4. Trajectory estimation

Problem Set due Apr 8, 2020 05:29 IST *Completed*

Problem 4. Trajectory estimation, Part I

2/2 points (graded)

Note: For this problem, you may find this summary useful. (This is also available at the bottom of Lecture 15, *12. Multiple parameters; trajectory estimation*.)

The vertical coordinate ("height") of an object in free fall is described by an equation of the form

$$x(t) = \theta_0 + \theta_1 t + \theta_2 t^2,$$

where θ_0, θ_1, and θ_2 are some parameters and t stands for time. At certain times $t_1, \ldots, t_n$, we make noisy observations $Y_1, \ldots, Y_n$, respectively, of the height of the object. Based on these observations, we would like to estimate the object's vertical trajectory.

We consider the special case where there is only one unknown parameter. We assume that θ_0 (the height of the object at time zero) is a known constant. We also assume that θ_2 (which is related to the acceleration of the object) is known. We view θ_1 as the realized value of a continuous random variable Θ_1. The observed height at time t_i is $Y_i = \theta_0 + \Theta_1 t_i + \theta_2 t_i^2 + W_i,\ i = 1, \ldots, n$, where W_i models the observation noise. We assume that $\Theta_1 \sim N(0,1)$, $W_1, \ldots, W_n \sim N(0, \sigma^2)$, and that all these random variables are independent.

In this case, finding the MAP estimate of Θ_1 involves the minimization of

$$\theta_1^2 + \frac{1}{\sigma^2} \sum_{i=1}^{n} (y_i - \theta_0 - \theta_1 t_i - \theta_2 t_i^2)^2$$

with respect to θ_1.

1. Carry out this minimization and choose the correct formula for the MAP estimate, $\hat{\theta}_1$, from the options below.

- [ ] $\hat{\theta}_1 = \dfrac{\sum_{i=1}^{n} t_i\left(y_i - \theta_0 - \theta_2 t_i^2\right)}{\sigma^2}$

- [x] $\hat{\theta}_1 = \dfrac{\sum_{i=1}^{n} t_i\left(y_i - \theta_0 - \theta_2 t_i^2\right)}{\sigma^2 + \sum_{i=1}^{n} t_i^2}$

- [ ] $\hat{\theta}_1 = \dfrac{\sum_{i=1}^{n} t_i\left(y_i - \theta_0 - \theta_2 t_i^2\right)}{\sigma^2 + \sum_{i=1}^{n} \theta_2 t_i^2}$

- [ ] none of the above

✔

2. The formula for $\hat{\theta}_1$ can be used to define the MAP estimator,$\hat{\Theta}_1$ (a random variable), as a function of $t_1, \ldots, t_n$ and the random variables $Y_1, \ldots, Y_n$. Identify whether the following statement is true:

   The MAP estimator $\hat{\Theta}_1$ has a normal distribution.

   True ✔ **Answer:** True

Solution:

1. Setting the partial derivative with respect to θ_1 equal to zero, we obtain

$$\theta_1 - \frac{1}{\sigma^2}\sum_{i=1}^{n} t_i\left(y_i - \theta_0 - \theta_1 t_i - \theta_2 t_i^2\right) = 0,$$

   yielding the MAP estimate

$$\hat{\theta}_1 = \frac{\sum_{i=1}^{n} t_i\left(y_i - \theta_0 - \theta_2 t_i^2\right)}{\sigma^2 + \sum_{i=1}^{n} t_i^2}.$$

2. We have

$$\hat{\Theta}_1 = \frac{\sum_{i=1}^{n} t_i\left(Y_i - \theta_0 - \theta_2 t_i^2\right)}{\sigma^2 + \sum_{i=1}^{n} t_i^2}.$$

Recall that the observation model is $Y_i = \theta_0 + \Theta_1 t_i + \theta_2 t_i^2 + W_i$, and so we can rewrite the estimator as

$$\begin{aligned}\hat{\Theta}_1 &= \frac{\sum_{i=1}^n t_i\left(\Theta_1 t_i + W_i\right)}{\sigma^2 + \sum_{i=1}^n t_i^2} \\ &= \frac{\Theta_1 \sum_{i=1}^n t_i^2 + \sum_{i=1}^n t_i W_i}{\sigma^2 + \sum_{i=1}^n t_i^2}.\end{aligned}$$

We see that $\hat{\Theta}_1$ is a linear function of Θ_1 and $W_1, \ldots, W_n$, which are all normal and independent. Since a linear function of independent normal random variables is normal, it follows that $\hat{\Theta}_1$ is normal.

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You have used 1 of 1 attempt

Answers are displayed within the problem

Problem 4. Trajectory estimation, Part II

3/3 points (graded)

1. Let $\sigma = 1$ and consider the special case of only two observations ($n = 2$). Write down a formula for the mean squared error $\mathbb{E}\left[\left(\hat{\Theta}_1 - \Theta_1\right)^2\right]$, as a function of t_1 and t_2. Enter **t_1** for t_1 and **t_2** for t_2.

   $\mathbb{E}\left[\left(\hat{\Theta}_1 - \Theta_1\right)^2\right] =$

   1/(1+t_1^2+t_2^2)

   Answer: 1/(1+(t_1)^2+(t_2)^2)

   $\frac{1}{1+t_1^2+t_2^2}$

2. Consider the "experimental design" problem of choosing when to make measurements. Under the assumptions of the previous part, and under the constraints $0 \leq t_1, t_2 \leq 10$, find the values of t_1 and t_2 that minimize the mean squared error associated with the MAP estimator.

   $t_1 =$ 10 **Answer:** 10

   $t_2 =$ 10 **Answer:** 10

STANDARD NOTATION

Solution:

1. Using the previous problem *Trajectory estimation Part 1*, we can see, for the special case of $\sigma = 1$ and $n = 2$, that the estimation error is

$$\tilde{\Theta}_1 \triangleq \hat{\Theta}_1 - \Theta_1 = \frac{t_1 W_1 + t_2 W_2 - \Theta_1}{1 + t_1^2 + t_2^2}.$$

Since Θ_1, W_1, W_2 are all zero-mean, independent normal random variables, $\tilde{\Theta}_1$ is also a zero-mean normal random variable. Hence, the mean squared error is

$$\begin{aligned}\mathbb{E}\left[(\hat{\Theta}_1 - \Theta_1)^2\right] = \mathbb{E}\left[\tilde{\Theta}_1^2\right] = \text{var}\left(\tilde{\Theta}_1\right) &= \frac{\text{var}\left(\Theta_1\right) + t_1^2 \text{var}\left(W_1\right) + t_2^2 \text{var}\left(W_2\right)}{\left(1 + t_1^2 + t_2^2\right)^2} \\ &= \frac{1 + t_1^2 + t_2^2}{\left(1 + t_1^2 + t_2^2\right)^2} \\ &= \frac{1}{1 + t_1^2 + t_2^2}.\end{aligned}$$

2. In order to minimize the mean squared error found in the previous part, we should choose the observation times to be as large as possible. Under the constraints $0 \le t_1, t_2 \le 10$, we should choose $t_1 = t_2 = 10$. The intuition is that (since θ_0 and θ_2 are known constants), we are effectively making observations of the form

$$Z_i = \Theta_1 t_i + W_i.$$

Or equivalently, we are making observations of the form

$$Z_i' = \frac{Z_i}{t_i} = \Theta_1 + \frac{W_i}{t_i}.$$

When are these observations most informative? When the noise term is smallest, more precisely, when its variance is smallest. This corresponds to choosing t_i as large as possible.

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You have used 2 of 4 attempts

Answers are displayed within the problem

Discussion

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- Part 1-1. More explanation on the partial derivative part is needed. — 5
  Hi, I am trying to understand the process of computation in the answer for Part 1-1. I cannot understand how $\theta1$^2+1/σ...
- ? II.2 Explanation for minimizing MSE — 1
- STAFF - Deadline — 4
  Dear Staff, I was looking at the deadline given for my timezone and wanted to complete the exercise before the deadlin...
- ? where did I go wrong in question 4.II.1, when using conditional MSE? — 1
  Below goes my answer. My desire is to understand which step is a misstep. I understand the given solution, and mine s...
- ? Could someone share a more thorough solution to part 1? — 2
  Now that the deadline has passed, I am hoping that someone would be willing to share a more detailed solution for thi...
- PART II - Solution — 3
  I've been looking at the Solutions to the problem and wanted to ask if anyone knows for the mean squared error soluti...
- [Staff] Few basic questions. — 5
  Community TA
- ? [STAFF] Can I get another attempt at question 1 of part 1? — 2
  So I got the second question in part 1, however, I accidentally clicked the wrong answer for the first question, can I plea...
- Hint for Trajectory estimation, Part II (1) — 13
- Is t_1 constrained by t_2? — 4
  The question is vague-ish on that point, but want to clarify. Thank you
- Interpret answer to 4.II.2 — 2
  The answer looks "wrong" to me, though it works out mathematically. How do we interpret this?
- ? Part I - Minimization - do you need a lot of algebra? — 5
  I'm having a hard time with this problem set overall. For the minimization in part 1, do you need a lot of algebra to find ...
- ? Prob. 4: Part II (2) — 2
- ? Problem 4 - Part II - 2. Is t in in the range 0,10 continuous [0,10] or discrete {1,2,3,4,...10}? — 6