Fault-Tolerant Control for LPV systems based on Fault Compensator

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Abstract: This paper proposes a fault-tolerant control (FTC) scheme for polytopic linear parameter varying (LPV) systems. We first propose a fault compensator whose structure is simple, but effective against actuator faults. Then, in order to show its basic idea, we consider a state feedback FTC scheme based on the fault compensator. Next, the FTC algorithm is extended to output feedback FTC scheme. The FTC scheme for LPV systems involves a fault compensator based on the estimated fault and a robust observer based on linear matrix inequality (LMI). The proposed FTC method is applicable for a variety of systems and guarantees the robust stability of the system in the event of actuator faults. Numerical examples are given to demonstrate its effectiveness.

Keywords: Fault tolerant control, actuator fault, fault estimation, fault compensator, linear parameter varying system, linear matrix inequality

1. INTRODUCTION

Fault detection and diagnosis (FDD) has become a crucial problem in practical engineering systems in recent years because of the following reasons: First, faults cause damage to control system and undesired performance. Second, if faults cannot be detected and an appropriate reconfiguration action cannot be taken, serious problems such as system deterioration and loss of lives can occur, and these accidents cause an environmental impact as well. Finally, when these incidents occur, a company suffers huge losses such as property loss and weakened brand, and consequently the company may go out of business. In addition, unfortunately, most physical systems in nature have various types of faults such as component, actuator, and sensor faults. Therefore, in order to prevent the above problems, it is clear that fault-tolerant control systems (FTCS) are needed for ensuring desired performance and safety in the event of faults.

Fault-tolerant control (FTC) is a control algorithm to satisfy system stability and nominal performance in the presence of faults, and it minimizes damage to systems. In the past, since little understanding of importance of faults, FTC hardly received any attention until the mid 1980s. However, over the past few decades, researchers and engineers have made many efforts for FTC to prevent accidents, because there has been a sharp rise in the number of accidents.

Recently, main results of FTC methods against various types of faults are summarized in Zhang and Jiang (2008) as a review paper. Especially, among such faults in practical engineering systems, actuator faults are typical and occur frequently. The control algorithms against such actuator faults have been studied in Zhang and Jiang (2002), Tao et al. (2002), Zhang and Jiang (2003), and Ye and Yang (2006). In these methods, it is assumed that the system state is measurable. However, such an assumption may be restrictive for practical systems. Therefore, concerning the output feedback FTC scheme, various control algorithms have been studied in Jiang et al. (2002), Chen and Jiang (2005), Patton and Klinkhieo (2009), and Zhang et al. (2010). However, since these control methods handle only linear time-invariant (LTI) systems, it may be desirable to develop FTC algorithms which can deal with more general class of systems such as linear time-varying (LTV) systems. More importantly, in most of control methods for FTC, the control gain is designed under abnormal conditions that faults exist, and the design method for abnormal conditions is more complex and difficult than that for normal conditions. For this reason, most of FTC methods are difficult to understand for practical engineers, because there are quite a few people who do not have the expertise on control theory, and they always ask for a simple algorithm which is easy to understand, but effective. However, in spite of such practical needs, there are not so many FTC algorithms for practical engineers.

From the above viewpoint, the goal of this paper is to propose a new FTC scheme which has the following three merits: First, it is based on a simple structure, but effective to compensate the effect of faults. Therefore, practical engineers who do not have the expertise on control theory can understand it without any difficulties, and the proposed FTC scheme is applicable for practical systems. Second, it is the control algorithm based on output feedback methods. Third, it is the robust control scheme for polytopic linear parameter varying (LPV) systems.

In this paper, we propose an FTC scheme for polytopic LPV systems. It is assumed that the time-varying parameter is measurable on-line, but its future behavior contained in a given polytope is uncertain. We first propose a fault compensator. The fault compensator produces the signal to compensate the effect of actuator faults from differences between desirable control in-
puts and manipulated control inputs with actuator faults. Then, in order to show its basic idea, we consider a state feedback FTC scheme based on the fault compensator. In the proposed FTC scheme, it is not necessary to redesign the controller when faults occur, the fault compensator is just added to the original controller which is already designed for normal conditions. Nevertheless, the proposed FTC scheme compensates actuator faults effectively and stabilizes the system well. Next, the algorithm is extended to an output feedback FTC scheme. The FTC scheme for LPV systems involves the fault compensator based on the estimated fault and the robust observer based on linear matrix inequality (LMI). The proposed FTC method is applicable for a variety of practical engineering systems and guarantees the robust stability of the system in the event of actuator faults. Numerical examples are given to demonstrate its effectiveness.

Notation: The symbol * is used for convenience to denote

\[
\begin{bmatrix}
M \\ N \\ H
\end{bmatrix}^* := \begin{bmatrix}
M^T \\ N^T \\ H
\end{bmatrix}.
\]

We denote transpose and inverse of a matrix \( M \) by \( M^T \) and \( M^{-1} \), respectively. The notation \( M > 0 \) means that \( M \) is a symmetric positive (semi-) definite matrix.

2. PROBLEM STATEMENT

2.1 System description

Consider a discrete-time LPV system represented as follows:

\[
\begin{align*}
x(k+1) &= A(p(k))x(k) + B(p(k))u(k), \\
y(k) &= Cx(k),
\end{align*}
\]

where \( x(k) \in \mathbb{R}^{n_x} \) is the state, and \( y(k) \in \mathbb{R}^{n_y} \) is the output which is measurable. \( u(k) \in \mathbb{R}^{n_u} \) is the manipulated control input, and \( p(k) \) is the time-varying parameter. We assume that \( [A(p(k))]B(p(k))] \) varies inside a corresponding polytope \( \Omega \) whose vertices consist of \( \ell \) local system matrices, i.e.,

\[
[A(p(k))]B(p(k))] \in \Omega, \ k \geq 0,
\]

\[
\Omega := \{ C_0[A_1B_1], A_2B_2, \ldots, A_{\ell}B_{\ell} \},
\]

where \( C_0 \) denotes the convex hull. In this paper, we assume that \( p(k) \) is measurable at each step \( k \). Then, the current system matrices \( [A(p(k))]B(p(k))] \) are known at each step \( k \). However, the future ones \( [A(p(k+i))]B(p(k+i))] \), \( i \geq 1 \), which vary inside the prescribed polytope \( \Omega \), are uncertain.

2.2 Actuator Fault

The illustration for modelling of the actuator fault is shown in Fig. 1. We first consider normal conditions that there is no actuator fault. Then, the manipulated control input \( u(k) \) modelled by control signal is represented as follows:

\[
\begin{align*}
u(k) &= u(c)(k), \\
u(k) &= u(a)(k).
\end{align*}
\]

Fig. 1. Modelling of the actuator fault

Next, in order to model actuator faults, we consider the manipulated control input \( u(k) \) with actuator faults can be represented as follows:

\[
\begin{align*}
u(k) &= u(a)(k) + f_a(k),
\end{align*}
\]

where \( u_a(k) \in \mathbb{R}^{n_u} \) is the control signal which is calculated in a computer, and it enters the actuator as the reference input for generating the actuator output. It means that the actuator generates the manipulated control input \( u(k) \) as the actuator output to control the system (1) when the control signal \( u_a(k) \) enters the actuator, and those have the same value. In addition, the control signal \( u_a(k) \) is represented as follows:

\[
u_a(k) = -Kx(k),
\]

where \( K \) is the control gain such that \( (A(p(k)) - B(p(k))K) \) is quadratically stable for any \( [A(p(k))]B(p(k))] \in \Omega \), i.e., \( x(k) \to 0 \) as \( k \to \infty \).

Next, to model actuator faults, we consider the manipulated control input \( u(k) \) with actuator faults can be represented as follows:

\[
\begin{align*}
u(k) &= u(a)(k) + f_a(k),
\end{align*}
\]

where \( f_a(k) \in \mathbb{R}^{n_u} \) is the actuator fault which is unmeasurable directly. Since there are many cases that actuator faults do not change within a given period after faults occurred once, we consider actuator faults represented as

\[
f_{a,j}(k) = \begin{cases} 
0, & j \neq k_j \\
\delta_j, & \text{otherwise},
\end{cases}
\]

where \( f_{a,j} \) denotes the fault of the \( j \)-th actuator and \( \delta_j \) denotes the magnitude of the fault of the \( j \)-th actuator. \( k_j \) represents the fault occurrence time, but the time is unknown.

3. STATE FEEDBACK FTC BASED ON FAULT COMPENSATOR

For practical applications, we propose a simple FTC scheme. In order to show its basic idea, in this section, it is assumed that the state \( x \) of the system (1) and the manipulated control input \( u(k) \) of (6) are measurable. Then, we propose a simple fault compensator design for a new state feedback FTC scheme.

Consider the FTC scheme represented in Fig. 2, it is the state feedback FTC scheme based on the fault compensator. Here, the control signal is represented as follows:

\[
u_a(k) = -Kx(k) - v(k)
\]

with

\[
v(k) = u(k - 1) - u_a(k - 1),
\]

where \( v(k) \in \mathbb{R}^{n_v} \) is the fault compensation input which is produced by the fault compensator. The control gain \( K \) of (8)
is given for normal conditions. There are many FTC methods which redesign or switch the control gain after the fault is detected. However, in the proposed FTC algorithm, without redesigning or switching the control gain for abnormal conditions, the control signal (8) guarantees the system stability, since the fault compensation input $v(k)$ continues the effort to compensate the actuator faults.

**Theorem 1.** The control signal (8) with the fault compensation input (9) quadratically stabilizes the system (1).

**Proof.** From (6), (8), and (9), the system (1) can be represented as follows:

$$
x(k + 1) = A(p(k))x(k) - B(p(k))Kx(k) + B(p(k))\Delta f_a(k)$$

where $\Delta f_a(k) := f_a(k) - f_a(k - 1)$. Since $\Delta f_a(k)$ is zero by (7) when $k \neq k_f$, the system state $x(k)$ converges zero as $k \to \infty$ by the control gain $K$.

Note that, generally, in most of FTC methods, the control gain is redesigned or switched after the fault is detected. However, in the proposed FTC scheme, it is not necessary to redesign or switch the control gain $K$, since the fault compensator is just added to the original controller which is designed for normal conditions. Nevertheless, the system can be stabilized by the controller combined with the fault compensator. In addition, the structure of the fault compensator is simple to understand. Therefore, the proposed FTC method is useful for engineers for practical applications. In addition, although we consider actuator faults represented as a form of (7), the proposed state feedback FTC scheme can be an effective method against the time-varying fault except the fault which varies fast. In Section 5, its effectiveness against such actuator faults is demonstrated. Then, in the next section, we extend this approach into the FTC algorithm based on output feedback methods for more practical applications.

### 4. OUTPUT FEEDBACK FTC SCHEME

In this section, we propose an output feedback FTC scheme for polytopic LPV systems based on the fault compensator.

In this section, since the state of system $x(k)$, the manipulated control input $u(k)$, and the actuator fault $f_a(k)$ are unmeasurable, we adopt the following robust observer to estimate the system state and the actuator fault:

$$\dot{\hat{x}}(k + 1) = A(p(k))\hat{x}(k) + B(p(k))u(k) + \hat{f}_a(k) + L_x(y(k) - C\hat{x}(k))$$

$$\hat{f}_a(k + 1) = \hat{f}_a(k) + L_f(y(k) - C\hat{x}(k)),$$

where $\hat{x}(k) \in \mathbb{R}^n$ is the estimated state of $x(k)$ and $\hat{f}_a(k) \in \mathbb{R}^m$ is the estimated actuator fault of $f_a(k)$. $L_x$ and $L_f$ are the observer gains to be determined. Note that, since we know the current system matrices $[A(p(k))B(p(k))]$, the output $y(k)$, the estimated state $\hat{x}(k)$, and the estimated fault $\hat{f}_a(k)$ at each step $k$, $\hat{x}(k + 1)$ and $\hat{f}_a(k + 1)$ can be calculated using (11) and (12), respectively.

#### 4.1 Robust Observer Design

We design the robust observer for LPV systems with actuator faults. From (1), (6), (11), and (12), the error dynamics can be derived as

$$e_x(k + 1) = x(k + 1) - \hat{x}(k + 1)$$

$$= (A(p(k)) - L_xC)\hat{x}(k) + B(p(k))e_f(k),$$

$$e_f(k + 1) = f_a(k + 1) - \hat{f}_a(k + 1)$$

$$= -L_fCe_f(k) + e_f(k) + \Delta f_a(k),$$

where $\Delta f_a(k) := f_a(k + 1) - f_a(k)$. The above error dynamics can be rewritten as

$$\dot{\hat{e}}(k + 1) = (\hat{A}(p(k)) - \hat{L}_C)\hat{e}(k) + \hat{D}\Delta f_a(k)$$

with

$$\hat{e}(k) = \begin{bmatrix} e_x(k) \\ e_f(k) \end{bmatrix}, \quad \hat{A}(p(k)) = \begin{bmatrix} A(p(k)) & B(p(k)) \\ 0 & I \end{bmatrix},$$

$$\hat{L} = \begin{bmatrix} L_x \\ L_f \end{bmatrix}, \quad \hat{C} = \begin{bmatrix} C & 0 \end{bmatrix}, \quad \hat{D} = \begin{bmatrix} 0 \\ I \end{bmatrix}.$$

Then, it is equivalent to

$$\dot{\hat{e}}(k + 1) = (\hat{A}(p(k)) - \hat{L}_C)\hat{e}(k),$$

where $[A(p(k))B(p(k))] \in \Omega$. In the following, we determine the observer gains $L_x$ and $L_f$ in terms of LMI. First, we define a quadratic function $E(\hat{e}(k))$ of the estimation error $\hat{e}(k)$ as

$$E(\hat{e}(k)) = \hat{e}(k)^TP\hat{e}(k), \quad P > 0.$$ (17)

If $E(\hat{e}(k))$ satisfies the following quadratic stability condition

$$E(\hat{e}(k + 1 + i)) - \rho^2E(\hat{e}(k + i)) < -\hat{e}(k + i)^TP\hat{e}(k + i)$$ (18)

for $i \geq 0$, the decay rate $\rho(0 < \rho < 1)$, and the suitable weighting matrix $L_P > 0$, which are given by a designer, then it is guaranteed that

$$\hat{e}(k) \to 0 \text{ as } k \to \infty.$$ (19)

Then the observer gains $L_x$ and $L_f$ satisfying (18) are determined by the following theorem.

**Theorem 2.** If there exist $P > 0$ and $\Lambda := \hat{P}\hat{L}$ satisfying the following LMI constraint

$$\begin{bmatrix} \rho^2P - L_P & * \\ \hat{P}\hat{A}_j - \hat{Y}\hat{C} & P \end{bmatrix} > 0, \quad j = 1, 2, \cdots, \ell,$$ (20)

then the observer gains $L_x$ and $L_f$ are obtained by $\hat{L} = P^{-1}Y$ and the stability of the error dynamics (16) is guaranteed. Therefore, the estimated state $\hat{x}(k)$ and the estimated fault $\hat{f}_a(k)$ converge to the system state $x(k)$ and the actuator fault $f_a(k)$, respectively; i.e., $\hat{x}(k) \to x(k)$ and $\hat{f}_a(k) \to f_a(k)$ as $k \to \infty$.

**Proof.** The inequality (18), the quadratic stability condition for the robust observer, is equivalent to

$$\rho^2P - L_P - \Lambda(k + i)^TP\Lambda(k + i) > 0,$$ (21)

where $\Lambda(k + i) := \hat{A}(p(k + i)) - \hat{L}_C$. Then, it can be rewritten as

$$\rho^2P - L_P - (P\Lambda(k + i))^TP^{-1}(P\Lambda(k + i)) > 0.$$ (22)

By using Schur complement, it is possible to cast the inequality (22) in the following form:

$$\begin{bmatrix} \rho^2P - L_P & * \\ \hat{P}\Lambda(k + i) & P \end{bmatrix} > 0.$$ (23)

Substituting $Y := \hat{P}\hat{L}$, we see that (23) is equivalent to
Fig. 3. Output feedback FTC scheme based on fault compensator

\[
\rho^2 P - L_e \hat{P} - \rho \hat{A}(p(k+i)) - Y \hat{C} P > 0. \tag{24}
\]

Since the inequality (24) is affine in \([A(p(k+i))B(p(k+i))\], it is satisfied for all

\[
[A(p(k+i))B(p(k+i))] \in \Omega \tag{25}
\]

if and only if there exist \(P > 0\) and \(Y\) such that

\[
\left[ \begin{array}{c}
\rho^2 P - L_e \hat{P} - \rho \hat{A}(p(k+i)) - Y \hat{C} P \\
\end{array} \right] > 0, \quad j = 1, 2, \ldots, \ell. \tag{26}
\]

Then, the observer gains \(L_e\) and \(L_f\) are obtained by \(\hat{L} = P^{-1}Y\).

4.2 Output feedback FTC based on Fault Compensator

We propose a new fault compensator based on the robust observer, but its structure is similar to that of (9). Fig. 3 illustrates the output feedback FTC scheme based on the fault compensator. In order to compensate the effect of faults and guarantee the system stability, we consider the following control signal.

\[
u_c(k) = -K \hat{x}(k) - v(k) \tag{27}
\]

with

\[
v(k) = u_c(k - 1) - u_c(k - 1), \tag{28}
\]

\[
u_c(k) = u_c(k) + f_a(k), \tag{29}
\]

where \(v(k) \in \mathbb{R}^n\) is the fault compensation input which is produced by the fault compensator. In the proposed output feedback FTC scheme, based on the estimated actuator fault at step \(k - 1\), the fault compensation input \(v(k)\) continues the effort to compensate the actuator faults. Then, the control input \(u(k)\) with unknown actuator faults \(f_a(k)\) is manipulated to the system (1), the system is stabilized by the control signal \(u_c(k)\) with \(v(k)\), which is produced by (28).

**Theorem 3.** The control signal (27) with the fault compensation input (28) quadratically stabilizes the system (1).

**Proof.** From (6) and (27), the system (1) can be represented as follows:

\[
\begin{align*}
x(k + 1) &= A(p(k))x(k) - B(p(k))K \hat{x}(k) \\
& \quad + B(p(k))(f_a(k) - \hat{f}_a(k - 1)). \tag{30}
\end{align*}
\]

Then, it is equivalent to

\[
\begin{align*}
x(k + 1) &= A(p(k))x(k) - B(p(k))K \hat{x}(k) \\
& \quad + B(p(k))f_a(k) - B(p(k))\hat{f}_a(k - 1),
\end{align*}
\]

5. NUMERICAL EXAMPLE

The effectiveness of the proposed FTC technique is demonstrated by numerical examples. The discrete-time LPV system is given by

\[
x(k + 1) = A(p(k))x(k) + Bu(k), \tag{32}
\]

where

\[
A(p(k)) = 10^{-3} \begin{bmatrix}
999.6 & 0.2699 & 0.1646 & -4.558 \\
0.4794 & 990 & -0.1761 & -40.01 \\
0.9992 & 3.65 + p(k) & 993 & 14.07 \\
0.005001 & 0.0183 & 9.965 & 1000
\end{bmatrix}, \quad C = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}.
\]

The initial states of the system (32) and the robust observer (11) are given as follows:

\[
x(0) = [-1.5 & -0.2 & 0.5 & -1]^T, \quad \hat{x}(0) = [-0.5 & 1.0 & -0.3]^T.
\]

We assume that the uncertain parameter \(p(k)\) belongs to the following region:

\[
p(k) \in [0, 5]. \tag{35}
\]

Fig. 4 shows the time-varying parameter \(p(k)\) of the LPV system (32). Under normal conditions, the control gain \(K\) is given as follows:

\[
K = \begin{bmatrix}
9.7672 & 0.0927 & -0.9981 & -4.1141 \\
6.1452 & -0.1364 & -0.5855 & -1.9789
\end{bmatrix}. \tag{36}
\]

In addition, the system disturbance and the sensor noise, added to the system (32), are considered for practical applications.
First of all, we have proposed the fault compensator that its structure is simple to understand, but the robust observer works well. Fig. 11 shows the control signal $u_{c}(k)$ which compensate the actuator faults. From this simulation results, it is obvious that the proposed output feedback FTC scheme works well.

### 5.1 Simulation with state feedback FTC

The effectiveness of the proposed state feedback FTC scheme is demonstrated. A fault scenario is used to demonstrate the effectiveness of the proposed state feedback FTC scheme. The fault scenario is that actuator faults occur at $k \geq 100$ and $k \geq 500$, respectively. As mentioned in Section 3, the proposed state feedback FTC scheme can be an effective method against the time-varying faults except the fault which varies fast. The actuator fault is shown in Fig. 5.

Under the above fault scenario, the fault compensation input (9) is updated on-line to compensate the effect of the actuator fault. Fig. 6 shows the system state $x_{1}(k)$ with and without the fault compensator. From this figure, it is obvious that although actuator faults occur, the system is stabilized by the proposed FTC scheme. Fig. 7 shows the control signal $u_{c}(k)$ which compensate the actuator faults. From this simulation results, it is obvious that the proposed state feedback FTC scheme works well.

### 5.2 Simulation with output feedback FTC

The effectiveness of the proposed output feedback FTC scheme is demonstrated. The decay rate $\rho$ and the weighting matrix $L_{c}$ are set as follows:

$$
\rho = \sqrt{0.6}, \quad L_{c} = \begin{bmatrix}
1.0108 & -0.0298 & -0.0424 & -0.0048 \\
-0.0344 & 1.3535 & 0.0273 & -0.0401 \\
-0.0463 & -0.0221 & 1.2948 & 0.0157 \\
-0.0002 & -1.0001 & -0.9885 & 1.0000 \\

\end{bmatrix}.
$$

Then, from Theorem 2, the observer gains $L_{c}$ and $L_{f}$ are obtained as

$$
L_{c} = \begin{bmatrix}
1.0108 & -0.0298 & -0.0424 & -0.0048 \\
-0.0344 & 1.3535 & 0.0273 & -0.0401 \\
-0.0463 & -0.0221 & 1.2948 & 0.0157 \\
-0.0002 & -1.0001 & -0.9885 & 1.0000 \\

\end{bmatrix},
$$

$$
L_{f} = \begin{bmatrix}
2.0118 & -5.2585 & -9.1187 & -0.0458 \\
1.4068 & -6.7403 & -4.1243 & -0.0207 \\

\end{bmatrix}.
$$

A fault scenario is used to demonstrate the effectiveness of the proposed FTC scheme. The fault scenario is that actuator faults occur at $k \geq 300$ in both the first and the second actuators simultaneously, the fault values in the first and second actuators are 14.5 and 9.5, respectively, i.e.,

$$
\begin{cases}
    f_{a,1}(k) = 14.5 & \text{if } k < 300 \\
    f_{a,1}(k) = 9.5 & \text{otherwise}
\end{cases}
$$

Under the above fault scenario, based on the estimated system states and the estimated faults, the fault compensation input (28) is updated on-line to compensate the effect of the actuator fault represented as a form of (40). Fig. 8 shows the system state $x_{1}(k)$ with and without the fault compensator. From this figure, it is obvious that although actuator faults occur, the system is stabilized by the proposed FTC scheme. Fig. 9 shows the system state error $x_{1}(k) - \hat{x}_{1}(k)$. The actuator fault $f_{a}(k)$ and the estimated fault $\hat{f}_{a}(k)$ are plotted in Fig. 10. Figs. 9 and 10 show that the proposed robust observer works well. Fig. 11 shows the control signal $u_{c}(k)$, which compensate the actuator faults (40). From this simulation results, it is obvious that the proposed output feedback FTC scheme works well.

### 6. CONCLUSION

We have proposed a new FTC scheme for polytopic LPV systems against actuator faults based on the fault compensator and the robust observer. First of all, we have proposed the fault compensator that its structure is simple to understand, but...
effective against actuator faults. Then, in order to show its basic idea, we have proposed the state feedback FTC scheme based on the fault compensator. In the proposed FTC scheme, it is not necessary to redesign or switch the control gain $K$, since the fault compensator is just added to the original controller designed under no fault conditions. Nevertheless, the system can be stabilized since the fault compensator works well. Next, the algorithm was extended to the output feedback FTC scheme. The FTC scheme for LPV systems involves the fault compensator based on the estimated faults and the robust observer based on LMI to estimate the system state and the actuator fault. The proposed FTC scheme for LPV systems can guarantee the robust stability of the system with actuator faults. In addition, though many practical engineers do not have the expertise on control theory, they can use this FTC scheme without difficulty, because the control algorithm is simple and easy to understand. Therefore, this FTC scheme is applicable for a class of practical systems. Simulation results have shown that the proposed FTC scheme works well.

As a future work, we will consider the FTC method for systems subject to input saturation. In addition, although it is assumed that time-varying parameter is measurable on-line, we will develop the output feedback FTC algorithm combined with the time-varying parameter estimation method.

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