Suction Cup-Type Prescribed Performance Fault-Tolerant Fuzzy Control for Nonlinear Systems Considering Actuator Power

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***Abstract*—Conventional fault-tolerant control schemes typically assume the exponent of the faulty input to be 1, overlooking its impact on actuator power. In this paper, we propose a novel fault-tolerant control strategy that extends the exponent to any positive odd integer, thus capturing higher-order fault effects. In addition, by integrating a Gaussian function to modify the constraint boundaries, a novel suction-cup-type prescribed performance function is proposed. Unlike existing prescribed performance functions, this design uses a suction cup module to regulate output overshoot without requiring asymmetric design. This design is globally effective, eliminating the initial feasibility conditions. Simulation results validate the effectiveness of the proposed scheme.**

***Index*—Actuator power, asymmetry-free, fault-tolerant control, initial-feasibility-condition-free, suction-cup-type prescribed performance.**

I. Introduction

Fuzzy control is a well-established and effective methodology widely used in nonlinear system control design [1]–[8]. However, prolonged operation often leads to actuator faults, jeopardizing system stability and safety. To address these challenges, fault-tolerant control (FTC) has become a key research focus. Actuator faults are generally classified into gain faults (affecting actuation efficiency) and bias faults (caused by sticking behavior) [9]–[20]. Conventional FTC approaches typically assume a power index of 1 for faulty inputs, implying no impact on power levels. Yet, this assumption contradicts real-world observations—actuator failures can unpredictably alter input power, creating discrepancies between theoretical models and actual performance [21]. Consequently, a revised fault model must account for power variations, where the power index of faulty inputs deviates from 1. This shift introduces additional complexity in control design, raising new challenges for FTC strategy development.

Thanks to its explicit capability to regulate control performance, prescribed performance control (PPC) has gained widespread popularity in recent years. In traditional PPC schemes [22]–[25], the constraint boundary is shaped in a funnel form, ensuring that the tracking error remains within the boundary through an error transformation technique. By fine-tuning parameters associated with convergence rates and initial/final error positions, prescribed performance specifications can be achieved, providing significant benefits for physical systems requiring precise tracking control [26]–[28]. However, rapid convergence inevitably leads to output overshoot. To address this issue, various asymmetric design schemes for PPC [29]–[32] have been proposed. Whether considering independent asymmetric designs [29], [30] or unified asymmetric designs [31], [32], overshoot adjustment requires continuous tuning of asymmetric parameters - an evidently time-consuming process. While such tuning can help optimize overshoot, it may not completely eliminate it, but rather compress it either upward or downward, with excessive adjustments potentially causing inverse overshoot [8]. Additionally, designing PPC with a tunnel-shaped constraint can also effectively mitigate output overshoot [33]–[35]. However, this approach compromises the convergence rate, and the tunnel's narrowness makes it difficult to satisfy the initial feasibility condition (IFC). In practice, the IFC serves as a fundamental requirement for PPC. Specifically, the IFC requires that the initial error must remain within the initial prescribed performance boundaries. If this condition is violated, it becomes necessary to reselect new and appropriately enlarged boundaries. However, the current asymmetric design [29]–[32] and shape modification designs [33]–[35] of PPC pay little attention to this point, making it impossible to achieve optimization of overshoot on a global scale. Consequently, the practicality of these PPC schemes remains relatively low. Moreover, solutions related to PPC with finite time [36], [37], fixed time [38], [39], predefined time

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[40], [41], and prescribed time [42], [43] have been developed, establishing an explicit connection between settling time and PPC. Given the aforementioned observations, it would be beneficial to develop a class of global PPC that simultaneously accounts for settling time and minimizes overshoot, without being constrained by the IFC. Furthermore, to the best of our knowledge, no prior work has achieved overshoot optimization under symmetric constraints.

In this paper, we propose a novel suction cup-type prescribed performance fuzzy control scheme for a class of nonlinear systems, while also considering a novel actuator fault mode. The primary contributions of this work are as follows:

1) This paper advances beyond conventional FTC approaches [9]–[20] by considering actuator faults that induce unknown power variations, where the input power index becomes an odd integer greater than 1. Building on this analysis, we develop a novel fault-tolerant fuzzy control algorithm with enhanced practical applicability.
2) Unlike existing PPC schemes [22]–[43], this paper proposes a novel suction cup-type prescribed performance design. This innovative suction cup design uniquely eliminates overshoot without the need for asymmetric configurations. Furthermore, it offers global applicability, eliminating the requirement for IFC, and provides the additional advantage of explicitly adjustable settling time.

The organization of this paper is as follows: Section II elaborates on the control problem under consideration with the unknown actuator power. Section III introduces the design method of the global suction cup-type prescribed performance function, and, based on the nonlinear mapping function and Section II, presents the controller design and stability analysis. Section IV conducts simulations using a mass-spring-damper system as an example and analyzes the results. Section V summarizes this work.

In this paper, we adopt the following notations: $\mathbb{R}$ denotes the set of real numbers, $\mathbb{R}^+$ denotes the set of nonnegative real numbers, and $\mathbb{R}^n$ denotes the set of n-dimensional real vectors. For any real number a, $|a|$ denotes its absolute value, and $\operatorname{sgn}(a)$ denotes the signum function, defined as: $\operatorname{sgn}(a) = -1$, if $a < 0$; $\operatorname{sgn}(a) = 0$, if $a = 0$; $\operatorname{sgn}(a) = 1$, if $a > 0$. A function is said to be C^1 (first-order continuously differentiable) if it is continuous and has a continuous first derivative.

II. Problem Formulation and Preliminaries

A. Problem Formulation

In the absence of faults, the nonlinear system admits the following form:

$$\begin{cases} \dot{x}_i = x_{i+1} + f_i\left(\bar{x}_i\right), i = 1, \ldots, n-1, \\ \dot{x}_n = u + f_n\left(x\right), \\ y = x_1, \end{cases} \tag{1}$$

where $x = \left[x_1, \ldots, x_n\right]^{\mathrm{T}} \in \mathbb{R}^n$ denotes the system state with the initial value $x\left(t_0\right) = x_0$, $u \in \mathbb{R}$ denotes the input, $y \in \mathbb{R}$ denotes the output, and $f_j : \mathbb{R}^n \rightarrow \mathbb{R}, j = 1, \ldots, n$ denotes the unknown continuous function.

Practical systems inevitably experience actuator faults, commonly represented by:

$$u = g\left(x\right)\nu + b\left(x\right), \tag{2}$$

where ν is the designed control input, $0 < g(x) \leq 1$ characterizes actuation effectiveness loss, and $b(x)$ represents the bias from stuck actuators.

While Model (2) represents the standard actuator fault characterization [9]–[20], practical systems exhibit power exponent variations due to degradation effects [21], [49], [50]. Accounting for this, we generalize (2) to:

$$u^q = \left(g\left(x\right)\nu + b\left(x\right)\right)^q, \tag{3}$$

where q represents the altered power characteristic.

Combining (1) and (3) yields

$$\begin{cases} \dot{x}_i = x_{i+1} + f_i\left(\bar{x}_i\right), i = 1, \ldots, n-1, \\ \dot{x}_n = \left(g\left(x\right)\nu + b\left(x\right)\right)^q + f_n\left(x\right), \\ y = x_1. \end{cases} \tag{4}$$

Remark 1: While classical works (e.g., [21], [51], [52]) have studied nonlinear systems with unknown powers (e.g., $\dot{x}_j = f_j(x) + x_{j+1}^{q_j}$), the interplay between unknown powers and actuator faults remains unexplored. This paper bridges that gap by proposing the model (3), which explicitly links these two issues. The coexistence of unknown powers and actuator faults not only distinguishes our system from prior work but also introduces significant design challenges, forming one of the core focuses of this study.

Remark 2: Physical degradation mechanisms (fatigue, aging, etc.) inherently exhibit nonlinear damage accumulation where $q > 1$ is physically justified. Established models like Coffin-Manson [53] (fatigue) and Arrhenius [54] (aging) demonstrate superlinear damage growth ($q > 1$) under stress/loading, explaining accelerated failure modes. While $q < 1$ may describe initial sublinear processes (e.g., early-stage creep), long-term degradation is dominated by $q > 1$ behavior, making model (3) with $q > 1$ empirically grounded.

Remark 3: Beyond odd positive integers, two alternative cases for q exist:

(i) Even positive q (e.g., $q = 2$): The system $\dot{x} = x + u^2$ demonstrates the fundamental limitation where both positive and negative inputs contribute positively, preventing guaranteed stabilization;
(ii) Time-varying $q(t)$ (e.g., $q(t) = \sin(t) + 5$): Introduces controller design challenges due to (a) stability verification difficulties; and (b) unpredictable control effects from varying input influence.

Thus, the restriction to odd positive integers preserves both theoretical and practical validity.

The dynamics described by (4) find practical application in modeling boiler-turbine units [55] and various mechanical systems with weak coupling, underactuation, or instability [49]. This model accounts for real-world factors like material hardening, spring aging, and operational variations that contribute to unknown power effects, thereby enhancing the scope and effectiveness of FTC strategies.

The objective of this study is to develop a state-feedback control strategy that guarantees:

(i) Boundedness of all closed-loop signals in the system (4); and

(ii) The tracking error $e(t) = y(t) - y_d(t)$ remains within prescribed performance boundaries and converges to a predefined arbitrarily small residual set within a finite time.

Some useful lemmas and assumptions are presented next.

Lemma 1 [6]: An unknown continuous function $F(\chi)$ can be effectively approximated by a fuzzy logic system (FLS) through the following representation:

$$F(\chi) = \Theta^{\mathrm{T}}\psi(\chi) + \epsilon(\chi), \left(|\epsilon(\chi)| \le \epsilon^*, \epsilon^* \in \mathbb{R}^+\right),$$

where $\epsilon(\chi)$ is the approximation error, Θ is the weight vector, and $\psi(\chi) = [\psi_1(\chi), \ldots, \psi_n(\chi)]^{\mathrm{T}} / \sum_{i=1}^{n} \psi_i(\chi)$ is the basis function, usually chosen as a Gaussian function:

$$\psi_i(\chi) = \exp\left[\frac{-(\chi - \delta_i)^{\mathrm{T}}(\chi - \delta_i)}{\varphi_i^2}\right]$$

with δ_i and φ_i, respectively, denoting the center and width.

Lemma 2 [21]: For any $h(t) \in C^1$ bounded as $\underline{h} < h(t) < \bar{h}$ and $s \in \mathbb{R}$, $|s|^h \le |s|^{\underline{h}} + |s|^{\bar{h}}$.

Lemma 3 [44]: Given $h(t) \in C^1$ with $h(t) \ge 1$ and $s_i \in \mathbb{R}$, $\sum_{i=1}^{n} |s_i|^h \le \left(\sum_{i=1}^{n} |s_i|\right)^h \le n^{h-1} \sum_{i=1}^{n} |s_i|^h$.

Assumption 1 [45]: The desired trajectory y_d and its first-order derivative $\dot{y}_d$ are continuous and bounded.

Assumption 2 [10]: The gain $g(x) \in [\underline{g}, \bar{g}] \subseteq (0, 1]$ and bias $|b(x)| \in [\underline{b}, \bar{b}]$ are bounded with known positive bounds $\underline{g}, \bar{g}, \underline{b}, \bar{b}$.

Assumption 3: The power q is bounded by known odd integers $\underline{q} \le q \le \bar{q}$.

Remark 4: Assumptions 1 and 2 ensure system controllability, a crucial property for both theoretical analysis and practical implementations [46]–[48]. Assumption 3 guarantees consistent control directionality between $(\cdot)^1$ and $(\cdot)^q$ operations, a fundamental requirement [9]–[21] for higher-power systems.

III. Main Results

A. Global Suction Cup-Type Prescribed Performance

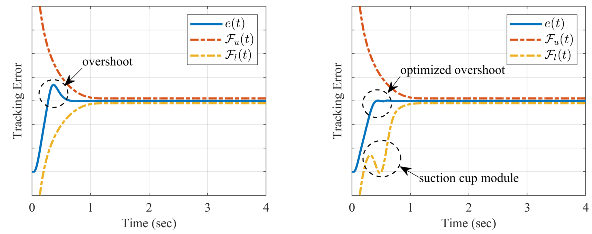
Define the finite-time prescribed performance function $\varrho(t)$ as

$$\varrho(t) = \begin{cases} (r_0 - r_f)\, e^{\frac{lt}{t-T}} + r_f, t \in [0, T), \\ r_f, t \in [T, +\infty), \end{cases}$$

where $0 < r_f \ll r_0$, $l \in \mathbb{R}^+$, and $T \in \mathbb{R}^+$ are design parameters. The function $\varrho(t)$ satisfies (i) $\varrho(0) = r_0$; (ii) $\lim_{t \to T^-} \varrho(t) = r_f$; and (iii) $\varrho(t) \in [r_f, r_0]$ for all $t \ge 0$.

To remove IFC and minimize output overshoot, a novel global suction-cup type prescribed performance function is proposed as follows. Let

$$\begin{aligned} \mathcal{F}_u(t) &= \tfrac{\varrho(t)}{[r_0 - \varrho(t)]^{\Lambda}} + \mathcal{S}_u \mathcal{G}_u, \\ \mathcal{F}_l(t) &= -\tfrac{\varrho(t)}{[r_0 - \varrho(t)]^{\Lambda}} - \mathcal{S}_l \mathcal{G}_l. \end{aligned} \quad (5)$$



(a) (b)

Fig. 1. (a) indicates overshoot under symmetry constraints; (b) shows that the overshoot in (a) is optimized in the presence of the suction cup module.

and

$$\mathcal{S}_u = \begin{cases} 1, & \text{if } e(0) > 0, \\ 0, & \text{if } e(0) = 0, \\ -1, & \text{if } e(0) < 0, \end{cases} \quad \mathcal{S}_l = \begin{cases} 1, & \text{if } e(0) < 0, \\ 0, & \text{if } e(0) = 0, \\ -1, & \text{if } e(0) > 0, \end{cases}$$

$$\mathcal{G}_u = \jmath_u \exp\left(-\tfrac{(t-\kappa_u)^2}{2\sigma_u^2}\right),$$
$$\mathcal{G}_l = \jmath_l \exp\left(-\tfrac{(t-\kappa_l)^2}{2\sigma_l^2}\right),$$

where $\mathcal{G}_u$, $\mathcal{G}_l$ denote suction cup modules, and $0 < \Lambda \le 1$, $\jmath_u$, $\jmath_l$, κ_u, κ_l, σ_u, and σ_l are design constants.

The prescribed performance boundaries in (5) consist of two components:

(i) Fundamental boundaries $\frac{\varrho(t)}{[r_0 - \varrho(t)]^{\Lambda}}$ that amplify the initial value of $\varrho(t)$ to infinity through division by $[r_0 - \varrho(t)]^{\Lambda}$ to remove the IFC; and

(ii) Auxiliary boundaries $\mathcal{S}_u\mathcal{G}_u$ and $\mathcal{S}_l\mathcal{G}_l$ for overshoot optimization, where $\mathcal{S}_u$ and $\mathcal{S}_l$ determine the activation of the upper or lower boundary suction cup $\mathcal{G}_u$ or $\mathcal{G}_l$ based on the overshoot direction.

The functions $\mathcal{F}_u(t)$ and $\mathcal{F}_l(t)$ satisfy (i) $\mathcal{F}_u(t) \to +\infty$ and $\mathcal{F}_l(t) \to -\infty$ if and only if $t \to 0^+$; (ii) $\lim_{t \to T^-} \mathcal{F}_u(t) = \frac{r_f}{|r_0 - r_f|^{\Lambda}}$, $\lim_{t \to T^-} \mathcal{F}_l(t) = -\frac{r_f}{|r_0 - r_f|^{\Lambda}}$; and (iii) for all $t \ge 0$, $\mathcal{F}_u(t) \in \left[\frac{r_f}{|r_0 - r_f|^{\Lambda}}, +\infty\right)$ and $\mathcal{F}_l(t) \in \left(-\infty, -\frac{r_f}{|r_0 - r_f|^{\Lambda}}\right]$.

Remark 5: In traditional PPC [22]–[25], the IFC is mandatory, meaning that the initial error $e(0)$ must satisfy the condition $\mathcal{F}_l(0) < e(0) < \mathcal{F}_u(0)$. However, in this paper, the initial boundaries are infinite, and any initial error $e(0)$ satisfies the condition $-\infty < e(0) < +\infty$, thereby removing the IFC and achieving the global PPC.

Remark 6: Conventional PPC methods [22]–[25] face a fundamental trade-off between convergence rate and overshoot, where faster convergence typically increases overshoot. While asymmetric designs [29]–[32] can reduce overshoot, they inherently limit global prescribed performance due to IFC constraints. Moreover, their parameter tuning is time-consuming and may cause inverse overshoot [8]. This paper proposes a breakthrough solution: a suction cup module that actively attracts and adjusts overshoot while maintaining symmetric constraints, enabling both overshoot optimization and global prescribed performance (Fig. 1). This approach overcomes the limitations of asymmetric methods while preserving design simplicity.

Remark 7: The suction cup module employs a Gaussian function defined by three parameter pairs:

1) $\jmath_u$ and $\jmath_l$ determine the amplitude of the Gaussian function, which corresponds to the height of the convexity.
2) κ_u and κ_l determine the center position of the Gaussian function, which corresponds to the location of the convexity.
3) σ_u and σ_l determine the standard deviation of the Gaussian function, which corresponds to the width of the convexity.

Remark 8: The parameter T offers a viable phase classification for the adjustment of the suction cup module. Specifically, the conditions $\kappa_u + \sigma_u \leq T$ and $\kappa_l + \sigma_l \leq T$ ensure that the regulation of overshoot in the suction cup module occurs only during transient phases, without compromising steady-state performance.

B. Control Design

Define the following nonlinear mapping function:

$$\mathcal{N}(t) = \ln\left(\frac{\Upsilon(t)}{1-\Upsilon(t)}\right), \tag{6}$$

where $\Upsilon(t) = \frac{e(t)-\mathcal{F}_l(t)}{\mathcal{F}_u(t)-\mathcal{F}_l(t)}$. Calculating the derivative of $\mathcal{N}(t)$ yields

$$\dot{\mathcal{N}}(t) = \wp\left[\dot{x}_1 - \dot{y}_d + \eth\right], \tag{7}$$

where $\wp = \frac{1}{\Upsilon(t)[1-\Upsilon(t)][\mathcal{F}_u(t)-\mathcal{F}_l(t)]} > 0$, $\eth = \frac{-e(t)\left[\dot{\mathcal{F}}_u(t)-\dot{\mathcal{F}}_l(t)\right]+\mathcal{F}_l(t)\dot{\mathcal{F}}_u(t)-\dot{\mathcal{F}}_l(t)\mathcal{F}_u(t)}{\mathcal{F}_u(t)-\mathcal{F}_l(t)}$.

The controller design will be implemented within the backstepping framework. Define the following error system:

$$\begin{cases} v_1 = \mathcal{N}, \\ v_j = x_j - \alpha_{j-1}, j = 2, \ldots, n-1, \\ v_n = x_n - \alpha_{n-1}, \\ \tilde{\Phi}_i = \Phi_i - \hat{\Phi}_i, i = 1, \ldots, n, \end{cases} \tag{8}$$

where $\hat{\Phi}_i$ is the estimated value of Φ_i with $\Phi_i = \|\Theta_i\|^2$, and α_j is the virtual control signal to be designed.

Step 1: Choose the candidate Lyapunov function (CLF) as

$$V_1 = \frac{1}{2}v_1^2 + \frac{1}{2\eta_1}\tilde{\Phi}_1^2, \tag{9}$$

where $\eta_1 \in \mathbb{R}^+$ denotes a design parameter.

Calculating the derivative of V_1 yields

$$\dot{V}_1 = \wp v_1\left[F_1(\chi_1) + \alpha_1\right] - \wp^2 v_1^2 - \frac{1}{\eta_1}\tilde{\Phi}_1\dot{\hat{\Phi}}_1, \tag{10}$$

where $F_1(\chi_1) = f_1 + v_2 - \dot{y}_d + \eth + \wp v_1$, $\chi_1 = [x_1, x_2, y_d]^{\mathrm{T}}$.

Lemma 1 suggests the use of FLSs for approximating $F_i(\chi_i)$, i.e., $F_i(\chi_i) = \Theta_i^{\mathrm{T}}\psi_i(\chi_i) + \epsilon_i(\chi_i)$, where $|\epsilon_i(\chi_i)| \leq \epsilon_i^*, \epsilon_i^* \in \mathbb{R}^+$, $i = 1, \ldots, n$.

According to $0 < \psi_i^{\mathrm{T}}(\cdot)\psi_i(\cdot) \leq 1$ and the mean inequality, one has

$$\begin{aligned} \wp v_1 F_1(\chi_1) &\leq |\wp v_1|\,|F_1(\chi_1)| \\ &\leq |\wp v_1|\,\|\psi_1(\mathbb{X}_1)\| \cdot \Phi_1^{1/2} + |\wp v_1|\,\epsilon_1^* \\ &\leq \frac{\wp^2 v_1^2\|\psi_1(\mathbb{X}_1)\|^2}{2} + \frac{\Phi_1}{2\|\psi_1(\mathbb{X}_1)\|^2} \\ &\quad + \frac{\wp^2 v_1^2}{2} + \frac{(\epsilon_1^*)^2}{2} \\ &= \frac{\wp^2 v_1^2 \Phi_1}{2\|\psi_1(\mathbb{X}_1)\|^2} + \wp^2 v_1^2 + \phi_1 \end{aligned} \tag{11}$$

where $\phi_1 = 1/2 + (\epsilon_1^*)^2/4$, $\mathbb{X}_1 = [x_1, y_d]^{\mathrm{T}}$.

Design α_1 and $\dot{\hat{\Phi}}_1$ as

$$\alpha_1 = -\frac{k_1}{\wp}v_1 - \frac{\wp v_1\hat{\Phi}_1}{2\|\psi_1(\mathbb{X}_1)\|^2}, \tag{12}$$

$$\dot{\hat{\Phi}}_1 = \frac{\eta_1\wp^2 v_1^2}{2\|\psi_1(\mathbb{X}_1)\|^2} - \beta_1\hat{\Phi}_1, \tag{13}$$

where k_1, $\beta_1 \in \mathbb{R}^+$ denote design parameters.

Substituting (11)–(13) into (10) yields

$$\dot{V}_1 \leq -k_1 v_1^2 + \frac{\beta_1}{\eta_1}\tilde{\Phi}_1\hat{\Phi}_1 + \phi_1. \tag{14}$$

Step j ($j = 2, \ldots, n-1$): Choose the CLF as

$$V_j = V_{j-1} + \frac{1}{2}v_j^2 + \frac{1}{2\eta_j}\tilde{\Phi}_j^2, \tag{15}$$

where $\eta_j \in \mathbb{R}^+$ denotes a design parameter.

Calculating the derivative of V_j yields

$$\dot{V}_j = \dot{V}_{j-1} + v_j\left[F_j(\chi_j) + \alpha_j\right] - v_j^2 - \frac{1}{\eta_j}\tilde{\Phi}_j\dot{\hat{\Phi}}_j, \tag{16}$$

where $F_j(\chi_j) = f_j + v_{j+1} - \dot{\alpha}_{j-1} + v_j$, $\chi_j = [x_1, x_2, \ldots, x_{j+1}, y_d]^{\mathrm{T}}$.

Similar to (11), one has

$$v_j F_j(\chi_j) \leq \frac{v_j^2\Phi_j}{2\|\psi_j(\mathbb{X}_j)\|^2} + v_j^2 + \phi_j, \tag{17}$$

where $\phi_j = 1/2 + (\epsilon_j^*)^2/4$, and $\mathbb{X}_j = [x_1, x_2, \ldots, x_j, y_d]^{\mathrm{T}}$.

Design α_j and $\dot{\hat{\Phi}}_j$ as

$$\alpha_j = -k_j v_j - \frac{v_j\hat{\Phi}_j}{2\|\psi_j(\mathbb{X}_j)\|^2}, \tag{18}$$

$$\dot{\hat{\Phi}}_j = \frac{\eta_j v_j^2}{2\|\psi_j(\mathbb{X}_j)\|^2} - \beta_j\hat{\Phi}_j, \tag{19}$$

where k_j, $\beta_j \in \mathbb{R}^+$ denote design parameters.

From (16)–(19), one has

$$\dot{V}_j \leq -\sum_{m=1}^{j} k_m v_m^2 + \sum_{m=1}^{j}\frac{\beta_m}{\eta_m}\tilde{\Phi}_m\hat{\Phi}_m + \sum_{m=1}^{j}\phi_m. \tag{20}$$

Step n: Choose the CLF as

$$V_n = V_{n-1} + \frac{1}{2}v_n^2 + \frac{1}{2\eta_n}\left(\tilde{\Phi}_n^*\right)^2, \tag{21}$$

where $\eta_n \in \mathbb{R}^+$ denotes a design parameter, $\tilde{\Phi}_n^* = \Phi_n^* - \hat{\Phi}_n^*$, and $\Phi_n^* = \frac{\Phi_n^{\frac{q+1}{2}} \|\psi_n(\mathbb{X}_n)\|^{q+1}}{q+1}$.

From (21), one has

$$\dot{V}_n = \dot{V}_{n-1} + v_n \left[(g\nu + b)^q - \dot{\alpha}_{n-1} + f_n\right] - \tfrac{1}{\eta_n} \tilde{\Phi}_n^* \dot{\hat{\Phi}}_n^*. \tag{22}$$

Note that

$$\begin{aligned}(g\nu + b)^q &= \begin{pmatrix} q \\ 0 \end{pmatrix} (g\nu)^q + \begin{pmatrix} q \\ 1 \end{pmatrix} (g\nu)^{q-1} b \\ &\quad + \begin{pmatrix} q \\ 2 \end{pmatrix} (g\nu)^{q-2} b^2 + \cdots \\ &\quad + \begin{pmatrix} q \\ q-1 \end{pmatrix} g\nu b^{q-1} + \begin{pmatrix} q \\ q \end{pmatrix} b^q \\ &= (g\nu)^q + \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} (g\nu)^{q-i} b^i + b^q,\end{aligned}$$

where $\begin{pmatrix} q \\ i \end{pmatrix} = \frac{q!}{i!(q-i)!}$.

According to Young's inequality, one has

$$\begin{aligned}&\begin{pmatrix} q \\ i \end{pmatrix} (g\nu)^{q-i} b^i \le \begin{pmatrix} q \\ i \end{pmatrix} |g\nu|^{q-i} |b|^i \\ &\le \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1 \tfrac{i}{q} |g\nu|^q + \vartheta_1{}^{-\frac{i}{q-i}} \tfrac{q-i}{q} |b|^q\right),\end{aligned}$$

where $\vartheta_1 \in \mathbb{R}^+$ is a design constant.

It follows that

$$\begin{aligned}&\sum_{i}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} (g\nu)^{q-i} b^i \\ &\le \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1 \tfrac{i}{q} |g\nu|^q + \vartheta_1{}^{-\frac{i}{q-i}} \tfrac{q-i}{q} |b|^q\right) \\ &\le \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1 \tfrac{i}{q} |g\nu|^q\right) + \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1{}^{-\frac{i}{q-i}} \tfrac{q-i}{q} |b|^q\right).\end{aligned}$$

Thus, one has

$$\begin{aligned}&v_n (g\nu + b)^q \\ &\le \left[v_n + |v_n| \operatorname{sgn}(g\nu) \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1 \tfrac{i}{q}\right)\right] (g\nu)^q \\ &\quad + \left[v_n + |v_n| \operatorname{sgn}(b) \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1{}^{-\frac{i}{q-i}} \tfrac{q-i}{q}\right)\right] b^q \\ &= \left[v_n + |v_n| \operatorname{sgn}(g\nu) \varsigma_1\right] (g\nu)^q \\ &\quad + \left[v_n + |v_n| \operatorname{sgn}(b) \varsigma_2\right] b^q,\end{aligned} \tag{23}$$

where

$$\begin{aligned}\varsigma_1 &= \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1 \tfrac{i}{q}\right), \\ \varsigma_2 &= \sum_{i=1}^{q-1} \begin{pmatrix} q \\ i \end{pmatrix} \left(\vartheta_1{}^{-\frac{i}{q-i}} \tfrac{q-i}{q}\right).\end{aligned}$$

From Assumptions 2–3, $b^q \le \max(\underline{b}^q, \bar{b}^q) \le \bar{b}^q$ holds universally since $|b| \in [\underline{b}, \bar{b}]$ and $q \in [\underline{q}, \bar{q}] \ge 1$.

Then, one has

$$v_n \left[1 + \operatorname{sgn}(v_n) \operatorname{sgn}(b) \varsigma_2\right] b^q \le (1 + \varsigma_2) |v_n| \bar{b}^q. \tag{24}$$

Substituting (24) into (23) yields

$$\begin{aligned}&v_n (g\nu + b)^q \\ &\le v_n \left[1 + \operatorname{sgn}(v_n) \operatorname{sgn}(g\nu) \varsigma_1\right] g^q \nu^q \\ &\quad + (1 + \varsigma_2) |v_n| \bar{b}^q.\end{aligned} \tag{25}$$

Substituting (25) into (22) yields

$$\begin{aligned}\dot{V}_n &\le \dot{V}_{n-1} + v_n \left(\varpi \nu^q - \dot{\alpha}_{n-1} + f_n\right) \\ &\quad + (1 + \varsigma_2) |v_n| \bar{b}^q - \tfrac{1}{\eta_n} \tilde{\Phi}_n^* \dot{\hat{\Phi}}_n^*,\end{aligned} \tag{26}$$

where $\varpi = \left[1 + \operatorname{sgn}(v_n) \operatorname{sgn}(g\nu) \varsigma_1\right] g^q$.

According to Young's inequality, one has

$$(1 + \varsigma_2) |v_n| \bar{b}^q \le \frac{1}{q+1} \bar{b}^{q+1} |v_n|^{q+1} + \frac{q}{q+1}, \tag{27}$$

Substituting (27) into (26) yields

$$\begin{aligned}\dot{V}_n &\le \dot{V}_{n-1} + v_n \left[\varpi \nu^q + F_n(\chi_n)\right] \\ &\quad + \tfrac{1}{q+1} \bar{b}^{q+1} |v_n|^{q+1} + \tfrac{q}{q+1} - \tfrac{1}{\eta_n} \tilde{\Phi}_n^* \dot{\hat{\Phi}}_n^*,\end{aligned} \tag{28}$$

where $F_n(\chi_n) = -\dot{\alpha}_{n-1} + f_n$, and $\chi_n = [x_1, x_2, \ldots, x_n, y_d]^{\mathrm{T}}$.

Similar to (11) and (17), one has

$$v_n F_n(\mathcal{Z}_n) \le \frac{\Phi_n^{\frac{q+1}{2}} \|\psi_n(\mathbb{X}_n)\|^{q+1} v_n^{q+1}}{q+1} + \phi_n, \tag{29}$$

where $\phi_n = 2q/(q+1) + (\epsilon_n^*)^{q+1}/(q+1)$, and $\mathbb{X}_n = \chi_n$.

Design ν and $\hat{\Phi}_n^*$ as

$$\nu = \begin{cases} -\left(\frac{1}{\xi_1} + \frac{1}{\xi_1^{\frac{1}{\bar{q}}}}\right) \Xi \left(v_n + v_n^{\bar{q}}\right), v_n \ge 0, \\ -\left(\frac{1}{\xi_2} + \frac{1}{\xi_2^{\frac{1}{\bar{q}}}}\right) \Xi \left(v_n + v_n^{\bar{q}}\right), v_n < 0, \end{cases} \tag{30}$$

$$\dot{\hat{\Phi}}_n^* = \eta_n |v_n|^{1+\bar{q}}, \tag{31}$$

where $\xi_1 = (1 - \varsigma_1) \underline{g}^{\bar{q}}$, $\xi_2 = (1 + \varsigma_1) \underline{g}^{\bar{q}}$, and $\Xi = \left(\hat{\Phi}_n^*\right)^{\frac{1}{\underline{q}}} + \left(\hat{\Phi}_n^*\right)^{\frac{1}{\bar{q}}}$.

where $\eta_n \in \mathbb{R}^+$ is a design constant.

Given $v_n \ge 0$, we obtain $\nu \le 0$ and therefore $g\nu \le 0$.

$$\begin{aligned}v_n \varpi \nu^q &= v_n \left[1 + \operatorname{sgn}(v_n) \operatorname{sgn}(g\nu) \varsigma_1\right] g^q \nu^q \\ &= v_n (1 - \varsigma_1) g^q \nu^q.\end{aligned} \tag{32}$$

With ϑ_1 chosen sufficiently small, $(1 - \varsigma_1) > 0$ holds, and (32) implies

$$(1 - \varsigma_1) g^q \ge (1 - \varsigma_1) \underline{g}^{\bar{q}} = \xi_1, \xi_1 > 0.$$

Substituting (31) into (32) yields

$$\begin{aligned}v_n \varpi \nu^q &= -v_n (1 - \varsigma_1) g^q \left(\tfrac{1}{\xi_1} + \tfrac{1}{\xi_1^{\frac{1}{\bar{q}}}}\right)^q \Xi^q (v_n + v_n^{\bar{q}})^q \\ &= -(1 - \varsigma_1) g^q \left(\tfrac{1}{\xi_1} + \tfrac{1}{\xi_1^{\frac{1}{\bar{q}}}}\right)^q \Xi^q |v_n| \left(|v_n| + |v_n|^{\bar{q}}\right)^q.\end{aligned} \tag{33}$$

By Lemma 2, $|v_n|^q \le |v_n|^{\underline{q}} + |v_n|^{\bar{q}}$. From Assumption 3, $1+\underline{q} \le 1+q \le 1+\bar{q} \le 1+\bar{q}q$ holds, yielding

$$0 < |v_n|^{1+\bar{q}} \le |v_n|^{1+\bar{q}q} + |v_n|^{1+\underline{q}},$$

and

$$-|v_n|\left(|v_n| + |v_n|^{\bar{q}}\right)^q \le -|v_n|^{1+\bar{q}}. \tag{34}$$

By Lemma 3, one has

$$\begin{aligned} &-(1-\varsigma_1)\, g^q \left(\tfrac{1}{\xi_1} + \tfrac{1}{\xi_1^{\frac{1}{\bar{q}}}}\right)^q \\ &\le -\xi_1 \left(\tfrac{1}{\xi_1^{q}} + \tfrac{1}{\xi_1^{\frac{q}{\bar{q}}}}\right) \le -\xi_1^{1-q} - \xi_1^{1-\frac{q}{\bar{q}}}. \end{aligned}$$

For $\xi_1 \ge 1$, both $-\xi_1^{1-q/\bar{q}} \le -1$ and $-\xi_1^{1-q} \le -1$ hold since $q \ge 1$. Then, one has

$$-(1-\varsigma_1)\, g^q \left(\frac{1}{\xi_1} + \frac{1}{\xi_1^{\frac{1}{\bar{q}}}}\right)^q \le -1. \tag{35}$$

Similar to (35), one has

$$-\left(\left(\hat{\Phi}_n^*\right)^{\frac{1}{q}} + \left(\hat{\Phi}_n^*\right)^{\frac{1}{\bar{q}}}\right)^q \le -\hat{\Phi}_n^*. \tag{36}$$

Substituting (34)–(36) into (33) yields

$$v_n \varpi \nu^q \le -\hat{\Phi}_n^* |v_n|^{1+\bar{q}}. \tag{37}$$

The $v_n < 0$ case follows analogously to $v_n \ge 0$ and is omitted for brevity.

From (28)–(31), and (37), one has

$$\begin{aligned} \dot{V}_n \le{}& \bar{\phi}_n + \tilde{\Phi}_n^* |v_n|^{1+\bar{q}} - \tfrac{1}{\eta_n}\tilde{\Phi}_n^* \dot{\hat{\Phi}}_n^* \\ &- \sum_{i=1}^{n-1} k_i v_i^2 + \sum_{i=1}^{n-1} \tfrac{\beta_i}{\eta_i} \tilde{\Phi}_i \hat{\Phi}_i, \\ \le{}& -\sum_{i=1}^{n-1} k_i v_i^2 + \sum_{i=1}^{n-1} \tfrac{\beta_i}{\eta_i} \tilde{\Phi}_i \hat{\Phi}_i + \bar{\phi}_n, \end{aligned} \tag{38}$$

where $\bar{\phi}_n = \sum_{i=1}^{n} \phi_i + \bar{b}^{q+1} |v_n|^{q+1} / (q+1) + q/(q+1)$.

Substituting the inequality $\tilde{\Phi}_i \hat{\Phi}_i \le \frac{1}{2}(\Phi_i^2 - \tilde{\Phi}_i^2)$ into (38) yields

$$\dot{V}_n \le -\sum_{i=1}^{n-1} k_i v_i^2 - \sum_{i=1}^{n-1} \tfrac{\beta_i}{2\eta_i} \tilde{\Phi}_i^2 + \phi, \tag{39}$$

where $\phi = \bar{\phi}_n + \sum_{i=1}^{n-1} \beta_i \Phi_i^2 / (2\eta_i)$.

Let $\mu = \min\limits_{1 \le i \le n-1} \{2k_i, \beta_i\}$, one has

$$\dot{V}_n \le -\mu V_n + \phi. \tag{40}$$

Integrating (40) yields

$$V_n \le V_n(0)\, e^{-\mu t} + \tfrac{\phi}{\mu} \le V_n(0) + \tfrac{\phi}{\mu}. \tag{41}$$

From (41), v_i, $\tilde{\Phi}_j$, and $\tilde{\Phi}_n^*$ ($i = 1, \ldots, n$; $j = 1, \ldots, n-1$) are bounded. Combining this result with (12), (13), (18), (19), (30), (31), and the definition of u^q, it follows that α_j, $\hat{\Phi}_j$, $\hat{\Phi}_n^*$, ν, and u^q remain bounded. Furthermore, the error system definition (8) guarantees the boundedness of both $\mathcal{N}$ and x_i. This ensures the boundedness of all closed-loop signals in system (4).

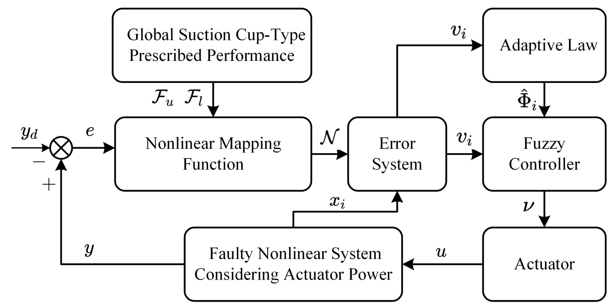


Fig. 2. Block diagram of proposed controller.

From the definition $\Upsilon(t) = \frac{e(t) - \mathcal{F}_l(t)}{\mathcal{F}_u(t) - \mathcal{F}_l(t)}$, when $\mathcal{F}_l(0) < e_0 < \mathcal{F}_u(0)$, we have $\Upsilon(0) \in (0,1)$. Equation (6) indicates that $\mathcal{N}(t) \to \infty$ if and only if $\Upsilon(t)$ approaches either 0^+ or 1^-. This implies that if $\Upsilon(0)$ is initially within (0,1) and $\mathcal{N}(t)$ remains bounded, then $\Upsilon(t) \in (0,1)$ for all $t > 0$. Consequently, the initial condition $\mathcal{F}_l(0) < e_0 < \mathcal{F}_u(0)$ (equivalent to $\Upsilon(0) \in (0,1)$) combined with bounded $\mathcal{N}(t)$ guarantees $\mathcal{F}_l(t) < e(t) < \mathcal{F}_u(t)$ for all $t > 0$. Furthermore, from (5), $\mathcal{F}_l(0) \to -\infty$ and $\mathcal{F}_u(0) \to +\infty$, meaning any finite initial error $e(0)$ automatically satisfies the condition, eliminating the IFC and ensuring the error remains within prescribed performance boundaries. In addition, the definition of $\varrho(t)$ implies that both $\mathcal{F}_l(t)$ and $\mathcal{F}_u(t)$ can specify the settling time T, guaranteeing that $e(t)$ converges to a predefined arbitrarily small residual set within a finite time. Fig. 2 provides a structural overview of the proposed controller.

Remark 9: This paper innovatively incorporates the unknown power variation induced by actuator faults into the control framework. For the case where the power exponent is an odd integer greater than 1 ($q > 1$ and $q \in \mathbb{Z}_{\text{odd}}$), a more general FTC strategy is proposed. By leveraging the *binomial theorem*, the nonlinear term $(g(x)\nu + b(x))^q$ is transformed into a polynomial form. Through inequality transformations (Lemma 2 and Lemma 3), the design and stability proof of this sophisticated fault-tolerant controller are rigorously established. Moreover, this study proposes a suction-cup type prescribed performance function, where the suction cup modules $\mathcal{G}_u$ and $\mathcal{G}_l$ are designed to suppress overshoot without requiring an asymmetric boundary design. By introducing the settling time T into the prescribed performance function, the residual error related to the finite-time prescribed performance bound is ensured. Additionally, the dynamic scaling term $\frac{\varrho(t)}{[r_0 - \varrho(t)]^\Lambda}$ extends the initial boundaries to infinity, thereby eliminating the IFC constraint and ensuring global applicability.

IV. Simulation Results

In this paper, the following mass-spring-damper system that takes into account the aging of the spring is employed for simulation validation:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = [g(x_1, x_2)\,\nu + b(x_1, x_2)]^q - \frac{1}{M} f(x_1, x_2), \\ y = x_1, \end{cases}$$

where the system parameters are selected as $M = 0.8$, $f(x_1, x_2) = 2x_1^2 + x_1^3 \sin(x_1 x_2) + 0.2 x_2^2 \cos(x_2^2)$,

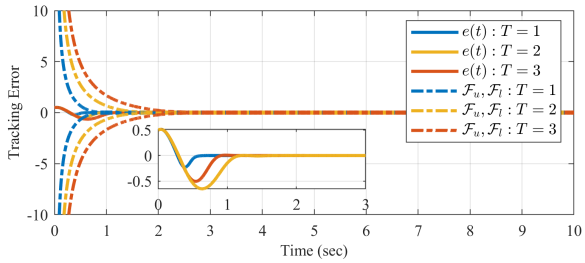


Fig. 3. Tracking error trajectory under different setting time T.

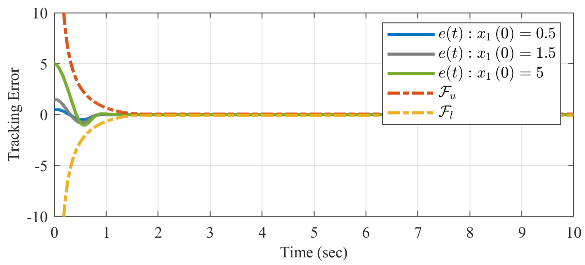


Fig. 4. Tracking error trajectories under different initial conditions $x(0)$.

$g(x_1,x_2) = 0.2 + 0.4\sin(x_1x_2)$, $b(x_1,x_2) = \cos(x_1^2x_2)$, and $q = 3$.

The control parameters are $k_1 = 5$, $\eta_1 = \eta_2 = 0.1$, $\beta_1 = 3$, $\vartheta_1 = 0.2$, $\bar{q} = 3$, $\underline{q} = 3$, $\underline{g} = 0.5$, $T = 2$, $r_0 = 1$, $r_f = 0.05$, $\Lambda = 1$, and $l = 2$. The initial conditions are $x_1(0) = 0.5$, $x_2(0) = 0.2$, $\hat{\Phi}_1(0) = 0.2$, and $\hat{\Phi}_2^*(0) = 0$. The desired trajectory is $y_d = 0.5\sin(t)$.

Figs. 3 and 4 illustrate the tracking performance without the use of suction cup modules. Fig. 3 illustrates the tracking error under different time settings. It can be observed that a smaller T leads to faster error convergence. Notably, this accelerated convergence results from the performance boundary's rapid compression of the error (squeeze theorem), rather than being directly related to system stability. Fig. 4 presents the tracking error under different initial states. The results demonstrate that the proposed method can adapt to varying initial conditions without requiring boundary redesign, which eliminates the IFC constraint and enables global PPC. Moreover, both Figs. 3 and 4 exhibit varying degrees of overshoot. Currently, the methods used to reduce overshoot in PPC predominantly rely on asymmetric designs [29]–[32]. These designs not only pose an additional obstacle to the implementation of global PPC but also involve a laborious tuning process. As a result, it becomes extremely difficult to achieve complete optimization of the overshoot.

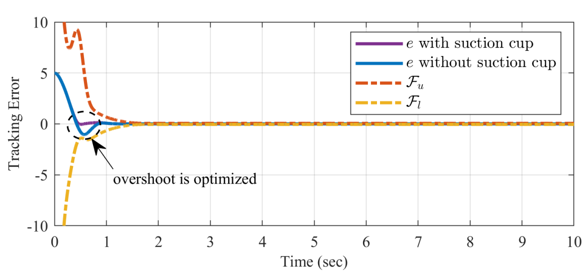


Fig. 5. Tracking error trajectories with/without suction cup.

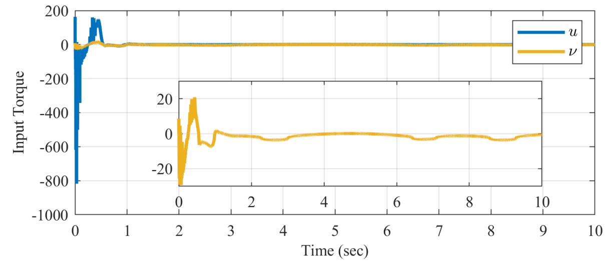


Fig. 6. Trajectories of u and ν with $p = 3$.

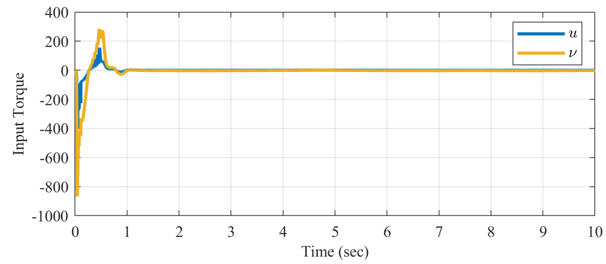


Fig. 7. Trajectories of u and ν with $p = 1$.

In this paper, we propose the use of suction cup modules to optimize overshoot under symmetrical conditions. The design parameters of the suction cup modules are set as $\jmath_u = 6$, $\jmath_l = 1.5$, $\kappa_u = \kappa_l = 0.45$, and $\sigma_u = \sigma_l = 0.1$. As demonstrated in Fig. 5, the presence of the suction cup modules enables the realization of optimized overshoot under symmetric constraints. Moreover, in the symmetric design, the suction cup-type PPC operates exclusively during the transient phase and eliminates the IFC. This method offers a novel perspective on optimizing transient performance within existing PPC schemes [22]–[43].

Figs. 6 and 7 illustrate the FTC inputs with ($q = 3$) and without ($q = 1$, representing traditional FTC techniques [9]–[20]) considering power effects, where ν is an intermediate control signal and u is the actual control signal applied to the system. From these two figures, it can be observed that since the control objectives are identical, the curves of the actual control input u exhibit similar behavior. However, when power effects are considered, ν must compensate for the cubic nonlinearity, and the fault impact is amplified geometrically. The physical significance lies in the fact that when an actuator fails, the cubic operation ($q = 3$) nonlinearly amplifies the fault characteristics, enabling the controller to detect minor faults earlier and trigger compensation. In contrast, a linear model ($q = 1$) exhibits lower sensitivity to faults and requires a larger ν to achieve the same compensation effect. Moreover, the significantly smaller amplitude of ν for $q = 3$ compared to $q = 1$ indicates that the controller achieves fault suppression with lower control energy. Therefore, the proposed power-considered FTC method has the potential to provide a more precise and nuanced assessment of actuator faults compared to traditional FTC techniques [9]–[20].

V. Conclusion

This paper proposes a novel prescribed performance FTC scheme for nonlinear systems. First, the actuator power index q is incorporated into the FTC framework, providing a more comprehensive evaluation of actuator faults. Next, the introduction of the suction cup modules $\mathcal{G}_u$ and $\mathcal{G}_l$ in PPC enables overshoot optimization under the global symmetric condition. Simulation experiments based on a mass-spring-damper system with faults due to the aging spring demonstrate the effectiveness of the proposed scheme.

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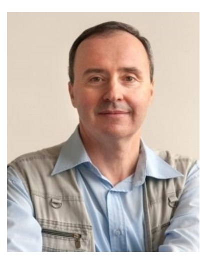

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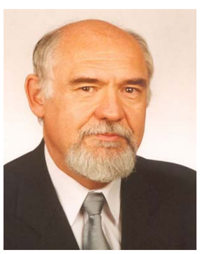

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