International Journal of Innovative
Computing, Information and Control
Volume 20, Number 2, April 2024

ICIC International ©2024 ISSN 1349-4198
pp. 591–602

FAILURE DETECTION USING AN EXTENDED SEMI-STRONGLY STABILIZING CONTROLLER

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Received May 2023; revised October 2023

Abstract. *A strongly stabilization is a control method to make control systems stable using stable controllers. Using this method, it is possible to construct a highly reliable control system, since it has robustness. However, when a strongly stabilizing controller is used, steady-state error remains when step disturbances and uncertainties exist in the control system because the strongly stabilizing controllers do not have a pole on the origin. To solve this problem, Hoshikawa et al. define semi-strongly stabilizing controllers that have a pole on the origin and rest of the poles in the open left half plane. However, the method of Hoshikawa et al. fail to place the poles on the imaginary axis. To be applied to the self-repairing system with failure detection using resonance proposed by Takahashi et al., the controller needs to have a pair of pole on the imaginary axis. Therefore, Kimura et al. define extended semi-strongly stabilizing controller with a pair of pole on the imaginary axis and the other poles in the open left half-plane. In this paper, by adapting the extended semi-strongly stabilizing controller by Kimura et al. to a self-repairing system with failure detection, we propose the control system with failure detection using resonance. We propose a design procedure for the control system with failure detection. The results of this paper enable the construction of a reliable system that detects failure and repairs itself.*
Keywords: Resonance, Extended semi-strongly stabilization, Parameterization

1. Introduction.

This paper concerns a design method for control system with failure detection using the parameterization of all extended semi-strongly stabilizing controllers and resonance. The parameterization is a method of finding all stabilizing controllers for a given plant [1, 2]. Using the parametrization, the stability of the control system is guaranteed. Various papers have been published on parameterization problems, such as Proportional-Integral-Derivative (PID) control [3], two-degree-of-freedom stabilizing

DOI: 10.24507/ijicic.20.02.591

controller [4], disturbance observer [5], modified Smith predictor [6], and internal model controller [7]. However, the stability of the controller obtained in the parametrization is not considered. If the controller is unstable, the control system will be highly sensitive when parameters under control change [8].

In order to be resilient to parameter changes, stable controllers should be used. Toward this problem, there exists a control method called a strongly stabilization. The strongly stabilization makes the control system stable using stable controllers. Using this method, we can overcome the problem of high sensitivity to disturbances and that of degradation of target tracking performance those occur when unstable controllers are used [8, 9, 10].

Unfortunately, for any plant, strongly stabilizing controllers do not necessarily exist. The condition that there exist strongly stabilizing controllers is known as the parity interlacing property condition [8, 11]. Wakaiki et al. examine the sensitivity reduction problem with stable controllers for the linear time-invariant multi-input/multi-output distributed parameter system [12, 13].

However, they do not clarify the class of strongly stabilizable plants. If the class of strongly stabilizable plants is clarified, we can obtain the parameterization of all stable stabilizing controllers. In addition, we can clarify the characteristic of strongly stabilizable plants. From this viewpoint, Hoshikawa et al. clarify the class of all strongly stabilizable plants [14]. In addition, Hoshikawa et al. [15] clarify the parameterization of all two-degree-of-freedom strongly stabilizing controllers.

Using strongly stabilizing controllers, when uncertainty in the plant or a step disturbance exists, the output of the control system cannot follow the step reference input without steady-state error. In many actual control systems, the output is required to follow the step reference input without steady-state error, even if the uncertainty in the plant or the step disturbance exists. To overcome this problem, an integrator must be introduced to offset elimination from a set point. From this viewpoint, Hoshikawa et al. extend the concept of strongly stabilization and propose a concept of semi-strongly stabilization, which is a stabilization by a controller that has a pole at the origin and rest of the poles in the open left half plane [16]. Then, a class of semi-strongly stabilizable plants and a controller design method are proposed [17]. Using these controllers, a robust and reliable control system can be designed. However, using these controllers, when the sensor failure occurs, the stability and performance of the control system cannot be guaranteed. For actuator failures, a class of robust adaptive event-triggered controllers is designed to compensate the effects of actuator faults [18]. In this paper, sensor failures are discussed. There exists a design method proposed by Takahashi [19], even if the sensor failure occurs. The method proposed by Takahashi uses resonance to destabilize the system only in case of an abnormality. After detecting a sensor failure, the failed sensor is replaced with a healthy backup sensor to keep the system stable [19]. However, since resonance is used, the poles need to be on the imaginary axis. Therefore, Kimura et al. define the extended strongly stabilizing controller [20]. Since this controller has a pair of complex conjugate poles on the imaginary axis and the others in the open left half-plane, this controller enables the design robust and reliable control systems and can be applied to a self-repairing system with failure detection using resonance. Existing technology detects failures by reading sensor values and detecting when the values deviate significantly from normal values or when certain abnormalities are detected. The method of failure detection using resonance intentionally causes resonance at the time of failure to detect abnormalities, enabling quick failure detection and detection of failures even when the sensor values do not show abnormalities. However, a failure detection system with extended semi-strongly stabilizing controller using resonance has not yet been proposed.

In this paper, we propose a control system with failure detection that automatically detects sensor faults and replaces them with backups by adapting the extended semi-strongly stabilizing controller to a self-repairing system with failure detection using resonance. Therefore, it is possible to construct a more reliable system that can repair itself against failure. This paper is organized as follows. In Section 2, the problem considered in this paper is explained. In Section 3, we propose structure of the control system with failure detection using resonance. In Section 4, we describe the stability of control system with failure detection. In Section 5, we describe a method for detecting sensor failure using resonance. In Section 6, we present design method for the control system with failure detection. In Section 7, a numerical example is illustrated to show the effectiveness of the proposed method. Section 8 gives concluding remarks.

2. **Problem Formulation.** Consider the control system written by

$$\begin{cases} y(s) = G(s)u(s) + d(s) \\ u(s) = C(s)(r(s) - y(s)) \end{cases}, \tag{1}$$

where $G(s) \in R(s)$ is the plant, $C(s) \in R(s)$ is the controller, $y(s)$ is the output, $u(s)$ is the control input, $d(s)$ is the disturbance and $r(s)$ is the step references input, that is,

$$r(t) = r_0 \in R. \tag{2}$$

$G(s)$ is assumed to be a semi-strongly stabilizable. That is, from [20], $G(s)$ is written by the form

$$G(s) = \frac{n_c(s)Q_2(s) + n_b(s)}{\frac{1 - n_b(s)Q_1(s)}{n_c(s)} - Q_1(s)Q_2(s)}, \tag{3}$$

where $n_c(s)$ is written by

$$n_c(s) = \frac{s^2 + \omega^2}{n_{cd}(s)}, \tag{4}$$

$n_{cd}(s)$ is any Hurwitz polynomial of 2 degrees and $\omega \in R$, $n_b(s) \in RH_\infty$ is an arbitrary function satisfying

$$1 - n_b(s)Q_1(s)\big|_{s=\pm j\omega} = 0, \tag{5}$$

and $Q_1(s) \in RH_\infty$ and $Q_2(s) \in RH_\infty$ are arbitrary functions satisfying

$$Q_1(s)\big|_{s=\pm j\omega} \neq 0. \tag{6}$$

The sensor that senses the value of output $y(t)$ has a backup sensor in case of failure. Initially, the original sensor is used. When a failure of the original sensor is detected, the sensor is switched from the original sensor to the backup sensor. Even if $C(s)$ is designed to stabilize the control system in (1), the sensor failures sometimes make the control system in (1) unstable. If we can detect failures of the control system in (1), the control system in (1) becomes a highly reliable control system.

In this paper, we propose a control system with failure detection using the extended semi-strongly stabilizing controller proposed by Kimura et al. [20] and a self-repairing system with failure sensor using resonance proposed by Takahashi [19].

3. **Control System with Failure Detection Using Resonance.** In this section, we propose a structure of control system with failure detection using resonance. This structure adapts the parameterization of all extended semi-strongly stabilizing controllers [20].

From [20], the extended semi-strongly stabilizing controller with a pair of poles on the imaginary axis can be written by

$$C(s) = \frac{Q_c(s)}{n_c(s)}. \tag{7}$$

According to [20], for the extended semi-strongly stabilizable plant $G(s)$ in (3), the parameterization of all extended semi-strongly stabilizing controllers $C(s)$ can be expressed by

$$C(s) = \frac{Q_1(s) + \left(\frac{1-n_b(s)Q_1(s)}{n_c(s)} - Q_1(s)Q_2(s)\right)P(s)}{n_c(s) - (n_b(s) + n_c(s)Q_2(s))\,P(s)}, \tag{8}$$

where $P(s) \in RH_\infty$ is a function written by

$$P(s) = n_c(s)Q(s), \tag{9}$$

$$Q(s) = \frac{1 - \hat{Q}(s)}{n_b(s) + n_c(s)Q_2(s)}. \tag{10}$$

$\hat{Q}(s) \in \mathcal{U}$ is a function that makes $Q(s)$ in (10) proper and satisfies

$$\left.\frac{1}{(s-s_i)^{m_i-1}}\left\{1 - \hat{Q}(s)\right\}\right|_{s=s_i} = 0 \ \forall i, \tag{11}$$

where $\mathcal{U}$ denotes the set of all unimodular functions, $s_i \in R$ is unstable zeros of $n_b(s) + n_c(s)Q_2(s)$ and m_i is its multiplicity.

Using above parameters, we propose the control system with failure detection as shown in Figure 1. Here $\tau(s)$ denotes Laplace transformation of $\tau(t)$ written by

$$\tau(t) = \delta\sin(\omega t), \tag{12}$$

and is an auxiliary signal. $\delta > 0$, $v(s)$ is the Laplace transformation of the detector output $v(t)$ that determines whether or not, the control system has failed. $Z(s)S_N(s)/S_D(s)$ is a detector and $S_N(s) \in RH_\infty(s)$, $S_D(s) \in RH_\infty(s)$ and $Z(s) \in RH_\infty(s)$ are written by

$$S_N(s) = \frac{s}{s+\sigma}, \tag{13}$$

$$S_D(s) = \frac{s^2+\omega^2}{(s+\sigma)^2} \tag{14}$$

and

$$Z(s) = \frac{\zeta}{s+\sigma}, \tag{15}$$

respectively, where $\zeta > 0$, $K > 0$ and $\sigma > 0$. When a failure occurs, detector output $v(t)$ resonates as the auxiliary signal $\tau(t)$ is added to the detector $Z(s)S_N(s)/S_D(s)$, and the failure can be detected by measuring the value of detector output $v(t)$. $n_c(s)$ is written by

$$n_c(s) = \frac{S_D(s)}{S_D(s)K + Z(s)S_N(s)} = \frac{s^2+\omega^2}{Ks^2+\zeta s+K\omega^2}. \tag{16}$$

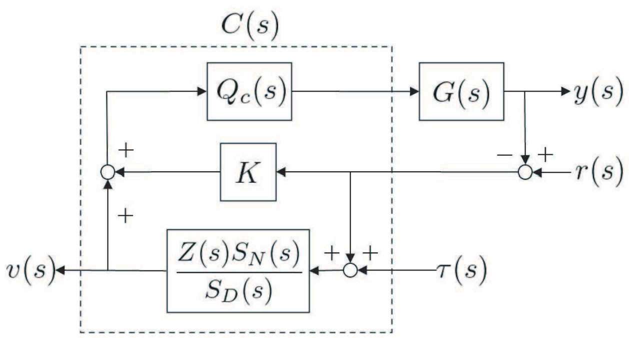

FIGURE 1. Control system with failure detection using resonance

In order for the controller $C(s)$ in Figure 1 to express all stabilizing controller for $G(s)$ in (3), that is, the controller $C(s)$ in Figure 1 is equal to the parametrization of all extended semi-strongly stabilizing controller in (8), $Q_c(s)$ in Figure 1 is given by

$$Q_c(s) = Q_1(s) + \frac{Q(s)}{1 - (n_b(s) + n_c(s)Q_2(s))Q(s)}. \tag{17}$$

4. **Stability of Control System in Figure 1.** In this section, we explain the stability of control system in Figure 1 with respect to auxiliary signal $\tau(s)$ and detector output $v(s)$.

From simple manipulation, transfer functions from auxiliary signal $\tau(s)$ to the output $y(s)$ and the control input $u(s)$ are

$$y(s) = \frac{G(s)C(s)}{1 + G(s)C(s)} \frac{n_c(s)Z(s)S_N(s)}{S_D(s)} \tau(s) \tag{18}$$

and

$$u(s) = \frac{C(s)}{1 + G(s)C(s)} \frac{n_c(s)Z(s)S_N(s)}{S_D(s)} \tau(s), \tag{19}$$

respectively. Since, $n_c(s) \in RH_\infty$, $Z(s) \in RH_\infty$, $S_N(s) \in RH_\infty$, $n_c(s)$ has unstable zeros at $\pm j\omega$ and that all unstable zeros of $S_D(s)$, $n_c(s)Z(s)S_N(s)/S_D(s)$ is also stable. Therefore, the transfer functions of (18) and (19) are stable. From simple manipulation, the transfer functions from reference input $r(s)$, disturbance $d(s)$ and auxiliary signal $\tau(s)$ to the detector output $v(s)$ are

$$v(s) = \frac{1}{1 + G(s)C(s)} \frac{Z(s)S_N(s)}{S_D(s)} r(s), \tag{20}$$

$$v(s) = -\frac{1}{1 + G(s)C(s)} \frac{Z(s)S_N(s)}{S_D(s)} d(s), \tag{21}$$

and

$$v(s) = \left(\frac{1}{1 + G(s)C(s)} \frac{Z(s)S_N(s)}{S_D(s)} + \frac{G(s)C(s)}{1 + G(s)C(s)} \frac{Kn_c(s)Z(s)S_N(s)}{S_D(s)} \right) \tau(s), \tag{22}$$

respectively. Since $n_c(s) \in RH_\infty$, $Z(s) \in RH_\infty$, $S_N(s) \in RH_\infty$, $n_c(s)$ and $1/(1+G(s)C(s))$ have unstable zeros at $\pm j\omega$ that is all unstable poles of $S_D(s)$, the transfer functions of (20), (21) and (22) are stable. Therefore, the control system with failure detection in Figure 1 is stable.

5. **Failure Detection.** In this section, we describe a method for detecting sensor failure using the detector $Z(s)S_N(s)/S_D(s)$.

Consider a situation, where a sensor fails and the sensor value is stuck as

$$y(s) = \frac{y_f}{s}. \tag{23}$$

Here, $y_f \in R$ is the value of $y(s)$ after the sensor failure. In this case, the correct output $y(s)$ is not feedback, that is, the control system in Figure 1 changes to a kind of feed-forward control system. Then from (2), $v(s)$ in Figure 1 is given by

$$v(s) = \frac{\zeta s}{s^2 + \omega^2} \left(\frac{r_0 - y_f}{s} + \frac{\delta\omega}{s^2 + \omega^2} \right). \tag{24}$$

This yields

$$v(t) = \mathcal{L}^{-1}[v(s)] = \zeta \left(\frac{r_0 - y_f}{\omega} + \frac{\delta}{2} t \right) \sin(\omega t). \tag{25}$$

This implies that when the sensor failure occurs, a resonance phenomenon occurs. Therefore, we can detect sensor failure if the minimum time exists such that

$$|v(t)| > \Gamma \in R. \tag{26}$$

When $|v(t)|$ satisfies (26), that is, a failure is detected, the sensor switches from the original failed sensor to a normal backup sensor. After switching to the normal backup sensor, the normal output value is feedback and the system returns to the normal state. Since the original control system is stable as shown in Section 4, the system returns to be stable. In this way, failure detection is performed.

6. **Design Method for the Control System with Failure Detection.** A design method is summarized as following procedure.

1) $K > 0$ and $S_N(s)$ are settled as (13).
2) $S_D(s)$ are settled as (14).
3) $Z(s)$ are settled as (15).
4) $n_c(s)$ is given by (16).
5) Extended semi-strongly stabilizable plant $G(s)$ can be factorized by (3).
6) Threshold Γ is set, so that if $v(s)$ satisfies (26), we find that the sensor failure occurs and the original sensor to the backup sensor.
7) $\hat{Q}(s)$ is designed so that $\hat{Q}(s) \in \mathcal{U}$ is designed to make $Q(s)$ in (10) proper and to satisfy (11). According to [20], $\hat{Q}(s)$ can be designed.
8) $Q_c(s)$ is given by (17). We can design the control system in Figure 1.
9) $\tau(s)$ is set by (12). The threshold Γ for failure detection in (26) is settled. The larger the amplitude δ of the auxiliary signal $\tau(t)$, the smaller the threshold Γ, the more sensitive the failure detection and the faster the time to failure detection. However, if the sensitivity is too high, a fault may be detected when there is no fault, so the value must be adjusted appropriately.

7. **Numerical Example.** In this section, a numerical example is shown to illustrate the effectiveness of the proposed method.

Consider the problem to design control system with failure detection for the plant $G(s)$ written by

$$G(s) = \frac{90.9 \times 10^3}{(s + 0.117)(s^2 + 3.97s + 2.02 \times 10^3)}, \tag{27}$$

which is considered in [20]. When $n_c(s)$ is settled by

$$n_c(s) = \frac{s^2 + 1}{1.01s^2 + 2s + 1.01}, \tag{28}$$

as (16), from simple manipulation, $G(s)$ in (27) is factorized by (3), where

$$Q_1(s) = 0.01, \tag{29}$$

$$Q_2(s) = \frac{-(s + 197.7)(s - 0.7893)(s + 0.3697)(s^2 + 6.766s + 1587)}{(s + 0.3142)(s^2 + 0.2564s + 1.821)(s^2 + 3.516s + 2018)}, \tag{30}$$

and

$$n_b(s) = \frac{s^2 + 200s + 1}{1.01s^2 + 2s + 1.01}. \tag{31}$$

Therefore, $G(s)$ in (27) is semi-strongly stabilizable.

K, $S_N(s)$, $S_D(s)$, $Z(s)$ in Figure 1 are set as

$$K = 1.01, \tag{32}$$

$$S_N(s) = \frac{s}{s^2+\sigma} = \frac{s}{s^2+0.1}, \tag{33}$$

$$S_D(s) = \frac{s^2+\omega^2}{(s+\sigma)^2} = \frac{s^2+1}{(s+0.1)^2} \tag{34}$$

and

$$Z(s) = \frac{\zeta}{s+\sigma} = \frac{2}{s+0.1}, \tag{35}$$

respectively, where $\omega = 1$, $\zeta = 2$ and $\sigma = 0.1$.

$\hat{Q}(s)$ is set as

$$\hat{Q}(s) = \frac{s^3+3s^2+3s+0.01}{(s+1)^3}. \tag{36}$$

From (17), we have

$$Q_c(s) = \frac{0.01011(s+0.2333)(s^2+0.613s+0.691)(s^2+4.133s+7.775)}{(s+1.997)(s^2+1.98s+1)(s^2+1.003s+0.9967)}. \tag{37}$$

The auxiliary signal $\tau(s)$ is set by (12), where $\delta = 0.1$ and the threshold for failure detection in (26) is $\Gamma = 1.3$.

When $t = t_F = 15$ [sec], we suppose that the sensor failure occurs. That is, after $t = t_F$, the output $y(t)$ is assumed to be

$$y(t) = y(t_F) \;\; (t \geq t_F). \tag{38}$$

If

$$t \geq t_D = \min\{t \mid |v(t)| \geq \Gamma\}, \tag{39}$$

we find that the sensor failure occurs and the failed sensor is changed to the backup sensors.

When $r(t) = 1$, the response of the output $y(t)$, the sensor value $y_S(t)$ and $|v(t)|$ of the control system in Figure 1 are shown in Figure 2. Here, in the upper figure, the solid line shows the response of the output $y(t)$, dashed line shows the response of the sensor value $y_s(t)$ and the dash-dotted line shows the response of the reference input $r(t) = 1$. In the lower figure, the solid line shows the response of $|v(t)|$ and the dash-dotted line shows threshold $\Gamma = 1.3$. From Figure 2, when $t_F = 15$ [sec] the sensor signal sticks, the value of the output $v(t)$ of the detector increases, indicating that it is resonant. Around 27 [sec], the value of $|v(t)|$ exceeds the threshold Γ, and the failed sensor is replaced by a backup as soon as it is detected. Therefore, the stability of the control system has been regained.

Next, we present the results of different numerical examples. Consider the problem to design control system with failure detection for the unstable plant $G(s)$ written by

$$G(s) = \frac{8.2(s+2)(s^2+0.9756s+0.5122)}{(s-0.1)(s+1)^2(s+2)}. \tag{40}$$

The plant $G(s)$ is set to be unstable in order to show that the controller $C(s)$ stabilizes the control system when the plant $G(s)$ is unstable. When $n_c(s)$ is settled by

$$n_c(s) = \frac{s^2+1}{s^2+2s+1}, \tag{41}$$

as (16), from simple manipulation, $G(s)$ in (40) is factorized by (3), where

$$Q_1(s) = 0.5, \tag{42}$$

$$Q_2(s) = 2, \tag{43}$$

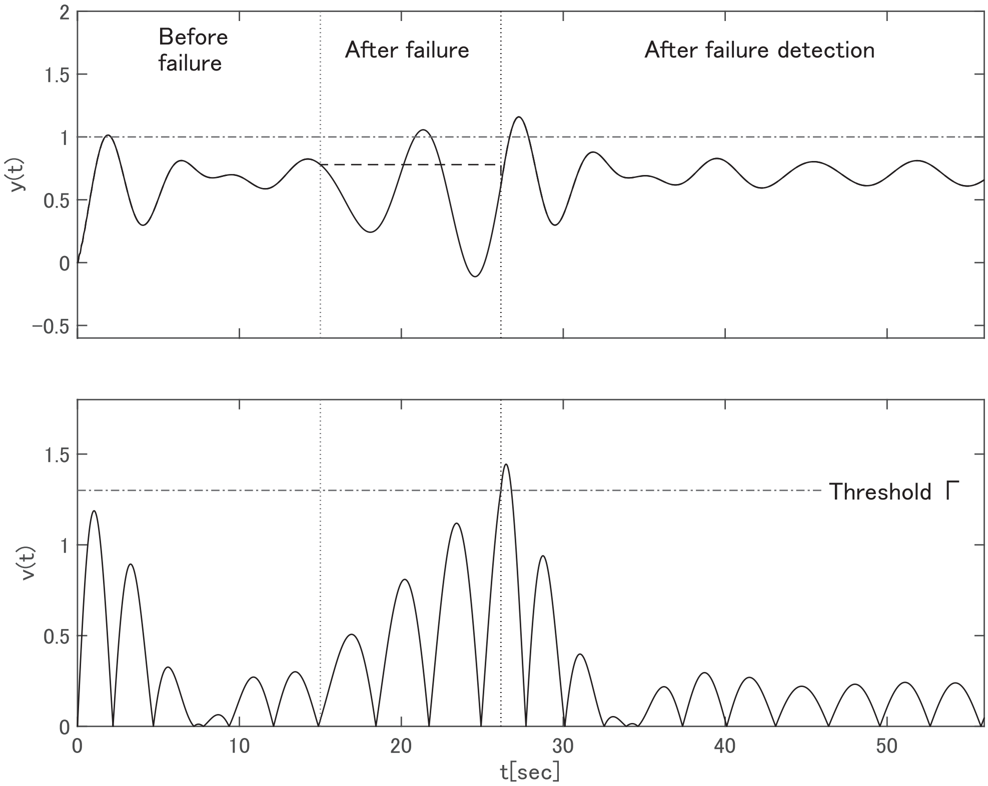

FIGURE 2. The output $y(t)$ and sensor value $y_S(t)$ (top), and absolute value of detector output $v(t)$ (bottom)

and

$$n_b(s) = \frac{-2(s-2)}{s+2}. \tag{44}$$

Therefore, $G(s)$ in (40) is semi-strongly stabilizable.

K, $S_N(s)$, $S_D(s)$, $Z(s)$ in Figure 1 are set as

$$K = 1, \tag{45}$$

$$S_N(s) = \frac{s}{s^2+\sigma} = \frac{s}{s^2+0.1}, \tag{46}$$

$$S_D(s) = \frac{s^2+\omega^2}{(s+\sigma)^2} = \frac{s^2+1}{(s+0.1)^2} \tag{47}$$

and

$$Z(s) = \frac{\zeta}{s+\sigma} = \frac{2}{s+0.1}, \tag{48}$$

respectively, where $\omega = 1$, $\zeta = 2$ and $\sigma = 0.1$.

$\hat{Q}(s)$ is set as

$$\hat{Q}(s) = \frac{s^3+3s^2+3s+0.01}{(s+1)^3}. \tag{49}$$

From (17), we have

$$Q_c(s) = \frac{0.5(s+0.301)(s^2+0.7324s+0.5688)(s^2+2.942s+2.851)}{(s+0.003345)(s^2+0.9756s+0.5122)(s^2+2.997s+2.99)}. \tag{50}$$

The auxiliary signal $\tau(s)$ is set by (12), where $\delta = 0.1$ and the threshold for failure detection in (26) is $\Gamma = 0.5$.

When $t = t_F = 15$ [sec], we suppose that the sensor failure occurs.

When $r(t) = 1$, the response of the output $y(t)$, the sensor value $y_S(t)$ and $|v(t)|$ of the control system in Figure 1 are shown in Figure 3. Here, in the upper figure, the solid line shows the response of the output $y(t)$, dashed line shows the response of the sensor value $y_s(t)$ and the dash-dotted line shows the response of the reference input $r(t) = 1$. In the lower figure, the solid line shows the response of $|v(t)|$ and the dash-dotted line shows threshold $\Gamma = 0.5$. From Figure 3, when $t_F = 15$ [sec] the sensor signal sticks, the value of the output $v(t)$ of the detector increases, indicating that it is resonant. Around 19 [sec], the value of $|v(t)|$ exceeds the threshold Γ, and the failed sensor is replaced by a backup as soon as it is detected. As can be seen in Figure 3, even if plant $G(s)$ is unstable, failure detection is possible and the system can be stabilized.

In this way, we can easily design self-repairing system using resonance.

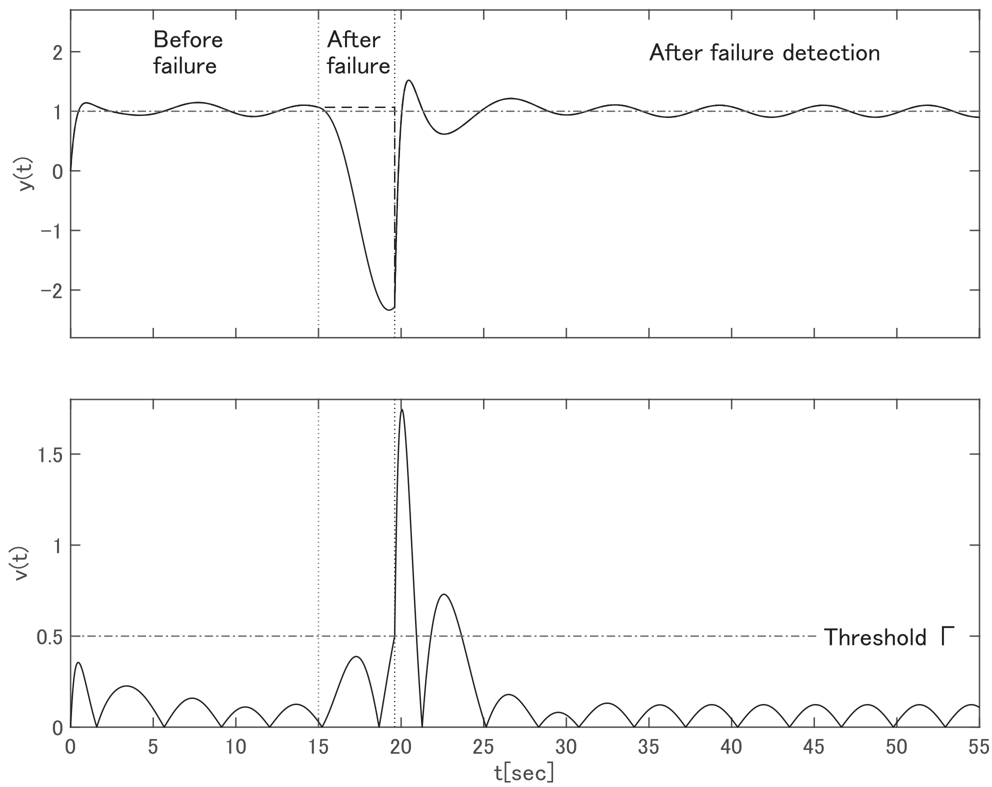

FIGURE 3. The output $y(t)$ and sensor value $y_S(t)$ (top), and absolute value of detector output $v(t)$ (bottom)

8. **Conclusions.** In this paper, we propose the control system that automatically detects sensor faults and replaces them with backups by adapting the extended semi-strongly stabilizing controller to a self-repairing system with failure detection using resonance. The proposed control structure can express all semi-strongly stabilizing controller. That is, the proposed controller is equivalent to the parameterization of all semi-strongly stabilizing controllers in [20]. The stability of the proposed control system was examined. A design method of control system was presented. Finally, a numerical example was illustrated to show the effectiveness of the proposed method.

For example, a distance sensor such as an infrared sensor is used to measure the distance from an obstacle for the mobile robot to avoid the obstacle. The mobile robot avoids obstacles by feeding back the value of the distance sensor. In this case, dirt on the infrared sensor may prevent it from measuring the correct value. In the case of distance sensors, it is difficult to determine whether the sensor value is faulty or not. In such cases, the failure detection method proposed in this paper can be applied to detecting abnormalities by intentionally causing resonance, thereby enabling rapid failure detection.

This method remains some problem. In Section 7, the output $y(t)$ does not follow the reference input $r(t)$ without steady state error. In addition, the output $y(t)$ is effected by auxiliary signal $\tau(t)$. To overcome these problems will be future work.

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