

**Exercise 6: Recursive Least Squares**  
(to be returned on Dec 9th, 8:15)

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In this exercise you will implement a Recursive Least Squares (RLS) estimator and a forward simulation of a differential drive robot with unicycle dynamics. We will apply the RLS algorithm to position data of a 2-DOF movement in the  $X$ - $Y$  plane, measured with a sampling time of 0.0159 s.

**1. Recursive Least Squares applied to position data**

In this task you will implement the Recursive Least Squares (RLS) algorithm in PYTHON and tune the *forgetting factors*. We approximate the position data by a fourth order polynomial in order to obtain a linear-in-the-parameters (LIP) model. You can assume that the noise on the  $X$  and  $Y$  measurements is independent. The experiment starts at  $t = 0$  s.

- (a) CODE: Fit a 4-th order polynomial through the data using linear least-squares. Plot the data and the fit for the  $X$ - and  $Y$ -coordinate.

*Hint: You need one estimator for each coordinate.*

PAPER: Does the fit seem reasonable? Why do you think that is? (1 point)

- (b) CODE: Implement the RLS algorithm as described in the script (*Check section 5.3.1*) to estimate 4-th order polynomials to fit the data. Do not use forgetting factors yet. Plot the result against the data on the same plot as the previous question.

PAPER: Compare the LS estimator from (a) with the RLS estimator you obtain after processing  $N$  measurements. Please give an explanation for your observation. (2 points)

- (c) CODE: Add a forgetting factor  $\alpha$  to your algorithm and try different values for  $\alpha$ . Plot the results against the data.

PAPER: How does  $\alpha$  influence the fit? What is a reasonable value for  $\alpha$ ? (1 point)

- (d) PAPER: How can you compute the covariance  $\Sigma_p$  of the position, if you know the covariance of the estimator  $\Sigma_{\hat{\theta}}$ ?

*Hint: For a random variable  $\gamma = A\theta$ , where  $A$  is a matrix,  $\text{cov}(\gamma) = A\text{cov}(\theta)A^T$ .* (1 point)

- (e) CODE: Compute the *one-step-ahead* prediction at each point (i.e. extrapolate your polynomial fit to the next time step). We also provided code to plot the  $1\text{-}\sigma$  confidence ellipsoid around this point, and the data.

PAPER: Do the confidence ellipsoids grow bigger or smaller as you take more measurements? Why do you think that is? (2 points)

**2. Covariance approximation**

Consider a nonlinear function  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  that maps a random vector  $X = (X_1, \dots, X_n)^T$  to a scalar random variable  $Y$ , i.e.

$$Y = f(X) = f(X_1, \dots, X_n).$$

We have  $\mathbb{E}\{X\} = \mu_x = (\mu_1, \dots, \mu_n)^T$  and  $\text{cov}(X) = \Sigma_x \in \mathbb{R}^{n \times n}$ .

- (a) PAPER: Give an approximation of the expected value  $\mathbb{E}\{Y\}$  and the covariance matrix  $\text{cov}(Y)$  of  $Y$  using a first order Taylor expansion of  $f$  around  $\mu_x$ . (2 points)
- (b) PAPER: Suppose  $X_1, \dots, X_n$  are independent. Simplify your covariance approximation from part (a). (1 point)

*This sheet gives in total 10 points*