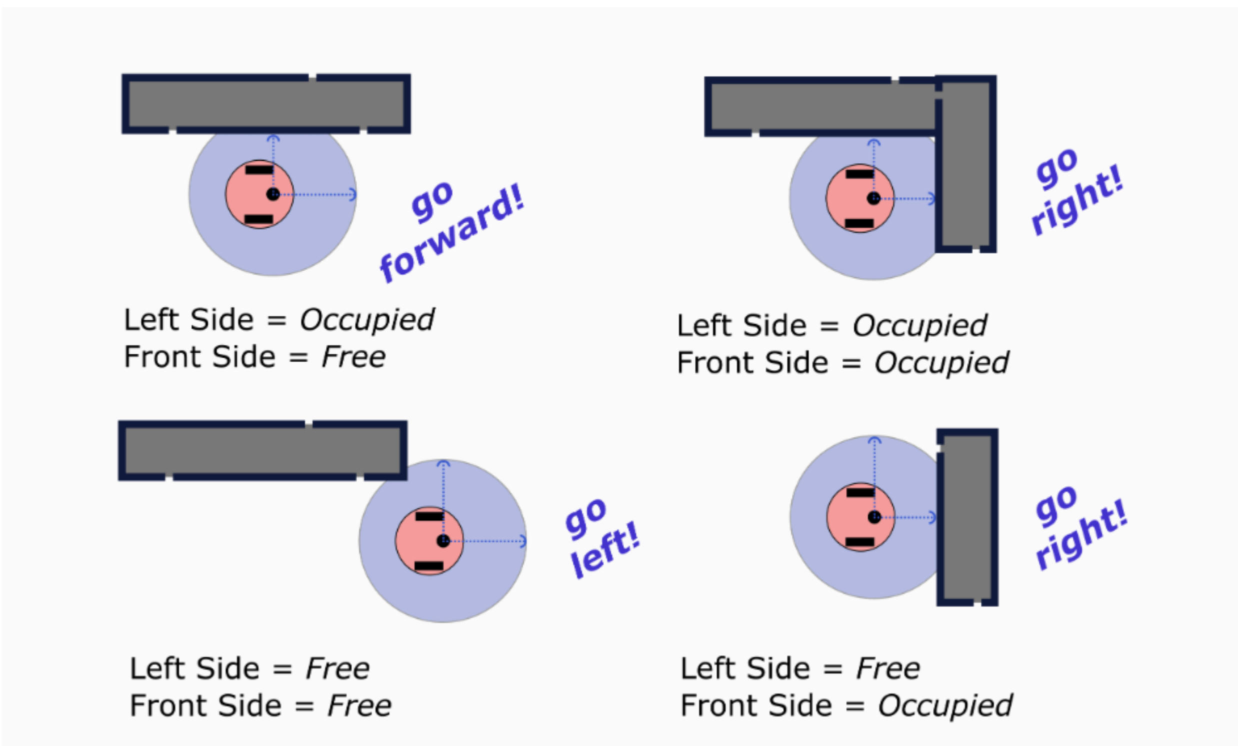
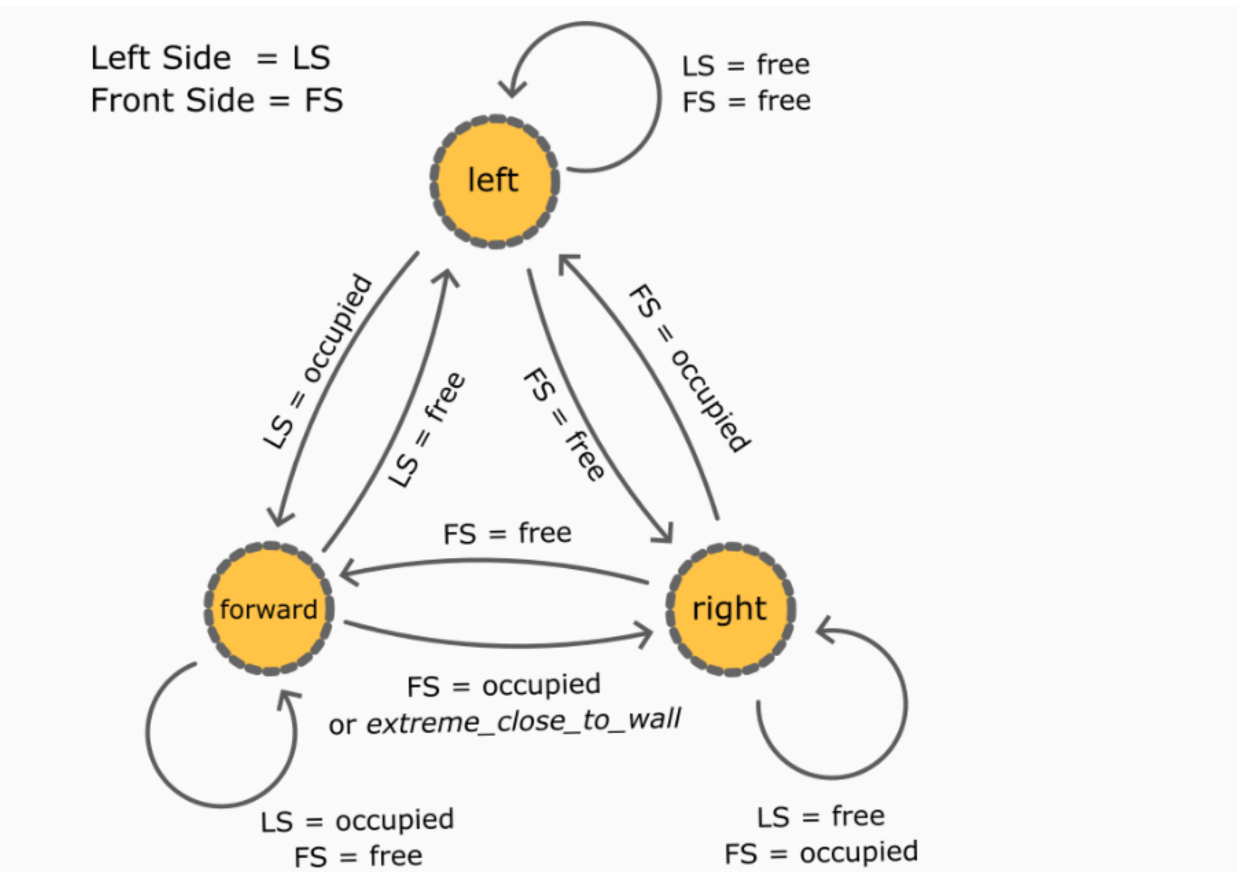
1. Problem Statement

The objective of this lab is to understand the finite state machine of the robot so the robot can move in the left-wall following based on Finite State Machine. By detailing the challenges associated with navigation and sensing, and outlining the methods to address them, we will also introduce the concept of a Finite State Machine (FSM). This FSM will be integrated into the development of our behavior framework. From that we can build the state for the robot to go left, go right, or go straight. The goal/objective of the robot is to follow the left wall.

The finite state machine:



Left Side	Front Side	Action
Free	Free	Left
Free	Occupied	Right
Occupied	Free	Forward
Occupied	Occupied	Right



2. Design Idea

The main goal of this lab is to create the open list for all the possible nodes that are connected to the start node

Once all the nodes are planned, the next step is to calculate the cost to take from each node to the other node

If one of the node is the obstacle or the obstacle is inside the closed_list, then it will be skipped

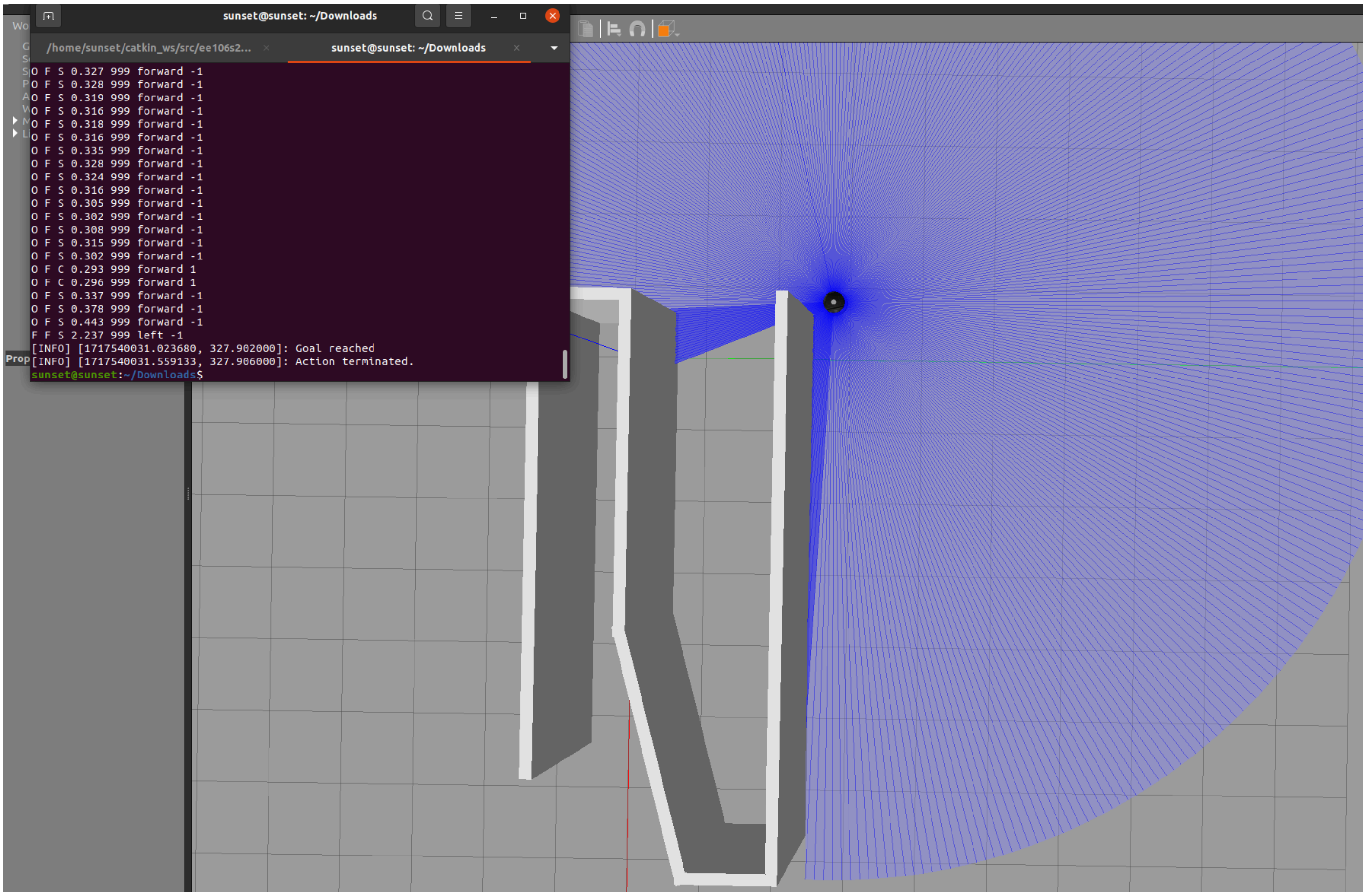
If the current node has a better path then it will add to the set or update to the cost of the node and add it to the parent node. If the node is found the shortest path, it will update the current node to that parent cost-to-go amount

It will keep repeating again, and again until it reaches the goal

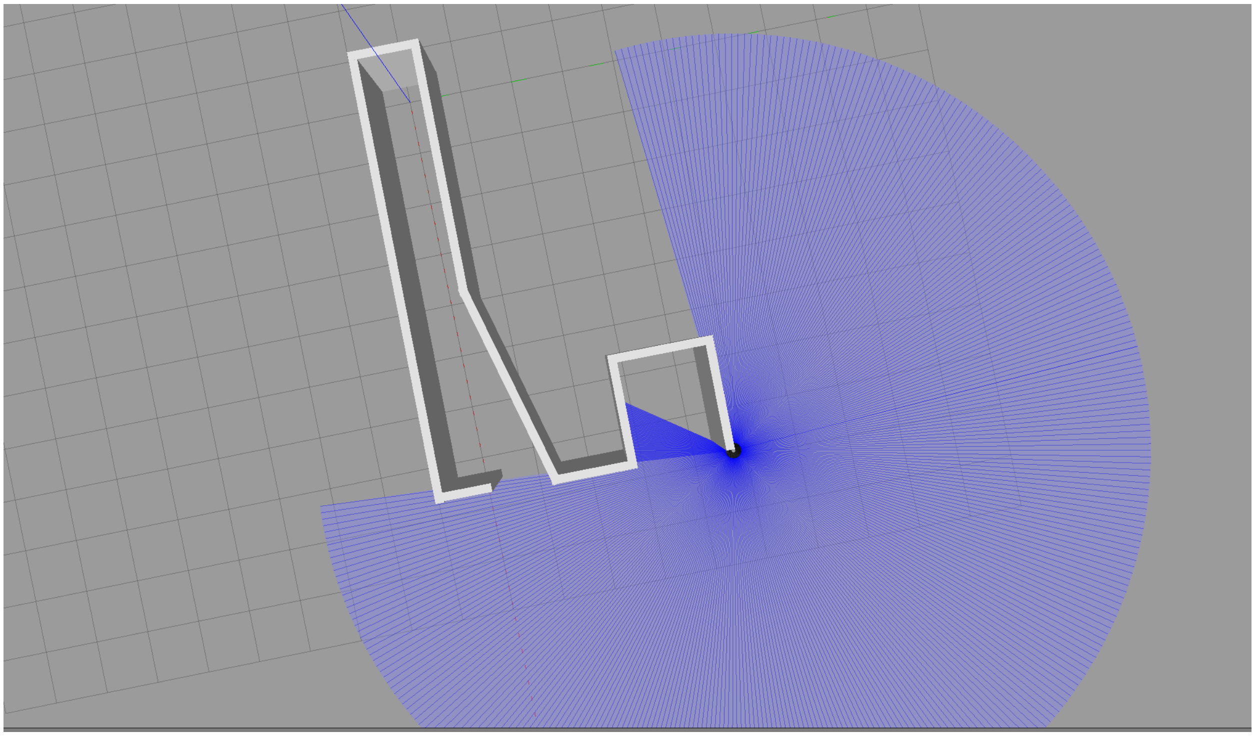
As the motion planning starts to mapping out all the possible nodes and paths, until it reaches the goal. Motion planning will calculate all the cost-to-go to each nodes and starts to eliminate all the longest cost to go from one node to other node, only leaves with small cost. After that, it will update to the current node. More explanation will be based on the “How to run code section”.

3. Results

For complex world result:



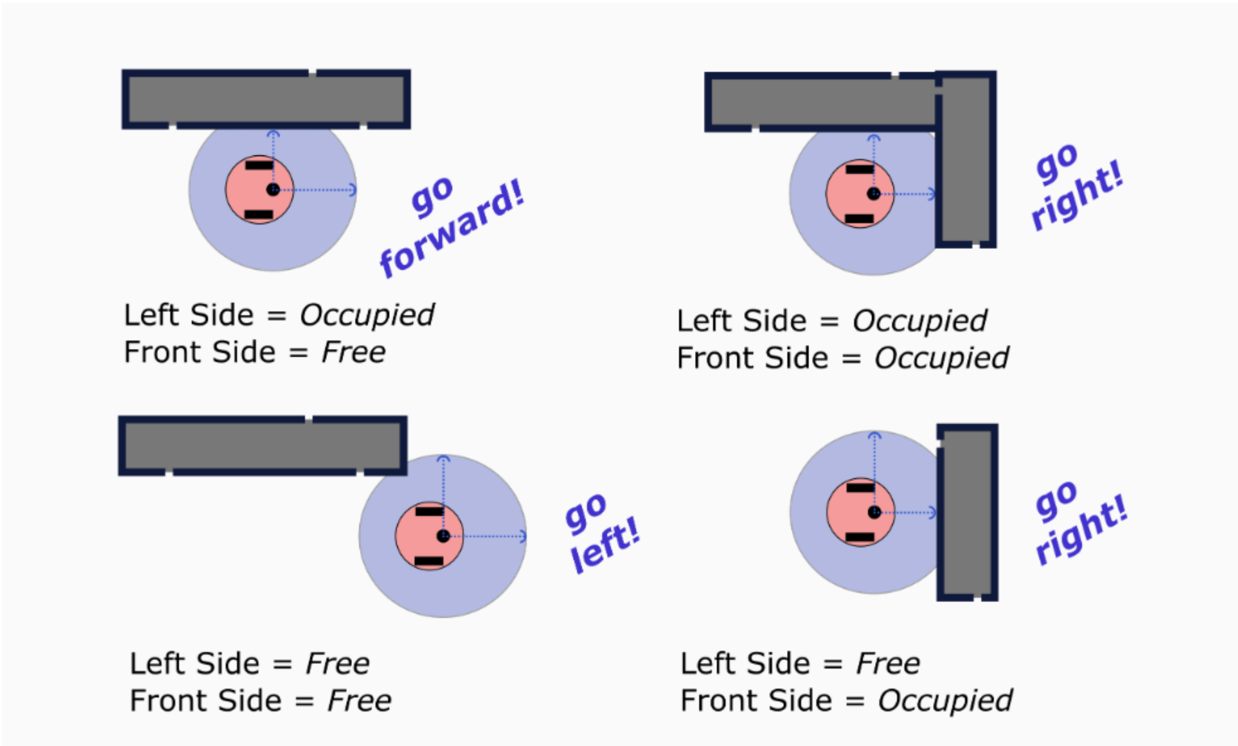
For more complex world result:



4. Appendix (optional)

1) How to run the code

Understanding the finite state machine for the left wall following:



For the complex world :

STEP 1:

Setting up the parameter for the PD controller:

class PDController:

```
def __init__(self, P=1.0, D=0.1, set_point=0.0):
    self.Kp = P
    self.Kd = D
    self.set_point = set_point  # reference (desired value)
    self.previous_error = 0

def update(self, current_value):
    # calculate P_term and D_term
    #  e = r - y
    error = self.set_point - current_value
    P_term = self.Kp * error
    D_term = self.Kd * (error - self.previous_error)
    self.previous_error = error
    return P_term + D_term
```

```
def setPoint(self, set_point):
    self.set_point = set_point
    self.previous_error = 0

def setPD(self, P=0.0, D=0.0):
    self.Kp = P
    self.Kd = D
```

STEP 2

Next, setting up all the parameters for the Publishers and Suscribers, and the TransformListerner for the robot

After that, setting up the state machine for the robot facing in which way/ directions, and the goal tolerance

Continue on, setting up the PDController() function to initialize the pd control for the robot

```
class Turtlebot():
  def __init__(self, goal_x, goal_y, csv_file):
      # Data to be taken from Launch File. Don't Edit
      self.goal_x = goal_x
      self.goal_y = goal_y
      self.csv_file = csv_file

      # Initialize subscribers and publishers
      self.lidar_sub = rospy.Subscriber('/scan', LaserScan, self.lidar_callback)
      self.vel_pub = rospy.Publisher("/mobile_base/commands/velocity", Twist,
queue_size=10)
      self.odom_sub = rospy.Subscriber("odom", Odometry, self.odom_callback)
      self.rate = rospy.Rate(10)
      self.listener = tf.TransformListener()

      # Initialize state variables
      self.left = "O"
      self.front = "F"
      self.wall = "S"
      self.state = "forward"
      self.current_facing = 0  # straight
```

```
    self.logging_counter = 0
    self.left_min_dist = 100
    self.forward_min_dist = 999
    self.pose = Pose2D()
    self.goal_tolerance = 0.3
    self.trajectory = list()
    self.angular_threshold = 0.003
    self.pd_control = PDController()
    self.pd_control.setPD(1.0, 0.1)
```

STEP 3:

Initialize the angle for the left state and the right state

Initialize the state of the robot is facing (directions)

```
self.control_list = [pi/2, pi]
    self.control_list2 = [pi/2, 0]
    # Define Finite-State Machine matrix by NumPy
    self.state_transition_matrix = np.array([
        # Left Side: Free
        [   # Front side: free  -> Left
            [1],
            # Front side: Occupied  -> Right
            [2]
        ],
        # Left Side: Occupied
        [   # Front side: free  -> Forward
            [0],
            # Front side: Occupied  -> Right
            [2]
        ]
    ])

    # Define state and condition encoding
    self.state_encoding = {'forward': 0, 'left': 1, 'right': 2}
    self.state_decoding = {0: 'forward', 1: 'left', 2: 'right'}
    self.condition_encoding = {'F': 0, 'O': 1}      # F: free; O: Occupied
```

```
    self.current_facing_decoding = {0: "straight", -1: "small_left", -2: "medium_left", -3: "large_left",
                                    1: "small_right", 2: "medium_right", 3: "large_right"}
```

Break out:

Intialize the angle

self.control_list = [pi/2, pi]

```
    self.control_list2 = [pi/2, 0]
```

self.control_list = [pi/2, pi] for the left state

self.control_list2 = [pi/2, 0] for the right state

Initialize the state of the robot is facing:

Define state and condition encoding

```
    self.state_encoding = {'forward': 0, 'left': 1, 'right': 2}
    self.state_decoding = {0: 'forward', 1: 'left', 2: 'right'}
    self.condition_encoding = {'F': 0, 'O': 1}      # F: free; O: Occupied
    self.current_facing_decoding = {0: "straight", -1: "small_left", -2: "medium_left", -3: "large_left",
                                    1: "small_right", 2: "medium_right", 3: "large_right"}
```

STEP 4:

```
def run(self):
    # Don't edit anything
    while not rospy.is_shutdown():
        self.update_state()  # Update the robot's state based on sensor readings
        # Publish velocity commands based on the current state
        self.publish_velocity()
        # Sleep to maintain the loop rate
        self.rate.sleep()
```

Publish velocity commands based on the current state

STEP 5:

```python
def update_state(self):
    # State machine to update the robot's state based on sensor readings
    current_state_encoding = self.state_encoding[self.state]
    left_cond_encoding = self.condition_encoding[self.left]
    front_cond_encoding = self.condition_encoding[self.front]

    # Write code to encode current state and conditions
    # Get the new state from the state transition matrix
    new_state_encoded = self.state_transition_matrix[left_cond_encoding,
front_cond_encoding][0]

    # Decode the new state
    self.state = self.state_decoding[new_state_encoded]
```

Update the state function

STEP 6: important step

```python
def publish_velocity(self):
    vel = Twist()
    # Publish velocity commands based on the current facing direction
    # Fill in the velocities, keep the values small
    # Keep editing values in the given range till the robot moves well.

    # Velocity values are good in the range of (0.01 to 0.2)
    # Angular Velocities are good in the range of (-0.08 to 0.08)
    if self.current_facing_decoding[self.current_facing] == "straight":  # 0
        vel.linear.x = 0.2
        vel.angular.z = 0.0
    if self.current_facing_decoding[self.current_facing] == "small_left":  # -1
        vel.linear.x = 0.1
        vel.angular.z = 0.03 #0.03
    if self.current_facing_decoding[self.current_facing] == "medium_left":  # -2
        vel.linear.x = 0.1
        vel.angular.z = 0.05  #0.05
    if self.current_facing_decoding[self.current_facing] == "small_right":  # 1
        vel.linear.x = 0.1
        vel.angular.z = -0.03 #0.03
    if self.current_facing_decoding[self.current_facing] == "medium_right":  # 2
        vel.linear.x = 0.1
```

```
        vel.angular.z = -0.05 #-0.05
    print(self.left + ' ' + self.front + ' ' + self.wall + ' ' +
        str(round(self.left_min_dist, 3)) + ' ' + str(round(self.forward_min_dist, 3)) +
        ' ' + self.state + ' ' + str(self.current_facing))

    if self.state == "left":
        '''if len(self.control_list) < 1:
            rospy.signal_shutdown('Received shutdown message')'''

        for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep()

        # use PD controller to control the angle: from Lab 5
        pd_control=PDController()
        pd_control.setPoint(self.control_list[0])
        while abs(self.pose.theta -self.control_list[0]) > self.angular_threshold:
            adjust_pos = pd_control.update(self.pose.theta)
            vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
            self.vel_pub.publish(vel)
            self.rate.sleep()
        rospy.loginfo("done with turning left")
        self.control_list.pop(0)

        # move forward a bit: from lab 4
        for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep()

    elif self.state == "right":

        if len(self.control_list2) < 1:
            rospy.signal_shutdown('Received shutdown message')
```

```
        # use PD controller to control the angle: from Lab 5
        pd_control=PDController()
        pd_control.setPoint(self.control_list2[0])
        while abs(self.pose.theta -self.control_list2[0]) > self.angular_threshold:
            adjust_pos = pd_control.update(self.pose.theta)
            vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
            self.vel_pub.publish(vel)
            self.rate.sleep()
        rospy.loginfo("done with turning right")
        self.control_list2.pop(0)

        for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep

    else:
        self.vel_pub.publish(vel)




def lidar_callback(self, data):
    self.left_min_dist = 100

    # Update the forward distance with the distance directly in front of the robot
    if str(data.ranges[0]) == "inf":
        self.forward_min_dist = 999
    else:
        self.forward_min_dist = data.ranges[0]
```

The main goal of this publish_velocity() function is to define the state of the robot.

```
    if self.current_facing_decoding[self.current_facing] == "straight":  # 0
```

```
        vel.linear.x = 0.2
        vel.angular.z = 0.0
```

```
if self.current_facing_decoding[self.current_facing] == "small_left":  # -1
    vel.linear.x = 0.1
    vel.angular.z = 0.03 #0.03
if self.current_facing_decoding[self.current_facing] == "medium_left":  # -2
    vel.linear.x = 0.1
    vel.angular.z = 0.05  #0.05
if self.current_facing_decoding[self.current_facing] == "small_right":  # 1
    vel.linear.x = 0.1
    vel.angular.z = -0.03 #0.03
if self.current_facing_decoding[self.current_facing] == "medium_right":  # 2
    vel.linear.x = 0.1
    vel.angular.z = -0.05 #-0.05
print(self.left + ' ' + self.front + ' ' + self.wall + ' ' +
      str(round(self.left_min_dist, 3)) + ' ' + str(round(self.forward_min_dist, 3)) +
      ' ' + self.state + ' ' + str(self.current_facing))
```

This state machine above will initialize all the forward movements and the angular movement of the robot.

When the state = left:

```
if self.state == "left":
```

```
'''if len(self.control_list) < 1:
    rospy.signal_shutdown('Received shutdown message')'''

for i in range(5):
    vel.linear.x = 0.2
    vel.angular.z = 0.0
    self.vel_pub.publish(vel)
    self.rate.sleep()

# use PD controller to control the angle: from Lab 5
pd_control=PDController()
pd_control.setPoint(self.control_list[0])
while abs(self.pose.theta -self.control_list[0]) > self.angular_threshold:
    adjust_pos = pd_control.update(self.pose.theta)
    vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
    self.vel_pub.publish(vel)
    self.rate.sleep()
rospy.loginfo("done with turning left")
```

```
self.control_list.pop(0)

# move forward a bit: from lab 4
for i in range(5):
    vel.linear.x = 0.2
    vel.angular.z = 0.0
    self.vel_pub.publish(vel)
    self.rate.sleep()
```

In the left state, first the robot will move forward a bit,

```
for i in range(5):
    vel.linear.x = 0.2
    vel.angular.z = 0.0
    self.vel_pub.publish(vel)
    self.rate.sleep()
```

Next :

```
# use PD controller to control the angle: from Lab 5
pd_control=PDController()
pd_control.setPoint(self.control_list[0])
while abs(self.pose.theta -self.control_list[0]) > self.angular_threshold:
    adjust_pos = pd_control.update(self.pose.theta)
    vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
    self.vel_pub.publish(vel)
    self.rate.sleep()
rospy.loginfo("done with turning left")
self.control_list.pop(0)
```

Based on this code above , the goal is rotating based on the desire rotaion on the left state. The robot will compare its current angle, self.pose.thetha, with the desire angle rotation, self.control_list[0]. If the range difference is greater than the threshold (0.003), then it keeps rotating based on the tunned PD controller . If the range difference is smaller than the threshold, the robot will stop.

After that , it will pop the first angle so the next angle rotation will be ready to be executed.

When the state = right:

The process is very similar to the left state

```
elif self.state == "right":
```

```
        if len(self.control_list2) < 1:
            rospy.signal_shutdown('Received shutdown message')







        # use PD controller to control the angle: from Lab 5
        pd_control=PDController()
        pd_control.setPoint(self.control_list2[0])
        while abs(self.pose.theta -self.control_list2[0]) > self.angular_threshold:
            adjust_pos = pd_control.update(self.pose.theta)
            vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
            self.vel_pub.publish(vel)
            self.rate.sleep()
        rospy.loginfo("done with turning right")
        self.control_list2.pop(0)

        for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep

    else:
        self.vel_pub.publish(vel)
```

```
# use PD controller to control the angle: from Lab 5
        pd_control=PDController()
        pd_control.setPoint(self.control_list2[0])
```

```
        while abs(self.pose.theta -self.control_list2[0]) > self.angular_threshold:
            adjust_pos = pd_control.update(self.pose.theta)
            vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
            self.vel_pub.publish(vel)
            self.rate.sleep()
        rospy.loginfo("done with turning right")
        self.control_list2.pop(0)
```

Based on this code above , the goal is rotating based on the desire rotaion on the right state. The robot will compare its current angle, self.pose.thetha, with the desire angle rotation, self.control_list[0]. If the range difference is greater than the threshold (0.003), then it keeps rotating based on the tunned PD controller . If the range difference is smaller than the threshold, the robot will stop.

After that , it will pop the first angle so the next angle rotation will be ready to be executed.

```
for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep

    else:
        self.vel_pub.publish(vel)
```

Continue moving forward

If the state is not left, or right, just publish the velocity of the robot.

For the LIDAR CALLBACK function():

```
def lidar_callback(self, data):
    self.left_min_dist = 100

    # Update the forward distance with the distance directly in front of the robot
    if str(data.ranges[0]) == "inf":
        self.forward_min_dist = 999
```

```
    else:
        self.forward_min_dist = data.ranges[0]

    # transform the lidar points frame /rplidar_link from to another frame: from lab 3 and
lab 2
    #listener = tf.TransformListener()
    (trans, rot) = self.listener.lookupTransform('/base_link', '/rplidar_link', rospy.Time(0))



    # Process the LIDAR data and transform the points to the robot's coordinate frame
(another frame you specified)
    for i in range(len(data.ranges)):
        # get the left side lidar data
        if i * data.angle_increment < 1.59 and i * data.angle_increment > 1.55:
            if str(data.ranges[i]) == "inf":
                dist = 9999
            else:
                dist = data.ranges[i]
            (x, y) = self.calculate_position_of_range(dist, i, data.angle_increment,
data.angle_min)

            transformed_point = np.dot(tf.transformations.quaternion_matrix(rot),
np.array([x, y, 0, 1]))

            left_dist = transformed_point[1]
            if left_dist < self.left_min_dist:
                self.left_min_dist = left_dist

    # Update left and forward state
    if self.left_min_dist < 0.5:
        self.left = "O"
    else:
        self.left = "F"
    if self.forward_min_dist < 0.5:
        self.front = "O"
    else:
        self.front = "F"

    # Set wall state
```

```
    if self.left_min_dist < 0.3:
        self.wall = "C"
    else:
        self.wall = "S"
```

Breakout the code explanation:

```
def lidar_callback(self, data):
    self.left_min_dist = 100

    # Update the forward distance with the distance directly in front of the robot
    if str(data.ranges[0]) == "inf":
        self.forward_min_dist = 999
    else:
        self.forward_min_dist = data.ranges[0]

    # transform the lidar points frame /rplidar_link from to another frame: from lab 3 and
lab 2
    #listener = tf.TransformListener()
    (trans, rot) = self.listener.lookupTransform('/base_link', '/rplidar_link', rospy.Time(0))
```

Initialize the transformation and rotation for the lidar

If the robot distance of the lidar is at infinity, so set the forward direction equals to 999

If not, then start the forward_min_dist

Next, processing the LIDAR data and transform the points to the robot's coordinate frame

If the data angle increment is < 1.59 or >1.55:

-> the range of the data is infinity

```
    for i in range(len(data.ranges)):
        # get the left side lidar data
        if i * data.angle_increment < 1.59 and i * data.angle_increment > 1.55:
            if str(data.ranges[i]) == "inf":
                dist = 9999
            else:
                dist = data.ranges[i]
```

```
        (x, y) = self.calculate_position_of_range(dist, i, data.angle_increment,
data.angle_min)

        transformed_point = np.dot(tf.transformations.quaternion_matrix(rot),
np.array([x, y, 0, 1]))

        left_dist = transformed_point[1]
        if left_dist < self.left_min_dist:
          self.left_min_dist = left_dist
```

For the segment code above, call the calculate_position_of_range()

The calculate_position_of_range() function is:

```
def calculate_position_of_range(self, range, index, angle_increment,
angle_min):
```

```
    # Calculate the position of a range measurement in the LIDAR frame
    angle = index * angle_increment + angle_min
    x = range * np.cos(angle)
    y = range * np.sin(angle)
    return x, y
```

The `range` is the distance measurement from the LIDAR sensor

`np.cos(angle)` calculates the cosine of the angle, and when this value is multiplied by the range, it gives the x-coordinate. Similar to the y-coordinate

4-dimensional for the transform_point

if left_dist < self.left_min_dist:

keep the minimum distance as the left_min_dist

For the FORWARD STATE:

Update left and forward state

```
if self.left_min_dist < 0.5:
    self.left = "O"
else:
    self.left = "F"
if self.forward_min_dist < 0.5:
    self.front = "O"
else:
    self.front = "F"

# Set wall state
if self.left_min_dist < 0.3:
    self.wall = "C"
else:
    self.wall = "S"
```

For the LEFT

Update current_facing direction

if the robot is too close, take the medium_right facing; if it is too far, take the medium_left facing

For this small_right and small_left are used to fine-tune the navigation.

```
    # The basic idea is:
    #  if the robot is too close, take the medium_right facing; if it is too far, take the
medium_left facing
    #  For this small_right and small_left are used to fine-tune the navigation.
  if self.left_min_dist < 0.3:
        self.current_facing = 1
    elif self.left_min_dist < 0.25:
        self.current_facing = 2
    elif (self.left_min_dist > 0.35) and (self.forward_min_dist < 2) :
        self.current_facing = 1
    elif (self.left_min_dist > 0.35) and (self.forward_min_dist < 1) :
        self.current_facing = 2
    elif (self.left_min_dist > 0.35) and (self.forward_min_dist > 2) :
        self.current_facing = -1
```

```
    elif (self.left_min_dist > 0.4)  :
        self.current_facing = -2
    else:
        self.current_facing = 0
```

For the ODOM_CALLBACK function():

```
def odom_callback(self, data):
```

```
    # get the position of the robot
    pose = data.pose.pose
    self.pose.x = pose.position.x
    self.pose.y = pose.position.y
    quaternion = (
        pose.orientation.x,
        pose.orientation.y,
        pose.orientation.z,
        pose.orientation.w
    )
    euler = tf.transformations.euler_from_quaternion(quaternion)
    self.pose.theta = euler[2]

    # Append pose data to the trajectory
    self.logging_counter += 1
    if self.logging_counter == 100:
        self.logging_counter = 0
        self.trajectory.append([self.pose.x, self.pose.y])
        rospy.loginfo("Save point")

    # If the goal is reached, stop the robot and save the trajectory
    if sqrt((self.pose.x - self.goal_x)**2 + (self.pose.y - self.goal_y)**2) < self.goal_tolerance:
        rospy.loginfo("Goal reached")
        self.stop()
        self.save_trajectory()
        rospy.signal_shutdown('Goal reached')
```

Breakout the code segment:

```
pose = data.pose.pose
```

```
    self.pose.x = pose.position.x
    self.pose.y = pose.position.y
    quaternion = (
        pose.orientation.x,
        pose.orientation.y,
        pose.orientation.z,
        pose.orientation.w
    )
    euler = tf.transformations.euler_from_quaternion(quaternion)
    self.pose.theta = euler[2]
```

Get the position of x,y for ROS of odometry

-> rospy.Subscriber("odom", Odometry, self.odom_callback)

```
quaternion = (
        pose.orientation.x,
        pose.orientation.y,
        pose.orientation.z,
        pose.orientation.w
    )
    euler = tf.transformations.euler_from_quaternion(quaternion)
    self.pose.theta = euler[2]
```

For the rotation of x,y,z,w

Next,

Append pose data to the trajectory

```
    self.logging_counter += 1
    if self.logging_counter == 100:
        self.logging_counter = 0
        self.trajectory.append([self.pose.x, self.pose.y])
        rospy.loginfo("Save point")
```

Next,

If the goal is reached, stop the robot and save the trajectory

To calculate the goal distance, the formula is

x= sqrt((self.pose.x - self.goal_x)**2 + (self.pose.y - self.goal_y)**2)

If x< self_goal.toleracne (0.003) then the goal is reached

```
    if sqrt((self.pose.x - self.goal_x)**2 + (self.pose.y - self.goal_y)**2) < self.goal_tolerance:
        rospy.loginfo("Goal reached")
        self.stop()
        self.save_trajectory()
        rospy.signal_shutdown('Goal reached')
```

Last step for the main function():

def main(args):

```
  # Initialize ROS Node
  rospy.init_node('left_wall_follower', anonymous=True)
  # Get parameters from the launch file
  goal_x = rospy.get_param('goal_x')
  goal_y = rospy.get_param('goal_y')
  csv_file = rospy.get_param('csv_file')

  # Create an instance of the Turtlebot class
  robot = Turtlebot(goal_x, goal_y, csv_file)
  try:
    rospy.spin()
  except KeyboardInterrupt:
    print("Shutting down")

if __name__ == '__main__':
  try:
    main(sys.argv)
  except rospy.ROSInterruptException:
    rospy.loginfo("Action terminated.")
```

FOR THE MORE COMPLEX WORLD:

The step is exactly the same as the complex world. The only thing we modified is adding the angle angle, pi, into the self arrayas the following below:

self.control_list = [pi/2, pi,pi/2) References

That's all for this lab.

The external source is only: [Welcome to UCR EE106 — UCR EE106 Spring 2024 0.1 documentation (ucr-ee106.readthedocs.io)]() and the help from TA

3) Scripts

For the complex world:

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

import roslib
roslib.load_manifest('ee106s24')
import rospy
import sys
import tf
import numpy as np
from math import pi, sqrt
from std_msgs.msg import String
from sensor_msgs.msg import LaserScan
from geometry_msgs.msg import Twist, Pose2D
from nav_msgs.msg import Odometry
import os

class PDController:
  def __init__(self, P=1.0, D=0.1, set_point=0.0):
     self.Kp = P
     self.Kd = D
     self.set_point = set_point  # reference (desired value)
     self.previous_error = 0

  def update(self, current_value):
     # calculate P_term and D_term
     #  e = r - y
     error = self.set_point - current_value
     P_term = self.Kp * error
     D_term = self.Kd * (error - self.previous_error)
     self.previous_error = error
     return P_term + D_term

  def setPoint(self, set_point):
```

```
    self.set_point = set_point
    self.previous_error = 0

  def setPD(self, P=0.0, D=0.0):
    self.Kp = P
    self.Kd = D

class Turtlebot():
  def __init__(self, goal_x, goal_y, csv_file):
    # Data to be taken from Launch File. Don't Edit
    self.goal_x = goal_x
    self.goal_y = goal_y
    self.csv_file = csv_file

    # Initialize subscribers and publishers
    self.lidar_sub = rospy.Subscriber('/scan', LaserScan, self.lidar_callback)
    self.vel_pub = rospy.Publisher("/mobile_base/commands/velocity", Twist,
queue_size=10)
    self.odom_sub = rospy.Subscriber("odom", Odometry, self.odom_callback)
    self.rate = rospy.Rate(10)
    self.listener = tf.TransformListener()

    # Initialize state variables
    self.left = "O"
    self.front = "F"
    self.wall = "S"
    self.state = "forward"
    self.current_facing = 0  # straight
    self.logging_counter = 0
    self.left_min_dist = 100
    self.forward_min_dist = 999
    self.pose = Pose2D()
    self.goal_tolerance = 0.3
    self.trajectory = list()
    self.angular_threshold = 0.003
    self.pd_control = PDController()
    self.pd_control.setPD(1.0, 0.1)

    # For the complex world map
    self.control_list = [pi/2, pi]
```

```python
    self.control_list2 = [pi/2, 0]
    # Define Finite-State Machine matrix by NumPy
    self.state_transition_matrix = np.array([
        # Left Side: Free
        [   # Front side: free  -> Left
            [1],
            # Front side: Occupied  -> Right
            [2]
        ],
        # Left Side: Occupied
        [   # Front side: free  -> Forward
            [0],
            # Front side: Occupied  -> Right
            [2]
        ]
    ])

    # Define state and condition encoding
    self.state_encoding = {'forward': 0, 'left': 1, 'right': 2}
    self.state_decoding = {0: 'forward', 1: 'left', 2: 'right'}
    self.condition_encoding = {'F': 0, 'O': 1}      # F: free; O: Occupied
    self.current_facing_decoding = {0: "straight", -1: "small_left", -2: "medium_left", -3:
"large_left",
                                    1: "small_right", 2: "medium_right", 3: "large_right"}
    self.run()

  def run(self):
    # Don't edit anything
    while not rospy.is_shutdown():
        self.update_state()  # Update the robot's state based on sensor readings
        # Publish velocity commands based on the current state
        self.publish_velocity()
        # Sleep to maintain the loop rate
        self.rate.sleep()

  def update_state(self):
    # State machine to update the robot's state based on sensor readings
    current_state_encoding = self.state_encoding[self.state]
    left_cond_encoding = self.condition_encoding[self.left]
    front_cond_encoding = self.condition_encoding[self.front]
```

```
        # Write code to encode current state and conditions
        # Get the new state from the state transition matrix
        new_state_encoded = self.state_transition_matrix[left_cond_encoding,
front_cond_encoding][0]

        # Decode the new state
        self.state = self.state_decoding[new_state_encoded]

    def publish_velocity(self):
        vel = Twist()
        # Publish velocity commands based on the current facing direction
        # Fill in the velocities, keep the values small
        # Keep editing values in the given range till the robot moves well.

        # Velocity values are good in the range of (0.01 to 0.2)
        # Angular Velocities are good in the range of (-0.08 to 0.08)
        if self.current_facing_decoding[self.current_facing] == "straight":  # 0
            vel.linear.x = 0.2
            vel.angular.z = 0.0
        if self.current_facing_decoding[self.current_facing] == "small_left":  # -1
            vel.linear.x = 0.1
            vel.angular.z = 0.03 #0.03
        if self.current_facing_decoding[self.current_facing] == "medium_left":  # -2
            vel.linear.x = 0.1
            vel.angular.z = 0.05  #0.05
        if self.current_facing_decoding[self.current_facing] == "small_right":  # 1
            vel.linear.x = 0.1
            vel.angular.z = -0.03 #0.03
        if self.current_facing_decoding[self.current_facing] == "medium_right":  # 2
            vel.linear.x = 0.1
            vel.angular.z = -0.05 #-0.05
        print(self.left + ' ' + self.front + ' ' + self.wall + ' ' +
              str(round(self.left_min_dist, 3)) + ' ' + str(round(self.forward_min_dist, 3)) +
              ' ' + self.state + ' ' + str(self.current_facing))

        if self.state == "left":
            '''if len(self.control_list) < 1:
                rospy.signal_shutdown('Received shutdown message')'''
```

```
        for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep()

        # use PD controller to control the angle: from Lab 5
        pd_control=PDController()
        pd_control.setPoint(self.control_list[0])
        while abs(self.pose.theta -self.control_list[0]) > self.angular_threshold:
            adjust_pos = pd_control.update(self.pose.theta)
            vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
            self.vel_pub.publish(vel)
            self.rate.sleep()
        rospy.loginfo("done with turning left")
        self.control_list.pop(0)

        # move forward a bit: from lab 4
        for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep()

    elif self.state == "right":

        if len(self.control_list2) < 1:
            rospy.signal_shutdown('Received shutdown message')




        # use PD controller to control the angle: from Lab 5
        pd_control=PDController()
        pd_control.setPoint(self.control_list2[0])
        while abs(self.pose.theta -self.control_list2[0]) > self.angular_threshold:
            adjust_pos = pd_control.update(self.pose.theta)
            vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.8))
            self.vel_pub.publish(vel)
```

```
            self.rate.sleep()
        rospy.loginfo("done with turning right")
        self.control_list2.pop(0)

        for i in range(5):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep

    else:
        self.vel_pub.publish(vel)




  def lidar_callback(self, data):
    self.left_min_dist = 100

    # Update the forward distance with the distance directly in front of the robot
    if str(data.ranges[0]) == "inf":
        self.forward_min_dist = 999
    else:
        self.forward_min_dist = data.ranges[0]

    # transform the lidar points frame /rplidar_link from to another frame: from lab 3 and
lab 2
    #listener = tf.TransformListener()
    (trans, rot) = self.listener.lookupTransform('/base_link', '/rplidar_link', rospy.Time(0))



    # Process the LIDAR data and transform the points to the robot's coordinate frame
(another frame you specified)
    for i in range(len(data.ranges)):
        # get the left side lidar data
        if i * data.angle_increment < 1.59 and i * data.angle_increment > 1.55:
            if str(data.ranges[i]) == "inf":
                dist = 9999
            else:
```

```
                dist = data.ranges[i]
            (x, y) = self.calculate_position_of_range(dist, i, data.angle_increment,
data.angle_min)

            transformed_point = np.dot(tf.transformations.quaternion_matrix(rot),
np.array([x, y, 0, 1]))

            left_dist = transformed_point[1]
            if left_dist < self.left_min_dist:
                self.left_min_dist = left_dist

      # Update left and forward state
      if self.left_min_dist < 0.5:
          self.left = "O"
      else:
          self.left = "F"
      if self.forward_min_dist < 0.5:
          self.front = "O"
      else:
          self.front = "F"

      # Set wall state
      if self.left_min_dist < 0.3:
          self.wall = "C"
      else:
          self.wall = "S"

      # Update current_facing direction
      # The basic idea is:
      #  if the robot is too close, take the medium_right facing; if it is too far, take the
medium_left facing
      #  For this small_right and small_left are used to fine-tune the navigation.
      if self.left_min_dist < 0.3:
          self.current_facing = 1
      elif self.left_min_dist < 0.25:
          self.current_facing = 2
      elif (self.left_min_dist > 0.35) and (self.forward_min_dist < 2) :
          self.current_facing = 1
      elif (self.left_min_dist > 0.35) and (self.forward_min_dist < 1) :
          self.current_facing = 2
```

```python
    elif (self.left_min_dist > 0.35) and (self.forward_min_dist > 2) :
        self.current_facing = -1
    elif (self.left_min_dist > 0.4)  :
        self.current_facing = -2
    else:
        self.current_facing = 0

def odom_callback(self, data):
    # get the position of the robot
    pose = data.pose.pose
    self.pose.x = pose.position.x
    self.pose.y = pose.position.y
    quaternion = (
        pose.orientation.x,
        pose.orientation.y,
        pose.orientation.z,
        pose.orientation.w
    )
    euler = tf.transformations.euler_from_quaternion(quaternion)
    self.pose.theta = euler[2]

    # Append pose data to the trajectory
    self.logging_counter += 1
    if self.logging_counter == 100:
        self.logging_counter = 0
        self.trajectory.append([self.pose.x, self.pose.y])
        rospy.loginfo("Save point")

    # If the goal is reached, stop the robot and save the trajectory
    if sqrt((self.pose.x - self.goal_x)**2 + (self.pose.y - self.goal_y)**2) < self.goal_tolerance:
        rospy.loginfo("Goal reached")
        self.stop()
        self.save_trajectory()
        rospy.signal_shutdown('Goal reached')

def stop(self):
    # Stop the robot
    vel = Twist()
    vel.linear.x = 0.0
    vel.angular.z = 0.0
```

```
    self.vel_pub.publish(vel)

  def save_trajectory(self):
    # Save the trajectory to a CSV file
    '''with open(self.csv_file, 'w') as f:
      for pose in self.trajectory:
        f.write(f"{pose[0]},{pose[1]}\n")'''
    np.savetxt(self.csv_file, np.array(self.trajectory), fmt='%f', delimiter=',')

  def calculate_position_of_range(self, range, index, angle_increment, angle_min):
    # Calculate the position of a range measurement in the LIDAR frame
    angle = index * angle_increment + angle_min
    x = range * np.cos(angle)
    y = range * np.sin(angle)
    return x, y

'''if __name__ == '__main__':
  try:
    # Initialize the ROS node
    rospy.init_node('turtlebot_navigation', anonymous=True)

    # Get parameters from the launch file
    goal_x = rospy.get_param("~goal_x", 5.0)
    goal_y = rospy.get_param("~goal_y", 5.0)
    csv_file = rospy.get_param("~csv_file", "/home/desktop/trajectory.csv")

    # Create the Turtlebot object and start the navigation
    turtlebot = Turtlebot(goal_x, goal_y, csv_file)
  except rospy.ROSInterruptException:
    pass'''
def main(args):
  # Initialize ROS Node
  rospy.init_node('left_wall_follower', anonymous=True)
  # Get parameters from the launch file
  goal_x = rospy.get_param('goal_x')
  goal_y = rospy.get_param('goal_y')
  csv_file = rospy.get_param('csv_file')

  # Create an instance of the Turtlebot class
  robot = Turtlebot(goal_x, goal_y, csv_file)
```

```
  try:
    rospy.spin()
  except KeyboardInterrupt:
    print("Shutting down")

if __name__ == '__main__':
  try:
    main(sys.argv)
  except rospy.ROSInterruptException:
    rospy.loginfo("Action terminated.")
```

MORE COMEPLEX WORLD:

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

import roslib
roslib.load_manifest('ee106s24')
import rospy
import sys
import tf
import numpy as np
from math import pi, sqrt
from std_msgs.msg import String
from sensor_msgs.msg import LaserScan
from geometry_msgs.msg import Twist, Pose2D
from nav_msgs.msg import Odometry
import os

class PDController:
  def __init__(self, P=1.0, D=0.1, set_point=0.0):
    self.Kp = P
    self.Kd = D
    self.set_point = set_point  # reference (desired value)
    self.previous_error = 0

  def update(self, current_value):
```

```python
        # calculate P_term and D_term
        #  e = r - y
        error = self.set_point - current_value
        P_term = self.Kp * error
        D_term = self.Kd * (error - self.previous_error)
        self.previous_error = error
        return P_term + D_term

    def setPoint(self, set_point):
        self.set_point = set_point
        self.previous_error = 0

    def setPD(self, P=0.0, D=0.0):
        self.Kp = P
        self.Kd = D

class Turtlebot():
    def __init__(self, goal_x, goal_y, csv_file):
        # Data to be taken from Launch File. Don't Edit
        self.goal_x = goal_x
        self.goal_y = goal_y
        self.csv_file = csv_file

        # Initialize subscribers and publishers
        self.lidar_sub = rospy.Subscriber('/scan', LaserScan, self.lidar_callback)
        self.vel_pub = rospy.Publisher("/mobile_base/commands/velocity", Twist, queue_size=10)
        self.odom_sub = rospy.Subscriber("odom", Odometry, self.odom_callback)
        self.rate = rospy.Rate(10)
        self.listener = tf.TransformListener()

        # Initialize state variables
        self.left = "O"
        self.front = "F"
        self.wall = "S"
        self.state = "forward"
        self.current_facing = 0  # straight
        self.logging_counter = 0
        self.left_min_dist = 100
        self.forward_min_dist = 999
        self.pose = Pose2D()
```

```
    self.goal_tolerance = 0.3
    self.trajectory = list()
    self.angular_threshold = 0.003
    self.pd_control = PDController()
    self.pd_control.setPD(1.0, 0.1)

    # For the complex world map
    self.control_list = [pi/2, pi,pi/2]
    self.control_list2 = [pi/2, 0]
    # Define Finite-State Machine matrix by NumPy
    self.state_transition_matrix = np.array([
        # Left Side: Free
        [   # Front side: free  -> Left
            [1],
            # Front side: Occupied  -> Right
            [2]
        ],
        # Left Side: Occupied
        [   # Front side: free  -> Forward
            [0],
            # Front side: Occupied  -> Right
            [2]
        ]
    ])

    # Define state and condition encoding
    self.state_encoding = {'forward': 0, 'left': 1, 'right': 2}
    self.state_decoding = {0: 'forward', 1: 'left', 2: 'right'}
    self.condition_encoding = {'F': 0, 'O': 1}       # F: free; O: Occupied
    self.current_facing_decoding = {0: "straight", -1: "small_left", -2: "medium_left", -3:
"large_left",
                                    1: "small_right", 2: "medium_right", 3: "large_right"}
    self.run()

  def run(self):
    # Don't edit anything
    while not rospy.is_shutdown():
        self.update_state()  # Update the robot's state based on sensor readings
        # Publish velocity commands based on the current state
        self.publish_velocity()
```

```
        # Sleep to maintain the loop rate
        self.rate.sleep()

  def update_state(self):
      # State machine to update the robot's state based on sensor readings
      current_state_encoding = self.state_encoding[self.state]
      left_cond_encoding = self.condition_encoding[self.left]
      front_cond_encoding = self.condition_encoding[self.front]

      # Write code to encode current state and conditions
      # Get the new state from the state transition matrix
      new_state_encoded = self.state_transition_matrix[left_cond_encoding,
front_cond_encoding][0]

      # Decode the new state
      self.state = self.state_decoding[new_state_encoded]

  def publish_velocity(self):
      vel = Twist()
      # Publish velocity commands based on the current facing direction
      # Fill in the velocities, keep the values small
      # Keep editing values in the given range till the robot moves well.

      # Velocity values are good in the range of (0.01 to 0.2)
      # Angular Velocities are good in the range of (-0.08 to 0.08)
      if self.current_facing_decoding[self.current_facing] == "straight":  # 0
        vel.linear.x = 0.2
        vel.angular.z = 0.0
      if self.current_facing_decoding[self.current_facing] == "small_left":  # -1
        vel.linear.x = 0.1
        vel.angular.z = 0.03 #0.03
      if self.current_facing_decoding[self.current_facing] == "medium_left":  # -2
        vel.linear.x = 0.1
        vel.angular.z = 0.05  #0.05
      if self.current_facing_decoding[self.current_facing] == "small_right":  # 1
        vel.linear.x = 0.1
        vel.angular.z = -0.03 #0.03
      if self.current_facing_decoding[self.current_facing] == "medium_right":  # 2
        vel.linear.x = 0.1
        vel.angular.z = -0.05 #-0.05
```

```
print(self.left + ' ' + self.front + ' ' + self.wall + ' ' +
      str(round(self.left_min_dist, 3)) + ' ' + str(round(self.forward_min_dist, 3)) +
      ' ' + self.state + ' ' + str(self.current_facing))

if self.state == "left":
    if len(self.control_list) < 1:
        rospy.signal_shutdown('Received shutdown message')




    for i in range(5):
        vel.linear.x = 0.15
        vel.angular.z = 0.0
        self.vel_pub.publish(vel)
        self.rate.sleep()

    # use PD controller to control the angle: from Lab 5
    pd_control=PDController()
    pd_control.setPoint(self.control_list[0])
    while abs(self.pose.theta -self.control_list[0]) > self.angular_threshold:
        adjust_pos = pd_control.update(self.pose.theta)
        vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.9))
        self.vel_pub.publish(vel)
        self.rate.sleep()
    rospy.loginfo("done with turning left")
    self.control_list.pop(0)

    # move forward a bit: from lab 4
    for i in range(15):
        vel.linear.x = 0.2
        vel.angular.z = 0.0
        self.vel_pub.publish(vel)
        self.rate.sleep()

elif self.state == "right":

    if len(self.control_list2) < 1:
        rospy.signal_shutdown('Received shutdown message')
```

```
        # use PD controller to control the angle: from Lab 5
        pd_control=PDController()
        pd_control.setPoint(self.control_list2[0])
        while abs(self.pose.theta -self.control_list2[0]) > self.angular_threshold:
            adjust_pos = pd_control.update(self.pose.theta)
            vel.angular.z = max(-0.8,min(adjust_pos*2.5,0.9))
            self.vel_pub.publish(vel)
            self.rate.sleep()
        rospy.loginfo("done with turning right")
        self.control_list2.pop(0)

        for i in range(6):
            vel.linear.x = 0.2
            vel.angular.z = 0.0
            self.vel_pub.publish(vel)
            self.rate.sleep

    else:
        self.vel_pub.publish(vel)




def lidar_callback(self, data):
    self.left_min_dist = 100

    # Update the forward distance with the distance directly in front of the robot
    if str(data.ranges[0]) == "inf":
        self.forward_min_dist = 999
    else:
        self.forward_min_dist = data.ranges[0]

    # transform the lidar points frame /rplidar_link from to another frame: from lab 3 and lab 2
    #listener = tf.TransformListener()
    (trans, rot) = self.listener.lookupTransform('/base_link', '/rplidar_link', rospy.Time(0))
```

```
        # Process the LIDAR data and transform the points to the robot's coordinate frame (another frame you specified)
        for i in range(len(data.ranges)):
            # get the left side lidar data
            if i * data.angle_increment < 1.59 and i * data.angle_increment > 1.55:
                if str(data.ranges[i]) == "inf":
                    dist = 9999
                else:
                    dist = data.ranges[i]
                (x, y) = self.calculate_position_of_range(dist, i, data.angle_increment, data.angle_min)

                transformed_point = np.dot(tf.transformations.quaternion_matrix(rot), np.array([x, y, 0, 1]))

                left_dist = transformed_point[1]
                if left_dist < self.left_min_dist:
                    self.left_min_dist = left_dist

        # Update left and forward state
        if self.left_min_dist < 0.5:
            self.left = "O"
        else:
            self.left = "F"
        if self.forward_min_dist < 0.5:
            self.front = "O"
        else:
            self.front = "F"

        # Set wall state
        if self.left_min_dist < 0.3:
            self.wall = "C"
        else:
            self.wall = "S"

        # Update current_facing direction
        # The basic idea is:
        #  if the robot is too close, take the medium_right facing; if it is too far, take the medium_left facing
```

```
    #  For this small_right and small_left are used to fine-tune the navigation.
    if self.left_min_dist < 0.3:
        self.current_facing = 1
    elif self.left_min_dist < 0.25:
        self.current_facing = 2
    elif (self.left_min_dist > 0.35) and (self.forward_min_dist < 2) :
        self.current_facing = 1
    elif (self.left_min_dist > 0.35) and (self.forward_min_dist < 1.5) :
        self.current_facing = 2
    elif (self.left_min_dist > 0.3) and (self.forward_min_dist > 2) :
        self.current_facing = -1
    elif (self.left_min_dist > 0.35)  :
        self.current_facing = -2
    else:
        self.current_facing = 0

def odom_callback(self, data):
    # get the position of the robot
    pose = data.pose.pose
    self.pose.x = pose.position.x
    self.pose.y = pose.position.y
    quaternion = (
        pose.orientation.x,
        pose.orientation.y,
        pose.orientation.z,
        pose.orientation.w
    )
    euler = tf.transformations.euler_from_quaternion(quaternion)
    self.pose.theta = euler[2]

    # Append pose data to the trajectory
    self.logging_counter += 1
    if self.logging_counter == 100:
        self.logging_counter = 0
        self.trajectory.append([self.pose.x, self.pose.y])


    # If the goal is reached, stop the robot and save the trajectory
    if sqrt((self.pose.x - self.goal_x)**2 + (self.pose.y - self.goal_y)**2) < self.goal_tolerance:
        rospy.loginfo("Goal reached")
```

```python
        self.stop()
        self.save_trajectory()
        rospy.signal_shutdown('Goal reached')

  def stop(self):
      # Stop the robot
      vel = Twist()
      vel.linear.x = 0.0
      vel.angular.z = 0.0
      self.vel_pub.publish(vel)

  def save_trajectory(self):
      # Save the trajectory to a CSV file
      '''with open(self.csv_file, 'w') as f:
         for pose in self.trajectory:
            f.write(f"{pose[0]},{pose[1]}\n")'''
      np.savetxt(self.csv_file, np.array(self.trajectory), fmt='%f', delimiter=',')

  def calculate_position_of_range(self, range, index, angle_increment, angle_min):
      # Calculate the position of a range measurement in the LIDAR frame
      angle = index * angle_increment + angle_min
      x = range * np.cos(angle)
      y = range * np.sin(angle)
      return x, y

'''if __name__ == '__main__':
  try:
      # Initialize the ROS node
      rospy.init_node('turtlebot_navigation', anonymous=True)

      # Get parameters from the launch file
      goal_x = rospy.get_param("~goal_x", 5.0)
      goal_y = rospy.get_param("~goal_y", 5.0)
      csv_file = rospy.get_param("~csv_file", "/home/desktop/trajectory.csv")

      # Create the Turtlebot object and start the navigation
      turtlebot = Turtlebot(goal_x, goal_y, csv_file)
  except rospy.ROSInterruptException:
      pass'''
def main(args):
```

```python
    # Initialize ROS Node
    rospy.init_node('left_wall_follower', anonymous=True)
    # Get parameters from the launch file
    goal_x = rospy.get_param('goal_x')
    goal_y = rospy.get_param('goal_y')
    csv_file = rospy.get_param('csv_file')

    # Create an instance of the Turtlebot class
    robot = Turtlebot(goal_x, goal_y, csv_file)
    try:
        rospy.spin()
    except KeyboardInterrupt:
        print("Shutting down")

if __name__ == '__main__':
    try:
        main(sys.argv)
    except rospy.ROSInterruptException:
        rospy.loginfo("Action terminated.")
```