Homework 3B: Current Sensor Fault

Report

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The homework exercise is based on a simulation of a DC motor. There are two models, one for healthy state and the other for faulty state. Two sensors are modelled: rotation speed and current. It is assumed that current sensor is not woking from time to time, and the task is to detect the faulty regions.

Steps to solve the problem

1) Create a model of DC motor with augmented unmeasurable load
2) Create faulty model
3) Check observability
4) Define noise properties
5) Implement IMM
6) Trace unmeasurable load
7) Compare the result with Kalman Filter using only rotation sensor

Problem 1: Design the bank of state-space models to model healthy and faulty behaviour.

Problem Statement:

```
% Design healthy (m=1) state-space model
% Design faulty  (m=2) state-space model
```

```
% Find controller gain K_p to keep current limited to 200 A and no
% overshoot
% Analyse observability of m1
% Analyse observability of m2
```

Solution:

Healthy:

$$\begin{bmatrix} \dot{\omega} \\ \dot{i} \\ \dot{T_{load}} \end{bmatrix} = \begin{bmatrix} 0 & \frac{K_m}{J} & 1/J \\ -\frac{K_p}{L} & -\frac{R+K_m}{L} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ i \\ T_{load} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_p}{L} \\ 0 \end{bmatrix} \omega_{ref} + \begin{bmatrix} e_\omega \\ e_i \\ e_{T_{load}} \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ i \\ T_{load} \end{bmatrix} + 0$$

, where e are random noises

Faulty:

$$\begin{bmatrix} \dot{\omega} \\ \dot{i} \\ \dot{T_{load}} \end{bmatrix} = \begin{bmatrix} 0 & \frac{K_m}{J} & 1/J \\ -\frac{K_p}{L} & -\frac{R+K_m}{L} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ i \\ T_{load} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_p}{L} \\ 0 \end{bmatrix} \omega_{ref} + \begin{bmatrix} e_\omega \\ e_i \\ e_{T_{load}} \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ i \\ T_{load} \end{bmatrix} + 0$$

```
% Motor parameters
R = 0.1;                    % Ohms
L = 0.5;                    % Henrys
Km = 0.5;                   % motor constant
J = 10;                     % kg.m^2/s^2

% Designed P controller gain
Kp = 2;
```

Disturbance (Load torque) has been modelled as pseudo-binary signal from -40 to 60 Nm, therefore depicting changing torque values with mean 50 and deviation +- 10 Nm.

Reference rotation speed was selected as a rising signal from 0 to 100 rad/s.

The number of samples is selected to be equal to 1500

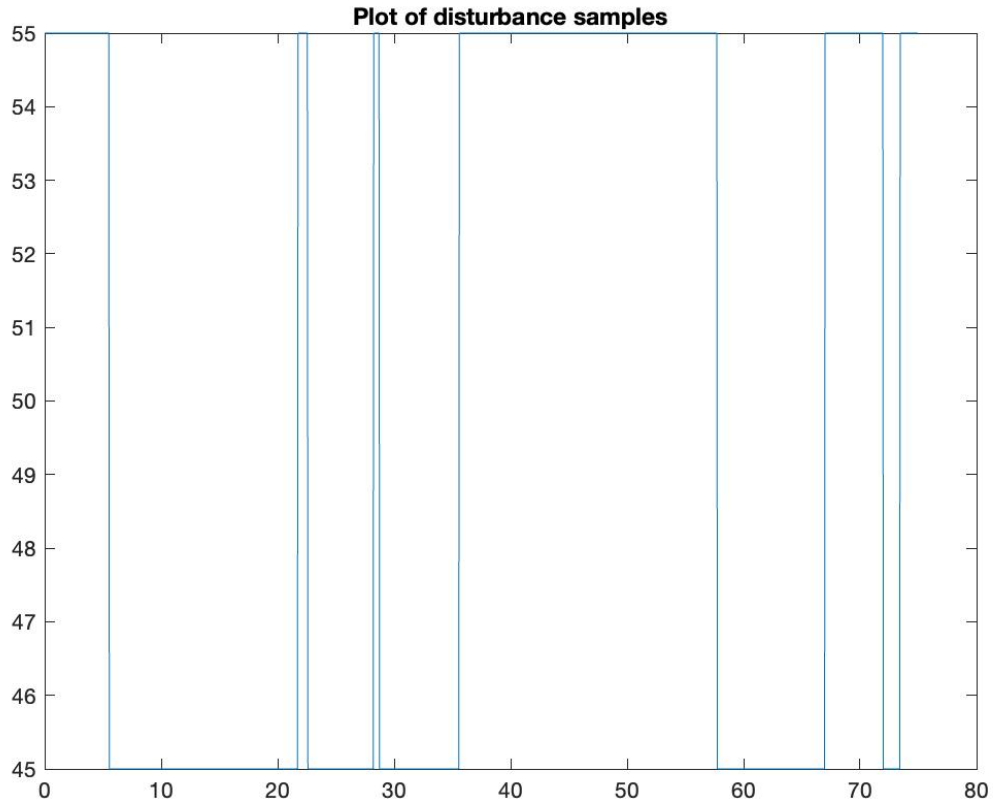

Fig.1 Disturbance (Nm) vs time (s)

It is possible to observe that even with simple P controller it is possible to achieve reasonable behaviour. Previously, it was thought that some more complicated PID controller could be beneficial. Nevertheless, the controller tracks the reference:

And the current is within bounds of +- 200 A:

Observability of the two systems have been identified with number of unobservable modes being equal to 0 for both cases.

Problem 2: Process-noise properties. Input-output data generation.

Problem Statement:

```
% Select and justify process noise properties
```

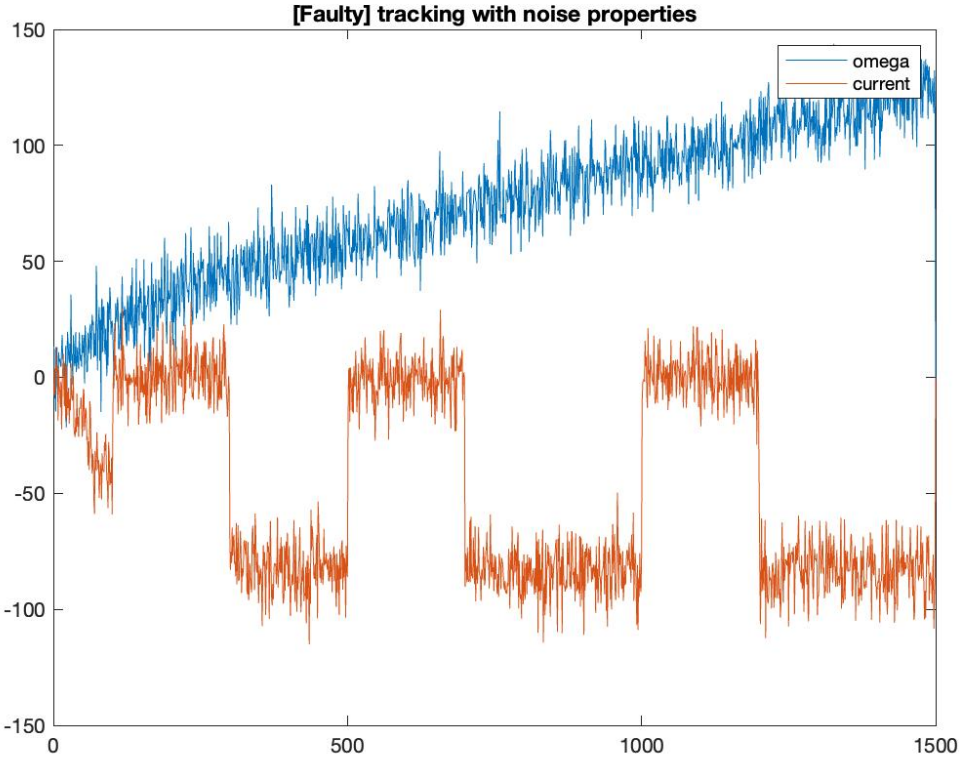

Fig.3 Response of system with faults

```
% Find input-output data with multiple sensor faults
```

Solution

For solving this task, the equations for noise properties of sampling were obtained. (Slide 108 in the course's lecture slides)

$$\epsilon = \frac{T_s - T_c}{T_s}$$
$$A_{async} = e^{A_c T_s}$$
$$B_{async} = \int_0^{T_s} e^{A_c \nu} d\nu B_c$$
$$C_{async} = C_c e^{A_c \epsilon Ts}$$
$$D_{async} = C_c \int_0^{\epsilon T_s} e^{A_c \nu} d\nu B_c$$
$$Q = \int_0^{T_s} e^{A_c \nu} Q_c e^{A_c^T \nu} d\nu$$

$$S = \int_0^{\epsilon T_s} e^{A_c \nu} Q_c e^{A_c^T \nu} C_c^T d\nu$$

$$R = \int_0^{\epsilon T_s} C_c e^{A_c \nu} Q_c e^{A_c^T \nu} C_c^T d\nu + R_c$$

Equations from slides, asynchronous schema

The controller time Tc is selected as 0.01. Sampling Ts time is given and is equal to 0.05 s.

With the selection of corresponding matrices A and A_f, B and B_f, C and C_f, D and D_f, the models of each of the two mode-dependent Kalman Filters were constructed.

The faulty signal is obtained by calculating state from faulty models at certain periods of the whole time of simulation. The Fig.3 that depicts the situation.

It can be observed that there are three occasions where sensor does not work and its signal is equal to zero.

Problem 3: IMM design. Faults detection. Estimation of load.

Problem Statement:

```
% Design IMM algorithm
% Evaluate unmeasurable load
% Detect faults of current sensor
% p12 = 0.001 transition to fault
% p21 = 0.005 recovery
```

Solution:

In order to implement Iteractive-Multiple Models filter that would track two modes of operation of the current sensor on DC motor, two Kalman filters that run at the same time were constructed. Unlike included in Matlab function "kalman", the algorithm had to run each step of the KF in parallel. This was achieved by taking each step of KF twice: one of mode "healthy" and one for mode “faulty”.

It can be seen that there are three noisy regions of estimated signal, exactly at points of faults. Corrupted current signal results in corrupted estimation of load. Fig.4

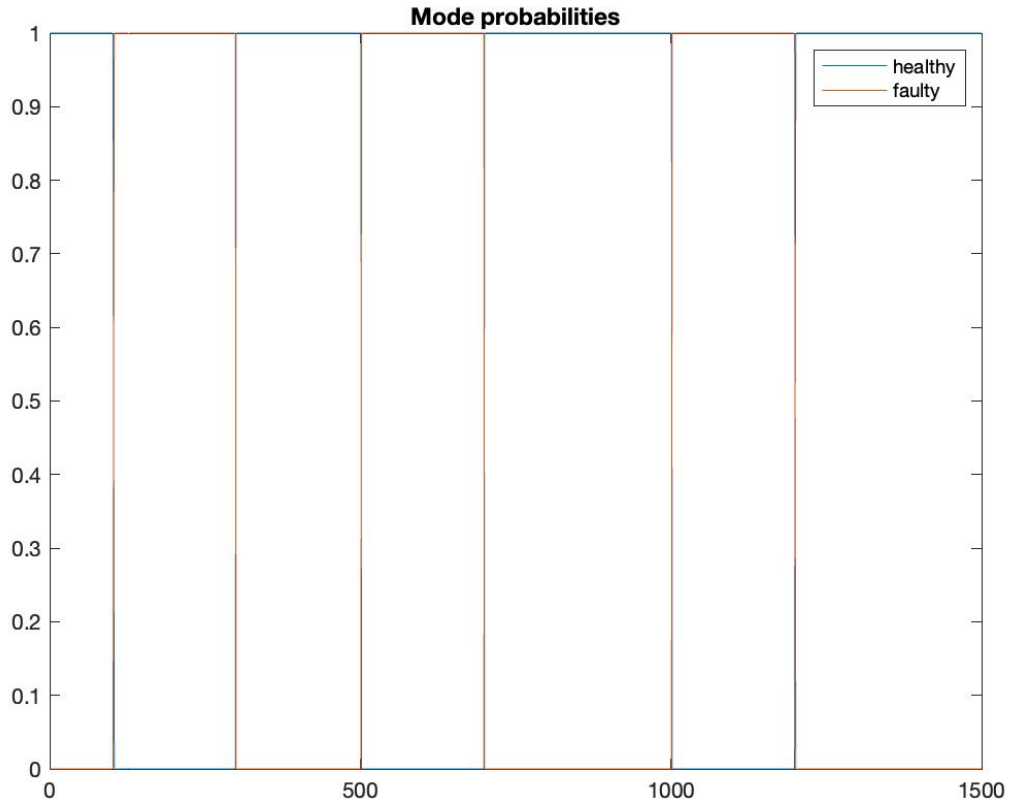

Fig. 4 Estimated load and ground truth load [Nm] vs samples (N=1500)

Unmeasurable torque is computed from the estimation of the third T_{load} state of the system. Fig.5

Problem 4: Analysis of performance, comparison to single rotation speed Kalman Filter, justification of usage of current sensor

Problem Statement:

```
% Analyse the performance of fault detection
% Compare IMM to KF using only rotation speed sensor
% Is it possible to justify use of current sensor?
```

Solution:

The performance of the algorithm is outstanding with MSE error less than 1.

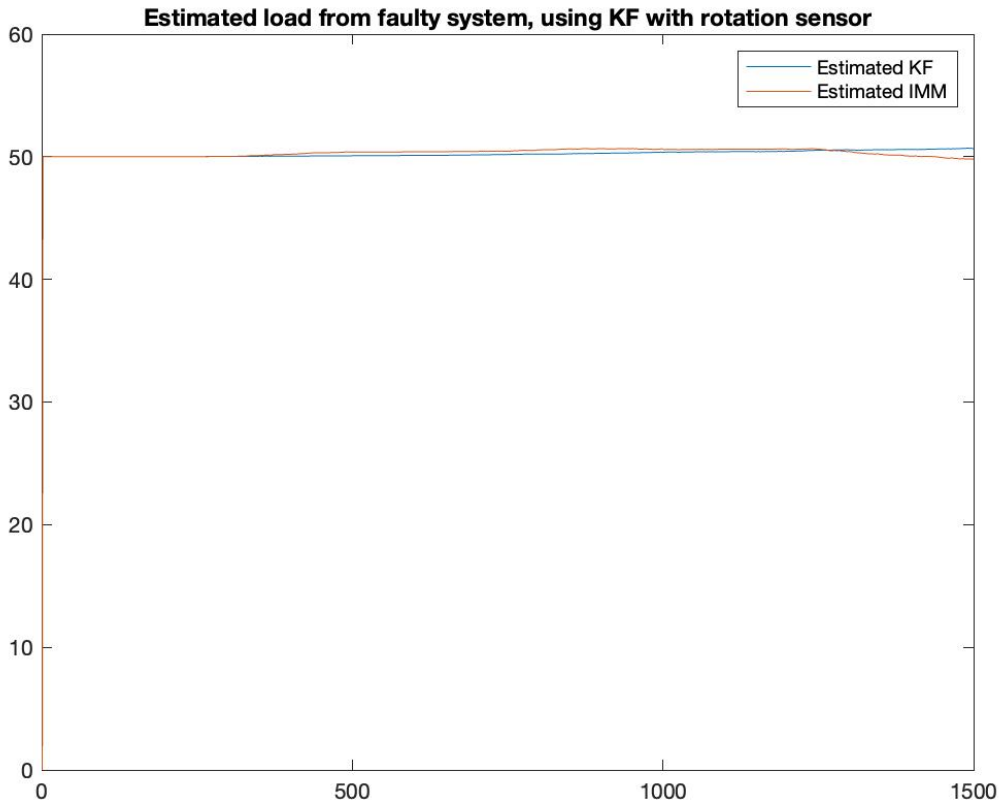

Fig. 5 Estimated from Kalman Filter and IMM

The difference between load estimation between IMM and KF is 1.3246

Problem 5: Lessons learned

1) IMM is best suited for fault detection

2) KF using only rotation speed sensor can be enough for estimation of load