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Control reconfiguration of physically interconnected systems by decentralized virtual actuators

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Abstract: This paper presents a new method for decentralized control reconfiguration after actuator failures in physically interconnected systems by decentralized linear virtual actuators (DELVA). In a decentralized control system, the direct application of the design method for linear virtual actuators (LVA) based on the model of the overall system results in a centralized reconfigured controller. This paper introduces an alternative reconfiguration method that reconfigures only the faulty subsystem, retains the decentralized control structure and guarantees stability for the reconfigured overall system. Depending on reconfigurability conditions for the faulty subsystem, different DELVAs, including appropriate design rules, are presented. The main result is a design method for a DELVA that stabilizes the reconfigured control loop without requiring an information exchange over a digital network. The DELVA is illustrated by an application to a thermo-fluid process.

Keywords: fault tolerance, control reconfiguration, decentralized control

1. INTRODUCTION

Fault-tolerant control (FTC) aims at increasing the availability of technical processes subject to faults or failures. The active fault-tolerant control scheme presented in Blanke et al. (2006) consists of two components. First a diagnosis unit has to detect, isolate and identify the fault f. Second a reconfiguration unit adapts the controller to the faulty process based on the fault estimate.

In this paper a new method for decentralized control reconfiguration after actuator failures in physically interconnected systems is presented. A physically interconnected system, as shown in Fig. 1(a), consists of N subsystems $\Sigma_{\mathrm{P}i}$ that are connected by an interconnection relation $\boldsymbol{L}$. In several applications, e.g. energy networks, it is desired to control such systems by a decentralized controller consisting of N control units $\Sigma_{\mathrm{C}i}$. For the reconfiguration after an actuator failure, an adequate method has been introduced in Steffen (2005) by the linear virtual actuator (LVA). However, applying the proposed methods in a decentralized control system, control reconfiguration results in a centralized controller. This is due to the fact that the conditions and design methods refer to the models of the nominal and faulty overall system.

The aim of decentralized control reconfiguration, which is introduced in this paper, is to reconfigure only the control unit of the faulty subsystem in order to preserve the decentralized control structure. The paper presents necessary and sufficient conditions for the reconfigurability of the faulty subsystem w.r.t. stability of the reconfigured overall system. Additionally, adequate design methods for distributed and decentralized virtual actuators are proposed, where a distributed LVA (DILVA) requires the exchange of signal information over a digital network.

The presented DILVA preserves the nominal behavior of the fault-free subsystems, which is not given for a distributed implementation of the centralized LVA and, furthermore, has a reduced model complexity as well as a reduced communication effort.

Finally, a design algorithm for a decentralized virtual actuator (DELVA) is presented. The DELVA requires only the model of the faulty subsystem and no information exchange. The design is based on controller synthesis by linear matrix inequalities (LMI). The decentralized reconfiguration method is illustrated by an application to a thermo-fluid process. The reconfiguration is performed, based on the common assumption from literature, that an accurate diagnosis result is given sufficiently fast.

Literature. The virtual actuator was introduced in Steffen (2005) for linear, time-invariant systems and extended in Richter (2011); Richter et al. (2012); Vey et al. (2015) extended to different classes of nonlinear systems and in Tabatabaeipour et al. (2012); Rotondo et al. (2014a) and Rotondo et al. (2014b) to different types of linear parameter varying (LPV) systems. In Seron et al. (2011); Seron and De Doná (2012) a bank of virtual actuators is also used for diagnostic residual generation, which was extended in Nazari et al. (2014) to convex polytopic LPV systems. Practical applications can be found in Blesa et al. (2012) for wind-turbines and in Bodenburg et al. (2014) for a thermo-fluid process.

Also FTC in networked control systems has received increasing attention in literature yet. Amani et al. (2011) considered the virtual actuator technique in networked control systems. However, this publications focuses on the attenuation or tolerance of network properties like delays and not on decentralized control reconfiguration.

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In contrast to the mentioned literature that consider a virtual actuator for the overall system, this paper considers control reconfiguration in a decentralized control structure. Decentralization of the reconfiguration task has for example been considered in Bodenburg et al. (2015), providing general small-gain conditions for decentralized controller re-adjustment, or in Amani et al. (2009), using predictive reconfiguration. In Amani et al. (2014) the authors propose a method to find admissible subsets of subsystems that allow cooperative stabilization, when the faulty subsystem is no longer stabilizable itself.

Outline. In Section 2 the models of the nominal and faulty decentralized control system and some notations are introduced. Section 3 summarizes the concept of centralized control reconfiguration by LVAs. In Section 4 the DILVA with reduced model complexity and communication effort is introduced. The DELVA is presented in Section 5. Section 6 contains a simulative evaluation of the DELVA by an application to a thermo-fluid process.

2. MODELS AND NOTATIONS

2.1 Model of the decentralized control system

The decentralized control system shown in Fig. 1(a) consists of N physically interconnected subsystems [1]

$$\Sigma_{\mathrm{P}i}:\begin{cases}\dot{\boldsymbol{x}}_i=\boldsymbol{A}_i\boldsymbol{x}_i+\boldsymbol{B}_i\boldsymbol{u}_{\mathrm{c}i}+\boldsymbol{F}_i\boldsymbol{s}_i, & \boldsymbol{x}_i(0)=\boldsymbol{x}_{i0}\\ \boldsymbol{y}_{\mathrm{c}i}=\boldsymbol{C}_i\boldsymbol{x}_i\\ \boldsymbol{u}_i=\boldsymbol{C}_{\mathrm{z}i}\boldsymbol{x}_i,\end{cases} \tag{1}$$

where $\boldsymbol{x}_i\in\mathbb{R}^{n_i}$ denotes the state, $\boldsymbol{u}_{\mathrm{c}i}\in\mathbb{R}^{m_i}$ the control input, $\boldsymbol{y}_{\mathrm{c}i}\in\mathbb{R}^{r_i}$ the measured output, $\boldsymbol{s}_i\in\mathbb{R}^{m_{s_i}}$ the coupling input and $\boldsymbol{z}_i\in\mathbb{R}^{r_{z_i}}$ the coupling output of the i-th subsystem. The overall system model is described by the subsystems (1) and the coupling relation

$$\boldsymbol{s}=\boldsymbol{L}\boldsymbol{z} \tag{2}$$

that represents the physical interconnection. Symbols without index i represent the augmented signal such as $\boldsymbol{s}=\begin{bmatrix}\boldsymbol{s}_1^{\mathrm{T}} & \cdots & \boldsymbol{s}_N^{\mathrm{T}}\end{bmatrix}^{\mathrm{T}}$. The coupling matrix $\boldsymbol{L}$ is, without loss of generality, assumed to have vanishing block diagonal entries $\boldsymbol{L}_{ii}=\boldsymbol{0}$, s.t. the self-couplings are contained in $\boldsymbol{A}_i$. The model of the overall system (1), (2) is abbreviated by

$$\Sigma_{\mathrm{P}}:\begin{cases}\dot{\boldsymbol{x}}=\boldsymbol{A}\boldsymbol{x}+\boldsymbol{B}\boldsymbol{u}_{\mathrm{c}}, & \boldsymbol{x}(0)=\boldsymbol{x}_0\\ \boldsymbol{y}_{\mathrm{c}}=\boldsymbol{C}\boldsymbol{x}\end{cases} \tag{3}$$

with

$$\boldsymbol{A}=\mathrm{diag}\left(\boldsymbol{A}_i\right)+\mathrm{diag}\left(\boldsymbol{F}_i\right)\boldsymbol{L}\,\mathrm{diag}\left(\boldsymbol{C}_{\mathrm{z}i}\right),$$
$$\boldsymbol{B}=\mathrm{diag}\left(\boldsymbol{B}_i\right),\quad \boldsymbol{C}=\mathrm{diag}\left(\boldsymbol{C}_i\right).$$

Nominal controller. As shown in Fig. 1(a), each subsystem is controlled by a decentralized controller

$$\Sigma_{\mathrm{C}i}:\boldsymbol{u}_{\mathrm{c}i}=\boldsymbol{f}_i(\boldsymbol{y}_{\mathrm{c}i},\boldsymbol{r}_i),\quad i=1,\ldots,N \tag{4}$$

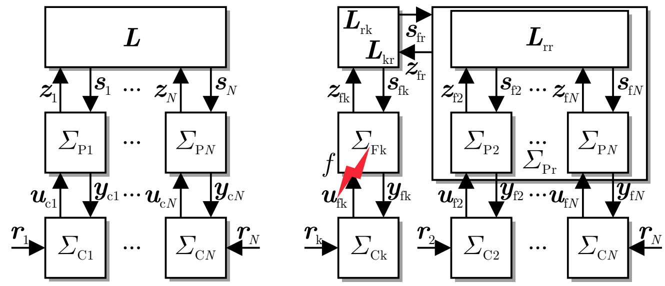
where $\boldsymbol{r}_i\in\mathbb{R}^{r_i}$ represents the reference input.

Assumption 1. The decentralized controller (4) *stabilizes the corresponding nominal subsystem* (1) *for a vanishing physical interconnection* $\boldsymbol{s}_i=\boldsymbol{0}$.

The composition of the N decentralized controllers (4) forms the nominal overall controller

$$\Sigma_{\mathrm{C}}:\boldsymbol{u}_{\mathrm{c}}=\mathrm{diag}\left(\boldsymbol{f}_i(\boldsymbol{y}_{\mathrm{c}i},\boldsymbol{r}_i)\right)=\boldsymbol{f}(\boldsymbol{y}_{\mathrm{c}},\boldsymbol{r}). \tag{5}$$

[1] The dependence of variables on time t is omitted when clear from the context.



(a) nominal (b) faulty

Fig. 1. Decentralized control loop

Assumption 2. The nominal overall controller (5) *stabilizes the nominal overall system* (3) *and satisfies the desired closed-loop performance.*

Faulty system. It is assumed that an actuator failure occurs only in one subsystem at a time, which is from now on indicated by the label k. For further analysis the overall system is split into the faulty subsystem Σ_{Fk} and a residual system Σ_{Pr}. The residual system Σ_{Pr} represents the composition of the fault-free subsystems as illustrated in Fig. 1(b). Throughout the paper the graphical illustrations will represent the case where the failure occurs in the first subsystem.

The failure of the j-th actuator $u_{\mathrm{k}j}$ in subsystem k is modeled by setting the corresponding column $\boldsymbol{b}_{\mathrm{k}j}$ in $\boldsymbol{B}_{\mathrm{k}}$ to zero. The faulty subsystem is then represented by

$$\Sigma_{\mathrm{Fk}}:\begin{cases}\dot{\boldsymbol{x}}_{\mathrm{fk}}=\boldsymbol{A}_{\mathrm{k}}\boldsymbol{x}_{\mathrm{fk}}+\boldsymbol{B}_{\mathrm{fk}}\boldsymbol{u}_{\mathrm{fk}}+\boldsymbol{F}_{\mathrm{k}}\boldsymbol{s}_{\mathrm{fk}}, & \boldsymbol{x}_{\mathrm{fk}}(t_{\mathrm{f}})=\boldsymbol{x}_{\mathrm{k}}(t_{\mathrm{f}})\\ \boldsymbol{y}_{\mathrm{fk}}=\boldsymbol{C}_{\mathrm{k}}\boldsymbol{x}_{\mathrm{fk}}\\ \boldsymbol{z}_{\mathrm{fk}}=\boldsymbol{C}_{\mathrm{zk}}\boldsymbol{x}_{\mathrm{fk}},\end{cases} \tag{6}$$

which holds for the time interval $t\geq t_{\mathrm{f}}$, where t_{f} denotes the time when the failure occurs. In (6), $\boldsymbol{x}_{\mathrm{fk}}\in\mathbb{R}^{n_{\mathrm{k}}}$ is the faulty state, $\boldsymbol{u}_{\mathrm{fk}}\in\mathbb{R}^{m_{\mathrm{k}}}$ the faulty control input, $\boldsymbol{y}_{\mathrm{fk}}\in\mathbb{R}^{r_{\mathrm{k}}}$ the faulty measured output, $\boldsymbol{s}_{\mathrm{fk}}\in\mathbb{R}^{m_{s_{\mathrm{k}}}}$ the faulty coupling input and $\boldsymbol{z}_{\mathrm{fk}}\in\mathbb{R}^{r_{z_{\mathrm{k}}}}$ the faulty coupling output. Note that an actuator failure in subsystem k only changes the input matrix $\boldsymbol{B}_{\mathrm{fk}}$ of the faulty subsystem. Therefore, the fault-free subsystems are still described by (1). For $i=1,\ldots,N, i\neq\mathrm{k}$ the signals $\boldsymbol{x}_i$, $\boldsymbol{u}_{\mathrm{c}i}$, $\boldsymbol{y}_{\mathrm{c}i}$, $\boldsymbol{s}_i$ and $\boldsymbol{z}_i$ have to be replaced by $\boldsymbol{x}_{\mathrm{f}i}$, $\boldsymbol{u}_{\mathrm{f}i}$, $\boldsymbol{y}_{\mathrm{f}i}$, $\boldsymbol{s}_{\mathrm{f}i}$ and $\boldsymbol{z}_{\mathrm{f}i}$, since they behave faulty due to the physical interconnection. The faulty coupling outputs $\boldsymbol{z}_{\mathrm{f}i}$ cause the faulty coupling input $\boldsymbol{s}_{\mathrm{fk}}$ in (6).

The residual system is then given by

$$\Sigma_{\mathrm{Pr}}:\begin{cases}\dot{\boldsymbol{x}}_{\mathrm{fr}}=\boldsymbol{A}_{\mathrm{r}}\boldsymbol{x}_{\mathrm{fr}}+\boldsymbol{B}_{\mathrm{r}}\boldsymbol{u}_{\mathrm{fr}}+\boldsymbol{F}_{\mathrm{r}}\boldsymbol{s}_{\mathrm{fr}}, & \boldsymbol{x}_{\mathrm{fr}}(t_{\mathrm{f}})=\boldsymbol{x}_{\mathrm{r}}(t_{\mathrm{f}})\\ \boldsymbol{y}_{\mathrm{fr}}=\boldsymbol{C}_{\mathrm{r}}\boldsymbol{x}_{\mathrm{fr}}\\ \boldsymbol{z}_{\mathrm{fr}}=\boldsymbol{C}_{\mathrm{zr}}\boldsymbol{x}_{\mathrm{fr}},\end{cases} \tag{7}$$

where the signal label r denotes the augmented signal for $i=1,\ldots,N, i\neq\mathrm{k}$. The matrices in (7) are

$$\boldsymbol{A}_{\mathrm{r}}=\mathrm{diag}\left(\boldsymbol{A}_i\right)+\mathrm{diag}\left(\boldsymbol{F}_i\right)\boldsymbol{L}_{\mathrm{rr}}\,\mathrm{diag}\left(\boldsymbol{C}_{\mathrm{z}i}\right)$$
$$\boldsymbol{B}_{\mathrm{r}}=\mathrm{diag}\left(\boldsymbol{B}_i\right),\quad \boldsymbol{C}_{\mathrm{r}}=\mathrm{diag}\left(\boldsymbol{C}_i\right).$$

The coupling matrix $\boldsymbol{L}_{\mathrm{rr}}$ results from the following decomposition of the coupling relation. As mentioned above the signals $\boldsymbol{x}_{\mathrm{f}i}$, $\boldsymbol{u}_{\mathrm{f}i}$, $\boldsymbol{y}_{\mathrm{f}i}$, $\boldsymbol{s}_{\mathrm{f}i}$, $\boldsymbol{z}_{\mathrm{f}i}$ and, therefore, the signals in (7) behave faulty due to the influence of the faulty subsystem (6) via the physical interconnection. For the time interval $t\geq t_{\mathrm{f}}$ the physical interconnection is represented by the decomposed coupling relation