Lab Assignment A
Estimation

Examination:

- Submitted report in CANVAS.
- Demonstration of the estimators during the second session

Preparation:

- If not familiar with the double tank, read the manual and examine the model equations.
- Task 1 - 5 need to be completed before the lab.

1 Introduction

In this lab assignment different estimation techniques to recover system states and a fault state from measurement will be developed and assessed. The main aim is to study the Kalman Filter (KF) and the Extended Kalman Filter (EKF). The use of the EKF is optional!

If you have not been working with the double tank system before and do not have a model of it from a prior course, then you should read and perform the work which is indicated in *R7014E Double tank system.pdf*.

In case you run into trouble and the trouble shooting is not helpful, please contact us right away!

2 Problem description

Your task is to design and implement state estimators which are able to recover all the states of the system, where the emphasis is on level h_1. In addition, the opening of the leakage valve need to be estimated.

The estimation shall only be based on the measurement of h_2 and the known input u. The measurement of h_1 is then used as a ground truth value for the level in the upper tank. The implementation shall be done in Simulink. Any blocks are allowed to be used.

Note: The system does not need to operate in closed loop, which means you can select a fixed input u to the process. You do not need to design a controller.

2.1 Assumption

- Measurements: level measurement of the lower tank h_2
- Control signal: pump voltage u
- The pump can be represented by a static map $f(u)$
- The sensor calibration map $g(h)$ is only needed to map the voltage from the sensor to a level value in centimeters

2.2 Estimators, required and optional

You will design at least one estimator for the problem statement. The design and testing will be done on the following:

- stationary KF, either discrete or continuous time (mandatory)
- non-stationary discrete time KF (optional)
- discrete time EKF (optional)

Note: We will not use the direct term implementation of the Kalman filter in this lab.

2.3 Important aspects

- The variance measures (intensity) can be derived from data of the process. Be aware of obscure behaviour and discard it if necessary.
- It should also be noted that the performance of the estimators should be such that they could be used for closed loop control, where the settling time of the closed loop should be less than 80 seconds.
- The implementation of the non-stationary observers is a challenge, since you will have to implement matrix multiplications and store matrixes between calculation steps.

3 Model for the double tank process

For the estimator design you will need both the linear and non-linear model for the double tank process. These models need to be derived, preferably before the lab assignment session.

Task 1 *Derive the non-linear model for the tank process on the basis of the manual for the double tank setup*

Task 2 *Derive a linearize model from the non-linear model.*

For testing prior to the lab assignment session the following values can be used for the different parameters:

Cross section area tank	$A = 33$ cm^2
Cross section area outlets	$a = 0.16$ cm^2
Time constant	$T = 35$ s
Gain	$K = 5$ cm/V

Example sensor curve $g(h)$:

Level [cm]	Voltage [V]
3	0.56
5	2.18
6	2.9
7	3.7
8	4.5
10	6.1
11	6.8
12	7.6
14	9.2
15	9.9

Example pump curve $f(u)$:

Flow rate $[cm^3/s]$	Voltage $[V]$
16.47	0.5
20.75	1
24.52	1.5
27.63	2
30.06	2.5
32.49	3
34.80	3.5
40.28	5
48.24	8
52.43	10

4 Creation of the development environment

The development environment should enable you to develop and test your estimators before you run it with the real-life tank process. This means that you can test you design on the model of the process

Task 3 *Implement the linear and non-linear model of the tank process in Simulink. You need to add noise to the measurement values. You can do that with assumed parameters in the model.*

Task 4 *Design a startup sequence or initialization routine such that you are able to start the estimator in a proper way. Assume, the estimator is a subsystem now that is getting u and h_2 as input and provides $\hat{h}_1$ and $\hat{h}_2$ as output.*

While any stationary estimator can be easily implemented in Simulink, estimators which operate non-stationary or have varying characteristics are more difficult to implement. Blocks which are freely programmable might simplify the implementation step. The next task shows you an example of that.

Task 5 *Analyze the `embeddedM_example.slx`, which is provided. Implement it in your estimator block as you see fit.*

Note: You may also use other approaches like S-functions or direct implementation in Simulink.

Now the development environment is ready for designing and test of your estimators.

5 Estimator design for h_1 and h_2

Before we can design díscrete time estimators we need to have a discrete time model.

Task 6 *Derive a discrete time state space representation for your process model that reflects the system behaviour well.*

An alternative approach is of course to design a continuous time estimator and then discretize for implementation.

for each of the estimator(s) perform the following tasks:

Task 7 *Design the estimator according to the textbook or lecture notes*

Task 8 *Implement the estimator in the development environment*

Task 9 *Test the estimator in the development environment*

Now you have designed the estimator(s) and tested them. You will discover that the performance of the estimator is usually not perfect directly. It actually means that you need to adjust the covariance matrices in the design of the Kalman filter.

6 Comparison and experiments in the development environment

The key performance indicator for the estimators is the estimation error. There are three important properties of the estimation error:

1. Convergence time
2. (root) mean square error
3. bias

In order to explore the performance the following experiments need to be performed:

1. Estimation during normal operation at the operating point.
2. Estimation at 12 cm.
3. Estimation in the presence of a leakage flow.

The above properties should be compared between the different estimators and discussed in the report. You should also conclude which estimator performs best and why.

Task 10 *Compare the estimators using the above performance indicator. Do also compare the kalman gain over time for the estimators.*

7 Run the estimators on the real-life tank system

Now that the estimators are implemented and tested, they can be run on the real life tank system.

Task 11 *Copy the estimator(s) to a new Simulink blockdiagram and run them in parallel with the real-life tank system, according to the above experiments.*

Task 12 *Compare the estimators using the above performance indicator. Discuss which estimator performs best.*

8 Estimation of the leakage

In order to estimate the leakage flow you need to develop a disturbance model for the leakage flow. Thereafter, introduce it to process model as discussed in lecture 2. Moreover, the development environment has to be updated such that the valve opening is included.

Task 13 *Develop a leakage model which represents the opening area for the leakage in the bottom of the upper tank. You will need to linearize the model.*

Task 14 *Augment the process model with the leakage model. The opening area for the leakage will now become a state in the augmented process model.*

Task 15 *Update the development environment such that it can consider the leakage valve opening as an input signal that you can freely adjust*

Task 16 *Perform the design of an estimator as before but for the augmented process model*

Task 17 *Test and evaluate the performance of the estimator in simulation at the operating point where you test different leakage openings. Analyze the performance and potentially improve your design.*

Now the estimator is designed and tested in simulation. The next natural step is to test it in real-life.

Task 18 *Redo the former task but with the real-life process.*

9 Discussion and reporting

Now the practical aspects of the lab are concluded. The designs and tests need to be analyzed, compared and discussed. Remember to use plots to provide evidence for your results. It is important that you summarize how you have arrived at your implementation and the results.