Self-tuned Local Feedback Gain Based Decentralized Fault Tolerant Control of Reconfigurable Manipulators

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Abstract

This paper investigates the decentralized fault tolerant control (DFTC) scheme based on self-tuned local feedback gain to against partial loss of actuator effectiveness of reconfigurable manipulators. Consider the entire system as a set of interconnected subsystems due to its modularity property, the decentralized control method is proposed by employing two neural networks for the system fault-free. For the subsystem suffers to partial loss of actuator effectiveness, the self-tuned local feedback gain is added to the proposed decentralized control method to guarantee the control performance. Finally, a simulation example is provided to demonstrate the effectiveness of the present DFTC scheme. The main contributions of this method are: i) The fault tolerant control structure is simple since it is no need to be redesigned in the presence of partial loss of actuator effectiveness; ii) The actuator fault can be handled in its local subsystem, it implies that the performance degradation of the faulty subsystem can not affect the fault-free subsystems.

Keywords: Fault tolerant control; Decentralized control; Neural networks; Partial loss of effectiveness; Reconfigurable manipulators.

1. Introduction

Reconfigurable manipulators consist of a set of joint and link modules in standard size and interface[1-2]. By adding or removing the modules, they can change their configurations and degree of freedoms (DOF) to adapt different tasks. Hence, the flexible structure serves plenty of potential applications. However, failures of actuators, sensors or other components will inevitably occur after working for a long time. They bring performance degradation or system damaged if they can not be repaired timely.

As the modularity property of reconfigurable manipulators, the decentralized control architecture is more feasible than the centralized one. Zhu et al.[3] proposed a decentralized adaptive fuzzy sliding mode control scheme so that the system was guaranteed to be stable joint by joint. K. Sato et al.[4] investigated a decentralized control scheme in which phasic and tonic control were well coordinated, this scheme obtained success on a snake-like robot. Liu et al.[5] presented a DFTC based on an observer for fault detection of modular reconfigurable robot with joint torque sensing. Motivated by it, Yuan et al.[6] developed an independent joint power efficiency estimation-based health monitoring and fault detection method. Zhao et al.[7] investigated an active DFTC strategy for reconfigurable manipulators based on local joint information and an unknown input observer. They also[8] proposed an active DFTC scheme based on signal reconstruction to against the sensor fault in reconfigurable manipulators.

This paper presents a self-tuned local feedback gain based FTC scheme for reconfigurable manipulators with partial loss of actuator effectiveness. For the fault-free system, a decentralized neural network control is developed to stabilize the closed-loop reconfigurable manipulator system. By adding a self-tuned local feedback gain, the trajectory tracking can be guaranteed to the acceptable level though the fault occurs. The simulation of 2-DOF reconfigurable manipulator shows the effectiveness of the proposed method.

2. Problem Statement

For the development of the decentralized control, each joint is considered as a subsystem of the entire manipulator system interconnected by coupling torques. And then the dynamical model of the *i*th subsystem suffers to partial loss of actuator effectiveness can be formulated in joint space as

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) + Z_i(q,\dot{q},\ddot{q}) = \rho_i u_i \quad (1)$$

with

$$\begin{aligned} Z_i(q,\dot{q},\ddot{q}) = &\left\{ \sum_{j=1, j\neq i}^{n} M_{ij}(q)\ddot{q}_j + \left[M_{ii}(q) - M_i(q_i)\right]\ddot{q}_i \right\} \\ &+ \left\{ \sum_{j=1, j\neq i}^{n} C_{ij}(q,\dot{q})\dot{q}_j + \left[C_{ii}(q,\dot{q}) - C_i(q_i,\dot{q}_i)\right]\dot{q}_i \right\} \\ &+ \left[\bar{G}_i(q) - G_i(q_i)\right] \end{aligned}$$

where $i = 1,2,\cdots,n$, $q_i, \dot{q}_i, \ddot{q}_i$ are the vectors of joint displacement, velocity and acceleration, $M_i(q_i)$ is the inertia matrix, $C_i(q_i,\dot{q}_i)$ is the Coriolis and centripetal force, $G_i(q_i)$ is the gravity term, $Z_i(q,\dot{q},\ddot{q})$ is the interconnected term, and u_i is the applied joint torque of the *i*th subsystem, respectively. ρ_i is the effectiveness factor of the *i*th subsystem with $0 < \rho_i \le 1$ holds, which presents the degree of fault.

Let $x_i = \left[x_{i1}, x_{i2}\right]^T = \left[q_i, \dot{q}_i\right]^T$, (1) can be expressed as

$$S_i : \begin{cases} \dot{x}_{i1} = x_{i2} \\ \dot{x}_{i2} = f_i(q_i,\dot{q}_i) + g_i(q_i)\rho_i u_i + h_i(q,\dot{q},\ddot{q}) \\ y_i = x_{i1} \end{cases} \quad (2)$$

where x_i and y_i are the state and the output of the subsystem S_i, respectively, and

$$f_i(q_i,\dot{q}_i) = M_i^{-1}(q_i)\left[-C_i(q_i,\dot{q}_i)\dot{q}_i - G_i(q_i)\right]$$
$$g_i(q_i) = M_i^{-1}(q_i)$$
$$h_i(q,\dot{q},\ddot{q}) = -M_i^{-1}(q_i)Z_i(q,\dot{q},\ddot{q})$$

The control objective is to design a DFTC scheme for the faulty subsystem of reconfigurable manipulators (1) to make the joint displacements to follow their desired trajectories.

3. Decentralized Fault Tolerant Controller Design

3.1. *Decentralized control design for the fault-free system*

Assumption 1. The desired trajectories are bounded as

$$\left\| \begin{matrix} q_{id} \\ \dot{q}_{id} \\ \ddot{q}_{id} \end{matrix} \right\| \le q_A \quad (3)$$

where $q_A > 0$ is a known constant.

Define the tracking error as

$$e_{i1} = x_{i1} - x_{i1d} \quad (4)$$

where x_{i1d} is the desired displacement of the *i*th joint.

Introducing a first order filter as

$$s_i = \lambda_i e_{i1} + \dot{e}_{i1} \quad (5)$$

where $\lambda_i > 0$ is a known constant.

Assumption 2. The interconnected term $h_i(q,\dot{q},\ddot{q})$ is norm-bounded as[3]

$$\left\|h_i(q,\dot{q},\ddot{q})\right\| \le \sum_{j=1}^{n} d_{ij} S_j \quad (6)$$

where $d_{ij} \ge 0$ and $S_j = 1 + \left|s_j\right| + \left|s_j\right|^2$.

For the system (1) in fault-free, i.e., $\rho_i = 1$, differentiating (5) and using (4), one has

$$\begin{aligned} \dot{s}_i &= \lambda_i \dot{e}_{i1} + \ddot{e}_{i1} \\ &= \lambda_i \dot{e}_{i1} + f_i(q_i,\dot{q}_i) + g_i(q_i)u_i + h_i(q,\dot{q},\ddot{q}) - \ddot{q}_{id} \end{aligned} \quad (7)$$

where the nonlinear terms $f_i(q_i,\dot{q}_i)$ and $g_i(q_i)$ are approximated by employing two ideal radial basis function (RBF) neural networks as

$$f_i(q_i,\dot{q}_i,W_{if}^T)=W_{if}^T\sigma_{if}(q_i,\dot{q}_i)+\varepsilon_{if},\left\|\varepsilon_{if}\right\|\le\varepsilon_1 \quad (8)$$

$$g_i(q_i,W_{ig}^T)=W_{ig}^T\sigma_{ig}(q_i)+\varepsilon_{ig},\left\|\varepsilon_{ig}\right\|\le\varepsilon_2 \quad (9)$$

where W_{if} and W_{ig} are the ideal weight vectors from the hidden layer to the output layer, σ_{if} and σ_{ig} are the basis function vectors, ε_{if} and ε_{ig} are their approximation errors, ε_1 and ε_2 are known positive constants, respectively.

Let $\hat{W}_{if}$ and $\hat{W}_{ig}$ be the estimation of W_{if} and W_{ig}, $\hat{\sigma}_{if}$ and $\hat{\sigma}_{ig}$ are the estimation of σ_{if} and σ_{ig}, we have

$$\hat{f}_i(q_i,\dot{q}_i,\hat{W}_{if}^T)=\hat{W}_{if}^T\hat{\sigma}_{if}(q_i,\dot{q}_i) \quad (8)$$

$$\hat{g}_i(q_i,\hat{W}_{ig}^T)=\hat{W}_{ig}^T\hat{\sigma}_{ig}(q_i) \quad (9)$$

Let $\tilde{W}_{if}=W_{if}-\hat{W}_{if}$, $\tilde{W}_{ig}=W_{ig}-\hat{W}_{ig}$ be the weight estimation errors, we have

$$\begin{aligned}&f_i(q_i,\dot{q}_i,W_{if})-\hat{f}_i(q_i,\dot{q}_i,\hat{W}_{if})\\&=\tilde{W}_{if}^T\hat{\sigma}_{if}(q_i,\dot{q}_i)+W_{if}^T\tilde{\sigma}_{if}(q_i,\dot{q}_i)+\varepsilon_{if}\end{aligned} \quad (10)$$

$$\begin{aligned}&g_i(q_i,W_{ig})-\hat{g}_i(q_i,\hat{W}_{ig})\\&=\tilde{W}_{ig}^T\hat{\sigma}_{ig}(q_i)+W_{ig}^T\tilde{\sigma}_{ig}(q_i)+\varepsilon_{ig}\end{aligned} \quad (11)$$

where the output errors of the basis functions $\sigma_{if}(\cdot)$ and $\sigma_{ig}(\cdot)$ are defined as

$$\tilde{\sigma}_{if}(q_i,\dot{q}_i)=\sigma_{if}(q_i,\dot{q}_i)-\hat{\sigma}_{if}(q_i,\dot{q}_i) \quad (12)$$

$$\tilde{\sigma}_{ig}(q_i)=\sigma_{ig}(q_i)-\hat{\sigma}_{ig}(q_i) \quad (13)$$

Define the whole approximated error as

$$\omega_i=W_{if}^T\tilde{\sigma}_{if}(q_i,\dot{q}_i)+W_{ig}^T\tilde{\sigma}_{ig}(q_i)u_i+\varepsilon_{if}+\varepsilon_{ig}u_i \quad (14)$$

Assumption 3. The whole approximated error ω_i is norm-bounded as

$$\left\|\omega_i\right\|\le\xi_i \quad (15)$$

where $\xi_i>0$ is a known constant.

The decentralized controller can be designed as

$$\begin{aligned}u_i=&-\Big(k_is_i+\hat{f}_i(q_i,\dot{q}_i,\hat{W}_{if}^T)+\hat{\delta}_i\operatorname{sgn}(s_i)S_i-\ddot{q}_{id}\\&+\lambda_i\dot{e}_{i1}+\hat{\xi}_i\operatorname{sgn}(s_i)\Big)\Big/\hat{g}_i(q_i,\hat{W}_{ig}^T)\end{aligned} \quad (16)$$

where $k_i>0$ is a known constant, $\hat{W}_{if}$, $\hat{W}_{ig}$, $\hat{\delta}_i$ and $\hat{\xi}_i$ are updated by

$$\dot{\hat{W}}_{if}=\Gamma_{if}s_i\hat{\sigma}_{if}(q_i,\dot{q}_i) \quad (17)$$

$$\dot{\hat{W}}_{ig}=\Gamma_{ig}s_i\hat{\sigma}_{ig}(q_i,\dot{q}_i)u_i \quad (18)$$

$$\dot{\hat{\delta}}_i=\Gamma_{i\delta}\left|s_i\right|S_i \quad (19)$$

$$\dot{\hat{\xi}}_i=\Gamma_{i\xi}\left|s_i\right| \quad (20)$$

where Γ_{if}, Γ_{ig}, $\Gamma_{i\delta}$ and $\Gamma_{i\xi}$ are positive constants.

Theorem 1. *For the system (1) in fault-free, consider the assumptions 1-3, the decentralized control law (16) with the adaptive updated laws (17)-(20) can guarantee the tracking errors of the closed-loop system converge to zero asymptotically.*

Proof. Define $\tilde{\delta}_i=\delta_i-\hat{\delta}_i$ and $\tilde{\xi}_i=\xi_i-\hat{\xi}_i$, and select the Lyapunov candidate function as

$$\begin{aligned}V_i=&\frac{1}{2}s_i^Ts_i+\frac{1}{2}\tilde{W}_{if}^T\Gamma_{if}^{-1}\tilde{W}_{if}+\frac{1}{2}\tilde{W}_{ig}^T\Gamma_{ig}^{-1}\tilde{W}_{ig}\\&+\frac{1}{2}\tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\tilde{\delta}_i+\frac{1}{2}\tilde{\xi}_i^T\Gamma_{i\xi}^{-1}\tilde{\xi}_i\end{aligned} \quad (21)$$

Taking its time derivative and noticing (7), we have

$$\begin{aligned}\dot{V}_i=&s_i^T\dot{s}_i-\tilde{W}_{if}^T\Gamma_{if}^{-1}\dot{\hat{W}}_{if}-\tilde{W}_{ig}^T\Gamma_{ig}^{-1}\dot{\hat{W}}_{ig}\\&-\tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i-\tilde{\xi}_i^T\Gamma_{i\xi}^{-1}\dot{\hat{\xi}}_i\\=&s_i^T(\lambda_i\dot{e}_{i1}+f_i+g_iu_i+h_i-\ddot{q}_{id})-\tilde{W}_{if}^T\Gamma_{if}^{-1}\dot{\hat{W}}_{if}\\&-\tilde{W}_{ig}^T\Gamma_{ig}^{-1}\dot{\hat{W}}_{ig}-\tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i-\tilde{\xi}_i^T\Gamma_{i\xi}^{-1}\dot{\hat{\xi}}_i\end{aligned} \quad (22)$$

Substituting (16) into (22), one can obtain

$$\begin{aligned}\dot{V}_i=&s_i^T(-k_is_i+f_i-\hat{f}_i+(g_i-\hat{g}_i)u_i+h_i\\&-\hat{\delta}_i\operatorname{sgn}(s_i)S_i-\hat{\xi}_i\operatorname{sgn}(s_i))-\tilde{W}_{if}^T\Gamma_{if}^{-1}\dot{\hat{W}}_{if}\\&-\tilde{W}_{ig}^T\Gamma_{ig}^{-1}\dot{\hat{W}}_{ig}-\tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i-\tilde{\xi}_i^T\Gamma_{i\xi}^{-1}\dot{\hat{\xi}}_i\\=&s_i^T(-k_is_i+\tilde{W}_{if}^T\hat{\sigma}_{if}+\tilde{W}_{ig}^T\hat{\sigma}_{ig}u_i+\omega_i+h_i\\&-\hat{\delta}_i\operatorname{sgn}(s_i)S_i-\hat{\xi}_i\operatorname{sgn}(s_i))-\tilde{W}_{if}^T\Gamma_{if}^{-1}\dot{\hat{W}}_{if}\\&-\tilde{W}_{ig}^T\Gamma_{ig}^{-1}\dot{\hat{W}}_{ig}-\tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i-\tilde{\xi}_i^T\Gamma_{i\xi}^{-1}\dot{\hat{\xi}}_i\end{aligned} \quad (23)$$

According to assumptions 2-3, and using (17)-(19), we have

$$\dot{V}_i\le-k_is_i^2+s_i^T\sum_{j=1}^{n}d_{ij}S_j-\hat{\delta}_i\left|s_i\right|S_i-\tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i \quad (24)$$

Then,

$$\begin{aligned}\dot{V} &= \sum_{i=1}^{n}\dot{V}_i \\ &= \sum_{i=1}^{n}(-k_i s_i^2 + s_i^T\sum_{j=1}^{n} d_{ij}S_j - \hat{\delta}_i\left|s_i\right|S_i - \tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i) \\ &\le \sum_{i=1}^{n}\Big(-k_i s_i^2 - \tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i) + \max_{ij}\{d_{ij}\}\sum_{i=1}^{n}\left|s_i\right|\sum_{j=1}^{n}S_j \\ &\quad -\hat{\delta}_i\left|s_i\right|S_i\Big)\end{aligned} \tag{25}$$

Noticing $\left|s_i\right| \le \left|s_j\right| \Leftrightarrow S_i \le S_j$, and using Chebyshev inequality, we have

$$\sum_{i=1}^{n}\left|s_i\right|\sum_{j=1}^{n}S_j \le n\sum_{i=1}^{n}\left|s_i\right|S_j \tag{26}$$

Thus we have

$$\begin{aligned}\dot{V} &\le \sum_{i=1}^{n}(-k_i s_i^2 - \hat{\delta}_i\left|s_i\right|S_i - \tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i) \\ &\quad + n\max_{ij}\{d_{ij}\}\sum_{i=1}^{n}\left|s_i\right|S_i\end{aligned} \tag{27}$$

Let $\delta = n\max_{ij}\{d_{ij}\}$, so we have

$$\dot{V} \le \sum_{i=1}^{n}(-k_i s_i^2 + \tilde{\delta}_i^T\left|s_i\right|S_i - \tilde{\delta}_i^T\Gamma_{i\delta}^{-1}\dot{\hat{\delta}}_i) \tag{28}$$

Substituting (20) into (28), we have

$$\dot{V} \le \sum_{i=1}^{n}(-k_i s_i^2) \le 0 \tag{29}$$

So we can know $V(t) \le V(0)$, which implies s_i is bounded. Integrating $\sum_{i=1}^{n}k_i s_i^2$ with respect to time

$$\int_0^t\sum_{i=1}^{n}k_i s_i^2 dt \le -\int_0^t\dot{V}dt = V(0) - V(t) \tag{30}$$

Because $V(0)$ is bounded, and $V(t)$ is bounded from below and is non-increasing with time, so the following result is obtained:

$$\lim_{t\to\infty}\int_0^t\sum_{i=1}^{n}k_i s_i^2 dt < \infty \tag{31}$$

It implies that $s_i \in L_2$. From (7), $\dot{s}_i$ is bounded for all time, so according to Barbalat's Lemma, it concludes that $\lim_{t\to\infty}s_i(t) = 0$, so the joint tracking error e_i will also converge to zero asymptotically. □

3.2. *Self-tuning local feedback gain based DFTC*

Through observing the system (1) with actuator failure, if we can estimate the effectiveness factor ρ_i in real-time, and then adding it to the decentralized control scheme proposed in section 3.1, the DFTC can be achieved.

The decentralized fault tolerant controller is designed as

$$\overline{u}_i = \hat{\rho}_i^{-1}u_i \tag{32}$$

where $\hat{\rho}_i$ can be updated by the following adaptive law:

$$\dot{\hat{\rho}}_i = \Gamma_{i\rho}\hat{\rho}_i^{-1}s_i^T\hat{g}_i u_i \tag{33}$$

where $\Gamma_{i\rho} > 0$ is a known constant.

Theorem 2. *Consider the system (1) with partial loss of actuator effectiveness, the proposed self-tuned local feedback gain based DFTC scheme can guarantee all the variables of the closed-loop system to be uniformly ultimately bounded (UUB).*

Proof. Define $\tilde{\rho}_i = \rho_i - \hat{\rho}_i$, and select the Lyapunov candidate function as

$$V_{if} = V_i + \frac{1}{2}\tilde{\rho}_i^T\Gamma_{i\rho}^{-1}\tilde{\rho}_i \tag{34}$$

So its time derivative is

$$\begin{aligned}\dot{V}_{if} &= \dot{V}_i + s_i^T\left(\tilde{\rho}_i^T\hat{g}_i\hat{\rho}_i^{-1}u_i + \tilde{\rho}_i^T\tilde{g}_i\hat{\rho}_i^{-1}u_i\right) - \tilde{\rho}_i^T\Gamma_{i\rho}^T\dot{\hat{\rho}}_i \\ &= -k_i s_i^2 + \tilde{\rho}_i^T\left(s_i^T\hat{g}_i\hat{\rho}_i^{-1}u_i - \Gamma_{i\rho}^T\dot{\hat{\rho}}_i\right) + s_i^T\tilde{\rho}_i^T\tilde{g}_i\hat{\rho}_i^{-1}u_i\end{aligned} \tag{35}$$

Assuming that $\left\|s_i^T\tilde{\rho}_i^T\tilde{g}_i\hat{\rho}_i^{-1}u_i\right\| \le \xi_{if}$, where $\xi_{if} > 0$ is a known constant. Substituting (33) into (35), we have

$$\dot{V}_{if} = -k_i s_i^2 + \xi_{if} \tag{36}$$

Thus $\dot{V}_{if} < 0$ as long as $\left|s_i\right| > \sqrt{\xi_{if}/k_i}$. According to Lyapunov direct method, the tracking error is UUB. □

4. Simulation Study

In this section, a 2-DOF reconfigurable manipulator (Configuration *a* in reference 3, as well as the dynamic model, the desired trajectories) is employed to verify the effectiveness of the proposed DFTC scheme.

The actuator failure is injected into joint 1, and the effectiveness factor is chosen as

$$\rho_1 = \begin{cases}1, t < 4s \\ 0.8, 4s \le t \le 10s\end{cases} \tag{37}$$

The control parameters are set as $\lambda_i = 5$, $k_i = 10$, $\Gamma_{if} = 0.002$, $\Gamma_{ig} = 0.002$, $\Gamma_{i\delta} = 500$, $\Gamma_{i\xi} = 400$ and $\Gamma_{i\rho} = 2000$.

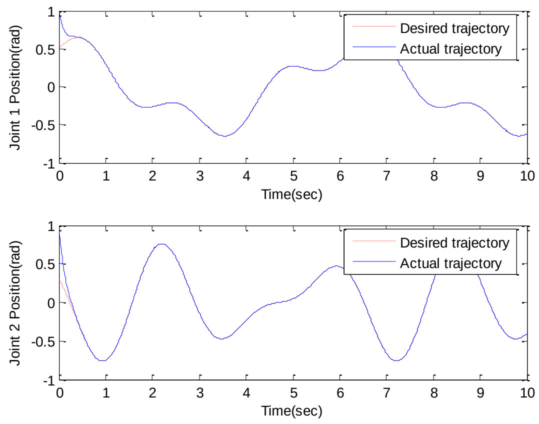

Fig.1. Tracking curves

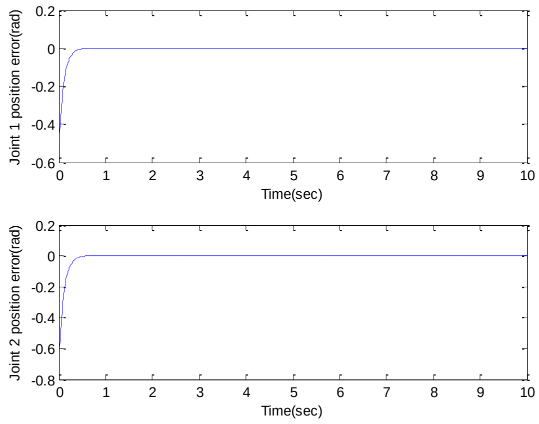

Fig.2. Tracking error curves

Fig.1 illustrates the trajectory tracking curves by using the proposed DFTC scheme, from where we can observe that the trajectory tracking is successfully guaranteed though the fault occurs after $t = 4s$. Meanwhile, the fault-free subsystem's control performance is not affected by the faulty one. The tracking errors in Fig.2 demonstrate this conclusion. Hence, the proposed self-tuned local feedback gain based DFTC is effective to deal with partial loss of actuator effectiveness.

5. Conclusions

A self-tuned local feedback gain based DFTC scheme is developed to deal with the partial loss of actuator effectiveness of reconfigurable manipulators. The decentralized neural network controller is designed for the fault-free system. Once the system suffers to partial loss of actuator effectiveness, only a self-tuned local feedback gain is added to guarantee the system stable. This control architecture is simple since it is no need to redesign the fault tolerant controller once the system suffers to the partial loss of actuator effectiveness. Meanwhile, the fault is handled only in its local subsystem, rather than the entire system.

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