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Plug-and-play diagnosis with limited model information

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1 Introduction

This project focuses on interconnected systems with N subsystems S_i controlled by N decentralised control stations C_i. It considers the local detection of a fault f which can occur in subsystem S_1 taking into account that the fault has also effects on the other subsystems through the physical couplings (Fig. 1).

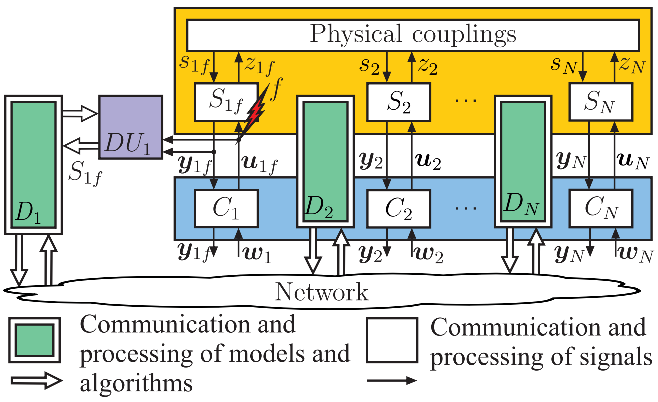


Figure 1: Plug-and-play diagnosis

Plug-and-play diagnosis is described here as a concept to organise the design steps of a local diagnostic unit without having a global coordinator available. In line with this concept, there exist N identical design agents D_i (double framed boxes in Fig. 1) which are assigned to the respective subsystem S_i. Each design agent stores the local models S_i and C_i of the corresponding subsystem and control station as well as the information about the couplings.

The design agent D_1 organises the design steps of the diagnostic unit DU_1, which particularly consists of a model-based residual generation and a residual evaluation in order to detect the fault. Accordingly, based on the initially available information, the design agent D_1 has to procure the models from other design agents D_i (double arrows in Fig. 1) to set-up a model with input $\boldsymbol{u}_{1f}(t)$ and output $\boldsymbol{y}_{1f}(t)$ that is used for the residual generation. In a second step, the design agent D_1 has to fix a detection threshold to guarantee the detection of the fault.

In summary, the project is devoted to the question:

> *Which models have to be communicated among the design agents D_i over the network so as to enable the design agent D_1 to design a local diagnostic unit?*

Previous projects have dealt with plug-and-play reconfiguration as a concept to organise the reconfiguration of C_1 without a global coordination [1,2]. By the combination of plug-and-play reconfiguration and plug-and-play diagnosis a comprehensive fault-tolerant control scheme for interconnected systems is created.

2 Limit the model information

From the local perspective of the design agent D_1 the faulty system with input $\boldsymbol{u}_{\mathrm{f}1}$ and output $\boldsymbol{y}_{\mathrm{f}1}$ consists of the faulty subsystem S_{1f}

$$S_{1f}: \begin{cases} \boldsymbol{y}_{1f}(t) &= \boldsymbol{S}_{\mathrm{yu}1f}(t) * \boldsymbol{u}_{1f}(t) + \boldsymbol{S}_{\mathrm{ys}1f}(t) * s_{1f}(t) \\ z_{1f}(t) &= \boldsymbol{S}_{\mathrm{zu}1f}^{\top}(t) * \boldsymbol{u}_{1f}(t) + S_{\mathrm{zs}1f}(t) * s_{f1}(t) \end{cases}$$

and of all controlled subsystems $F_i|_{w_i=0}$, $(i{=}2, ..., N)$

$$F_i|_{w_i=0}: \; z_i(t) = F_{\mathrm{zs}i}(t) * s_i(t) \qquad (1)$$

illustrated in Fig. 2. In this project a local interconnection structure is considered, represented by the interconnection model

$$K: \begin{pmatrix} s_{\mathrm{f}1}(s) \\ s_2(s) \\ \vdots \\ s_N(s) \end{pmatrix} = \begin{pmatrix} 0 & l_{12} & \cdots & 0 \\ l_{21} & 0 & \ddots & 0 \\ \vdots & \ddots & 0 & l_{N-1N} \\ 0 & 0 & l_{NN-1} & 0 \end{pmatrix} \cdot \begin{pmatrix} z_{\mathrm{f}1}(s) \\ z_2(s) \\ \vdots \\ z_N(s) \end{pmatrix}.$$

Due to this coupling structure, the dynamics of the faulty system can essentially be characterised by the dynamics of S_{1f} and of some controlled subsystems $F_i|_{w_i=0}$, $(i{=}2, .., w{-}1)$ combined to the model P_{1f}, shown in Fig. 2. In contrast to this, the dynamics of the other controlled subsystems $F_i|_{w_i=0}$, $(i{=}w, .., N)$ have a negligible influence and are combined to the error system

$$E_1: \; q_1(t) = E_1(t) * p_1(t).$$

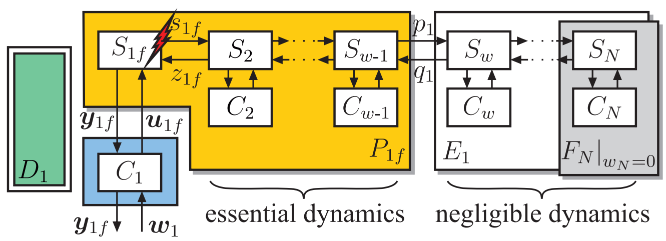


Figure 2: Limit the model information for diagnosis

To limit the amount of model information for diagnosis, the dynamics $F_{\mathrm{zs}i}(t)$, $(i{=}w, .., N)$ of (1) are only known as upper bounds $\bar{F}_{\mathrm{zs}i}(t) \geq |F_{\mathrm{zs}i}(t)|$. The combination of these upper bounds yields an upper bound on the error dynamics $\bar{E}_1(t) \geq |E_1(t)|$.

Without a global coordinator, the design agent D_1 initially knows only the local model S_{1f}, C_1 and K. Hence, D_1 has to search for the relevant models $F_i|_{w_i=0}$ and has to gather these models through the network using Alg. 1.

3 Local diagnosis

The local diagnostic unit DU_1 consists of a residual generation and a residual evaluation described in the following.

The residual generator only makes use of the relevant models, combined in the model P_1. The residual generator denoted by O_1 is represented by the I/O-oriented model

$$O_1 : \ \boldsymbol{r}_1(t) = \boldsymbol{O}_{\mathrm{ru}1}(t) * \boldsymbol{u}_1(t) + \boldsymbol{O}_{\mathrm{ry}1}(t) * \boldsymbol{y}_1(t). \qquad (2)$$

As there is neither a global models available for the residual generation nor for the analysis of the residual, there exists a residual $\boldsymbol{r}_1(t)$ in the fault-free case, which is only known to be located in a tube

$$|\boldsymbol{r}_1(t)| \in \mathbb{T}_1(t) = \Big[\boldsymbol{0},\ \bar{\boldsymbol{r}}_{\Delta 1}(t)\Big].$$

The tube can be determined by the connection of the locally known models P_1, C_1, $\bar{E}_1$ and O_1. Similarly, in the faulty case, a tube around the residual $\boldsymbol{r}_{1f}(t)$ results to

$$|\boldsymbol{r}_{1f}(t)| \in \mathbb{T}_{1f}(t) = \Big[\max(\boldsymbol{0},\ |\hat{\boldsymbol{r}}_{1f}(t)| - \bar{\boldsymbol{r}}_{\Delta 1f}(t)),\ |\hat{\boldsymbol{r}}_{1f}(t)| + \bar{\boldsymbol{r}}_{\Delta 1f}(t)\Big]$$

from the analysis of the combination of the models P_{1f}, C_1, $\bar{E}_1$ and O_1.

Both tubes $\mathbb{T}_1(t)$ and $\mathbb{T}_{1f}(t)$ are known by D_1 during the design process of the diagnostic unit. From the evaluation of these tubes, the next theorem has been derived in [3].

Theorem 1. (Guaranteed fault detection with limited model information) *Consider the residual generator* (2). *There exists a constant detection threshold* $\boldsymbol{\mu}$, *if*

1. *the fault is detectable with limited model information*

$$\exists t \in [t_{\mathrm{f}}, \infty) : \quad \mathbb{T}_{1f}(t) \cap \mathbb{T}_1(t) = \emptyset, \qquad (3)$$

2. *a false alarm is avoided*

$$\exists t \in [t_{\mathrm{f}}, \infty) : \quad \mathbb{T}_{1f}(t) > \max_t \mathbb{T}_1(t). \qquad (4)$$

Consequently, the fault is detected online, if

$$|\boldsymbol{r}_{1f}(t)| > \boldsymbol{\mu} =: \max_t \mathbb{T}_1(t). \qquad (5)$$

4 Plug-and-play diagnosis of a multizone furnace

This section proposes the organisation steps D_1 has to perform in order to design the local diagnostic unit. It is shown that D_1 can decide with locally available model information whether the model $F_i|_{w_i=0}$ is relevant or not.

The procedure is applied to a multizone furnace, which consists of four locally interconnected heating zones shown in Fig. 3. The considered fault is a reduced actuator action in zone 1, modelled by S_{1f}. To design the local diagnostic unit DU_1, the design agent D_1 runs Alg. 1.

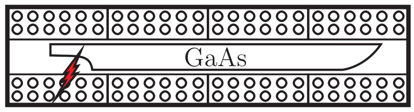


Figure 3: Multizone furnace

Algorithm 1. (Plug-and-play diagnosis by D_1)

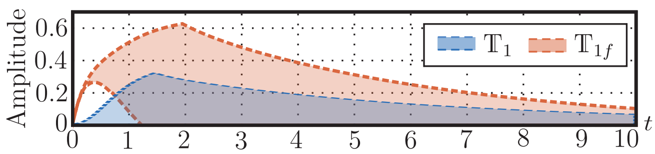
Given: • *D_1 knows S_1, C_1, K and S_{1f}*
• *D_i knows S_i, C_i, $(i = 2, ..., N)$*

Proceed at D_1:

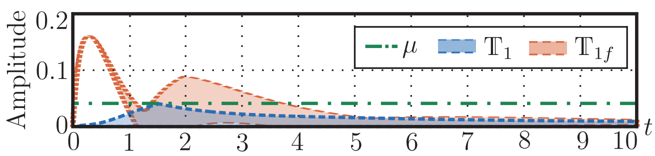
1. *Procure upper bounds: Request $\bar{F}_{\mathrm{zs}i}(t) \geq |F_{\mathrm{zs}i}(t)|$ from D_i, $(i = 2, ..., N)$ and set $k = 2$*
2. *Design O_1 and determine $\mathbb{T}_1(t)$ and $\mathbb{T}_{1f}(t)$*
3. *Check the condition* (3) *and* (4). `If` *the conditions are satisfied,* `then` *choose $\boldsymbol{\mu}$ in accordance with* (5) *and STOP (DU_1 exists),* `else` *goto 4.*
4. `If` *$k \leq N$,* `then` *D_k transmits the local models S_k, C_k through the network to D_1, $k = k + 1$ and goto 2.,* `else` *STOP (DU_1 does not exist).*

Result: Local diagnostic unit DU_1.

At Step 1, the upper bounds are gathered from the design agents D_i, $(i = 2, 3, 4)$ so as D_1 can design the residual generator O_1 and can analyse the tubes (Step 2). Fig. 4(a) shows that although the fault is detectable, no constant detection threshold exists. Hence, D_1 requests the model $F_2|_{w_2=0}$ from D_2 (Step 4) and redesigns O_1 considering the neighbouring subsystem's dynamics. For this case, the tubes are shown in Fig. 4(b). It can be seen, that by using only the model of zone 2, the considered fault can be detected by a constant detection threshold μ.



(a) Tubes from the exact models of D_1



(b) Tubes from the exact models of D_1 and D_2

Figure 4: Resulting tubes during the design process

References

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[3] S. Bodenburg, and J. Lunze. Plug-and-play diagnosis of locally interconnected systems with limited model information. In *Proc. 3rd Conference on Control and Fault-Tolerant Systems*, 2016, (submitted).