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Plug-and-play reconfiguration with limited model information

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1 Plug-and-play reconfiguration

This project focuses on interconnected systems with N subsystems S_i controlled by N decentralised control stations C_i. It considers the situation that an actuator failure or sensor failure occurs at subsystem S_1 and the control station C_1 has to be reconfigured using only local information. The crucial point of this situation is that due to the physical interaction between the faulty subsystem $S_{\mathrm{f}1}$ and the other subsystems S_i, $(i{=}2, ..., N)$ overall system stability can no longer be guaranteed.

Plug-and-play reconfiguration states an automated solution to this problem. The focus is on the modelling of subsystem $S_{\mathrm{f}1}$ under the influence of the physical interactions to reconfigure the control station C_1 in order to satisfy global system stability. The main idea is to use N design agents D_i that have a local view of the overall system. The design agent D_1 of the faulty subsystem has available only local information, i.e., exact model information of its subsystem S_1, its faulty subsystem $S_{\mathrm{f}1}$, its control station C_1 and information about the physical coupling K. First, the design agent D_1 has to organise the online exchange of model information among other design agents (shown as double arrows in Fig. 1) to model the effect of the physical interactions. Second, the control station C_1 is reconfigured automatically based on the gathered model information, now available to design agent D_1, to guarantee overall system stability.

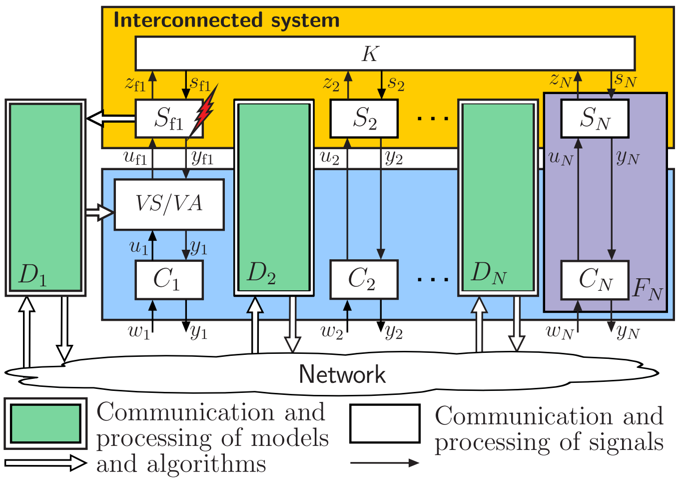

Figure 1: Plug-and-play reconfiguration

For reconfiguration, a virtual sensor (*VS*) or a virtual actuator (*VA*) [1] is utilised. Results of the previous project have been highlighted that a *VS*/*VA* can be designed based only on the local information of the design agent D_1 [2, 3] with the consequence of conservative stability conditions. In addition, a framework for exchanging models for MATLAB/Simulink is given [4]. In summary, the project aims are twofold:

1. Modelling of $S_{\mathrm{f}1}$ under the influence of the physical interconnection
   (a) procurement of models over the network and
   (b) composition of the model information
2. Analysis of the interactions among the design agents

2 Reconfiguration of C_1 with a *VS*

The reconfiguration of C_1 with a *VS* after the occurrence of a sensor failure at subsystem S_1 is considered. The model $S_{\mathrm{f}1}$ of the faulty subsystem is given by

$$S_{\mathrm{f}1}: \begin{cases} y_{\mathrm{f}1}(s) = S_{\mathrm{yuf}1}(s)u_{\mathrm{f}1}(s) + S_{\mathrm{ysf}1}(s)s_{\mathrm{f}1}(s), \\ z_{\mathrm{f}1}(s) = S_{\mathrm{zu}1}(s)u_{\mathrm{f}1}(s) + S_{\mathrm{zs}1}(s)s_{\mathrm{f}1}(s) \end{cases}$$

influencing all other subsystems through the couplings

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

Fig. 2 shows that from the local view of D_1, all other subsystems are classified in strongly coupled subsystems which have a major effect on the I/O-pair (z_1, s_1), lumped together to $\hat{R}_1{=}comb\big(\{S_i\}_{i=1,..,\mathrm{s}}, \{C_i\}_{i=1,..,\mathrm{s}}, K\big)$, where

$$\hat{R}_1: \begin{cases} s_1(s) = \hat{R}_{\mathrm{sz}1}(s)z_1(s) + \hat{R}_{\mathrm{sq}1}(s)q_1(s), \\ p_1(s) = \hat{R}_{\mathrm{pz}1}(s)z_1(s) + \hat{R}_{\mathrm{pq}1}(s)q_1(s) \end{cases}$$

and weakly coupled subsystems which have a minor effect on the I/O-pair (z_1, s_1) combined to $E_1{=}comb\big(\{S_i\}_{i=\mathrm{s}+1,..,N}, \{C_i\}_{i=\mathrm{s}+1,..,N}, K\big)$, where

$$E_1:\ q_1(s) = E_1(s)p_1(s).$$

The *VS* together with the faulty subsystems $S_{\mathrm{f}1}$ mimics the behaviour of the fault-free subsystem S_1. Therefore, the virtual sensor is designed based on the model $S_{\mathrm{f}1}$ of the faulty subsystem and the model S_1 of the healthy subsystem, both under the influence of relevant physical couplings $\hat{R}_1$ to satisfy robust stability against the less important dynamics E_1. For robustness purpose, the error model is known as upper bound

$$\bar{E}_1:\ \bar{q}_1(\mathrm{j}\omega) = \bar{E}_1(\mathrm{j}\omega)|p_1(\mathrm{j}\omega)|,$$

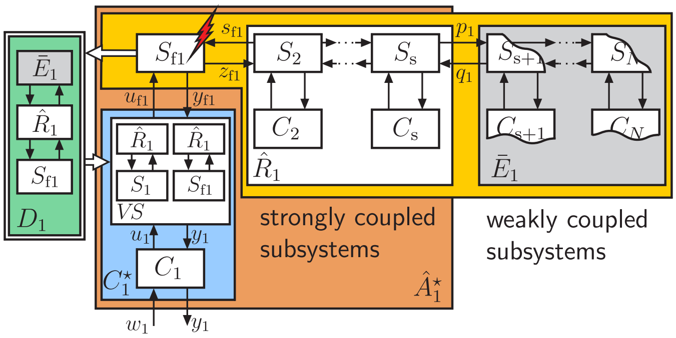

Figure 2: Reconfigured control station C_1 with VS

where $\bar{E}_1(\mathrm{j}\omega) \geq |E_1(\mathrm{j}\omega)|$ for the input $|p_1(\mathrm{j}\omega)|$.

To guarantee overall system stability, the virtual sensor has to be design in order that

$$\mathcal{A}_1 : \begin{cases} \text{1. the reconfigured extended controlled subsystem } \hat{A}_1^\star \text{ is stable w.r.t. all its inputs and outputs,} \\ \text{2. there exist a small-gain between the reconfigured extended controlled subsystem } \hat{A}_1^\star \text{ and the upper bound } \bar{E}_1 \text{, i.e., } |\hat{A}^\star_{\mathrm{pq1}}(\mathrm{j}\omega)| \cdot |\bar{E}_1(\mathrm{j}\omega)| < 1,\ \forall\omega \in \mathbb{R}. \end{cases}$$

3 Procurement of model information for reconfiguration of C_1

Now, the following questions need to be answered:

- Which model information is needed to reconfigure C_1?
- What is the modelling aim?

As mentioned before, the strongly coupled subsystems are those controlled subsystems F_i which have a major influence on the I/O pair (z_1, s_1). From this it is derived that the controlled subsystem S_{l+1} is strongly coupled with the subsystem S_1, if for a given threshold γ_1

$$\hat{R}^{(l)}_{\mathrm{sz1}}(\mathrm{j}\omega) - \hat{R}^{(l-1)}_{\mathrm{sz1}}(\mathrm{j}\omega) \geq \gamma_1,\ \forall\omega \in \mathbb{R},$$

where l indicates the neighbour-degree of subsystem S_1. The following algorithm states the procurement and classification of model information from the perspective of D_1:

Algorithm. Modelling of the faulty subsystem

Given: γ_1, $\hat{R}_1^{(0)}$, $\bar{E}_1^{(0)}$ *and* K *at* D_1 *and* S_i, C_i *at* D_i

Init: $l = 1$, $\gamma_1^{(0)} = \gamma_1$

while $l < N$

1) D_1 *calculates* $\gamma_1^{(l)}$ *based on* γ_1 *and* $\hat{R}^{(l-1)}_{\mathrm{sz1}}(\mathrm{j}\omega)$

2) D_1 *requests* S_{l+1}, C_{l+1} *from* D_{l+1} *: send* $\gamma_1^{(l)}$

3) D_{l+1} *sends:* $\begin{cases} S_{l+1}, C_{l+1}, \textit{ when } |F_{\mathrm{zs}l+1}(\mathrm{j}\omega)| \geq \gamma_1^{(l)} \\ \bar{F}_{l+1}, \textit{ otherwise} \end{cases}$

4) D_1 *combines:* $\begin{cases} \hat{R}_1^{(l)} = comb(\hat{R}_1^{(l-1)}, S_{l+1}, C_{l+1}) \\ \bar{E}_1^{(l)} = comb(\bar{E}_1^{(l-1)}, \bar{F}_{l+1}) \end{cases}$

5) set $l = l + 1$ *and goto 1)*

Result: $\hat{R}_1$ *and* $\bar{E}_1$ *available to* D_1

4 Example: Electric Power network

To illustrate the procurement of model information, the algorithm is applied to a network of electric power plants (Fig. 3). A sensor in plant S_1 fails which initiates D_1 to gather and classify the models required for reconfiguration.

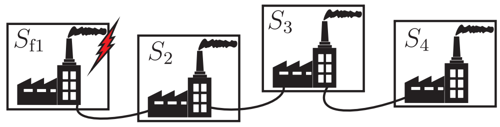

Figure 3: Network of four electric power plants

The threshold is given by $\gamma_1{=}0.3 \cdot \sup_\omega |S_{\mathrm{zs1}}(\mathrm{j}\omega)|{=}0.52$. Fig. 4 shows the processing of the Alg. 1 and the communication graph $\mathcal{G}_\mathrm{D}(k){=}(\mathcal{V}_\mathrm{D}, \mathcal{E}_\mathrm{D}(k))$, where the vertex set $\mathcal{V}_\mathrm{D}{=}\{1,2,3,4\}$ represents the design agents and the edge set $\mathcal{E}_\mathrm{D}(k)$ represents the communication between the design agents at the k-th iteration of Alg. 1. As it can be seen, $|F_{\mathrm{zs2}}(\mathrm{j}\omega)|$ exceeds the threshold so that subsystem S_2 is categorised as strongly coupled in contrast to the subsystems S_3 and S_4 which are labelled as weakly coupled (grey vertices).

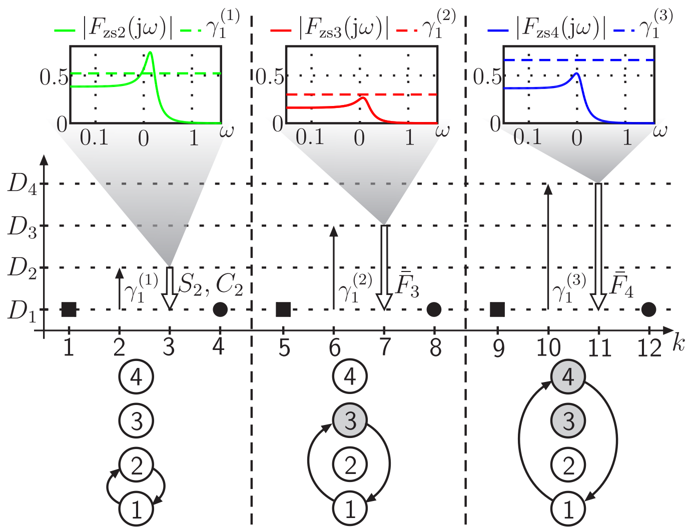

Figure 4: Information flow and processing diagram (■: calculate $\bar{e}_l$, ●: combine models, →: request model, ⇒: transmit model) and communication graph $\mathcal{G}_\mathrm{D}(k)$

References

[1] M. Blanke, M. Kinnaert, J. Lunze and M. Staroswiecki. *Diagnosis and Fault-Tolerant Control*, Springer, 2006

[2] S. Bodenburg, D. Vey and J. Lunze. Plug-and-play reconfiguration of decentralised controller of interconnected systems. In *Proc. 9th Symposium of Fault Detection, Supervision and Safety of Technical Processes*, 2015. (accepted).

[3] D. Vey, S. Hügging, S. Bodenburg and J. Lunze. Controller reconfiguration of physically interconnected systems by decentralized virtual actuators. In *Proc. 9th Symposium of Fault Detection, Supervision and Safety of Technical Processes*, 2015. (accepted).

[4] S. Bodenburg and J. Lunze. Plug-and-Play Control - definition and realisation in MATLAB. *Automatisierungstechnik*, 61:487-494, 2013