SLAM - Simultaneous Localization and Mapping

Overview

In this project, you will implement Simultaneous Localization and Mapping (SLAM) using an Extended Kalman Filter (EKF). The robot moves through a continuous plane containing landmarks (you can assume the landmarks are points on the plane). The robot receives noisy motion and noisy range–bearing observations of landmarks within its field-of-view (FOV). From the noisy data stream, your task is to estimate the following two parameters:

1) The robot's trajectory (i.e., localization)

2) The landmark positions (i.e., mapping)

This is a capstone project that brings together probability, state estimation, simulation, and robotics.

Tasks

Your implementation should perform the following:

1) The EKF prediction step

The EKF (Extended Kalman Filter) prediction step is where the robot applies a control input to its non-linear motion model. The robot predicts its next state and the uncertainty (caused by the motion).

The simplest motion model is the unicycle model (see ChatGPT). Since the motion model is non-linear, you will need to linearize the model by finding the Jacobian (hello Calculus 1&2, old friends). This step is what differentiates the Extended Kalman Filter (EKF) from the ordinary Kalman Filter where everything is already linear.

For your project, you can impose a trajectory that the robot must follow (i.e., a circle or a racetrack). However, since the motion model has noise, the robot's position can deviate from the ideal position (per the unicycle model) when a control input is applied. So you will also need to have simple feedback control that adjusts the control input based on where the robot thinks it is, or more precisely, how far off the robot thinks it is from the imposed trajectory (see ChatGPT).

2) The EKF measurement update

The robot only receives observations from landmarks within it's FOV. Prior to receiving an observation from a landmark, the robot uses meaningless data to populate the SLAM state for that landmark. The first time the robot receives a measurement from a landmark is when the robot "initializes" the state and predicts the location of the landmark.

All subsequent measurements from this landmark are used in the EKF update step, where the robot adjusts its estimation of the landmark position in the SLAM state. Prior to initialization, the estimate of the landmark is never updated.

This raises the question of how the robot knows a particular measurement corresponds to a particular landmark (see next task). The robot only updates the landmarks from which it receives measurements (i.e., those within its FOV).

3) Data Association

The robot receives measurements from landmarks within its FOV. However, there might be many such landmarks, each generating a noisy measurement. The robot does not know with certainty, which measurement corresponds to which landmark.

You will need to implement some logic which makes this association.

4) Visualization of Convergence

The robot's initial estimate of its own state and the landmark positions will be noisy. One could imagine a Gaussian blur around the true state that begins to clear as the robot continues along its trajectory receiving additional measurements along the way.

The trajectory itself should smoothen out as the robot improves the estimate of its own position and thus avoids over-correcting (or under correcting) to stay on the path. You should create a video of this process showing the true trajectory and landmark positions and the evolution of the SLAM state as it converges (hopefully) to the truth.

You can also play with the noise and see how long it takes for the "blur" to clear for different variances. You can plot the decrease in the mean-square error over a moving window as the robot laps around the predetermined trajectory. This gives you a feel for the EKF and its effectiveness.

Deliverables

1) A short technical report (5-6) pages that describes your implementation/derivation of steps 1-3. Include all equations pertaining to your model, prediction, update, and Jacobians. Also describe your rule for data association. Include your code. This deliverable focuses on the content not on the aesthetics. (10 points).

2) Plots and video showing convergence for both localization and mapping (10 points).

3) The report and plots should be well-organized and aesthetically pleasing with appropriate sections so I can easily follow your steps and train-of-thought. (10 points).

Due Date: December 15, 2025