Responses to Prof. Attila Magyar as dissertation reviewer

by **Wijaya Kurniawan**

University of Pannonia
Hungary
2024

First, I would like to thank Prof. Attila Magyar for his attention, time, and effort in reviewing my dissertation titled *Model based fault diagnosis in networked linear time invariant systems.* His reviews are very valuable in increasing the quality of my dissertation since my home defence. Following his suggestions, I could improve the format and figures in my dissertation. Also, by his comments, I have been able to enhance the content so that the readers can easily understand the motivations, problem statements, and the position of my work compared to others.

Then, in the following, I provide my responses to his comments and questions related to my dissertation's final version for my final defence.

Comments / Questions 1

"However, it is not clear to me why the overviews at the beginning of the chapters and in section 1.1 (Background and motivations) were separated."

Answer:
The purpose of Section 1.1. (Background and motivations) is to provide the big picture about the position of my research work as a whole related to the current situation. Also, it tries to explain why the chosen objects are robot platoons and heat exchanger networks.

Meanwhile, the overviews at the beginning of each chapter provide the position of that specific research object compared to other existing works (e.g. the overview at the beginning of Chapter 3 gives a picture of model based fault diagnosis research that has been done in robot platoons).

Comments / Questions 2

"The results of Chapter 3 were developed for wheeled mobile robot platoons, which means a linear formation. How could the proposed sensor and actuator fault diagnosis methods be generalized for formations different from straight line, e.g. for vehicles moving in closed formation (square, triangle, etc)?"

Answer:
The movement of the mentioned closed formation can be described in two-axis coordinates compared to the movement in a straight line that is only along one-axis. One simple example can be seen in Appendix A.1 in the dissertation as follows:

An object in a two-dimensional (2D) space moves in xy coordinate system where (x_0, y_0) is its initial condition and (v_x, v_y) is its velocity as shown in Fig 1.

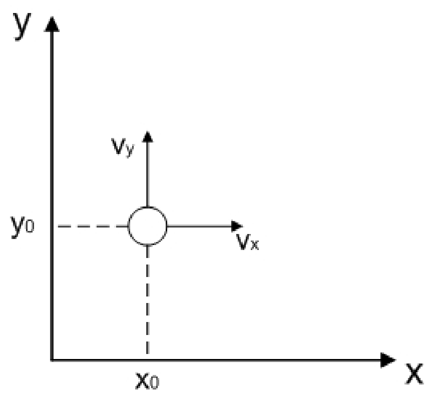

Figure 1: A mechanical system example

It is assumed that the object's acceleration $\dot{\boldsymbol{v}}$ depends on its related position $\boldsymbol{p}$, velocity $\boldsymbol{v}$, and a control input u. The measurement is done on the object's position.

Then, the model of the object's motion can be written as:

$$\begin{aligned}
\begin{bmatrix} \dot{p_x} \\ \dot{p_y} \\ \dot{v_x} \\ \dot{v_y} \end{bmatrix} &= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ c_1 & 0 & c_2 & 0 \\ 0 & c_3 & 0 & c_4 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ v_x \\ v_y \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ c_5 \\ c_6 \end{bmatrix} u \\
\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ v_x \\ v_y \end{bmatrix}
\end{aligned} \tag{1}$$

where c_1, c_2, c_3, c_4, c_5, and c_6, are system parameters.

Now, by referring to Sections 3.3.1. in the dissertation, consider a closed formation consisting of N number of objects/agents where each of them moves as in the previous example. Furthermore, to maintain a specific desired formation, the control of each agent are influenced by the neighbour's outputs so that the dynamics can be written in a general form as follows:

$$\begin{aligned}
\dot{\boldsymbol{x}}^{(\boldsymbol{j})} &= A^{(j)}\boldsymbol{x}^{(\boldsymbol{j})} + B^{(j)}\boldsymbol{u_c}^{(\boldsymbol{j})} + I^{(j)}\boldsymbol{i}^{(\boldsymbol{j})} \\
\boldsymbol{y}^{(\boldsymbol{j})} &= C^{(j)}\boldsymbol{x}^{(\boldsymbol{j})}
\end{aligned} \tag{2}$$

where $j = 1, 2, 3 \ldots N$ represents the jth agent, $\boldsymbol{u_c}^{(\boldsymbol{j})}$ is the local control input, and $\boldsymbol{i}^{(\boldsymbol{j})}$ is the interconnection input.

Also:

$$i^{(j)} = Ly^{(k)}$$

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ . \\ . \\ . \\ i_N \end{bmatrix} = \begin{bmatrix} 0 & L_{12} & L_{13} & . & . & . & L_{1N} \\ L_{21} & 0 & L_{23} & . & . & . & L_{2N} \\ L_{31} & L_{32} & 0 & . & . & . & L_{3N} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ L_{N1} & L_{N2} & L_{N3} & . & . & . & 0 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ . \\ . \\ . \\ y_N \end{bmatrix} \tag{3}$$

Here, $\boldsymbol{i}^{(j)}$ represents the effect of the neighbour's outputs $\boldsymbol{y}^{(k)}$ on each agent j via the adjacency matrix L.

After that, the sensor and/or actuator fault that wants to be diagnosed can be inserted into the agent's dynamics in Eqs (2) and (3) to form a generalized model as follows:

$$\begin{aligned} \dot{\boldsymbol{x}}^{(j)} &= A^{(j)}\boldsymbol{x}^{(j)} + B^{(j)}(\boldsymbol{u}^{(j)} + \boldsymbol{f_a}^{(j)}) + I^{(j)}(\boldsymbol{i}^{(j)} + \boldsymbol{\delta i}^{(j)}) \\ \boldsymbol{y}^{(j)} &= C^{(j)}\boldsymbol{x}^{(j)} + \boldsymbol{f_s}^{(j)} + \boldsymbol{w}^{(j)} \end{aligned} \tag{4}$$

where $\boldsymbol{f_a}^{(j)}$ is the actuator fault, $\boldsymbol{f_s}^{(j)}$ is the sensor fault, $\boldsymbol{w}^{(j)}$ is the measurement noises, and $\boldsymbol{\delta i}^{(j)}$ is the disturbance term that describes the faults propagation through network.

Thus, as long as the assumptions and some observability conditions are satisfied, the proposed actuator and sensor fault diagnosis method (see Sections 3.3.2. and 3.5. in the dissertation) can be applied to this closed formation case because the methods are built based on the general model shown in Eq (4).

Comments / Questions 3

"It is clear that each thesis is strongly application-centric. Do you see potential application areas that are different from the current ones (robot sections, heat exchangers) but belong to a similar problem class as the ones investigated?"

Answer:

In the case of sensor fault diagnosis method, the proposed method can be applied for a more general class of LTI systems as it is described in Section 3.3.1. of the dissertation.

For the results of heat exchangers, one potential application area is the transport mechanism of chemical reactions between chemical reactors. As an example, consider three connected chemical reactors with first order reaction in each as shown in Fig 2.

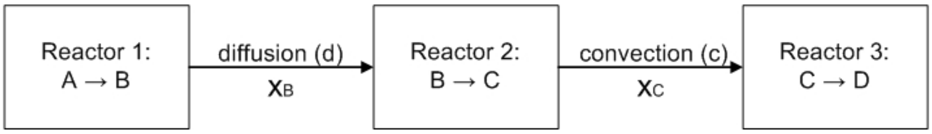

Figure 2: A simple example of transport mechanism for chemical concentration.

Now, let us focus on the diffusion d and convection c as the transport mechanism for substance B from reactor 1 to reactor 2 and substance C from reactor 2 to reactor 3 respectively. The states are the concentration of B (x_B) and C (x_C). Also, assume that the connections d and c consist of n lumped sections for each of them.

Then, for diffusion connection, the state equations for the transport mechanism can be written as follows:

$$\begin{aligned}
&\dot{\boldsymbol{x}} = A_d\boldsymbol{x} + B_d\boldsymbol{u}\\
&\boldsymbol{y} = C_d\boldsymbol{x}\\
&\boldsymbol{x} = \begin{bmatrix} x_{B1} & x_{B2} & x_{B3} & \ldots & x_{Bn}\end{bmatrix}^T \quad ,\\
&\boldsymbol{u} = \begin{bmatrix} u_1 & u_2\end{bmatrix}^T \quad , \quad \boldsymbol{y} = \begin{bmatrix} y_1 & y_2\end{bmatrix}^T \quad ,\\
&A_d = \begin{bmatrix} -2d & d & 0 & 0 & \ldots & \ldots & \ldots & 0\\ d & -2d & d & 0 & \ldots & \ldots & \ldots & 0\\ 0 & d & -2d & d & \ldots & \ldots & \ldots & 0\\ 0 & \ldots & \ldots & \ldots & \ldots & d & -2d & d\\ 0 & \ldots & \ldots & \ldots & \ldots & 0 & d & -2d\end{bmatrix}\\
&B_d = \begin{bmatrix} 1 & 0 & 0 & \ldots & 0\\ 0 & 0 & 0 & \ldots & 1\end{bmatrix}^T \quad , \quad C_d = \begin{bmatrix} 0 & 0 & 0 & \ldots & d\\ d & 0 & 0 & \ldots & 0\end{bmatrix}
\end{aligned} \tag{5}$$

where x_{Bi} for $i = 1, 2, 3 \ldots n$ is the concentration of B at the ith lumps and d is the diffusion coefficient.

On the other hand, for convection connection, the state equations can be written as follows:

$$\begin{aligned}
&\dot{\boldsymbol{x}} = A_c\boldsymbol{x} + B_c\boldsymbol{u}\\
&\boldsymbol{y} = C_c\boldsymbol{x}\\
&\boldsymbol{x} = \begin{bmatrix} x_{C1} & x_{C2} & x_{C3} & \ldots & x_{Cn}\end{bmatrix}^T \quad ,\\
&\boldsymbol{u} = u \quad , \quad \boldsymbol{y} = y \quad ,\\
&A_c = \begin{bmatrix} -v & 0 & 0 & \ldots & \ldots & 0\\ v & -v & 0 & \ldots & \ldots & 0\\ 0 & v & -v & \ldots & \ldots & 0\\ 0 & \ldots & \ldots & v & -v & 0\\ 0 & \ldots & \ldots & \ldots & v & -v\end{bmatrix}\\
&B_c = \begin{bmatrix} 1 & 0 & 0 & \ldots & 0\end{bmatrix}^T \quad , \quad C_c = \begin{bmatrix} 0 & 0 & 0 & \ldots & v\end{bmatrix}
\end{aligned} \tag{6}$$

where x_{Ci} for $i = 1, 2, 3 \ldots n$ is the concentration of C at the ith lumps and v is the convection coefficient.

From both Eqs (5) and (6), it can be seen that they are similar to the heat exchangers dynamical system model in Chapters 4 and 5 of the dissertation (see also the note about Metzler matrix in Appendix A.2 in the dissertation). Since the proposed fault diagnosis method is built based on that model, then it should also apply to the chemical concentration transport mechanism problem.

Finally, I remark that the generalization of the fault isolation method with loops in heat exchangers (see Appendix E in the dissertation) has been accepted to be presented at the 10th International Conference on Control, Decision, and Information Technologies 2024 (CODIT 2024).

Veszprem, 2 May 2024

Wijaya Kurniawan