International Journal of Innovative Computing, Information and Control
Volume **21**, Number **1**, February **2025**
 ISSN 1349-4198
pp. **227–237**

A DESIGN METHOD OF FAULT TOLERANT CONTROL SYSTEMS USING FAULT ESTIMATOR FOR MULTI-PLANT SYSTEMS

Sura Laptawee[1,2], Hiroki Tani[2], Nghia Thi Mai[3], Kotaro Hashikura[2]
Md Abdus Samad Kamal[2], Iwanori Murakami[2], Wimol San-Um[1]
and Kou Yamada[2]

[1]Faculty of Engineering
Thai-Nichi Institute of Technology
1771/1, Pattanakarn Road, Suan Luang, Bangkok 10250, Thailand
{ sura.l; wimol }@tni.ac.th

[2]Graduate School of Science and Technology
Gunma University
1-5-1 Tenjincho, Kiryu, Gunma 376-8515, Japan
{ t192b002; t201b060; k-hashikura; maskamal; murakami; yamada }@gunma-u.ac.jp

[3]Faculty of Electronics Engineering 1
Posts and Telecommunications Institute of Technology
122 Hoang Quoc Viet Road, Cau Giay District, Hanoi 11355, Vietnam
nghiamt@ptit.edu.vn

Received March 2024; revised June 2024

Abstract. *This paper proposes a simple design method for fault tolerance control based on fault estimator. The tolerance is formulated as a fault in one of the correlated two plants, or, in other words, the system is under an uncertain state. To estimate the system under an uncertain state, the fault estimator that detects the difference in output in both normal and post-faults is proposed. To design the fault estimator, we also clarify the parameterization of all fault estimators. Using a fault estimator, the system will be effectively recovered by compensating for lost outputs via a newly designated feedback parameter, in the case where system fault is detected. The proposed technique offers simplicity in the self-recovery of fault tolerance controls in an unstable system.*
Keywords: Multi-plant control system, Fault tolerant control, Fault estimator

1. **Introduction.** Component fault in control systems can lead to instability and degraded performance, making it essential for control systems to prevent faults from intensifying into full system faults while maintaining performance and stability [1]. This requirement is crucial in multi-plant systems and environments demanding high reliability, such as production plants and human-interactive systems [2, 3, 4, 5]. For instance, next-generation steer-by-wire vehicle systems require superior fault tolerance compared to traditional steering systems [6]. To address this need, many researchers have focused on developing fault-tolerant control systems [1, 7, 8].

Blanke and Jørgensen introduced methods for fault handling based on fault mode analysis [9], while Alwi and Edwards proposed sliding mode-based fault-tolerant control [10]. The use of electronically controlled actuators and force feedback to enhance safety and adaptability in steering systems has been highlighted by Tian et al. [11]. However, redundancy in sensors, actuators, and microprocessors, as emphasized by Ito and Hayakawa,

DOI: 10.24507/ijicic.21.01.227

often increases costs and weight [12]. Takahashi's self-repairing control system using a discontinuous fault detection filter exemplifies efforts to enhance reliability [13].

Typically, fault-tolerant control approaches are classified into active and passive types. Active fault-tolerant control involves real-time fault detection and system adjustment [1, 14], but poses challenges like the time required for fault diagnosis and implementation of new control schemes [8]. In contrast, passive fault-tolerant control designs controllers to maintain stability despite faults, though this often results in conservative designs and reduced performance [14].

On the other hand, as fault is often regarded as the perturbation of components in the system, disturbance observers have been proposed. Theoretically, disturbance observers maintain steady-state error close to zero by appropriately adjusting plant parameters [15, 16]. These features have led researchers to explore fault-tolerant control using disturbance observers [17, 18, 19]. Sun et al. proposed a composite fault-tolerant control with a disturbance observer for stochastic systems with disturbances and faults [17]. Han et al. developed disturbance and fault estimation observers for fuzzy systems with local nonlinear models and external disturbances [18]. Kwon et al. introduced a fault-tolerant control scheme for active suspension systems in vehicles, using a suspension state observer and a disturbance observer to determine feedback control inputs [19]. Anjum et al. proposed a disturbance observer-based composite fixed-time trajectory tracking control method, integrating fixed-time non-singular fast terminal sliding control and disturbance observer information to achieve fixed-time convergence despite uncertainties, disturbances, and actuator faults [20]. However, most designs using disturbance observers focus on estimating perturbations rather than faults, leading to complex system designs.

To address this issue, we propose a design method for fault-tolerant control based on a fault estimator. Our method is motivated by the need for a simpler and more effective solution that can handle catastrophic faults, where the system becomes unstable due to component fault, by detecting faults and compensating for lost outputs. The proposed method involves a control system that detects faults and stabilizes the system by compensating for lost output due to component malfunctions in multi-plant control systems. Unlike existing complex techniques, our fault-tolerant control system based on a fault estimator simplifies the design process. The fault estimator operates similarly to a disturbance observer, treating all errors as disturbances within a feedback loop. To stabilize the system and compensate for output under uncertain conditions, additional techniques such as stable controllers, parameterization, or compound H_∞ controllers may be required [21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. This paper addresses the stability of control systems with uncertain states, building on the results of previous studies like [21]. Our proposed fault-tolerant control system offers a simpler and more effective solution compared to conventional methods using disturbance observers.

By simplifying the design and focusing on direct fault estimation, our approach aims to enhance system reliability and performance without the drawbacks of existing methods. This paper is organized as follows. Section 2 outlines the problem and defines the fault estimator. Section 3 details the parameterization of fault estimators. Section 4 presents our design method. Section 5 provides a numerical example, and Section 6 concludes the paper.

2. **Problem Formulation.** Consider the control system in Figure 1, where $G(s) \in R^{1\times 2}(s)$ is the plant, $u(s) \in R^{2\times 1}(s)$ is the input, $y(s) \in R(s)$ is the output and $r(s) \in R^2$ is a reference input. $F_1(s) \in RH_\infty^{1\times 2}$ and $F_2(s) \in RH_\infty$ are to estimate the fault and $\hat{F}(s) \in R^2(s)$ is the controller for fault. $\hat{d}(s)$ represents the fault estimator and written by

$$\hat{d}(s) = F_1(s)u(s) + F_2(s)y(s). \tag{1}$$

From Figure 1, $G(s) \in R^{1\times 2}(s)$ and $u(s) \in R^{2\times 1}(s)$, we can denote $y(s)$ as

$$y(s) = G(s)u(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}. \tag{2}$$

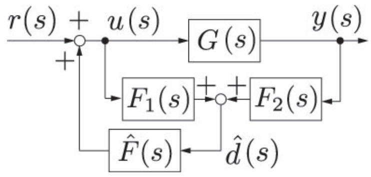

FIGURE 1. Control system

It is assumed that when the plant $G(s)$ is normal,

$$G_1(s) \neq 0. \tag{3}$$

Conversely, when the plant is broken,

$$G_1(s) = 0. \tag{4}$$

When the plant is broken, we denote the plant $\hat{G}(s)$, that is,

$$\hat{G}(s) = \begin{bmatrix} 0 & G_2(s) \end{bmatrix}, \tag{5}$$

and the output $\hat{y}(s)$ in response to the same input $u(s)$ is given by

$$\hat{y}(s) = \hat{G}(s)u(s). \tag{6}$$

It is desired that the response of the system when the plant is normal should be the same as the response when the plant is broken. In other words, we generate the input $u(s)$ that satisfies the following condition:

$$\lim_{t\to\infty} (y(t) - \hat{y}(t)) = 0. \tag{7}$$

To achieve this, we need to estimate the difference between the outputs $y(s)$ and $\hat{y}(s)$. If the plant is normal, we do not need to estimate this difference, and the input $u(s)$ satisfies

$$\hat{d}(s) = 0. \tag{8}$$

On the other hand, if the plant is broken, we need to estimate the difference between the outputs, and the input $u(s)$ must satisfy

$$\hat{d}(s) = \left(G(s) - \hat{G}(s)\right) u(s) = G_1(s)u_1(s). \tag{9}$$

We can find the fault occurs using $\hat{d}(s)$. Thus, we call $\hat{d}(s)$ a fault estimator if (8) and (9) are satisfied.

3. **Fault Estimator.**

In this section, we explain the parameterization of all fault estimator $\hat{d}(s)$ in Figure 1.

The parameterization of all $F_1(s)$ and $F_2(s)$ that satisfy (8) is summarized in the following theorem.

Theorem 3.1. *All $F_1(s)$ and $F_2(s)$ that satisfy (8) are given by*

$$F_1(s) = \begin{bmatrix} G_1(s)(1 + Q(s)) & G_2(s)(1 + Q(s)) \end{bmatrix} \tag{10}$$

and

$$F_2(s) = -1 - Q(s), \tag{11}$$

respectively.

The proof of this theorem requires the following lemma.

Lemma 3.1. [31] *Assume that* $A(s) \in RH_\infty^{m\times n}$, $B(s) \in H_\infty^{q\times p}$, $C(s) \in RH_\infty^{m\times p}$ *and*

$$\text{rank} \left[\begin{array}{cc} A^T(s) & B^T(s) \end{array} \right] = \gamma \tag{12}$$

are satisfied. There exist $X(s) \in RH_\infty$ *and* $Y(s) \in RH_\infty$ *satisfying*

$$X(s)A(s) + Y(s)B(s) = C(s), \tag{13}$$

if and only if there exists $U(s) \in \mathcal{U}$ *satisfying*

$$\left[\begin{array}{c} A(s) \\ B(s) \\ C(s) \end{array} \right] = U(s) \left[\begin{array}{c} A(s) \\ B(s) \\ O \end{array} \right]. \tag{14}$$

When $X_0(s) \in RH_\infty$ *and* $Y_0(s) \in RH_\infty$ *are solutions to (13), then all solutions to (13) are given by*

$$\left[\begin{array}{cc} X(s) & Y(s) \end{array} \right] = \left[\begin{array}{cc} X_0(s) & Y_0(s) \end{array} \right] + Q(s) \left[\begin{array}{cc} W_1(s) & W_2(s) \end{array} \right], \tag{15}$$

where $W_1(s)$ *and* $W_2(s)$ *satisfy*

$$W_1(s)A(s) + W_2(s)B(s) = 0 \tag{16}$$

and

$$\text{rank} \left[\begin{array}{cc} W_1(s) & W_2(s) \end{array} \right] = n + q - \gamma \tag{17}$$

and $Q(s) \in RH_\infty^{p\times(N+q-\gamma)}$ *is any function.*

We show proof of Theorem 3.1 using Lemma 3.1.

Proof: When the plant is normal, from (8), we have

$$F_1(s)u(s) + F_2(s)y(s) = 0. \tag{18}$$

From (7), (18) is rewritten by the form in

$$(F_1(s) + F_2(s)G(s))\, u(s) = 0. \tag{19}$$

From the assumption that (19) is satisfied for any control input $u(s)$, we have

$$F_1(s) + F_2(s)G(s) = 0. \tag{20}$$

Since $F_1(s) \in RH_\infty^{1\times 2}$, (20) is rewritten by

$$\left[\begin{array}{cc} F_{11}(s) + F_2(s)G_1(s) & F_{12}(s) + F_2(s)G_2(s) \end{array} \right] = 0, \tag{21}$$

where $F_{11}(s)$ and $F_{12}(s)$ are a function denoted by

$$F_1(s) = \left[\begin{array}{cc} F_{11}(s) & F_{12}(s) \end{array} \right]. \tag{22}$$

Using Lemma 3.1, we obtain the parameterization of all $F_{11}(s)$ and $F_2(s)$ satisfying (21), and given by

$$\left[\begin{array}{cc} F_{11}(s) & F_2(s) \end{array} \right] = \left[\begin{array}{cc} G_1(s) & -1 \end{array} \right] + Q(s) \left[\begin{array}{cc} G_1(s) & -1 \end{array} \right], \tag{23}$$

where $Q(s) \in RH_\infty$ is any function.

In a similar way, from Lemma 3.1 and (21), the parameterization of all $F_{12}(s)$ and $F_2(s)$ is written by

$$\left[\begin{array}{cc} F_{12}(s) & F_2(s) \end{array} \right] = \left[\begin{array}{cc} G_2(s) & -1 \end{array} \right] + Q'(s) \left[\begin{array}{cc} G_2(s) & -1 \end{array} \right], \tag{24}$$

where $Q'(s) \in RH_\infty$ is any function. From (23) and (24), it is necessary to satisfy

$$Q(s) = Q'(s). \tag{25}$$

Thus, the parameterization of all $F_1(s)$ and $F_2(s)$ is written by (10) and (11), respectively.
We have thus proved Theorem 3.1. □

In the case that the plant has broken, from (9), we have

$$F_1(s)u(s) + F_2(s)\hat{y}(s) = \left(G(t) - \hat{G}(t)\right) u(t). \tag{26}$$

Substitution of (6) to (26) gives

$$\left(F_1(s) + F_2(s)\hat{G}(s)\right) u(s) = \left(G(s) - \hat{G}(s)\right) u(s). \tag{27}$$

For any $u(s)$, (27) needs to be satisfied, that is,

$$F_1(s) + F_2(s)\hat{G}(s) = G(s) - \hat{G}(s). \tag{28}$$

Equation (28) is rewritten by

$$\left[\begin{array}{cc} F_{11}(s) & F_{12}(s) + F_2(s)G_2(s) \end{array} \right] = \left[\begin{array}{cc} G_1(s) & 0 \end{array} \right]. \tag{29}$$

From this equation and Theorem 3.1, $Q(s)$ in (10) and (11) is given by

$$Q(s) = 0. \tag{30}$$

From Theorem 3.1 and (30), we have the following theorem.

Theorem 3.2. *All $F_1(s)$ and $F_2(s)$ that satisfy (8) and (9) are given by*

$$F_1(s) = \left[\begin{array}{cc} G_1(s) & G_2(s) \end{array} \right] \tag{31}$$

and

$$F_2(s) = -1, \tag{32}$$

respectively.

Proof: The proof is obvious from Theorem 3.1 and (30). □

4. **Design Method for Control System.** In this section, we present a design method for control system in Figure 1.

For safety, even if the system is broken, the output $\hat{y}(t)$ is better to be equivalent to $y(t)$. If

$$\hat{G}(s)\hat{F}(s)\hat{d}(s) = \left(G(s) - \hat{G}(s)\right) u(s) \tag{33}$$

is satisfied, then the output $\hat{y}(s)$ is equivalent to $y(s)$. In this case, even if the system is broken, the output $\hat{y}(t)$ is equivalent to $y(t)$. From simple manipulation, if

$$\hat{F}(s) = \left[\begin{array}{c} \hat{F}_1(s) \\ \hat{F}_2(s) \end{array} \right] = \left[\begin{array}{c} 0 \\ \dfrac{1}{G_2(s)} \end{array} \right], \tag{34}$$

then (33) is satisfied. However, in general, $1/G_2(s)$ is improper. Therefore, we present a design method of $\hat{F}(s)$ as

$$\hat{F}(s) = \left[\begin{array}{c} \hat{F}_1(s) \\ \hat{F}_2(s) \end{array} \right] = \left[\begin{array}{c} 0 \\ \dfrac{q(s)}{G_2(s)} \end{array} \right], \tag{35}$$

where $q(s) \in RH_\infty$ is low-pass filter to make $q(s)/G_2(s)$ proper.

5. **Numerical Example.** In this section, we illustrate a numerical example to show the effectiveness of the proposed method.

The plant $G^{1\times 2}(s)$ and $\hat{G}^{1\times 2}(s)$ are written by

$$G(s) = \left[\begin{array}{cc} G_1(s) & G_2(s) \end{array}\right] = \left[\begin{array}{cc} \dfrac{s+3}{(s+1)(s+2)} & \dfrac{s+6}{(s+4)(s+5)} \end{array}\right] \tag{36}$$

and

$$\hat{G}(s) = \left[\begin{array}{cc} G_1(s) & G_2(s) \end{array}\right] = \left[\begin{array}{cc} 0 & \dfrac{s+6}{(s+4)(s+5)} \end{array}\right], \tag{37}$$

respectively. The reference input is

$$r(t) = \left[\begin{array}{c} r_1(t) \\ r_2(t) \end{array}\right] = \left[\begin{array}{c} \sin(0.4\pi t) \\ \sin(0.4\pi t) \end{array}\right]. \tag{38}$$

From (31) and (36), $F_1(s)$ is designed by

$$F_1(s) = \left[\begin{array}{cc} F_{11}(s) & F_{12}(s) \end{array}\right] = \left[\begin{array}{cc} \dfrac{s+3}{(s+1)(s+2)} & \dfrac{s+6}{(s+4)(s+5)} \end{array}\right]. \tag{39}$$

From (32), $F_2(s)$ is

$$F_2(s) = -1. \tag{40}$$

First, when the plant is normal, we confirm the relationship between $\hat{d}(t)$ and $G_1(s)u_1(s)$ as shown in Figure 2. Here, the solid line shows the response of $\hat{d}(t)$ and the dotted line shows that of $\mathcal{L}^{-1}[G_1(s)u_1(s)](t)$. From Figure 2, $\hat{d}(t) = 0$ anytime. Next, when the plant is broken, we confirm the relationship between $\hat{d}(t)$ and $\mathcal{L}^{-1}[G_1(s)u_1(s)](t)$ as shown in Figure 3. Here, the solid line shows the response of $\hat{d}(t)$ and the dotted line shows that of $\mathcal{L}^{-1}[G_1(s)u_1(s)](t)$. From Figure 3, $\hat{d}(t) = \mathcal{L}^{-1}[G_1(s)u_1(s)](t)$ anytime.

$\hat{F}(s)$ is designed by (35), where

$$q(s) = \frac{1}{0.01s+1}. \tag{41}$$

The relationship between $y(t)$ and $\mathcal{L}^{-1}G_2(s)u_2(s)$ will be explained. Assume that the system is normal until $t = 10$[s]. When $t > 10$[s], the system is broken. The response of

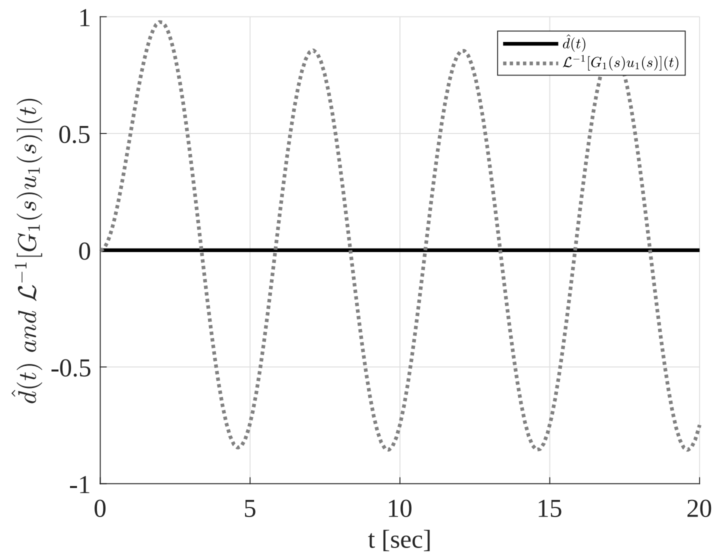

FIGURE 2. $\hat{d}(t)$ and $\mathcal{L}^{-1}[G_1(s)u_1(s)](t)$ when plant is normal

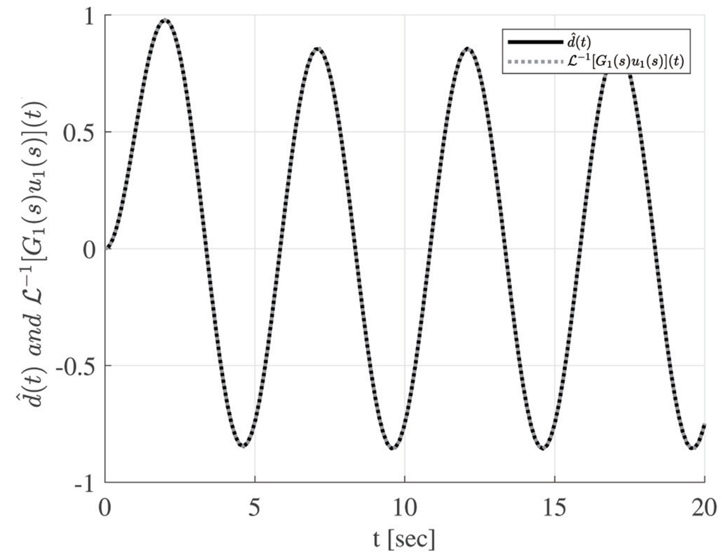

FIGURE 3. $\hat{d}(t)$ and $\mathcal{L}^{-1}\left[G_1(s)u_1(s)\right](t)$ in the case that the plant is broken

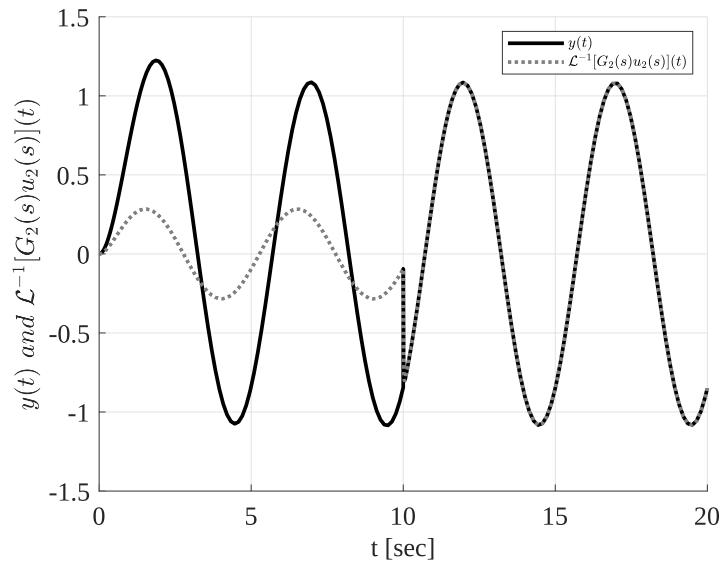

FIGURE 4. $y(t)$ and $\mathcal{L}^{-1}\left[G_2(s)u_2(s)\right](t)$ in the case that the plant is broken at $t = 10$[s]

$y(t)$ is shown in Figure 4. Here, the solid line shows the response of $y(t)$ and the dotted line shows that of $\mathcal{L}^{-1}\left[G_2(s)u_2(s)\right](t)$. From Figure 4, we confirmed that $y(t)$ is equal to $\hat{y}(t)$ even if the plant is broken.

In comparison to existing methods, such as those described in [12], our proposed design method for fault-tolerant control is more straightforward and generic. [12] presents a complex approach to fault-tolerant control that relies heavily on redundancy and disturbance observers. Our method simplifies the design process by using a fault estimator to treat all errors as disturbances within a feedback loop, providing robust control under uncertainty with reduced complexity. Specifically, our method addresses the limitations of [12] by eliminating the need for extensive redundancy and focusing on a fault estimator that ensures system stability and performance through direct compensation of lost outputs. This approach not only simplifies the implementation but also enhances the system's ability to handle catastrophic faults efficiently. We have demonstrated through numerical examples that our method effectively maintains system stability and performance post-fault, showcasing its practical applicability and robustness compared to existing methods.

6. **Conclusions.** In this paper, we have proposed a design method for a fault-tolerant control system using a fault estimator. First, we presented the structure for the fault estimator and the necessary conditions for the fault estimator. Next, the parameterization of all fault estimators is clarified. In addition, even if the plant is broken, it is clarified the condition that the control input $u(t)$ is equivalent to that of $u(t)$ before the plant broken. Using this parameterization, we developed a design method for control systems. A numerical example is provided to demonstrate the effectiveness of the proposed method.

The proposed method is applied to stable plants. Design methods for unstable plants will be described in another article. In addition, in the future, we aim to solidify the proposed method's practicality and applicability, contributing to the advancement of fault-tolerant control systems in various high-reliability applications.

REFERENCES

[1] M. Blanke, M. Kinnaert, J. Lunze and M. Staroswiecki, *Diagnosis and Fault-Tolerant Control*, 3rd Edition, Springer Heidelberg, 2016.
[2] H. Maeda and T. Sugie, *Theory of Systems and Control for Advanced Control*, Asakura Publishing Co., Ltd., 1990.
[3] D. C. Youla, J. J. Bongiorno, Jr. and C. N. Lu, Single-loop feedback-stabilization of linear multivariable dynamical plants, *Automatica*, vol.10, pp.159-173, 1974.
[4] K. Zhou, J. C. Doyle and K. Glover, *Robust and Optimal Control*, Prentice-Hall, New Jersey, 1996.
[5] T. Sakuishi, K. Yubai and J. Hirai, A direct design from input/output data of fault-tolerant control system based on GIMC structure, *IEEJ Transactions on Industry Applications*, vol.128, no.6, pp.758-766, 2008.
[6] C. Huang, F. Naghdy, H. Du and H. Huang, Fault tolerant steer-by-wire systems: An overview, *Annual Reviews in Control*, no.47, pp.98-111, 2019.
[7] X. Wang, S. An and H. Liu, An adaptive disturbance suppression based fault-tolerant control approach against the control surface faults, *International Journal of Innovative Computing, Information and Control*, vol.19, no.1, pp.213-227, 2023.
[8] J. Jiang and X. Yu, Fault-tolerant control systems: A comparative study between active and passive approaches, *Annual Reviews in Control*, vol.36, no.1, pp.60-72, 2012.
[9] M. Blanke and R. B. Jørgensen, Fault handling design for integrated marine systems, *IFAC Proceedings Volumes*, vol.28, no.2, pp.86-95, 1995.
[10] H. Alwi and C. Edwards, Fault tolerant control using sliding modes with on-line control allocation, *Automatica*, vol.44, pp.1859-1866, 2008.
[11] C. Tian, C. Zong, L. He, X. Wang and Y. Dong, Fault tolerant control method for steer-by-wire system, *2009 International Conference on Mechatronics and Automation*, Changchun, pp.291-295, 2009.
[12] A. Ito and Y. Hayakawa, Design of fault tolerant control system for steer-by-wire depending on drive system, *Transactions of the Society of Instrument and Control Engineers*, vol.48, no.12, pp.872-881, 2012.
[13] M. Takahashi, Self-repairing control using a discontinuous fault detection filter, *IEEJ Transactions on Electronics, Information and Systems*, vol.141, no.7, pp.812-821, 2021.
[14] J. Stoustrup and V. D. Blondel, Fault tolerant control: A simultaneous stabilization result, *IEEE Transactions on Automatic Control*, vol.49, no.2, pp.305-310, 2004.
[15] T. Mita, M. Hirata and K. Murata, Theory of H_∞ control and disturbance observer, *IEEJ Transactions on Electronics, Information and Systems*, vol.115, no.8, pp.1002-1011, 1995.
[16] K. Ohnishi, Industry applications of disturbance observer, *International Conference on Recent Advances in Mechatronics*, pp.72-77, 1995.
[17] S. Sun, X. Wei, H. Zhang, H. R. Karimi and J. Han, Composite fault-tolerant control with disturbance observer for stochastic systems with multiple disturbances, *Journal of the Franklin Institute*, vol.355, no.12, pp.4897-4915, 2018.

[18] J. Han, H. Zhang, Y. Wang and Y. Liu, Disturbance observer based fault estimation and dynamic output feedback fault tolerant control for fuzzy systems with local nonlinear models, *ISA Transaction*, vol.59, pp.114-124, 2015.
[19] B. Kwon, D. Kang and K. Yi, Fault-tolerant control with state and disturbance observers for vehicle active suspension systems, *Proc. of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol.234, no.7, pp.1912-1929, 2020.
[20] Z. Anjum, Z. Sun and B. Chen, Disturbance-observer-based fault-tolerant control of robotic manipulator: A fixed-time adaptive approach, *IET Control Theory & Applications*, pp.1-16, 2024.
[21] D. Zhang, K. Hashikura, T. Suzuki and K. Yamada, The characteristic of all strongly stabilizale MIMO plants, *ICIC Express Letters*, vol.13, no.7, pp.601-607, 2019.
[22] T. Hoshikawa, J. Li, Y. Tatsumi, T. Suzuki and K. Yamada, The class of strongly stabilizable plants, *ICIC Express Letters*, vol.11, no.11, pp.1593-1598, 2017.
[23] Z. X. Chen, K. Yamada, N. T. Mai, I. Murakami, Y. Ando, T. Hagiwara and T. Hoshikawa, A design method for internal model controllers for minimum-phase unstable plants, *ICIC Express Letters*, vol.4, no.6(A), pp.2045-2050, 2010.
[24] M. Wakaiki, Y. Yamamoto and H. Ozbay, Stable controllers for robust stabilization of systems with infinitely many unstable poles, *Systems and Control Letters*, vol.62, no.6, pp.511-516, 2013.
[25] Y. S. Chou, T. Z. Wu and J. L. Leu, On strong stabilization and H_∞ strong stabilization problems, *The 42nd IEEE Conference on Decision and Control*, vol.5, pp.5155-5160, 2003.
[26] K. Yamada, A parameterization for the class of all proper stabilizing controllers for linear minimum phase systems, *Preprints of the 9th IFAC/IFORS/IMACS/IFIP/ Symposium on Large Scale Systems: Theory and Applications*, pp.578-583, 2001.
[27] T. Hagiwara, K. Yamada, T. Sakanushi, S. Aoyama and A. C. Hoang, The parameterization of all plants stabilized by proportional controller, *The 25th International Technical Conference on Circuit/Systems Computers and Communications CD-ROM*, pp.76-78, 2010.
[28] W. Zhang, F. Allgower and T. Liu, Controller parameterization for SISO and MIMO plants with time delay, *Systems and Control Letters*, vol.55, pp.794-802, 2001.
[29] H. Ito, H. Ohmori and A. Sano, Design of stable controllers attaining low H^∞ weighed sensitivity, *IEEE Transactions on Automatic Control*, vol.38, pp.485-488, 1993.
[30] M. Zeren and H. Ozbay, On the strong stabilization and stable H_∞ controller design problems for MIMO systems, *Automatica*, vol.36, pp.1675-1684, 2000.
[31] M. Vidyasagar, *Control System Synthesis – A Factorization Approach*, MIT Press, 1985.

Author Biography

Sura Laptawee received the B.Sc. degree in Electronics Physics from Thammasat University, Thailand in 2008, and the M. Eng. degree in Engineering Technology from Thai-Nichi Institute of Technology (TNI), Thailand in 2012 and the Dr. Eng. degree from Gunma University, Gunma, Japan in 2024. His research interests include a design method for fault tolerant control systems.

Hiroki Tani received the B.S. degree and M.S. degree in Science and Technology from Gunma University, Japan, 2020 and 2022, respectively. Since 2022, he works as a systems engineer at Nippon Algorithm Co., Ltd. His research interest includes fault tolerant control system design.

Nghia Thi Mai received the B.S., M.S. and Dr. Eng. degrees from Gunma University, Gunma, Japan in 2009, 2011 and 2014, respectively. From 2014 to 2015, she was with the Human Resources Cultivation Center, Gunma University, Gunma, Japan as a research associate. From 2015 to 2021, she worked on research on damping control for automobiles at Exedy Co., Ltd. Since 2022, she has been working as a lecturer at the Faculty of Electronics Engineering 1, Posts and Telecommunications Institute of Technology (PTIT). In addition, she is currently working as a visiting associate professor and part-time lecturer at the Department of Electronics and Mechanical Engineering, Gunma University. Her research interest includes Smith predictor, internal model control and robotics.

Kotaro Hashikura received the B.S. degree in Mechanical Engineering from Kyushu Institute of Technology, Fukuoka, Japan, 2006; the M.S. degree of Informatics from Kyoto University, Kyoto, Japan, 2010; and the Doctor degree in Engineering from Tokyo Metropolitan University, Tokyo, Japan, 2014. From 2014 until 2018, he had been a project research associate at the Faculty of System Design, Tokyo Metropolitan University.

He is currently an assistant professor at Graduate School of Science and Technology, Gunma University, Japan. His research interests include time-delay-related control techniques, such as deadbeat, preview-prediction and repetitive controls. He is a member of IEEE, ISCIE and SICE.

Md Abdus Samad Kamal received the B.Sc. degree in Electrical and Electronic Engineering from Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh in 1997; Master and Doctor degrees from Kyushu University from Graduate School of Information Science and Electrical Engineering, Japan in 2003 and 2006, respectively. He was a post-doctoral fellow in Kyushu University till November 2006.

He is currently an associate professor at Graduate School of Science and Technology, Gunma University, Japan. His current research interests are reinforcement learning, intelligent transportation systems, and multiagent systems. He is a member of IEEE and SICE.

Iwanori Murakami received his Ph.D. Eng. from Gunma University in 1997. He is currently an associate professor at Gunma University. His research interests include robotics, applied electromagnetics and machines, and superconducting levitation applications.

Wimol San-Um received the B.Eng. degree in Electrical Engineering and the M.Sc. degree in Telecommunications from the Sirindhorn International Institute of Technology, Thammasat University, Thailand, in 2003 and 2006, respectively, and the Ph.D. degree in Mixed-Signal LSI Circuit Designs from the Kochi University of Technology, Japan, in 2010. In 2007, he was a research scholar with the University of Applied Science Ravensburg-Weingarten, Germany. In 2011, he joined the Computer Engineering Department, Thai-Nichi Institute of Technology (TNI). From 2015 to 2017, he was an Associate Dean of the Graduate School and an Assistant Dean of the Faculty of Engineering for International Relations, Thai-Nichi Institute of Technology (TNI).

He is currently a part-time assistant professor at Division of Electrical Engineering, the Director of the Center of Excellence in Intelligent Systems Integration, and the Director of the Digital Engineering Program, Thai-Nichi Institute of Technology (TNI). His areas of research interests are chaos theory, artificial neural networks, secure digital image processing, secure communications, nonlinear dynamics, and chaotic circuits and systems. He is a Committee Member of the Thai Embedded Systems Association and the Artificial Intelligence Association of Thailand. He received TNI Excellent Teaching and Research Awards in 2014, 2016, and 2017. He also received distinguished paper awards from several IEEE refereed conferences, such as ICACT 2013, South Korea, MEC 2013, China, ICBIR 2014 and MITiCON2014, Thailand, IoTBD 2016, Italy, and ICESIT 2017, Thailand. He has served as the General Chair for MITiCON 2016, the IEEE Japan-Thailand Academic Joint Forum 2016, and ICESIT 2017. He served as an Invited Reviewer for various journals, including the IEEE Transactions on Circuits and Systems and the IEEE Access.

Kou Yamada received B.S. and M.S. degrees in Electrical and Information Engineering from Yamagata University, Yamagata, Japan, 1987 and 1989, respectively; and the Dr. Eng. Degree from Osaka University, Osaka, Japan in 1997.

He is currently a full-time professor at Graduate School of Science and Technology, Gunma University, Japan. His research interests include robust control, repetitive control, process control and control theory for inverse systems and infinite-dimensional systems. Dr. Yamada received the 2005 Yokoyama Award in Science and Technology, the 2005 Electrical Engineering/Electronics, Computer, Telecommunication, and Information Technology International Conference (ECTI-CON2005) Best Paper Award, the Japanese Ergonomics Society Encouragement Award for Academic Paper in 2007, the 2008 Electrical Engineering/Electronics, Computer, Telecommunication, and Information Technology International Conference (ECTI-CON2008) Best Paper Award and 4th International Conference on Innovative Computing, Information and Control Best Paper Award in 2009, the 14th International Conference on Innovative Computing, Information and Control Best Paper Award in 2019, Outstanding Achievement Award from Kanto Branch of Japanese Society for Engineering Education in 2022, JSME (The Japan Society of Mechanical Engineers) Education Award in 2023 and the 2024 Electrical Engineering/Electronics, Computer, Telecommunication, and Information Technology International Conference (ECTI-CON2024) Best Paper Award. He is a member of IEEE and SICE and a Fellow of JSME.