令和 6 年度 博士論文

A Design Method for Fault Tolerant Control System

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Contents

Chapter 1

Introduction

For centuries, control theories have assumed that system components work properly and precisely. However, this assumption is not always valid, as systems are susceptible to faults and failures that can degrade performance and destabilize controllers. The increasing demand for reliable and safe controllers has brought fault-tolerant control (FTC) systems to the forefront of research in control theories. Numerous beneficial review articles have been published, providing overviews of recent techniques and achievements in FTC.

In 1991, Stengel published a review paper on FTC, investigating the basics of FTC concepts and the application of artificial intelligence in FTC systems [1]. In 1997, Patton presented a comprehensive critique of FTC design and analysis, highlighting key issues [2]. Luze and Richter further commented on the state-of-the-art achievements in FTC design through an introductory tutorial focusing on reconfiguration [3]. Alwi et al. reviewed various types of faults and failures in control systems, along with fault detection, isolation (FDI), and FTC approaches [4].

Several papers have critically examined the development of active and passive FTC systems, investigating their challenges and advantages [5][6][7][8]. Additionally, FDI and FTC have been reviewed in the context of aerospace systems and the combination of active and passive approaches [9]. Surveys have also explored the application of FTC in specific domains such as spacecraft attitude control [10], single-rotor aircraft [11], electric speed systems [12][13], photovoltaic (PV) systems [14], and power electronic systems [15][16]. FDI approaches have been categorized into four subcategories: model-based, signal-based, knowledge-based, and hybrid/active approaches [17][18].

Despite decades of effort to develop comprehensive FTC and FDI approaches, most papers have focused on hardware redundancy, with analytical redundancy still under investigation. Furthermore, many works have reviewed FTC and FDI separately, and the connection between them for achieving active FTC remains a subject of ongoing research. The significant number of successful research efforts in control systems and the increasing desire for reliable control systems inspire continued research in this field.

1.1 General Approaches to Fault-Tolerant Control Systems

FTC design can be categorized into two main approaches: passive and active, depending on how redundancy is utilized. In the passive approach, potential system component failures are known a priori, and the control system is designed to account for these failure modes from the outset. Once the control system is implemented, it remains fixed throughout its operation, maintaining performance even when components fail. However, passive FTC can only guarantee system performance for scenarios considered during the design stage, leaving the system vulnerable to unanticipated failures. As a result, the designed controller must be conservative to ensure stability across various component failures, often at the cost of optimal performance.

In contrast, active FTC responds dynamically to system component failures by reconfiguring the control system to maintain sufficient performance. Based on real-time fault detection and diagnosis, active FTC adjusts the system to accommodate changing conditions and component states. Key factors for successful active FTC include speed, accuracy, and robustness. Properly designed active FTC can handle unforeseen faults and increase the likelihood of achieving optimal performance.

A critical consideration in the design and implementation of active FTC systems is the real-time aspect, as the system must respond promptly to integrate both online and real-time fault detection/diagnosis schemes with control system reconfiguration. Given the limited time and information available, it may not always be possible to pinpoint the exact nature and location of faults, making stochastic stability a key factor for active FTC.

1.2 Development of Passive Fault-Tolerant Control Systems

Passive fault-tolerant control focuses on using multiple controllers to create a reliable control system. In the early 1980s, a multiple disjoint decentralized control structure was initially studied theoretically. Fault tolerance was successful when the reliability of the resulting control system was improved beyond using individual controllers. Redundancy and decentralized control were essential concepts in these early works.

Theoretical studies illustrated the use of diversified actuators in dynamic systems, investigated in the context of multi-variable control systems. System integrity, defined as the stability of the closed-loop system despite component failures, was a key focus [20]. Necessary and sufficient conditions for achieving integrity against sensor failures were obtained using stable co-prime factorization approaches [21][22].

Incorporating the concept of redundant control elements allowed existing control system design techniques to be adapted for passive fault-tolerant control. For example, a linear quadratic optimal control approach was improved by applying state feedback controller implementation [23]. Frequency domain analysis using transfer function matrices provided necessary and sufficient conditions for system integrity [24]. Similar issues were addressed using matrix equations [25], and the linear quadratic regulator (LQR) viewpoint was explored [26], relying on Riccati or Lyapunov equations applicable to open-loop asymptotically stable systems. A linear quadratic controller was also proposed to handle both stable and unstable systems [27].

Figure 1.1 shows a typical structure of a passive FTC system, where a null value indicates that the i-th actuator has failed, preventing the control signal from passing through that channel. The design challenge in passive FTC is to ensure that the closed-loop system remains stable despite various combinations of element failures.

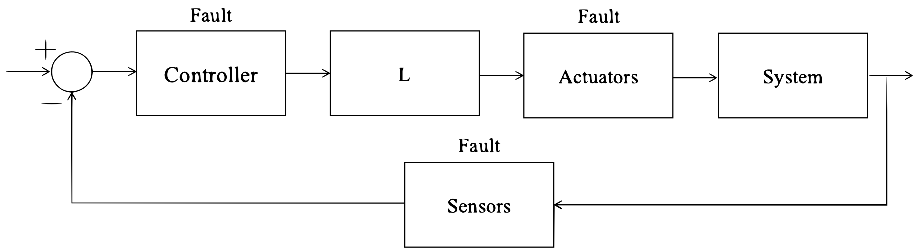

Fig. 1.1: Structure of passive fault-tolerant control systems

Passive FTC for actuator failures has been explored using H_2 optimization, leading to centralized and decentralized fault-tolerant control systems with specific stability and H_2 norm bounds [28][29]. The design also extended to discrete systems using the δ operator methodology [30].

When a system component fails, it causes changes in the system that can be represented by a failure parameter. Fault tolerance is achieved if the control system is designed to be insensitive to these changes. This led to the development of passive FTC using the parameter space approach [31][32]. A closed-loop system could be designed to remain stable despite sensor and actuator failures by selecting appropriate controller structures and system parameters.

The reliable stabilization problem in passive FTC involves designing a set of controllers that can stabilize a single system [33]. A set of controllers or a combination can stabilize the system, which is particularly useful for dealing with controller failures. This redundancy in control strategy is known as simultaneous stabilization, where a single controller can stabilize multiple systems [34]. The performance of this approach, however, has not always been incorporated.

A new approach to passive FTC design has been proposed, focusing on the roles of redundant actuators in a dynamic system [35]. The concept of actuator redundancies and the use of dynamic pre-compensators to equalize the dynamic properties of each actuator channel toward system output simplifies passive FTC design. This approach has the advantage of providing a clear physical definition and role for each actuator during operation. Incorporating proportional and integral control actions can maintain both closed-loop stability and steady-state tracking ability despite actuator failures [36]. In literature, passive FTC is often referred to as “ reliable control. ”

1.3 Development of Active Fault-Tolerant Control Systems

Active fault-tolerant systems have been extensively researched, particularly in flight control systems for aircraft. The goal is to equip onboard flight control systems with “ self-repairing ” capabilities to ensure safe landing in the event of component failures [37]. This research was partly inspired by commercial aircraft accidents in the late 1970s. For example, on April 12, 1977, Delta Airline Flight 1080 experienced a jammed elevator at 19 degrees up, which was not communicated to the pilots. The pilot managed to reconfigure the remaining control components and land safely due to redundant actuation on the L-1011 aircraft [38][39]. Another case was American Airlines DC-10 Flight 191 in May 1979, where the plane crashed due to an attempt to accelerate with insufficient response time to failures [39]. For military aircraft, active FTC is also an attractive method for dealing with complex air territory challenges [40].

Unlike passive FTC, active FTC dynamically responds to diagnosed failures by manipulating redundancies based on real-time information to maintain acceptable performance and system stability [41]. Active FTC involves a trade-off to cope with degraded performance due to limited redundancies. Active fault-tolerant control systems are also referred to as self-repairing, reconfigurable, or re-structure-able control systems [38][42][43].

An active FTC system typically consists of three components, as shown in Figure 1.2: (a) fault detection/diagnosis scheme; (b) controller reconfiguration mechanism; and (c) reconfigurable controller. These components must work harmoniously to form an effective active FTC system in real time.

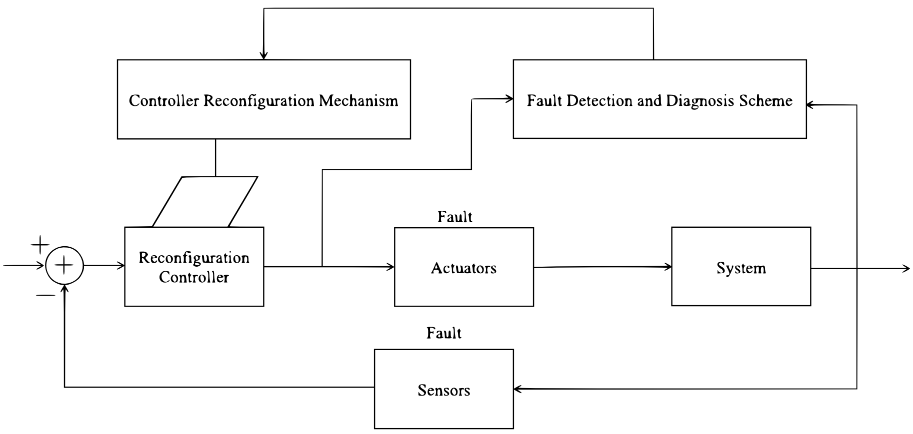

Fig. 1.2: Structure of active fault-tolerant control systems

1.4 Steer-by-wire technology

Steer-by-wire (SBW) technology represents a significant advancement in automotive engineering, replacing the traditional mechanical and hydraulic linkages between the steering wheel and the wheels with electronic controls. This innovation offers numerous benefits, including improved vehicle handling, reduced weight, and greater design flexibility. These benefits are particularly advantageous for electric and autonomous vehicles, where the elimination of mechanical components can lead to substantial improvements in efficiency and design freedom.

However, the shift to electronic systems introduces new challenges, particularly concerning reliability and safety. In traditional steering systems, mechanical linkages provide a direct and fail-safe connection between the driver and the wheels. In contrast, SBW systems rely on electronic signals to transmit steering commands, which can be susceptible to faults such as sensor failures, actuator malfunctions, and communication errors. These faults can have severe consequences, including loss of vehicle control, necessitating the integration of robust fault detection and diagnosis (FDD) mechanisms.

The design of a control system for SBW must therefore incorporate methods to detect and manage faults effectively to ensure continuous, safe operation. This involves detailed system modeling to understand the behavior of the vehicle under various conditions and to predict potential fault scenarios. Advanced control algorithms, such as Proportional-Integral-Derivative (PID) controllers, Linear Quadratic Regulators (LQR), and model predictive control, are developed to maintain desired steering performance. Additionally, redundant control systems are often implemented to take over in case of a primary system failure.

Fault detection and diagnosis (FDD) is a critical component of the SBW control system. Signal-based methods, such as residual generation techniques, use parity space and observers to detect discrepancies between expected and actual signals. Model-based methods compare real-time data with the system model to identify inconsistencies. Data-driven methods utilize machine learning algorithms to analyze patterns and detect anomalies. These methods are integrated to provide a comprehensive fault detection strategy.

Fault-tolerant control strategies are devised to reconfigure the system or degrade its functionality gracefully in the presence of faults. This can include switching to redundant controllers, adjusting control parameters, or activating fail-safe modes that allow the vehicle to be driven safely to a service location. The system undergoes extensive testing through simulations, Hardware-in-the-Loop (HIL) testing, and real-world field tests to validate performance and reliability.

The integration of redundant sensors and actuators, along with safety protocols and software update capabilities, further enhances the system's robustness. Redundancy ensures that a single point of failure does not compromise the entire system, while safety protocols provide guidelines for emergency responses. Software updates allow for continuous improvement and adaptation to new fault scenarios.

By addressing these challenges, SBW systems can provide enhanced performance and safety, paving the way for broader adoption in modern vehicles. The technology is particularly beneficial in electric and autonomous vehicles, where it can integrate seamlessly with other advanced systems to improve overall vehicle performance and user experience. [44, 45].

1.5 The Purpose and Contents

In this thesis, we propose the design and implementation of fault-tolerant control systems that are crucial in ensuring the reliability and stability of Systems and advanced automotive technologies. Component failures in control systems can lead to significant instability and degraded performance, making it imperative to develop methods that can effectively handle faults and maintain optimal performance.

In Chapter 2, we focus on developing a fault-tolerant control method. Plant, often used in environments requiring high reliability, such as production plants and human-interactive systems, need robust control strategies to manage component failures without compromising performance. The chapter introduces a fault estimator-based approach, which simplifies the design process and enhances system reliability by detecting and compensating for faults, ensuring stability even under component failure conditions.

In Chapter 3, we address the specific application of fault-tolerant control in steer-by-wire systems for vehicles. Steer-by-wire technology eliminates mechanical connections between the steering wheel and the wheels, offering numerous benefits such as improved fuel efficiency, enhanced safety, and greater design flexibility. However, this technology also poses significant challenges in terms of fault management. This chapter proposes a fault detector-based control method that ensures safe and reliable steering operation even in the event of system malfunctions, thus enhancing the overall robustness and reliability of steer-by-wire systems.

In Chapter 4, we summarize the results of the present study and draw conclusions based on our findings.

Chapter 2

A Design Method of Fault Tolerant Control Systems Using Fault Detector

2.1 Introduction

Component faults in control systems can result in significant instability and degraded performance. To prevent these faults from escalating into complete system failures while maintaining optimal performance and stability, it is crucial to implement effective fault-tolerant control systems [46]. This necessity is particularly acute in Plant and environments demanding high reliability, such as production facilities and human-interactive systems [47, 48, 49, 50]. For example, next-generation steer-by-wire vehicle systems require a higher degree of fault tolerance compared to traditional steering mechanisms [51]. In response, many researchers have concentrated on developing advanced fault-tolerant control methodologies [46, 52, 53].

Early work by Blanke et al. introduced techniques for fault management based on fault mode analysis [54], while Alwi and Edwards advanced a sliding mode-based approach for fault-tolerant control [55]. The application of electronically controlled actuators and force feedback to improve safety and adaptability in steering systems has been notably emphasized by Chengwei Tian et al. [56]. Nonetheless, Ito and Hayakawa highlighted that adding redundancy in sensors, actuators, and microprocessors often increases costs and weight [57]. Another approach by Takahashi involved a self-repairing control system using a discontinuous fault detection filter, showcasing efforts to bolster system reliability [58].

Fault-tolerant control strategies are generally divided into active and passive types. Active fault-tolerant control involves the real-time detection and adjustment of system faults [46, 59], but it faces challenges such as the time required for fault diagnosis and the implementation of new control schemes [53]. Conversely, passive fault-tolerant control designs aim to maintain system stability despite the presence of faults, although this often leads to conservative designs and diminished performance [59].

Recognizing faults as perturbations within system components, disturbance observers have been proposed to address these issues. Disturbance observers maintain steady-state error close to zero by dynamically adjusting plant parameters [60, 61]. This principle has driven researchers to investigate fault-tolerant control systems utilizing disturbance observers [62, 63, 64]. For instance, Sun et al. proposed a composite fault-tolerant control with a disturbance observer for stochastic systems experiencing disturbances and faults [62]. Han et al. developed disturbance and fault estimation observers for fuzzy systems with local nonlinear models and external disturbances [63]. Kwon et al. presented a fault-tolerant control scheme for vehicle active suspension systems, employing both a suspension state observer and a disturbance observer to inform feedback control inputs [64]. Additionally, Anjum et al. introduced 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 [65]. However, most designs that utilize disturbance observers focus on estimating perturbations rather than faults, resulting in complex system designs.

To address these challenges, we propose a design method for fault-tolerant control based on a fault estimator. This approach aims to offer a simpler and more effective solution capable of handling catastrophic faults, where the system may become unstable due to component failures, by detecting faults and compensating for lost outputs. Our proposed method includes 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 functions 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 [66, 67, 68, 69, 70, 71, 72, 73, 74, 75]. this chapter explores the stability of control systems with uncertain states, building on the results of previous studies like [66]. Our proposed fault-tolerant control system presents a simpler and more effective alternative to conventional methods employing disturbance observers.

By simplifying the design and focusing on direct fault estimation, our approach aims to enhance system reliability and performance without the complexities associated with existing methods. this chapter is structured as follows: Section 2.2 outlines the problem and defines the fault estimator. Section 2.3 details the parameterization of fault estimators. Section 2.4 presents our design method. Section 2.5 provides a numerical example, and Section 2.6 concludes the paper.

2.2 Problem Formulation

Consider the control system in Fig. 2.1, 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

$$\hat{d}(s) = F_1(s)u(s) + F_2(s)y(s). \tag{2.1}$$

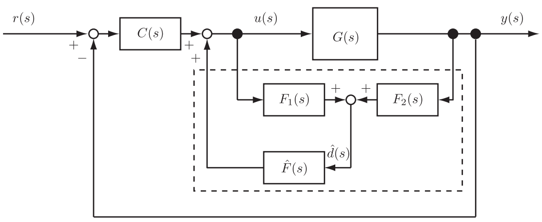

Fig. 2.1: Control System

From Fig. 2.1, $G(s) \in R^{1\times 2}(s)$ and $u(s) \in R^{2\times 1}(s)$, we can denotes $y(s)$ as

$$\begin{aligned} y(s) &= G(s)u(s) \\ &= \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}. \end{aligned} \tag{2.2}$$

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

$$G_1(s) \neq 0. \tag{2.3}$$

Conversely, when the plant is broken,

$$G_1(s) = 0. \tag{2.4}$$

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

$$\hat{G}(s) = \begin{bmatrix} 0 & G_2(s) \end{bmatrix}. \tag{2.5}$$

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

$$\hat{y}(s) = \hat{G}(s)u(s). \tag{2.6}$$

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:

$$\lim_{t\to\infty} (y(t) - \hat{y}(t)) = 0 \tag{2.7}$$

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

$$\hat{d}(s) = 0 \tag{2.8}$$

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

$$\begin{aligned} \hat{d}(s) &= (G(s) - \hat{G}(s))u(s) \\ &= G_1(s)u_1(s), \end{aligned} \tag{2.9}$$

We can find the fault occurs using $\hat{d}(s)$. Thus we call $\hat{d}(s)$ a fault estimator if (2.8) and (2.9) are satisfied.

2.3 Fault Estimator

In this section, we describe the parameterization of the fault estimator $\hat{d}(s)$ as depicted in Figure 2.1.

The parameterization of all $F_1(s)$ and $F_2(s)$ that satisfies equation (2.8) is outlined in the following theorem.

Theorem 2.3.1 *All $F_1(s)$ and $F_2(s)$ that satisfy equation (2.8) are given by:*

$$F_1(s) = \begin{bmatrix} G_1(s)(1+Q(s)) & G_2(s)(1+Q(s)) \end{bmatrix} \tag{2.10}$$

and

$$F_2(s) = -1 - Q(s). \tag{2.11}$$

respectively.

The proof of this theorem relies on the following lemma.

Lemma 2.3.1 *[76] 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*

$$\text{rank} \begin{bmatrix} A^T(s) & B^T(s) \end{bmatrix} = \gamma. \tag{2.12}$$

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

$$X(s)A(s) + Y(s)B(s) = C(s) \tag{2.13}$$

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

$$\begin{bmatrix} A(s) \\ B(s) \\ C(s) \end{bmatrix} = U(s) \begin{bmatrix} A(s) \\ B(s) \\ O \end{bmatrix}. \tag{2.14}$$

When $X_0(s) \in RH_\infty$ and $Y_0(s) \in RH_\infty$ are solutions to (2.13), then all solutions to (2.13) are given by

$$\begin{bmatrix} X(s) & Y(s) \end{bmatrix} = \begin{bmatrix} X_0(s) & Y_0(s) \end{bmatrix} + Q(s) \begin{bmatrix} W_1(s) & W_2(s) \end{bmatrix}, \tag{2.15}$$

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

$$W_1(s)A(s) + W_2(s)B(s) = 0 \tag{2.16}$$

and

$$\text{rank} \begin{bmatrix} W_1(s) & W_2(s) \end{bmatrix} = n + q - \gamma \tag{2.17}$$

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

We show proof of Theorem 2.3.1 using Lemma 2.3.1.

proof 2.3.1 *When the plant is normal, from (2.8), we have*

$$F_1(s)u(s) + F_2(s)y(s) = 0. \tag{2.18}$$

From (2.7), (2.18) is rewritten by the form in

$$(F_1(s) + F_2(s)G(s))\, u(s) = 0. \tag{2.19}$$

From the assumption that (2.19) is satisfied for any control input $u(s)$, we have

$$F_1(s) + F_2(s)G(s) = 0. \tag{2.20}$$

Since $F_1(s) \in RH_\infty^{1\times 2}$, (2.20) is rewritten by

$$\begin{bmatrix} F_{11}(s) + F_2(s)G_1(s) & F_{12}(s) + F_2(s)G_2(s) \end{bmatrix} = 0, \tag{2.21}$$

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

$$F_1(s) = \begin{bmatrix} F_{11}(s) & F_{12}(s) \end{bmatrix}. \tag{2.22}$$

Using Lemma 2.3.1, we obtain the parameterization of all $F_{11}(s)$ *and* $F_2(s)$ *satisfying (2.21), and given by*

$$\begin{bmatrix} F_{11}(s) & F_2(s) \end{bmatrix} = \begin{bmatrix} G_1(s) & -1 \end{bmatrix} + Q(s)\begin{bmatrix} G_1(s) & -1 \end{bmatrix}, \tag{2.23}$$

where $Q(s) \in RH_\infty$ *is any function. In a similar way, from Lemma 2.3.1 and (2.21), the parameterization of all* $F_{12}(s)$ *and* $F_2(s)$ *is written by*

$$\begin{bmatrix} F_{12}(s) & F_2(s) \end{bmatrix} = \begin{bmatrix} G_2(s) & -1 \end{bmatrix} + Q'(s)\begin{bmatrix} G_2(s) & -1 \end{bmatrix}, \tag{2.24}$$

where, $Q'(s) \in RH_\infty$ *is any function. From (2.23) and (2.24), it is necessary to satisfy*

$$Q(s) = Q'(s). \tag{2.25}$$

Thus the parameterization of all $F_1(s)$ *and* $F_2(s)$ *are written by*

$$F_1(s) = \begin{bmatrix} G_1(s)(1+Q(s)) & G_2(s)(1+Q(s)) \end{bmatrix} \tag{2.26}$$

and

$$F_2(s) = -1 - Q(s), \tag{2.27}$$

respectively.

We have thus proved Theorem 2.3.1.

In the case that the plant has broken, from (2.9), we have

$$F_1(s)u(s) + F_2(s)\hat{y}(s) = (G(t) - \hat{G}(t))u(t). \tag{2.28}$$

Substitution of (2.6) to (2.28) gives

$$(F_1(s) + F_2(s)\hat{G}(s))u(s) = (G(s) - \hat{G}(s))u(s) \tag{2.29}$$

For any $u(s)$, (2.29) need to be satisfied, that is,

$$F_1(s) + F_2(s)\hat{G}(s) = G(s) - \hat{G}(s). \tag{2.30}$$

Equation (2.30) is rewritten by

$$\begin{bmatrix} F_{11}(s) & F_{12}(s) + F_2(s)G_2(s) \end{bmatrix} = \begin{bmatrix} G_1(s) & 0 \end{bmatrix}. \tag{2.31}$$

From this equation and Theorem 2.3.1, $Q(s)$ in (3.26) and (2.11) is given by

$$Q(s) = 0. \tag{2.32}$$

From Theorem 2.3.1 and (2.32), we have following Theorem

Theorem 2.3.2 *All* $F_1(s)$ *and* $F_2(s)$ *that satisfies (2.8) and (2.9) are given by*

$$F_1(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix} \tag{2.33}$$

and

$$F_2(s) = -1. \tag{2.34}$$

respectively.

proof 2.3.2 *The proof is obvious from Theorem 2.3.1 and (2.32).*

2.4 Design method for control system

In this section, we present a design method for the control system in Fig. 2.1.

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

$$\hat{G}(s)\hat{F}(s)\hat{d}(s) = (G(s) - \hat{G}(s))u(s) \tag{2.35}$$

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

$$\hat{F}(s) = \begin{bmatrix} \hat{F}_1(s) \\ \hat{F}_2(s) \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{1}{G_2(s)} \end{bmatrix} \tag{2.36}$$

then (2.35) is satisfied. However in general $1/G_2(s)$ is improper. Therefore we present a design method of $\hat{F}(s)$ as

$$\hat{F}(s) = \begin{bmatrix} \hat{F}_1(s) \\ \hat{F}_2(s) \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{q(s)}{G_2(s)} \end{bmatrix}, \tag{2.37}$$

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

2.5 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

$$G(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix} = \begin{bmatrix} \frac{s+3}{(s+1)(s+2)} & \frac{s+6}{(s+4)(s+5)} \end{bmatrix} \tag{2.38}$$

and

$$\hat{G}(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix} = \begin{bmatrix} 0 & \frac{s+6}{(s+4)(s+5)} \end{bmatrix}, \tag{2.39}$$

respectively. The reference input is

$$r(t) = \begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix} = \begin{bmatrix} \sin(0.4\pi t) \\ \sin(0.4\pi t) \end{bmatrix}. \tag{2.40}$$

From (2.33) and (2.38), $F_1(s)$ is designed by

$$F_1(s) = \begin{bmatrix} F_{11}(s) & F_{12}(s) \end{bmatrix} = \begin{bmatrix} \frac{s+3}{(s+1)(s+2)} & \frac{s+6}{(s+4)(s+5)} \end{bmatrix}. \tag{2.41}$$

From (2.34), $F_2(s)$ is

$$F_2(s) = -1. \tag{2.42}$$

First, when the plant is normal, we confirm the relationship between $\hat{d}(t)$ and $G_1(t)u_1(t)$ as shown in Fig. 2.2. Here the solid line shows the response of $\hat{d}(t)$ and the dotted line shows that of $\mathcal{L}^{-1}\left[G_1(s)u_1(s)\right](t)$. From

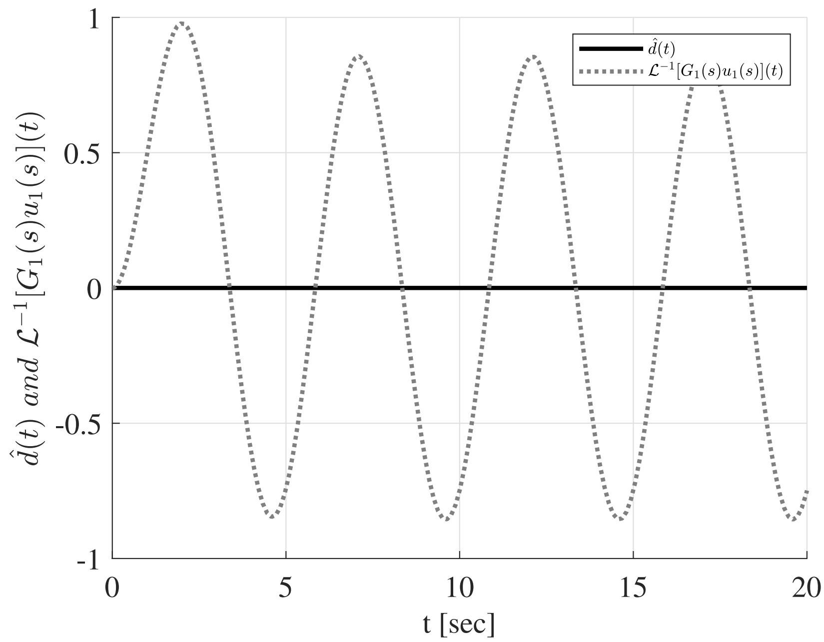

Fig. 2.2: $\hat{d}(t)$ and $\mathcal{L}^{-1}\left[G_1(t)u_1(t)\right](t)$ when plant is normal

Fig. 2.2, $\hat{d}(t) = 0$ anytime. Next, when the plant is broken, we confirm the relationship between $\hat{d}(t)$ and $\mathcal{L}^{-1}\left[G_1(s)u_1(s)\right]$ as shown in Fig. 2.3. Here the solid line shows the response of $\hat{d}(t)$ and the dotted line shows that of $\mathcal{L}^{-1}\left[G_1(s)u_1(s)\right]$. From Fig. 2.3, $\hat{d}(t) = \mathcal{L}^{-1}\left[G_1(s)u_1(s)\right]$ anytime.

$\hat{F}(s)$ is designed by (2.37), where

$$q(s) = \frac{1}{0.01s+1}. \tag{2.43}$$

The relationship between $y(t)$ and $\mathcal{L}^{-1}G_2(s)u_2(s)$. Assume that the system is normal until $t = 10$[s]. When $t > 10$[s], the system is broken. The response of $y(t)$ is shown in Fig. 2.4. 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 Fig. 2.4, 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 [57] our proposed design method for fault-tolerant control is more straightforward and generic. Reference [57] presents a complex approach to fault-tolerant

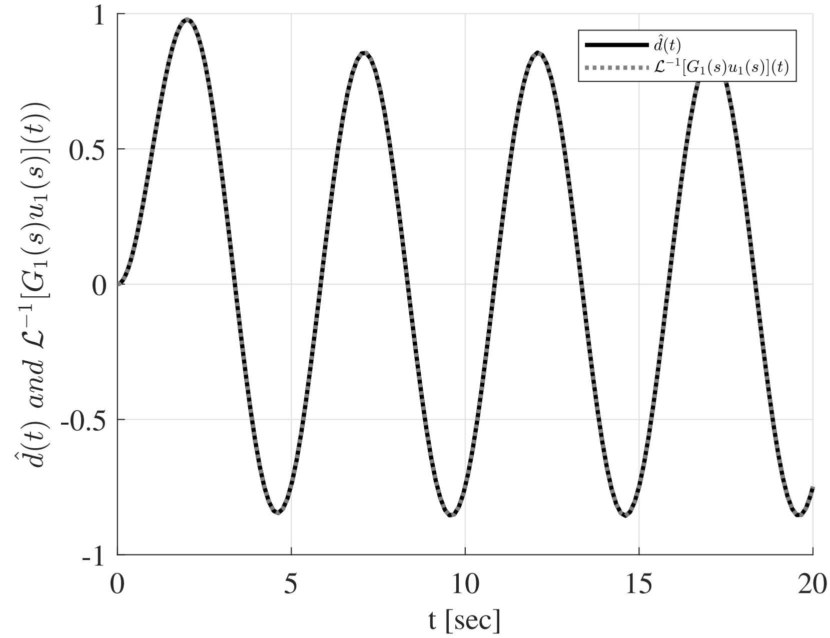

Fig. 2.3: $\hat{d}(t)$ and $\mathcal{L}^{-1}\left[G_1(s)u_1(s)\right](t)$ in the case that the plant is broken

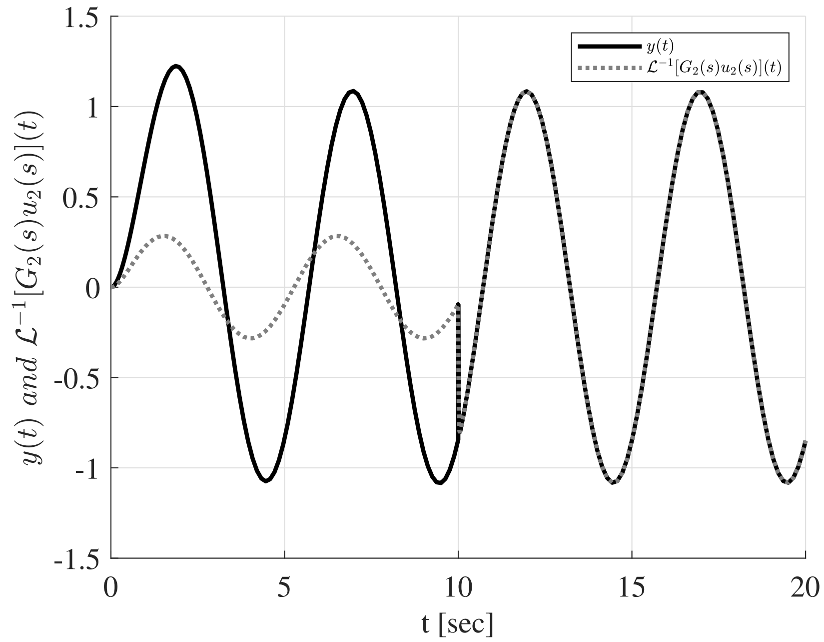

Fig. 2.4: $y(t)$ and $\mathcal{L}^{-1}\left[G_2(s)u_2(s)\right](t)$ in the case that the plant is broken at $t = 10$[s]

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 [57] 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.

2.6 Conclusions

In this chapter, we have introduced a design method for a fault-tolerant control system utilizing a fault estimator. Initially, we outlined the structure of the fault estimator and the necessary conditions it must satisfy. We then clarified the parameterization of all potential fault estimators. Furthermore, we identified the condition under which the control input $u(t)$ remains equivalent even if the plant fails. Using this parameterization, we developed a comprehensive design method for control systems. A numerical example is provided to demonstrate the effectiveness of the proposed method.

The proposed method applies to stable plants. Design methods for unstable plants will be addressed in a future article. Additionally, we aim to enhance the practicality and applicability of the proposed method, thereby advancing fault-tolerant control systems in various high-reliability applications.

Chapter 3

A design method for control system for steer-by-wire using fault detector

3.1 Introduction

The drive-by-wire system has garnered significant interest in the next-generation automotive manufacturing industry. Historically, vehicle steering systems have evolved through various technologies: (i) pure mechanical systems, (ii) hydraulic power-assisted systems, (iii) electro-hydraulic power-assisted steering, and (iv) electric power-assisted steering, leading up to the recent advancements in drive-by-wire systems. In a drive-by-wire system, the mechanical transmission mechanism is eliminated, and the driver's intentions are converted into electric signals, which then drive the actuator via the controller. This system offers several advantages, including improved fuel efficiency, enhanced preventive safety technology, better collision safety, and increased flexibility in mounting position and design freedom. Additional benefits include vehicle weight reduction, expanded interior space, and improved driving comfort [77].

Previous studies have examined various by-wire systems, such as steer-by-wire, shift-by-wire, and brake-by-wire systems [78]. This research focuses primarily on the steer-by-wire system, which uses a wire harness instead of a traditional steering shaft. Specifically, we investigate the lateral stability control of four-wheel-drive electric vehicles based on coordinated control of torque distribution and ESP differential braking [79], which emphasizes four-wheel-drive electric vehicles.

A significant drawback of the steer-by-wire system is its vulnerability to failure or malfunction, which can prevent steering operations and thus compromise safety [85]. To address this critical issue, effective control techniques for failure compensation are essential. In automotive applications, it is particularly important for a vehicle to independently control the driving force of the rear wheels using an in-wheel motor [80].

In this chapter, we propose a design method for a steer-by-wire control system using a fault-tolerant control technique for a 4-wheeled vehicle, where the steering can independently control the left and right rear wheels through an in-wheel motor. The proposed fault-tolerant control technique includes a fault detector, which functions similarly to a disturbance observer, to estimate system failures and facilitate rapid self-recovery to stabilize the overall system. Mathematical models and numerical analysis examples are included. This research is organized as follows: Section 3.2 describes the steer-by-wire system and problem formulation. Section 3.3 proposes a new design method for fault-tolerant controls. Section 3.4 presents numerical examples to illustrate the effectiveness of the proposed method. Concluding remarks are provided in Section 3.5.

3.2 Problem formulation

Considering a vehicle with a steer-by-wire system that can control the left and right rear wheels independently, as shown in Figure 3.1. The equivalent three-wheel model corresponding to Figure 3.1 and the steering system model considered in this research are shown in Figures 3.2 and 3.3, respectively. The meanings of the symbols used in Figures 3.2 and 3.3 are summarized in Table 3.1.

We assume that transient phenomena, such as sudden acceleration or deceleration of the vehicle, are not considered. Additionally, we do not consider scenarios involving sudden large steering operations. Under these assumptions, the vehicle's running speed can be regarded as constant [80].

Under these assumptions, from Figures 3.2 and 3.3, the equations of motion are written as follows:

$$m\dot{V} = 2X_f + X_{rr} + X_{rl}, \tag{3.1}$$

$$mV(\dot{\beta} + \gamma) = 2Y_f + Y_{rr} + Y_{rl}, \tag{3.2}$$

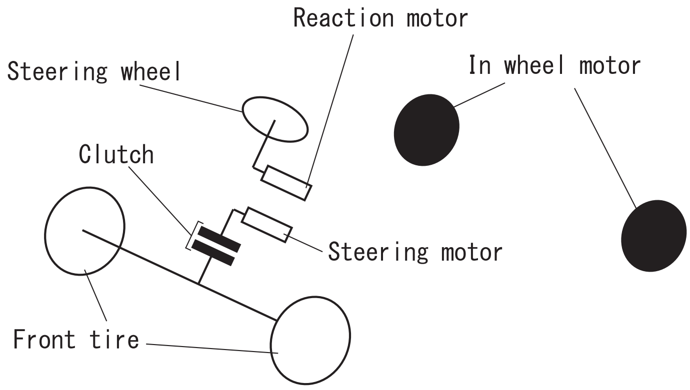

Fig. 3.1: Vehicle structure

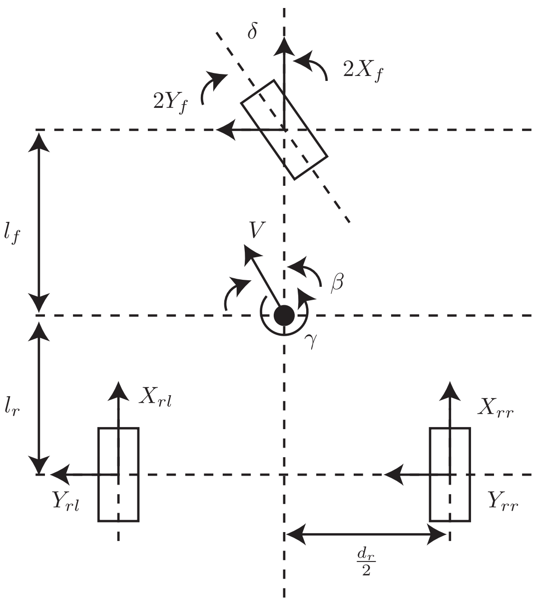

Fig. 3.2: Vehicle model

$$J\dot{\gamma} \quad = \quad 2Y_f l_f - (Y_{rr} + Y_{rl})l_r + \frac{d_r}{2}X_{diff}(s) \tag{3.3}$$

and

$$J_s\ddot{\delta} + C_s\dot{\delta} = T(s) - 2\xi Y_f, \tag{3.4}$$

where

$$Y_f \quad = \quad -K_f\left(\beta + \frac{l_f}{V}\gamma - \delta\right), \tag{3.5}$$

$$Y_{rr} \quad = \quad Y_{rl} = -K_r\left(\beta - \frac{l_r}{V}\gamma\right) \tag{3.6}$$

and

$$X_{diff} \quad = \quad X_{rr} - X_{rl}. \tag{3.7}$$

The behavior of the vehicle when acceleration is generated is examined. There are two types of acceleration generated by steering operation. One is a lateral acceleration in the case of emergency avoidance. The other is a yaw rate in case that the vehicle turn. When we consider steering response, we need to examine the vehicle behavior of both lateral acceleration and yaw rate. A new physical quantity denoted by $D^*(t)$ that linearly combines the response of yaw rate and lateral acceleration is defined as

$$D^*(t) = (\dot{\beta} + \gamma)dV + \gamma(1-d)V, \tag{3.8}$$

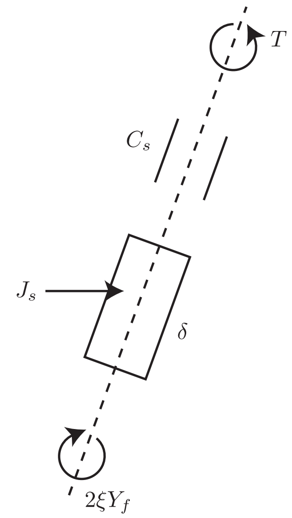

Fig. 3.3: Steering model

where $d(0 \le d \le 1)$ is association constant [81]. We regard $T(s)$ and $X_{diff}(s)$ as input and $D^*(t)$ as an output of the plant.

From the assumption that vehicle speed is constant, (3.1)∼(3.8) are expressed by the state space expression written by

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases}, \tag{3.9}$$

where

$$x(t) = \begin{bmatrix} \beta \\ \gamma \\ \dot{\delta} \\ \delta \end{bmatrix}, \tag{3.10}$$

$$u(t) = \begin{bmatrix} T(t) \\ X_{diff}(t) \end{bmatrix}, \tag{3.11}$$

$$y(t) = D^*(t), \tag{3.12}$$

$$A = \begin{bmatrix} -\frac{2(K_f + K_r)}{mV} & -\left\{1 + \frac{2(l_f K_f - l_r K_r)}{mV^2}\right\} & 0 & \frac{2K_f}{mV} \\ -\frac{2(l_f K_f - l_r K_r)}{J} & -\frac{2(l_f^2 K_f + l_r^2 K_r)}{JV} & 0 & \frac{2 l_f K_f}{J} \\ \frac{2\xi K_f}{J_s} & \frac{2\xi K_f l_f}{J_s V} & -\frac{C_s}{J_s} & -\frac{2\xi K_f}{J_s} \\ 0 & 0 & 1 & 0 \end{bmatrix}, \tag{3.13}$$

$$B = \begin{bmatrix} B_1 & B_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{d_r}{2J} \\ \frac{1}{J_s} & 0 \\ 0 & 0 \end{bmatrix}, \tag{3.14}$$

and

$$C = \begin{bmatrix} -\frac{2d(K_f + K_r)}{m} & -\frac{2d(l_f K_f - l_r K_r)}{mV} + (1-d)V & 0 & \frac{2dK_f}{m} \end{bmatrix}. \tag{3.15}$$

The transfer function from u to y in (3.9) is written by

$$y(s) = G(s)u(s) \in R(s), \tag{3.16}$$

Table 3.1: The meaning of symbols

Symbol	Meaning	Unit
m	Vehicle mass	kg
V	Vehicle velocity	m/s
X_f	Front tire driving/braking force	N
X_{rr}	Rear right tire driving/braking force	N
X_{rl}	Rear left tire driving/braking force	N
β	Vehicle slip angle	rad
γ	Yaw rate	rad/s
Y_f	Front tire cornering force	N
Y_{rr}	Rear right tire cornering force	N
Y_{rl}	Rear left tire cornering force	N
J	Moment of vehicle inertia	kgm^2
l_f	Distance between front tire and center	m
l_r	Distance between rear tire and center	m
d_r	Rear tread	m
X_{diff}	Rear tire driving force difference	N
δ	Vehicle-wheel steering angle	rad
J_s	Moment of steering inertia	kgm^2
C_s	Damping coefficient of steering	kgm^2/s
T	Steering motor torque	Nm
ξ	Trail	m
K_f	Front tire cornering stiffness	N/rad
K_r	Rear tire cornering stiffness	N/rad

where

$$G(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix} \in RH_\infty^{1\times 2}, \tag{3.17}$$

$$G_1(s) = C(sI - A)^{-1}B_1, \tag{3.18}$$

$$G_2(s) = C(sI - A)^{-1}B_2, \tag{3.19}$$

and

$$u(s) = \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \in R^2(s). \tag{3.20}$$

In the case that the handle motor torque breaks, that is the system has a failure,the plant $G(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix}$ is changed to $G(s) = \begin{bmatrix} 0 & G_2(s) \end{bmatrix}$.

The problem considered in this research is to propose a design method for a control system that makes the output $y(s)$ follow the reference input $r(s)$ even when the system is a failure or not, where $r(s) \in R(s)$. Therefore, we design a control system that satisfies the following equation

$$\lim_{t\to\infty} \{r(t) - y(t)\} = 0. \tag{3.21}$$

3.3 Controller Design

In this section, we propose a design method for a control system that makes the output $y(s)$ follow the reference input $r(s)$ even when the system is failure or not. To solve this problem, the control system in Fig. 3.4 is considered. Here, $C(s) \in R^2(s)$ is a controller to stabilize the control system in Fig. 3.4, $G(s) \in RH_\infty^{1\times 2}$ is the plant such that when the system is normal

$$G(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix} \tag{3.22}$$

, and when the system is failure

$$G(s) = \begin{bmatrix} 0 & G_2(s) \end{bmatrix} \tag{3.23}$$

$\hat{d}(s) \in R(s)$ works as a fault detector, $F_1(s) \in RH_\infty^{1\times 2}$ and $F_2(s) \in RH_\infty$ are controllers for fault detector and $\hat{F}(s) \in RH_\infty^{2\times 1}$ is a controller to compensate the influence of the failure.

Next we explain the controllers in Fig. 3.4. $\hat{d}(s)$ works as a fault detector, that is following expressions hold

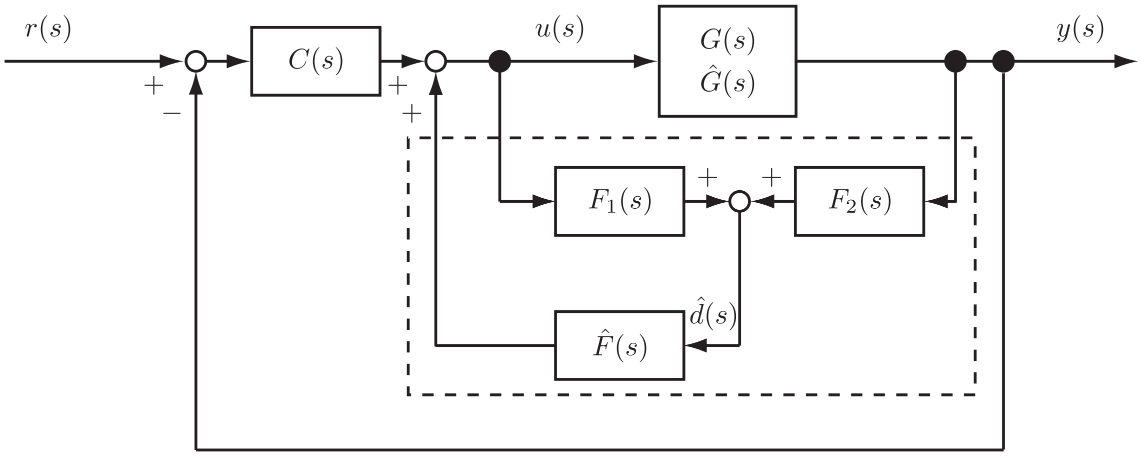

Fig. 3.4: Fault tolerant control system

1. when the system is normal, that is $G(s)$ is written by (3.22),

$$\hat{d}(s) = 0 \tag{3.24}$$

   is satisfied.

2. when the system is failure, that is $G(s)$ is written by (3.23),

$$\begin{aligned} \hat{d}(s) &= (G(s) - \hat{G}(s))u(s) \\ &= G_1(s)u_1(s). \end{aligned} \tag{3.25}$$

   is satisfied.

From simple manipulations, when $F_1(s)$ and $F_2(s)$ are settled by

$$F_1(s) = \begin{bmatrix} G_1(s) & G_2(s) \end{bmatrix}, \tag{3.26}$$

and

$$F_2(s) = -I, \tag{3.27}$$

then $\hat{d}(s)$ works as a fault detector.

It is necessary to design $\hat{F}(s)$ so that the output difference between normal state and failure state of the system and the output difference when $\hat{F}(s)\hat{d}(s)$ input to $G(s)$ when the system is failure are equal. Therefore, $\hat{F}(s)$ is designed to satisfy the following equation

$$G_2(s)\hat{F}(s)\hat{d}(s) = G_1(s)u_1(s). \tag{3.28}$$

There is no $\hat{F}(s)$ satisfying (3.28) for any $u_1(s)$ and any $\hat{d}(s)$. In order to satisfy in (3.28) in the low-frequency range, $\hat{F}(s)$ is designed by

$$\hat{F}(s) = \begin{bmatrix} 0 \\ \dfrac{1}{G_{2o}(s)}q(s) \end{bmatrix}, \tag{3.29}$$

where $q(s)$ is a low pass filter written by

$$q(s) = \frac{1}{(1+\tau s)^{\alpha}}, \tag{3.30}$$

τ is small positive number, α is a positive integer to make $q(s)$ in (3.30) proper and $G_{2o}(s)$ is an outer function of $G_2(s)$ satisfying

$$G_2(s) = G_{2i}(s)G_{2o}(s) \tag{3.31}$$

and $G_{2i}(s)$ is an inner function satisfying $G_{2i}(0) = 1$. Note that in the low frequency range ω satisfying $q(j\omega) \simeq 1$, (3.28) is satisfied. Therefore in order to satisfy $q(j\omega)$ in the wide frequency range, τ in (3.30) is settled small.

Next, a design method for $C(s)$ in Fig. 3.4 is explained. Since $G(s)$ in (3.17) is stable and the parameterization of all stabilizing controllers by [82], $C(s)$ written by

$$C(s) = \begin{bmatrix} \dfrac{Q(s)}{1 - Q(s)G_1(s)} \\ 0 \end{bmatrix}. \tag{3.32}$$

stabilizes control system in Fig. 3.4 under the assumption that $Q(s) \in RH_\infty$. In order to make the output $y(s)$ follow the step reference input $r(s)$ without a steady state error, $Q(s)$ is settled by

$$Q(s) = \frac{1}{G_1(s)}\hat{q}(s), \tag{3.33}$$

where

$$\hat{q}(s) = \frac{1}{(1 + \tau_q)^{\alpha_q}}, \tag{3.34}$$

τ_q is a positive number and α_q is a positive integer to make $\hat{q}(s)$ in (3.34) proper.

Table 3.2: Parameters for simulation

Symbol	Value	Unit
m	1400	kg
J	2457	kgm^2
l_f	1.02	m
l_r	1.58	m
d_r	1.48	m
J_s	11.98	kgm^2
C_s	9	kgm^2/s
K_f	33700	N/rad
K_r	56200	N/rad
ξ	0.05	m
V	10	m/s
d	0.5	-

3.4 Numerical Example

In this section, we show a numerical example to illustrate the effectiveness of the proposed method. Table 3.2 shows the related parameters for vehicle model [77].

From Table 3.2 and (3.17), $G_1(s)$ and $G_2(s)$ are given by

$$G_1(s) = \frac{2.0093s^2 + 46.2900s + 413.5481}{s^4 + 27.8684s^3 + 494.8547s^2 + 5.6161 \cdot 10^3 s + 2.0333 \cdot 10^4} \tag{3.35}$$

and

$$G_2(s) = \frac{0.0023s^3 + 0.00352s^2 + 0.8719s + 5.8851}{s^4 + 27.8684s^3 + 494.8547s^2 + 5.6161 \cdot 10^3 s + 2.0333 \cdot 10^4}. \tag{3.36}$$

For the plant $G(s)$ in (3.17), we design a control system in Fig. 3.4. $F_1(s)$ and $F_2(s)$ in Fig. 3.4 are settled by (3.26) and (2.11), respectively. $\hat{F}(s)$ in Fig. 3.4 is designed by (3.29), where Low pass filter $q(s)$ is chosen as

$$q(s) = \frac{1}{0.001s + 1}. \tag{3.37}$$

Then $\hat{F}(s)$ is written by

$$\hat{F}(s) = \begin{bmatrix} 0 \\ \dfrac{s^4 + 27.8684s^3 + 494.8547s^2 + 5.6161 \cdot 10^3 s + 2.0333 \cdot 10^4}{(0.001s + 1)(0.023s^3 + 0.00352s^2 + 0.8719s + 5.8851)} \end{bmatrix}. \tag{3.38}$$

$C(s)$ in Fig. 3.4 is designed by (3.32), where $Q(s)$ is given by (3.33) and

$$\hat{q}(s) = \frac{1}{(0.001s + 1)^2}. \tag{3.39}$$

Then we have

$$C(s) = \begin{bmatrix} \dfrac{s^4 + 27.8684s^3 + 494.8547s^2 + 5.6161 \times 10^3 s + 2.0333 \times 10^4}{0.00000201s^4 + 0.04023229s^3 + 0.09299355s^2 + 0.8270962s} \\ 0 \end{bmatrix}. \tag{3.40}$$

Using the above parameters, we show the response of Fig. 3.4. When $r(t) = 1$ and the failure occurs at $t = 10$[sec], that is after $t = 10$[sec], $G_1(s) = 0$, the response of the error

$$e(t) = r(t) - y(t) \tag{3.41}$$

is shown in Fig. 3.5, where the dotted line shows the response of error $e(t)$. Fig. 3.5 shows that

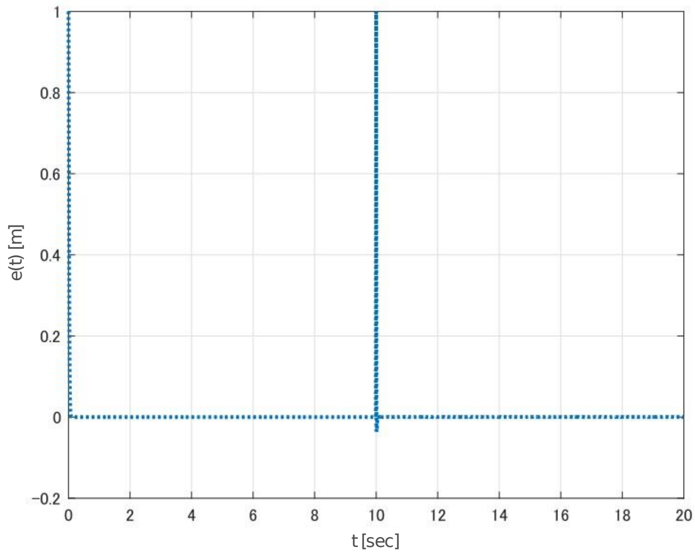

Fig. 3.5: Response of the error $e(t) = r(t) - y(t)$

1. when the system is normal, the control system in Fig. 3.4 is stable.
2. when the system is normal, the output $y(t)$ follows the step reference input without steady-state error.
3. Even if the system is a failure, the control system in Fig. 3.4 is stable.
4. when the system is a failure, the output $y(t)$ follows the reference input without steady-state error.

When $r(s) = \sin(5t)$ and the failure occurs at $t = 10$[s], that is after $t = 10$[s], $G_1(s) = 0$, the response of the error

$$e(t) = r(t) - y(t) \tag{3.42}$$

is shown in Fig. 3.6, where the dotted line shows the response of error $e(t)$. Fig. 3.6 shows that

1. when the system is normal, the control system in Fig. 3.4 is stable.
2. when the system is normal, the output $y(t)$ follow the reference input with small steady state error. From the discussion in Section 3.3, in order to make the steady state error smaller, τ_q in (3.34) is set smaller.
3. even if the system is failure, the control system in Fig. 3.4 is stable.
4. when the system is failure, the output $y(t)$ follow the reference input with small steady state error. From the discussion in Section 3.3, in order to make the steady state error smaller, τ_q in (3.34) is set smaller.

3.5 Conclusions

In this chapter, we presented a design method for a steer-by-wire control system utilizing a fault-tolerant control technique for a 4-wheeled vehicle, enabling independent control of the left and right rear wheels through an in-wheel motor. The proposed technique incorporates a fault detector that operates similarly to a disturbance

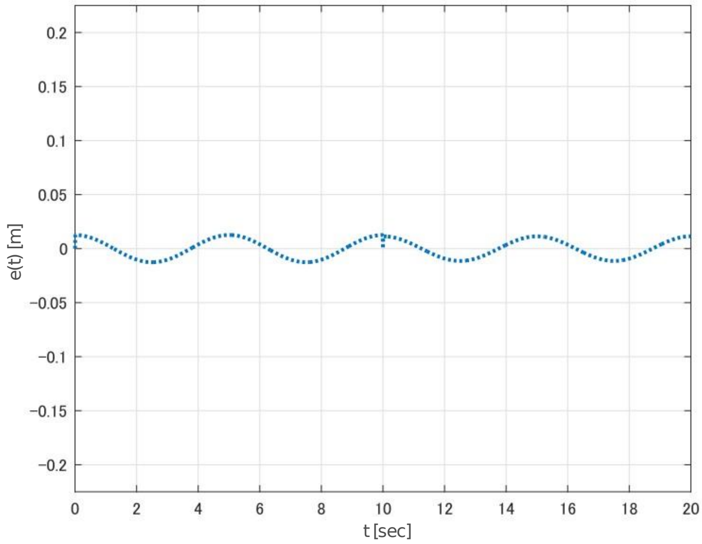

Fig. 3.6: Response of the error $e(t) = r(t) - y(t)$

observer, estimating system failures and enabling rapid self-recovery to stabilize the overall system. Through mathematical models and numerical analysis examples, we demonstrated that the proposed control system maintains stability and achieves the desired performance even in the presence of failures. Specifically, the system follows reference inputs without steady-state error under normal conditions and continues to do so with minimal steady-state error when failures occur. Future work will extend this method to address unstable plants and further enhance its practicality and applicability, contributing to advancements in fault-tolerant control techniques for high-reliability applications, especially in the automotive industry.

Chapter 4

Conclusions

In this thesis, We proposed a novel fault-tolerant control design method based on fault estimators for. Our approach simplifies the design process compared to conventional methods that heavily rely on redundancy and disturbance observers. By treating all errors as disturbances within a feedback loop, the fault estimator ensures system stability and compensates for lost outputs due to component malfunctions.

In chapter 2, we propose a novel design method for fault-tolerant control systems that utilize a fault estimator, addressing the critical need for maintaining stability and performance in environments requiring high reliability, such as production plants and human-interactive systems. Our method leverages a fault estimator, akin to a disturbance observer, to detect and compensate for lost outputs due to component malfunctions, simplifying the design process and enhancing the system's ability to handle catastrophic faults effectively. Key contributions include the detailed parameterization of fault estimators, demonstrating the conditions under which they can effectively detect and compensate for faults, and a design methodology that involves stabilizing the system and compensating for output under uncertain conditions using techniques such as stable controllers, parameterization, or compound H_∞ controllers. We further illustrate the practical applicability and robustness of our proposed method through a numerical example, showing its effectiveness in maintaining system stability and performance post-fault. Overall, this fault-tolerant control system offers a simpler and more effective solution compared to conventional methods, providing robust control under uncertainty with reduced complexity.

In chapter 3, we introduce a design method specifically tailored for control systems in steer-by-wire applications, which are pivotal in next-generation automotive manufacturing. Steer-by-wire systems, which replace mechanical transmission mechanisms with electrical signals, offer substantial benefits including improved fuel efficiency, enhanced safety, reduced vehicle weight, and greater design flexibility. Our proposed method addresses the critical issue of ensuring safety under failure or malfunction conditions by employing a fault-tolerant control technique. We formulated the problem considering a vehicle capable of independently controlling the left and right rear wheels through in-wheel motors, providing equations of motion and state space representations to model the system dynamics. The proposed design method uses a fault detector, akin to a disturbance observer, to estimate system failures and stabilize the overall system, ensuring the output follows the reference input even in the presence of faults. Numerical simulations demonstrate the effectiveness of this approach, showing that the control system maintains stability and performance under both normal and fault conditions, effectively compensating for failures and ensuring the desired output response. This method simplifies the design process for steer-by-wire systems, enhancing safety and reliability while preserving the advantages of reduced weight and increased design flexibility.

In future work, we could focus on extending the design methods to handle unstable plants and systems with more complex dynamics. Additionally, integrating advanced machine learning techniques for real-time fault detection and adaptive control could enhance system responsiveness and robustness. Experimenting with real-world applications would further validate the practicality and robustness of the proposed methods in diverse high-reliability environments, ensuring their effectiveness and adaptability in various scenarios.

Acknowledgements

I extend my deepest gratitude and sincere thanks to Prof. Dr. Kou Yamada for his invaluable guidance and advice, which were instrumental in the completion of this study. His unwavering support was crucial to its success.

Additionally, I am immensely grateful to Patinya Ketthong, Jirayu Samkunta, Daisuke Koyama, Chawannat Chaichumporn, Koki Sakamoto, Hiroki Tani, Dr. Nghia Thi Mai, Asst. Prof. Dr. Kotaro Hashikura, Asst. Prof. Dr. Md Abdus Samad Kamal, Asst. Prof. Dr. Iwanori Murakami, and Asst. Prof. Dr. Wimol San-um for their insightful opinions and valuable information that significantly contributed to this study.

My appreciation also goes to the members of the laboratory, who provided advice and encouragement during challenging moments in my research.

Lastly, I express my heartfelt thanks to my family for their enduring support and encouragement. Their belief in me has been a source of strength and motivation.

October 2024 Sura Laptawee

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Publication papers

Chapter 2 ○ S. Laptawee, H. Tani, Ngh. T. Mai, K. Hashikura, M. A. S. Kamal, I. Murakami, W. San-Um and K. Yamada, A design method of fault tolerant control systems, International Journal of Innovative Computing, Information and Control (IJICIC), (Accepted for publication).

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