonitorTask` class:

```
class MonitorTask(Task):
    """
        Turn a ROS subscriber into a Task.
    """
    def __init__(self, name, topic, msg_type, msg_cb, wait_for_message=True, timeout=5):
        super(MonitorTask, self).__init__(name)

        self.topic = topic
        self.msg_type = msg_type
        self.timeout = timeout
        self.msg_cb = msg_cb

        rospy.loginfo("Subscribing to topic " + topic)
```

```python
        if wait_for_message:
            try:
                rospy.wait_for_message(topic, msg_type, timeout=self.timeout)
                rospy.loginfo("Connected.")
            except:
                rospy.loginfo("Timed out waiting for " + topic)

        # Subscribe to the given topic with the given callback function executed via run()
        rospy.Subscriber(self.topic, self.msg_type, self._msg_cb)

    def _msg_cb(self, msg):
        self.set_status(self.msg_cb(msg))

    def run(self):
        return self.status

    def reset(self):
        pass
```

The `MonitorTask` subscribes to a given ROS topic and executes a given callback function. The callback function is defined by the user and is responsible for returning one of the three allowed task status values: `SUCCESS`, `FAILURE` or `RUNNING`.

```python
class ServiceTask(Task):
    """
        Turn a ROS service into a Task.
    """
    def __init__(self, name, service, service_type, request, result_cb=None, wait_for_service=True,
timeout=5):
        super(ServiceTask, self).__init__(name)

        self.result = None
        self.request = request
        self.timeout = timeout
        self.result_cb = result_cb

        rospy.loginfo("Connecting to service " + service)

        if wait_for_service:
            rospy.loginfo("Waiting for service")
            rospy.wait_for_service(service, timeout=self.timeout)
            rospy.loginfo("Connected.")

        # Create a service proxy
        self.service_proxy = rospy.ServiceProxy(service, service_type)

    def run(self):
        try:
            result = self.service_proxy(self.request)
            if self.result_cb is not None:
                self.result_cb(result)
            return TaskStatus.SUCCESS
        except:
            rospy.logerr(sys.exc_info())
            return TaskStatus.FAILURE

    def reset(self):
        pass
```

The `ServiceTask` wraps a given ROS service and optionally executes a user-defined callback function. By default, a `ServiceTask` will simply call the corresponding ROS service and return `SUCCESS` unless the service call itself fails in which case it returns `FAILURE`. If the user passes in a callback function, this function may simply execute some arbitrary code or it may also return a task status.

```python
class SimpleActionTask(Task):
    """
        Turn a ROS action into a Task.
    """
```

```python
    def __init__(self, name, action, action_type, goal, rate=5, connect_timeout=10, result_timeout=30,
reset_after=False, active_cb=None, done_cb=None, feedback_cb=None):
        super(SimpleActionTask, self).__init__(name)

        self.action = action
        self.goal = goal
        self.tick = 1.0 / rate
        self.rate = rospy.Rate(rate)

        self.result = None
        self.connect_timeout = connect_timeout
        self.result_timeout = result_timeout
        self.reset_after = reset_after

        if done_cb == None:
            done_cb = self.default_done_cb
        self.done_cb = done_cb

        if active_cb == None:
            active_cb = self.default_active_cb
        self.active_cb = active_cb

        if feedback_cb == None:
            feedback_cb = self.default_feedback_cb
        self.feedback_cb = feedback_cb

        self.action_started = False
        self.action_finished = False
        self.goal_status_reported = False
        self.time_so_far = 0.0

        # Goal state return values
        self.goal_states = ['PENDING', 'ACTIVE', 'PREEMPTED',
                            'SUCCEEDED', 'ABORTED', 'REJECTED',
                            'PREEMPTING', 'RECALLING', 'RECALLED',
                            'LOST']

        rospy.loginfo("Connecting to action " + action)

        # Subscribe to the base action server
        self.action_client = actionlib.SimpleActionClient(action, action_type)

        rospy.loginfo("Waiting for move_base action server...")

        # Wait up to timeout seconds for the action server to become available
        try:
            self.action_client.wait_for_server(rospy.Duration(self.connect_timeout))
        except:
            rospy.loginfo("Timed out connecting to the action server " + action)

        rospy.loginfo("Connected to action server")

    def run(self):
        # Send the goal
        if not self.action_started:
            rospy.loginfo("Sending " + str(self.name) + " goal to action server...")
            self.action_client.send_goal(self.goal, done_cb=self.done_cb, active_cb=self.active_cb,
feedback_cb=self.feedback_cb)
            self.action_started = True

        ''' We cannot use the wait_for_result() method here as it will block
            the entire tree so we break it down in time slices of duration
            1 / rate.
        '''
        if not self.action_finished:
            self.time_so_far += self.tick
            self.rate.sleep()
            if self.time_so_far > self.result_timeout:
                self.action_client.cancel_goal()
                rospy.loginfo("Timed out achieving goal")
                return TaskStatus.FAILURE
            else:
                return TaskStatus.RUNNING
        else:
```

```
            # Check the final goal status returned by default_done_cb
            if self.goal_status == GoalStatus.SUCCEEDED:
                  self.action_finished = True
                  if self.reset_after:
                      self.reset()
                  return TaskStatus.SUCCESS
            elif self.goal_status == GoalStatus.ABORTED:
                self.action_started = False
                self.action_finished = False
                return TaskStatus.FAILURE
            else:
                self.action_started = False
                self.action_finished = False
                self.goal_status_reported = False
                return TaskStatus.RUNNING

    def default_done_cb(self, status, result):
        # Check the final status
        self.goal_status = status
        self.action_finished = True

        if not self.goal_status_reported:
            rospy.loginfo(str(self.name) + " ended with status " + str(self.goal_states[status]))
            self.goal_status_reported = True

    def default_active_cb(self):
        pass

    def default_feedback_cb(self, msg):
        pass

    def reset(self):
        self.action_started = False
        self.action_finished = False
        self.goal_status_reported = False
        self.time_so_far = 0.0
```

The `SimpleActionTask` mimics the `SimpleActionState` defined in `SMACH`. Its main function is to wrap a ROS simple action client and therefore takes an action name, action type, and a goal as arguments. It can also take arguments specifying user-defined callback functions for the standard `active_cb`, `done_cb` and `feedback_cb` callbacks that are passed to the ROS simple action client. In particular, the `SimpleActionTask` defines default `done_cb` function reports the final status of the action which is then turned into a corresponding task status to be used in the rest of the behavior tree.

We will examine the `SimpleActionTask` more closely in the context of a number of example programs that we turn to next.

A Patrol Bot example using behavior trees

We have already seen how we can use `SMACH` to program a robot to patrol a series of waypoints while monitoring its battery level and recharging when necessary. Let's now see how we can do the same using the `pi_trees` package.
Our test program is called `patrol_tree.py` and is located in the `rbx2_tasks/nodes` subdirectory. Before looking at the code, let's try it out.
Begin by bringing up the fake TurtleBot, blank map, and fake battery simulator:

```
$ roslaunch rbx2_tasks fake_turtlebot.launch
```

Next, bring up `RViz` with the `nav_tasks.rviz` config file:

```
$ rosrun rviz rviz -d `rospack find rbx2_tasks`/nav_tasks.rviz
```

Finally, run the `patrol_tree.py` script:

```
$ rosrun rbx2_tasks patrol_tree.py
```

The robot should make two loops around the square, stopping to recharge when necessary, then stop. Let's now look at the code.

Link to source: patrol_tree.py

```python
#!/usr/bin/env python

import rospy
from std_msgs.msg import Float32
from geometry_msgs.msg import Twist
from rbx2_msgs.srv import *
from pi_trees_ros.pi_trees_ros import *
from rbx2_tasks.task_setup import *

class Patrol():
    def __init__(self):
        rospy.init_node("patrol_tree")

        # Set the shutdown function (stop the robot)
        rospy.on_shutdown(self.shutdown)

        # Initialize a number of parameters and variables
        setup_task_environment(self)

        # Create a list to hold the move_base tasks
        MOVE_BASE_TASKS = list()

        n_waypoints = len(self.waypoints)

        # Create simple action navigation task for each waypoint
        for i in range(n_waypoints + 1):
            goal = MoveBaseGoal()
            goal.target_pose.header.frame_id = 'map'
            goal.target_pose.header.stamp = rospy.Time.now()
            goal.target_pose.pose = self.waypoints[i % n_waypoints]

            move_base_task = SimpleActionTask("MOVE_BASE_TASK_" + str(i), "move_base", MoveBaseAction, goal)

            MOVE_BASE_TASKS.append(move_base_task)

        # Set the docking station pose
        goal = MoveBaseGoal()
        goal.target_pose.header.frame_id = 'map'
        goal.target_pose.header.stamp = rospy.Time.now()
        goal.target_pose.pose = self.docking_station_pose

        # Assign the docking station pose to a move_base action task
        NAV_DOCK_TASK = SimpleActionTask("NAV_DOC_TASK", "move_base", MoveBaseAction, goal, reset_after=True)

        # Create the root node
        BEHAVE = Sequence("BEHAVE")

        # Create the "stay healthy" selector
        STAY_HEALTHY = Selector("STAY_HEALTHY")

        # Create the patrol loop decorator
        LOOP_PATROL = Loop("LOOP_PATROL", announce=True, iterations=self.n_patrols)
```

```
        # Add the two subtrees to the root node in order of priority
        BEHAVE.add_child(STAY_HEALTHY)
        BEHAVE.add_child(LOOP_PATROL)

        # Create the patrol iterator
        PATROL = Iterator("PATROL")

        # Add the move_base tasks to the patrol task
        for task in MOVE_BASE_TASKS:
            PATROL.add_child(task)

        # Add the patrol to the patrol loop
        LOOP_PATROL.add_child(PATROL)

        # Add the battery check and recharge tasks to the "stay healthy" task
        with STAY_HEALTHY:
            # The check battery condition (uses MonitorTask)
            CHECK_BATTERY = MonitorTask("CHECK_BATTERY", "battery_level", Float32, self.check_battery)

            # The charge robot task (uses ServiceTask)
            CHARGE_ROBOT = ServiceTask("CHARGE_ROBOT", "battery_simulator/set_battery_level", SetBatteryLevel, 100, result_cb=self.recharge_cb)

            # Build the recharge sequence using inline construction
            RECHARGE = Sequence("RECHARGE", [NAV_DOCK_TASK, CHARGE_ROBOT])

            # Add the check battery and recharge tasks to the stay healthy selector
            STAY_HEALTHY.add_child(CHECK_BATTERY)
            STAY_HEALTHY.add_child(RECHARGE)

        # Display the tree before beginning execution
        print "Patrol Behavior Tree"
        print_tree(BEHAVE)

        # Run the tree
        while not rospy.is_shutdown():
            BEHAVE.run()
            rospy.sleep(0.1)

    def check_battery(self, msg):
        if msg.data is None:
            return TaskStatus.RUNNING
        else:
            if msg.data < self.low_battery_threshold:
                rospy.loginfo("LOW BATTERY - level: " + str(int(msg.data)))
                return TaskStatus.FAILURE
            else:
                return TaskStatus.SUCCESS

    def recharge_cb(self, result):
        rospy.loginfo("BATTERY CHARGED!")

    def shutdown(self):
        rospy.loginfo("Stopping the robot...")
        self.move_base.cancel_all_goals()
        self.cmd_vel_pub.publish(Twist())
        rospy.sleep(1)

if __name__ == '__main__':
    tree = Patrol()
```

Let's take a look at the key lines of the script:

```
from pi_trees_ros.pi_trees_ros import *
```

We begin by importing the pi_trees_ros library which in turn imports the core pi_trees classes from the pi_trees_lib library. The first key block of code involves the creating of the navigation tasks shown below:

```
        for i in range(n_waypoints + 1):
            goal = MoveBaseGoal()
            goal.target_pose.header.frame_id = 'map'
            goal.target_pose.header.stamp = rospy.Time.now()
            goal.target_pose.pose = self.waypoints[i % n_waypoints]

            move_base_task = SimpleActionTask("MOVE_BASE_TASK_" + str(i), "move_base", MoveBaseAction, goal, reset_after=False)

            MOVE_BASE_TASKS.append(move_base_task)

        # Set the docking station pose
        goal = MoveBaseGoal()
        goal.target_pose.header.frame_id = 'map'
        goal.target_pose.header.stamp = rospy.Time.now()
        goal.target_pose.pose = self.docking_station_pose

        # Assign the docking station pose to a move_base action task
        NAV_DOCK_TASK = SimpleActionTask("NAV_DOC_TASK", "move_base", MoveBaseAction, goal, reset_after=True)
```

Here we see nearly the same procedure as we used with SMACH although now we are using the SimpleActionTask from the pi_trees library instead of the SimpleActionState from the SMACH library.

Note the parameter called reset_after in the construction of a SimpleActionTask. We set this to False for the move_base tasks assigned to waypoints but we set it to True for the docking move_base task for the following reason. Recall that when a behavior or task in a behavior tree succeeds or fails, it retains that status indefinitely unless it is reset. This "memory" property is essential because on every execution cycle, we poll the status of every node in the tree. This enables us to continually check condition nodes whose status might have changed since the last cycle. However, if the robot has just successfully reached a waypoint, we want that status to be retained on the next pass through the tree so that the parent node will advance the sequence to the next waypoint. On the other hand, when it comes to recharging, we need to reset the navigation task once the robot is docked so that it can be executed again the next time the battery runs low.
Once we have the navigation and docking tasks created, we move on to building the rest of the behavior tree. The order in which we create the nodes in the script is somewhat flexible since it is the parent-child relations that determine the actual structure of the tree. If we start at the root of the tree, our first behavior nodes would look like this:

```
        BEHAVE = Sequence("BEHAVE")

        # Create the "stay healthy" selector
        STAY_HEALTHY = Selector("STAY_HEALTHY")

        # Create the patrol loop decorator
        LOOP_PATROL = Loop("LOOP_PATROL", iterations=self.n_patrols)

        # Build the full tree from the two subtrees
        BEHAVE.add_child(STAY_HEALTHY)
        BEHAVE.add_child(LOOP_PATROL)
```

The root behavior is a Sequence labeled BEHAVE that will have two child branches; one that starts with the Selector labeled STAY_HEALTHY and a second branch labeled LOOP_PATROL that uses the Loop decorator to loop over the patrol task. We then add the two child branches to the root node in the order that defines their priority. In this case, the `STAY_HEALTHY` branch has higher priority than `LOOP_PATROL`.

```
        # Create the patrol iterator
        PATROL = Iterator("PATROL")

        # Add the move_base tasks to the patrol task
        for task in MOVE_BASE_TASKS:
            PATROL.add_child(task)

        # Add the patrol to the patrol loop
        LOOP_PATROL.add_child(PATROL)
```

Next we take care of the rest of the patrol nodes. The patrol sequence itself is constructed as an `Iterator` called `PATROL`. We then add each `move_base` task to the iterator. Finally, we add the entire patrol to the `LOOP_PATROL` task.

```
        # Add the battery check and recharge tasks to the "stay healthy" task
        with STAY_HEALTHY:
            # The check battery condition (uses MonitorTask)
            CHECK_BATTERY = MonitorTask("CHECK_BATTERY", "battery_level", Float32,
self.check_battery)

            # The charge robot task (uses ServiceTask)
            CHARGE_ROBOT = ServiceTask("CHARGE_ROBOT", "battery_simulator/set_battery_level",
SetBatteryLevel, 100, result_cb=self.recharge_cb)

            # Build the recharge sequence using inline construction
            RECHARGE = Sequence("RECHARGE", [NAV_DOCK_TASK, CHARGE_ROBOT])
```

Here we flesh out the `STAY_HEALTHY` branch of the tree. First we define the `CHECK_BATTERY` task as a `MonitorTask` on the ROS topic `battery_level` using the callback function `self.check_battery` (described below). Next we define the `CHARGE_ROBOT` behavior as a `ServiceTask` that connects to the ROS service `battery_simulator/set_battery_level` and sends a value of `100` to recharge the fake battery.

We then construct the `RECHARGE` task as a `Sequence` whose child tasks are `NAV_DOCK_TASK` and `CHARGE_ROBOT`. Note how we have used the inline syntax to illustrate how we can add child tasks at the same time that we construct the parent. Equivalently, we could have used the three lines:

```
            RECHARGE = Sequence("RECHARGE")
            RECHARGE.add_child(NAV_DOCK_TASK)
            RECHARGE.add_child(CHARGE_ROBOT)
```

You can use whichever syntax you prefer.

```
            STAY_HEALTHY.add_child(CHECK_BATTERY)
            STAY_HEALTHY.add_child(RECHARGE)
```

We complete the `STAY_HEALTHY` branch of the tree by adding the `CHECK_BATTERY` and `RECHARGE` tasks . Note again that the order is important since we want to check the battery first to see if we need to recharge.

```
        # Display the tree before beginning execution
        print "Patrol Behavior Tree"
        print_tree(BEHAVE)

        # Run the tree
        while not rospy.is_shutdown():
            BEHAVE.run()
```

```
            rospy.sleep(0.1)
```

Before starting execution, we use the `print_tree()` function from the `pi_trees` library to display a representation of the behavior tree on the screen. The tree itself is executed by calling the `run()` function on the root node. The `run()` function makes one pass through the nodes of the tree so we need to place it in a loop.

Finally, we have the `check_battery()` callback:

```
    def check_battery(self, msg):
        if msg.data is None:
            return TaskStatus.RUNNING
        else:
            if msg.data < self.low_battery_threshold:
                rospy.loginfo("LOW BATTERY - level: " + str(int(msg.data)))
                return TaskStatus.FAILURE
            else:
                return TaskStatus.SUCCESS
```

Recall that this function was assigned to the `CHECK_BATTERY` `MonitorTask` which monitors the `battery_level` topic. We therefore check the battery level against the `low_battery_threshold` parameter. If the level is below threshold, we return a task status of `FAILURE`. Otherwise we return `SUCCESS`. Because the `CHECK_BATTERY` task is the highest priority task in the `STAY_HEALTHY` selector, if it returns `FAILURE`, then the selector moves on to its next subtask which is the `RECHARGE` task. The `patrol_tree.py` script illustrates an important property of behavior trees that helps distinguish them from ordinary hierarchical state machines like `SMACH`. You'll notice that after a recharge, the robot continues its patrol where it left off even though nowhere in the script did we explicitly save the last waypoint reached. Remember that in the `SMACH` example (`patrol_smach_concurrence.py`), we had to save the last state just before a recharge so that the robot would know where to continue after being charged. Behavior trees inherently store their state by virtue of each node's `status` property. In particular, if the robot is on its way to a waypoint, the navigation task doing the work of moving the robot has a status of `RUNNING`. If the robot is then diverted to the docking station for a recharge, the status of the previously active navigation status is still `RUNNING`. This means that when the robot is fully charged and the `CHECK_BATTERY` task returns `SUCCESS`, control returns automatically to the running navigation node.

A housing cleaning robot using behavior trees

Earlier in the chapter we used `SMACH` to simulate a house cleaning robot. Let us now do the same using behavior trees. Our new script is called [clean_house_tree.py]() and is found in the `rbx2_tasks/nodes` subdirectory. The program is similar to the `patrol_tree.py` script but this time we will add a few tasks that simulate vacuuming, scrubbing and mopping just as we did with the `SMACH` example. We will also include battery checking and recharge behavior.

Before describing the code, let's try it out. If you don't already have the `fake_turtlebot.launch` file running, bring it up now:

```
$ roslaunch rbx2_tasks fake_turtlebot.launch
```

Recall that this launch file also runs a `move_base` node, the map server with a blank map, and the fake battery node with a default runtime of `60` seconds.

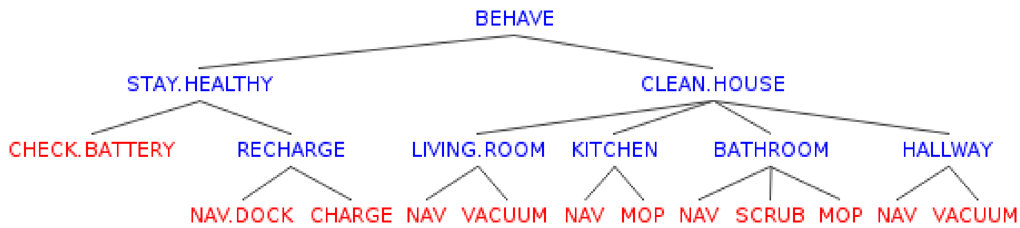
Next, bring up `RViz` with the `nav_tasks.rviz` config file:

```
$ rosrun rviz rviz -d `rospack find rbx2_tasks`/nav_tasks.rviz
```

Finally, run the `clean_house_tree.py` script:

```
$ rosrun rbx2_tasks clean_house_tree.py
```

The robot should make one circuit of the square, performing cleaning tasks in each room and recharging when necessary.
The overall behavior tree implemented by the `clean_house_tree.py` script looks like this:



In addition to the main tasks shown above, we also require a few condition nodes such as "is the room already clean" and "are we at the desired location?" The need for these condition checks arises from the recharge behavior of the robot. For example, suppose the robot is in the middle of mopping the kitchen floor when its battery level falls below threshold. The robot will navigate out of the kitchen and over to the docking station. Once the robot is recharged, control will return to the last running task—mopping the kitchen floor—but now the robot is no longer in the kitchen. If we don't check for this, the robot will start mopping the docking station! So to get back to the kitchen, we include a task that checks the robot's current location and compares it to where it is supposed to be. If not, the robot navigates back to that location.

A good way to understand the behavior tree we will create is to imagine that you are asked to clean a room yourself. If you were asked to clean the bathroom, you might use a strategy like the following:

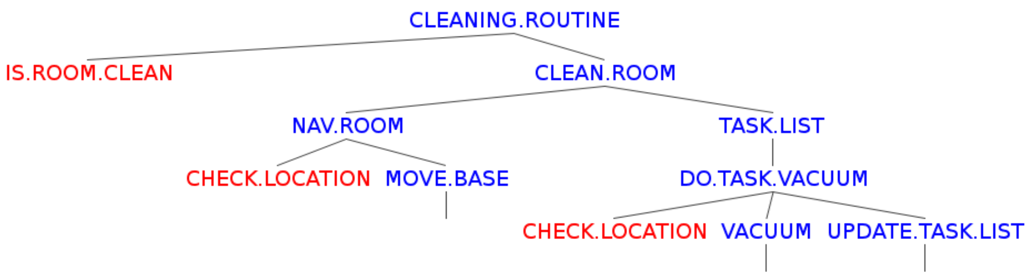
- First find out if the bathroom even needs cleaning. Perhaps your roommate felt energetic and took care of it already. If there is a task checklist somewhere such as on the refrigerator, make sure the bathroom isn't already checked off.
- If the bathroom does need cleaning, you need to be in the bathroom to clean it. If you are already in the bathroom, then you can start cleaning. If not, you have to navigate your way through the house to the bathroom.
- Once you are in the bathroom, check the list of tasks to perform. After each task is completed, put a check mark beside the task on the list.
-

We can mimic this very same process in a behavior tree. For a given room, the subtree will look something like the following. In parenthesis beside each task, we have indicated the type of task it is: selector, sequence, iterator, condition, or action.

- `CLEANING_ROUTINE (selector)`
  - `IS_ROOM_CLEAN (condition)`
  - `CLEAN_ROOM (sequence)`
    - `NAV_ROOM (selector)`
      - `CHECK_LOCATION (condition)`

        - MOVE_BASE (action)
- TASK_LIST(iterator)
    - DO_TASK_1(sequence)
        - CHECK_LOCATION (condition)
        - EXECUTE_TASK (action)
        - UPDATE_TASK_LIST (action)
    - DO_TASK_2(sequence)
        - CHECK_LOCATION (condition)
        - EXECUTE_TASK (action)
        - UPDATE_TASK_LIST (action)
    - ETC

Here's how the tree would look if the only task was to vacuum the living room and we omit the battery checking subtree:



We interpret this tree as follows. The top level node (CLEANING_ROUTINE) is a selector so if the condition node IS_ROOM_CLEAN returns SUCCESS, then we are done. Otherwise we move to selector's next child task, CLEAN_ROOM.

The CLEAN_ROOM task is a sequence whose first sub-task is NAV_ROOM which in turn is a selector. The first sub-task in the NAV_ROOM selector is the condition CHECK_LOCATION. If this check returns SUCCESS, then NAV_ROOM also returns SUCCESS and the CLEAN_ROOM sequence can move to the next behavior in its sequence which is the TASK_LIST iterator. If the CHECK_LOCATION task returns FAILURE, then we execute the MOVE_BASE behavior. This continues until CHECK_LOCATION returns SUCCESS.

Once we are at the target room, the TASK_LIST iterator begins. First we check that we are still at the correct location, then we execute each task in the iterator and update the task list.
To make our script more readable, the simulated cleaning tasks can be found in the file cleaning_tasks_tree.py under the rbx2_tasks/src folder. We then import this file at the top of the clean_house_tree.py script. Let's look at the definition of one of these simulated tasks:

```
class VacuumFloor(Task):
    def __init__(self, name, room, timer, *args):
        super(VacuumFloor, self).__init__(self, name, *args)
        self.name = name
        self.room = room
        self.counter = timer
        self.finished = False
        self.cmd_vel_pub = rospy.Publisher('cmd_vel', Twist)
        self.cmd_vel_msg = Twist()
        self.cmd_vel_msg.linear.x = 0.05

    def run(self):
        if self.finished:
```

```
            return TaskStatus.SUCCESS
        else:
            rospy.loginfo('Vacuuming the floor in the ' + str(self.room))

            while self.counter > 0:
                self.cmd_vel_pub.publish(self.cmd_vel_msg)
                self.cmd_vel_msg.linear.x *= -1
                rospy.loginfo(self.counter)
                self.counter -= 1
                rospy.sleep(1)
                return TaskStatus.RUNNING

            self.finished = True
            self.cmd_vel_pub.publish(Twist())
            message = "Finished vacuuming the " + str(self.room) + "!"
            rospy.loginfo(message)
```

The `VacuumFloor` class extends the basic `Task` class. Since we want to move the robot back and forth in a simulated vacuuming motion, we create a ROS publisher to send `Twist` message to the `cmd_vel` topic. We then override the `run()` function which creates the desired motion. Since the `run()` function is visited on every pass through the behavior tree, we return a status of `RUNNING` until the motion is complete at which time we return a status of `SUCCESS`.

The `clean_house_tree.py` script is similar to the `patrol_tree.py` program we have already described in detail earlier. Let's therefore focus only on the key differences.

```
class BlackBoard():
    def __init__(self):
        # A list to store rooms and tasks
        self.task_list = list()

        # The robot's current position on the map
        self.robot_position = Point()
```

Recall that some behavior trees use an object called the global "black board" for tracking certain properties of the tree and the world. In Python, the black board can be a simple class with a number of variables to hold the data. At the top of the `clean_house_tree.py` script we define the `BlackBoard()` class shown above with a `list` variable to store the task list and a ROS `Point` variable to track the robot's current coordinates on the map.

```
black_board = BlackBoard()

# Create a task list mapping rooms to tasks
black_board.task_list = OrderedDict([
    ('living_room', [Vacuum(room="living_room", timer=5)]),
    ('kitchen', [Mop(room="kitchen", timer=7)]),
    ('bathroom', [Scrub(room="bathroom", timer=9), Mop(room="bathroom", timer=5)]),
    ('hallway', [Vacuum(room="hallway", timer=5)])
    ])
```

Next we create an instance of the `BlackBoard` class and create an ordered list of cleaning tasks using the task definitions from the file `clean_house_tasks_tree.py` in the `src/rbx2_tasks` subdirectory. This task list will be convenient for iterating through all the tasks assigned to the robot. It also means that we can add or remove tasks by simply editing the list here at the top of the script.

The heart of the script involves creating the desired behavior tree from this task list. Here is the relevant block in its entirety.

```
    for room in black_board.task_list.keys():
        # Convert the room name to upper case for consistency
        ROOM = room.upper()

```

```
        # Initialize the CLEANING_ROUTINE selector for this room
        CLEANING_ROUTINE[room] = Selector("CLEANING_ROUTINE_" + ROOM)

        # Initialize the CHECK_ROOM_CLEAN condition
        CHECK_ROOM_CLEAN[room] = CheckRoomCleaned(room)

        # Add the CHECK_ROOM_CLEAN condition to the CLEANING_ROUTINE selector
        CLEANING_ROUTINE[room].add_child(CHECK_ROOM_CLEAN[room])

        # Initialize the CLEAN_ROOM sequence for this room
        CLEAN_ROOM[room] = Sequence("CLEAN_" + ROOM)

        # Initialize the NAV_ROOM selector for this room
        NAV_ROOM[room] = Selector("NAV_ROOM_" + ROOM)

        # Initialize the CHECK_LOCATION condition for this room
        CHECK_LOCATION[room] = CheckLocation(room, self.room_locations)

        # Add the CHECK_LOCATION condition to the NAV_ROOM selector
        NAV_ROOM[room].add_child(CHECK_LOCATION[room])

        # Add the MOVE_BASE task for this room to the NAV_ROOM selector
        NAV_ROOM[room].add_child(MOVE_BASE[room])

        # Add the NAV_ROOM selector to the CLEAN_ROOM sequence
        CLEAN_ROOM[room].add_child(NAV_ROOM[room])

        # Initialize the TASK_LIST iterator for this room
        TASK_LIST[room] = Iterator("TASK_LIST_" + ROOM)

        # Add the tasks assigned to this room
        for task in black_board.task_list[room]:
            # Initialize the DO_TASK sequence for this room and task
            DO_TASK = Sequence("DO_TASK_" + ROOM + "_" + task.name)

            # Add a CHECK_LOCATION condition to the DO_TASK sequence
            DO_TASK.add_child(CHECK_LOCATION[room])

            # Add the task itself to the DO_TASK sequence
            DO_TASK.add_child(task)

            # Create an UPDATE_TASK_LIST task for this room and task
            UPDATE_TASK_LIST[room + "_" + task.name] = UpdateTaskList(room, task)

            # Add the UPDATE_TASK_LIST task to the DO_TASK sequence
            DO_TASK.add_child(UPDATE_TASK_LIST[room + "_" + task.name])

            # Add the DO_TASK sequence to the TASK_LIST iterator
            TASK_LIST[room].add_child(DO_TASK)

        # Add the room TASK_LIST iterator to the CLEAN_ROOM sequence
        CLEAN_ROOM[room].add_child(TASK_LIST[room])

        # Add the CLEAN_ROOM sequence to the CLEANING_ROUTINE selector
        CLEANING_ROUTINE[room].add_child(CLEAN_ROOM[room])

        # Add the CLEANING_ROUTINE for this room to the CLEAN_HOUSE sequence
        CLEAN_HOUSE.add_child(CLEANING_ROUTINE[room])
```

As you can see, the behavior tree is built by looping over all the tasks in the task list stored on the black board. The inline comments should make clear how we build a subtree for each room and its tasks. We then add each subtree to the overall `CLEAN_HOUSE` task.

Parallel tasks

Some times we want the robot to work on two or more tasks simultaneously. The `pi_trees` library includes the `Parallel` task type to handle these situations. There are two flavors of `Parallel` task. The `ParallelAll` type returns `SUCCESS` if *all* the simultaneously running tasks succeed. The `ParallelOne` type returns `SUCCESS` as soon as any *one* of the tasks succeeds.
The sample script called `parallel_tree.py` in the `rbx2_tasks/nodes` directory illustrates the `ParallelAll` task type. In this script, the first task prints the message "Take me to your leader" one word at a time. The second task counts to `10`. Try out the script now:

```
$ rosrun rbx2_tasks parallel_tree.py
```

You should see the following output:

```
Behavior Tree Structure
 --> PRINT_AND_COUNT
     --> PRINT_MESSAGE
     --> COUNT_TO_10
Take 1 me 2 to 3 your 4 leader! 5 6 7 8 9 10
```

Notice how both the message task and the counting task run to completion before the script exits but that the output alternates between the two tasks since they are running in parallel.
Let's take a look at the core part of the code:

```
class ParallelExample():
    def __init__(self):
        # The root node
        BEHAVE = Sequence("behave")

        # The message to print
        message = "Take me to your leader!"

        # How high the counting task should count
        n_count = 10

        # Create a PrintMessage() task as defined later in the script
        PRINT_MESSAGE = PrintMessage("PRINT_MESSAGE", message)

        # Create a Count() task, also defined later in the script
        COUNT_TO_10 = Count("COUNT_TO_10", n_count)

        # Initialize the ParallelAll task
        PARALLEL_DEMO = ParallelAll("PRINT_AND_COUNT")

        # Add the two subtasks to the Parallel task
        PARALLEL_DEMO.add_child(PRINT_MESSAGE)
        PARALLEL_DEMO.add_child(COUNT_TO_10)

        # Add the Parallel task to the root task
        BEHAVE.add_child(PARALLEL_DEMO)

        # Display the behavior tree
        print "Behavior Tree Structure"
        print_tree(BEHAVE)

        # Initialize the overall status
        status = None

        # Run the tree
        while not status == TaskStatus.SUCCESS:
            status = BEHAVE.run()
            time.sleep(0.1)
```

The construction of the behavior tree shown above should be fairly self explanatory from the inline comments. Note that the `PrintMessage()` and `Count()` tasks are defined later in the script and are fairly straightforward so we will not display them here.

If you modify the `parallel_tree.py` script so that the `ParallelAll` task on line `19` above is replaced with a `ParallelOne` task instead, the output should look like this:

```
Behavior Tree Structure
 --> PRINT_AND_COUNT
     --> PRINT_MESSAGE
     --> COUNT_TO_10
Take 1 me 2 to 3 your 4 leader!
```

Now the script exits as soon as one of the tasks finishes. In this case, the `PRINT_MESSAGE` task completes before the `COUNT_TO_10` task so we do not see the numbers `5-10`.

Adding and removing tasks

One of the key features of behavior trees is the ability to add or remove behaviors in a modular fashion. For example, suppose we want to add a "dish washing" task to the house cleaning robot when it is in the kitchen. All we need to do is define this new task and add it to our task list at the top of our script and we are done. There is no need to worry about how this new task interacts with other tasks in the behavior tree. It simply becomes another child task in the `TASK_LIST` iterator for the kitchen. Conversely, suppose your robot does not a have a docking station and you want to eliminate the recharging task from the behavior tree but you still want to be notified when the battery is low. Then we can simply comment out the line that adds the `RECHARGE` behavior to the `STAY_HEALTHY` task, then add a new task that sends us an email or cries for help.

The addition or removal of nodes or even whole branches of the behavior tree can even be done dynamically at run time. The sample script `add_remove_tree.py` demonstrates the concept. The script is identical to the `parallel_tree.py` script described in the previous section except that at the end of alternate cycles through the tree, we remove the counting task so that only the words are displayed. On the next cycle, we add back the counting task. Here is the key block of code that does the work:

```
remove =  True

while True:
    status = BEHAVE.run()
    time.sleep(0.1)

    if status == TaskStatus.SUCCESS:
        BEHAVE.reset()

        if remove:
            PARALLEL_DEMO.remove_child(COUNT_TO_10)
        else:
            PARALLEL_DEMO.add_child(COUNT_TO_10)

        remove = not remove
```

Try out the script with the command:

```
$ rosrun rbx2_tasks add_remove_tree.py
```

The output should start out the same as the `parallel_tree.py` script except that on successive loops through the script, the counting task will be omitted then reappear, and so on.

It's not hard to imagine a behavior tree where nodes or branches are added or pruned based a robot's experience to better adapt to the conditions on hand. For example, one could add or remove entire branches of the tree depending on which room the robot is in or switch its behavior from cleaning to patrolling by simply snipping one branch of the tree and adding the other.