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微手系统的鲁棒无源跟踪控制

步　妮[†], 李小永, 张玉义

(青岛科技大学 自动化与电子工程学院, 山东 青岛 266061)

摘要: 近年来, 微手系统作为机器人技术的一个热门研究领域, 受到了越来越多的关注. 由于微手系统是复杂且具有非线性的, 因此在实际应用当中很难达到精确跟踪的性能. 为了解决微手系统的精准控制问题, 本文讨论了微手系统的鲁棒无源跟踪控制. 首先, 运用基于演算子理论的鲁棒右互质分解方法, 建立了微手系统的动态模型. 然后, 通过结合无源补偿算子, 设计了无源鲁棒控制器, 保证了系统的鲁棒稳定性和无源性. 进而提出了基于双Bezout恒等式的鲁棒跟踪控制方案, 使整个非线性系统具有较强的鲁棒性和良好的跟踪性能. 最后, 通过仿真进一步验证了所提出方法的有效性.

关键词: 鲁棒控制; 非线性系统; 无源性; Bezout 恒等式; 鲁棒跟踪控制

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Robust passive tracking control for micro-hand system

BU Ni[†], LI Xiao-yong, ZHANG Yu-yi

(College of Automation and Electronic Engineering, Qingdao University of Science and Technology, Qingdao Shandong 266061, China)

Abstract: In recent years, as a hot research topic in the field of robotics, the research of the micro-hand system has gained more and more attention. Since the micro-hand system is complex with nonlinearity, it is difficult to realize the accurate tracking performance for some real applications. Therefore, in order to solve the accurate control problem of the micro-hand system, the robust passive tracking control for the micro-hand system is studied in this paper. Firstly, using the operator-based robust right coprime factorization method, a dynamic model of the micro-hand system is established. Secondly, combined with the passive compensator, the passive robust controller is designed to ensure robust stability and passivity of the system. Thirdly, the robust tracking control scheme based on dual Bezout identity is proposed, which makes the whole nonlinear systems hold robustness and perfect tracking performance. Finally, the effectiveness of the proposed method is further verified by the simulation.

Key words: robust control; nonlinear system; passivity; Bezout identity; robust tracking control

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1 Introduction

Micro-hand is a kind of soft actuators, which is mostly driven by pneumatic, which can also be driven by fluid, electrically active polymer materials and so on [1–2]. The actuator is mostly made of rubber material, which has the characteristics of low cost, flexible movement, high efficiency and simple operation. It can be used in medical surgery, emergency rescue, geological exploration and other fields [3–5]. There are many excellent research achievements on rigid actuators, but soft actuators are quite different from traditional rigid actuators in design and manufacture, drive and sensing, structure and material technology. Therefore, it is necessary to conduct separate and in-depth researches on soft actuators [6–8].

For the controlled systems with nonlinear characteristics, there are always various uncertainties in real systems, such as unmodeled dynamic characteristics, errors between measurement parameters and real values, and external disturbances which will have a certain impact on the modeling of the system, and may lead to system instability. Hence, due to the particularity of rubber materials and the multiple degrees of freedom of micro-hand, adopting appropriate research methods to study micro-hand is crucial. For micro-hand systems, most of the motion processes are nonlinear and usually present complex internal mechanisms and nonlinear characteristics, which leads to some inner variables of

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[†]Corresponding author. E-mail: bunihan@qust.edu.cn; Tel.: +86 15963008239.
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micro-hand cannot be defined and measured. As a result, it is difficult to relate with the physical meaning and real phenomenon of micro-hand using the traditional state space method. Meanwhile the operator-based robust right coprime factorization (RRCF) method is attracting more and more attention because i) only input-output model is used and measurements of the states in the real system are avoided; ii) the extended Banach space is more suitable for the system control theory and engineering; iii) robust stability of the nonlinear system can be guaranteed by a Bezout identity and a norm inequality. Therefore, owing to the structure and the material of the micro-hand system, the operator-based RRCF method is preferred [9–10].

The systems with right coprime factorization can be stable and robust by satisfying the Bezout identity. Although the robust issue is discussed, however, the condition is so limited that it cannot be applied widely in [9]. Further, some robust conditions for the plant with right coprime factorization under unknown but bounded interferences are derived. The RRCF is extended to the robust control design of more general nonlinear feedback systems by proposing an inequality condition based on the definition of Lipschitz norm [11–12], by which the output tracking and fault detection issues are discussed.

Moreover, the isomorphism idea is introduced to explore the feasibility conditions of RRCF of the systems, and the design problems of nonlinear systems is studied [13–15]. Through researches, it is found that it is difficult to get the inverse of the right factor because of the nonlinear part. Thus, the robust schemes are designed to ensure the robustness of nonlinear systems with uncertain as well as asymptotic tracking of input and output problems [16–17]. The RRCF combined with the passivity property is discussed [18–19], wherein the robust condition and the storage function is respectively discussed by which the robustness and the passivity are both ensured.

In this paper, robust tracking control for uncertain micro-hand systems is studied. The contributions are summarized as follows:

i) The dynamic model of micro-hand system is established by using the operator-based RRCF method.

ii) A passive robust controller is designed to ensure the robustness and passivity of the system.

iii) The robust control scheme of dual Bezout is proposed, by which not only the robustness and passivity for the micro-hand systems but also the perfect tracking performance can be achieved.

The following is the framework of this paper: In Section 2, the preliminary mathematical knowledge, including right coprime factorization and passivity, and the modeling of the micro-hand model are given. In Section 3, the passive control and robust control of nonlinear system are studied, and the control schemes based on dual Bezout identity by using RRCF is proposed to realize more precise tracking control of in-out. In Section 4, the effectiveness of the proposed method is verified by simulation. Section 5 describes the conclusion and future work.

2 Micro-hand and RRCF

The structure and mathematical model of micro-hand and some definitions of RRCF [9] will be introduced in this part.

2.1 Micro-hand

The structure of micro-hand is shown in Fig. 1, where the actuator is circular arc shape. Due to the supplying air pressure, the studied micro-hand actuator is bent. According to Fig. 2, simplified diagram of the actuator is obtained, where the pressure p (Pa) is the input and the bending angle θ (rad) is the output. The parameters of the model are shown in Table 1.

Fig. 1 Micro-hand

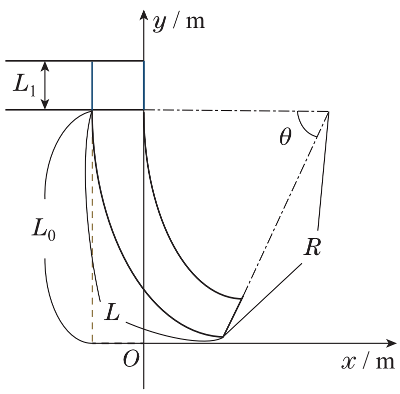

Fig. 2 Analysis model of the actuator

Table 1 Parameters

Parameter name	Parameter	Unit
Natural length of the actuator	L_0	m
Length of the constant part	L_1	m
Length of the bellows side	L	m
Radius of the approximate circle	R	m
Rubber radius	r_a	m
Radius of the cross-section actuator	a	m
Thickness of the actuator	b	m

In Fig. 3, the cross section of micro-hand is obtained, where a (m) is the inside radius. Further, b (m) is the symbol of the maximum thickness. The center of the flat side is defined as the origin of polar coordinate system. The radius vector is r (m) and the argument is ϕ (rad). r_a (m) is rubber radius, which was shown as a fixed value $r_a = a + b/2$ in previous studies. In fact, r_a is variable during inflation and expansion of the micro-hand actuator. It is imprecise to regard r_a as a fixed value. For the sake of rigor, the value of r_a will be identified using the RLS method in the simulation part. It is worth mentioning that a is supposed to be changeless and the changes in tube shape and size are considered as the uncertain part of the system.

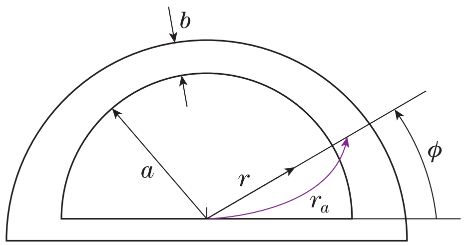

Fig. 3 Cross section of the actuator

The force f_1 generated by pneumatic pressure in a small area of the end section of the actuator is shown as:

$$\mathrm{d}f_1 = pr\mathrm{d}\phi\mathrm{d}r. \tag{1}$$

The moment of the force generated by pneumatic pressure M_1 is shown as:

$$M_1 = p\int_0^a\int_0^\pi (r^2\sin\phi + rb)\mathrm{d}r\mathrm{d}\phi = \frac{4a^3+3\pi a^2 b}{6}p. \tag{2}$$

Then, the opposite direction force f_2 generated by spring in a small area of the bellows side:

$$\mathrm{d}f_2 = -\frac{E\theta(r_a\sin\phi + b)}{L_0}r_a b\mathrm{d}\phi, \tag{3}$$

where r_a is the rubber radius, and E (Pa) is the Young's modulus. Assuming that the modulus of elasticity varies with the elongation of the rubber, then E is defined as: $E = \dfrac{E_0 L_0}{L_0 + \theta(r_a\sin\phi + b)}$, where E_0 (Pa) is the initial Young's modulus.

The moment of the force generated by spring force M_2:

$$M_2 = -\int_0^\pi \mathrm{d}f_2(r_a\sin\phi + b) = -r_a b E_0\theta\int_0^\pi \frac{(r_a\sin\phi+b)^2}{L_0+\theta(r_a\sin\phi+b)}\mathrm{d}\phi. \tag{4}$$

From the balance between the moment generated by pneumatic pressure and the one generated by spring force in the end section of the actuator

$$M_1 + M_2 = 0. \tag{5}$$

Then, the nonlinear system model can be obtained from (2) (4)–(5)

$$\begin{cases} y(t) = -\dfrac{L_0}{b}\left(1 + \dfrac{2r_a(t)+b\pi}{\gamma u(t) - 2r_a(t) - b\pi}\right), \\ \gamma = \dfrac{4a^3+3\pi a^2 b}{6r_a(t)bE_0}, \end{cases} \tag{6}$$

where the u and y are used to represent the input p and the output θ, γ is the time-varying parameter of the model.

2.2 Robust right coprime factorization

Definition 1 Suppose one operator F can be factorized into N and D^{-1}. Then if the two operators A and B exist while B has an inverse form, which are both stable and satisfy:

$$AN + BD = M, \tag{7}$$

where $A: \boldsymbol{Y} \to \boldsymbol{U}$ and $B: \boldsymbol{U} \to \boldsymbol{U}$, which is called to be the Bezout identity, for a unimodular operator $M: \boldsymbol{W} \to \boldsymbol{U}, M \in \S(\boldsymbol{W}, \boldsymbol{U})$, then N and D^{-1} is the right coprime factorization of F.

Assuming that the above system are well-posed and internal stability system and satisfies the bounded input and bounded output (BIBO) stability. Some definitions of these nouns have been defined in [9]. Based on the above analysis, a nonlinear system with disturbances is obtained, which shows in Fig. 4. In detail, the actual plant has the modeling error and the disturbance, which are regarded as the uncertainties. Then, the RRCF of the actual plant $\tilde{F}$ is described as $F + \Delta F = (N + \Delta N)D^{-1}$, where ΔN is regarded as the uncertain operator that is unknown, but it is limited.

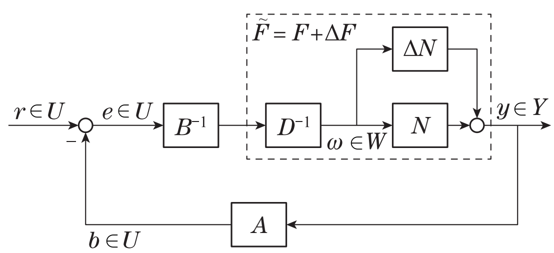

Fig. 4 The uncertain feedback nonlinear system

Definition 2 Suppose a nonlinear operator F : $\boldsymbol{D}^e \to \boldsymbol{Y}^e$ ($\boldsymbol{D}^e \subset \boldsymbol{U}^e$) is the generalized Lipschitz operator on $\boldsymbol{D}^e$, if there exists a constant number ε

$$\left\|[F(x)]_T - [F(\hat{x})]_T\right\|_{\boldsymbol{Y}^e} \leqslant \varepsilon\left\|x_T - \hat{x}_T\right\|_{\boldsymbol{U}^e}, \tag{8}$$

where $\forall x, \hat{x} \in \boldsymbol{D}^e$, especially, Lip $(\boldsymbol{D}^e): \boldsymbol{D}^e \to \boldsymbol{D}^e$. ε is regarded as Lipschitz norm of F and can be obtained by the following formula:

$$\|F\|_{\text{Lip}} := \sup_{T\in[0,\infty)} \sup_{\substack{x,\hat{x}\in \boldsymbol{D}^e \\ x_T\neq \hat{x}_T}} \frac{\|[F(x)]_T-[F(\hat{x})]_T\|_{\boldsymbol{Y}^e}}{\|x_T-\hat{x}_T\|_{\boldsymbol{U}^e}}. \tag{9}$$

Lemma 1 Let $\boldsymbol{D}^e\subset \boldsymbol{U}^e$, if the following conditions are all true:

$$\big(A(N+\Delta N)-AN\big)M^{-1}\in \text{Lip}(\boldsymbol{D}^e), \tag{10}$$

$$AN+BD=M\in\mu(\boldsymbol{W},\boldsymbol{U}), \tag{11}$$

$$A(N+\Delta N)+BD=\tilde{M}, \tag{12}$$

$$\|(A(N+\Delta N)-AN)M^{-1}\|<1, \tag{13}$$

where $\tilde{M}\in \S(U,Y)$ is unimodular, *A* and *B* are the designed controllers. Meanwhile, in Fig. 4, if the system with uncertain has robust stability, then $\tilde{F}$ is said to have a RRCF.

3 Micro-hand system design

In this part, the RRCF method is used to ensure the robust stability of the micro-hand system. Meanwhile, the passivity of the system with uncertain is ensured by designing robust controllers; further, the robust tracking control based on dual Bezout identity is applied to deal with the precise tracking for micro-hand with uncertainties.

3.1 System design of micro-hand model

The nonlinear plant $F+\Delta F$ is defined as

$$y(t)\triangleq (F+\Delta F)(u)(t)= \\ -(1+\zeta)\frac{L_0}{b}(1+\frac{2r_a(t)+b\pi}{\gamma u(t)-2r_a(t)-b\pi}), \tag{14}$$

where ζ is the parameter of the uncertain plant applying the nonlinear feedback system, $F+\Delta F$ can be factorized into the following two parts:

$$(N+\Delta N)(\omega)(t)=-(1+\zeta)\frac{L_0}{b}\omega(t), \tag{15}$$

$$D^{-1}(u)(t)=(1+\frac{2r_a(t)+b\pi}{\gamma u(t)-2r_a(t)-b\pi}). \tag{16}$$

The compensator H^{-1} shown in Fig. 5 is designed as

$$H^{-1}(\tilde{u}_2)(t)=\frac{(2r_a(t)+b\pi)\tilde{u}_2(t)}{\gamma\big(1+\frac{b}{L_0}+\tilde{u}_2(t)\big)}, \tag{17}$$

and

$$\tilde{D}^{-1}(\tilde{u}_1)(t)=-\frac{L_0}{b}\tilde{u}_1(t), \tag{18}$$

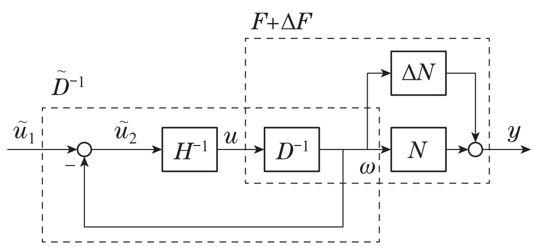

Fig. 5 The nonlinear system with the compensator H^{-1}

where $\tilde{D}^{-1}$ is compensated by H^{-1}, which can be equivalent to the original feedback system and can be described in [14]. $\tilde{u}_1$ is the new input signal which can satisfy the designed uncertain nonlinear feedback system.

According to Fig. 6, the controllers *A* and *B* can be designed as

$$A(y)(t)=(1-K)y(t), \tag{19}$$

$$B(\tilde{u}_1)(t)=\frac{KL_0^2}{b^2}\tilde{u}_1(t), \tag{20}$$

where *K* is the parameter which is designed to satisfy (12). Then, $\tilde{M}$ is obtained as

$$\tilde{M}(\omega)(t)=-\frac{L_0\big(1+\zeta(1-K)\big)}{b}\omega(t). \tag{21}$$

Since $\tilde{M}$ is unimodular, the system with perturbance shown in Fig. 6 has the robust stability.

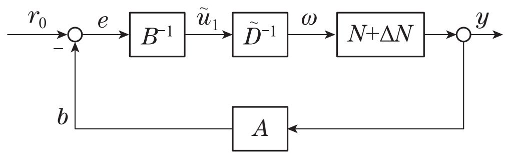

Fig. 6 The passive feedback system

3.2 Passivity-based nonlinear system

In this part, the passivity of the micro-hand system is guaranteed by designing the robust passive controllers using the passivity-based control.

The nonlinear plant $F+\Delta F$ can be factorized into $(N+\Delta N)$ and D^{-1}. To design the passive system, the passivity-based robust control with compensator H^{-1} is designed by using isomorphism idea as shown in Fig. 5, and the compensator can be described as

$$H^{-1}=D(\tilde{D}-I)^{-1}, \tag{22}$$

among them, *I* is regarded as the identity operator. The isomorphic passive nonlinear system design with uncertainty $(N+\Delta N)$ is shown in Fig. 6, while it can also be equivalent to Fig. 7, where $\tilde{M}=A(N+\Delta N)+B\tilde{D}$.

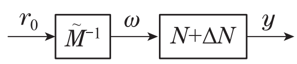

Fig. 7 The equivalent system of Fig. 6

The storage function $V(\omega)$ is designed as that

$$V(\omega)(t)=\int_0^t \tilde{M}D(\omega)(\tau)\mathrm{d}\tau, \tag{23}$$

where $\big(|\tilde{M}(\omega)(t)|\geqslant|(N+\Delta N)(\omega)(t)|\big)$. The differential $\dot{V}(\omega)(t)$ of $V(\omega)(t)$ is obtained as

$$\dot{V}(\omega)(t)=\tilde{M}D(\omega)(t), \tag{24}$$

where $\big(|\tilde{M}(\omega)(t)|\geqslant|(N+\Delta N)(\omega)(t)|\big)$. Then the passive condition is satisfied

$$\dot{V}(\omega)(t)\leqslant y(t)u(t), \tag{25}$$

where $y(t)u(t)=(N+\Delta N)D(\omega)(t)$.

According to (25), the micro-hand system is passive. It is of great physical significance to study the system from the perspective of energy, the nonlinear control feedback system is controlled to be stable and passive with the designed controllers by using RRCF.

3.3 Tracking control based on dual Bezout

After designing robust stability and passivity, tracking performance is considered. However, in the real applications, the uncertainties will damage the stability and various performances of micro-hand system. Hence, in order to improve the tracking performance, a robust tracking control scheme based on dual Bezout is proposed. In detail, by designing the controllers S and Q which can satisfy Bezout identity again, the tracking performance of the system can be realized.

In Fig. 6, assume that the system is stabilized, where robust controllers A and B are designed to ensure the robust stability of the system. Based on $A(N+\Delta N)+B\tilde{D}=\tilde{M}$, the equivalent system in Fig. 8 can be obtained, where S^{-1} and $\tilde{M}^{-1}$ are reversible, in order to satisfy

$$Q(N+\Delta N)+S\tilde{M}=\hat{M}, \tag{26}$$

where $\hat{M}$ is unimodular, the controllers Q and S are designed as follows:

$$Q=\begin{cases}1-\alpha, & |y(t)-r_0(t)|\leqslant\eta,\\ \beta-\dfrac{1}{(|y(t)-r_0(t)|-\eta)^2}, & |y(t)-r_0(t)|>\eta,\end{cases} \tag{27}$$

and

$$S=\begin{cases}\dfrac{(1-K)}{\alpha}, & |y(t)-r_0(t)|\leqslant\eta,\\ \dfrac{(1-K)}{1-\beta+\dfrac{1}{(|y(t)-r_0(t)|-\eta)^2}}, & |y(t)-r_0(t)|>\eta,\end{cases} \tag{28}$$

where α, β and η are the design parameters, according to (9)

$$\begin{aligned}\hat{M}(\omega)(t)=\ & Q(N+\Delta N)+S\tilde{M}=\\ & -\frac{L_0}{b}((1-\alpha)(1+\zeta)+\\ & \frac{1-K}{\alpha}(1+\zeta(1-K)))\omega(t).\end{aligned} \tag{29}$$

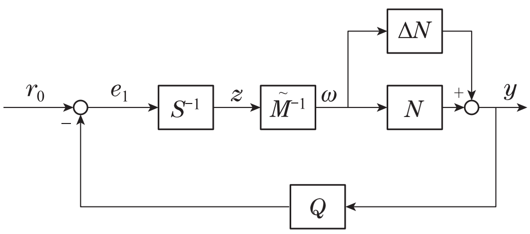

Fig. 8 Tracking control based on dual Bezout

Then, Fig. 9 is obtained, which is equivalent to Fig. 8.

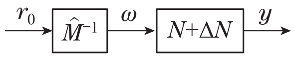

Fig. 9 The equivalent system of Fig. 8

Let

$$(N+\triangle N)\hat{M}^{-1}\to I, \tag{30}$$

then, from Fig. 8,

$$\begin{aligned}r_0(t)=Q(N+\Delta N)(\omega)(t)+S\tilde{M}(\omega)(t)=\\ \hat{M}(\omega)(t)\to(N+\Delta N)(\omega)(t)\to y(t).\end{aligned} \tag{31}$$

Through the above relationship, it is concluded that under the premise of robust stability of nonlinear feedback system, error signals are guaranteed that it get as close as possible to zero using the designed robust tracking controllers Q and S.

4 Simulation

In this section, a simulation for micro-hand with uncertainties and external disturbances will be given to verify the effectiveness of the proposed scheme.

However, there is a problem with the validation process: the shape of the bellows will change when the input pressure increases. In more detail, since the rubber radius r_a is changing during rubber inflation and expansion, it is very difficult to design the compensator H^{-1}. Hence, the identification of r_a based on RLS method is carried out [20].

It is clear from Table 2 and Fig. 10 that the data has convergence. In detail, as the amount of data increases, the accuracy of parameter estimation will be higher. Finally, $r_a=1.0701\times10^{-3}$ (m) with $\sigma^2=0.05^2$ are chosen as the estimated radius when designing some controllers that include r_a.

Table 2 The RLS estimates and errors of model parameter.

σ^2	t	r_a	δ/%
0.05^2	150	0.0010603	1.35485
	300	0.0010642	1.01493
	450	0.0010662	0.83048
	600	0.0010672	0.71460
	800	0.0010693	0.54717
	950	0.0010701	0.43285
0.10^2	150	0.0010442	2.87612
	300	0.0010502	2.29774
	450	0.0010533	2.01108
	600	0.0010554	1.85508
	800	0.0010573	1.65614
	950	0.0010585	1.52935
0.50^2	150	0.0009904	7.87537
	300	0.0010301	4.18324
	450	0.0010364	3.63212
	600	0.0010387	3.35903
	800	0.0010416	3.08605
	950	0.0010437	2.92723
Actual value		0.0010750	

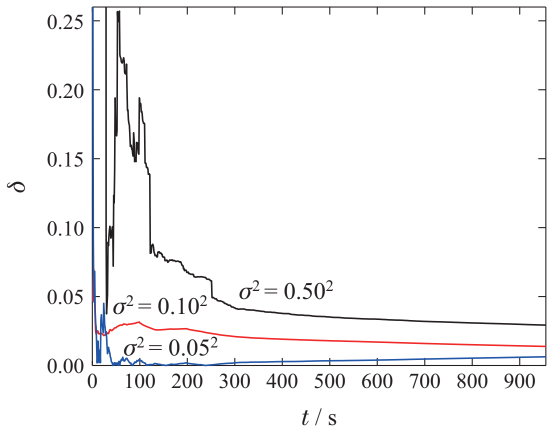

Fig. 10 Identification parameter error of r_a under different noises

According to (29)–(30), the related parameters are chosen to be $\zeta = 0.6, K = 0.67$ and the reference input $r_0 = 2.5 - \dfrac{1}{1+\mathrm{e}^{-0.48t+40\times3}} + \dfrac{1}{2(1+\mathrm{e}^{-0.48t+80\times3})} - \dfrac{1}{1+\mathrm{e}^{-0.48t+120\times3}}$ (rad). The structural and adjustment parameters are shown in Table 3 and the simulation results are as follows.

Table 3 Parameters of the simulation

Parameter	Size
Radius of the actuator	$a = 1\times10^{-3}$ m
Thickness of the actuator	$b = 0.15\times10^{-3}$ m
Natural length of the actuator	$L_0 = 1.35\times10^{-2}$ m
Initial Young modulus	$E_0 = 3\times10^{6}$ kPa
Design parameter	$\alpha = 0.5$
Design parameter	$\beta = 0.5$
Design parameter	$\eta = 0.1$

Fig. 11 shows the angular position tracking of flexible actuator. For the convenience of observation, the simulation running time is set to 100 s, and the error result is shown in Fig. 12. According to Fig. 12, it can be clearly seen that the tracking error is within acceptable limits, and it is close to zero within the range of ± 0.5. In order to verify the superiority of the tracking method based on dual Bezout, the angular position tracking by RRCF is shown in Fig. 13. By contrast, the RRCF tracking method has a big error between the reference input and the output while the tracking method based on dual Bezout realizes perfect tracking performance. These simulation results illustrate that the robust tracking control scheme based on dual Bezout method realizes the accurate tracking of plant output. Further, the tracking error of micro-hand using this method can maintain high accuracy and also ensure the robustness of the micro-hand system. The passivity performance for micro-hand system shown in Fig. 14.

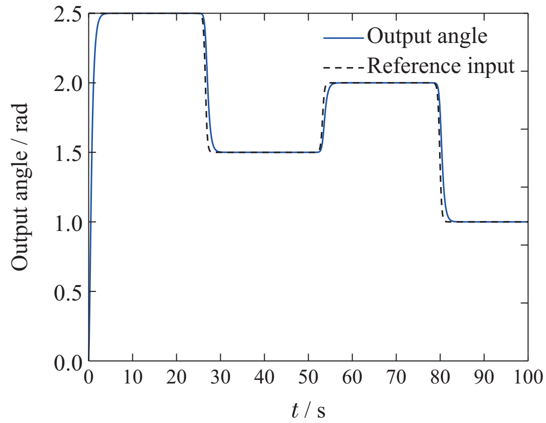

Fig. 11 The position tracking based on dual Bezout

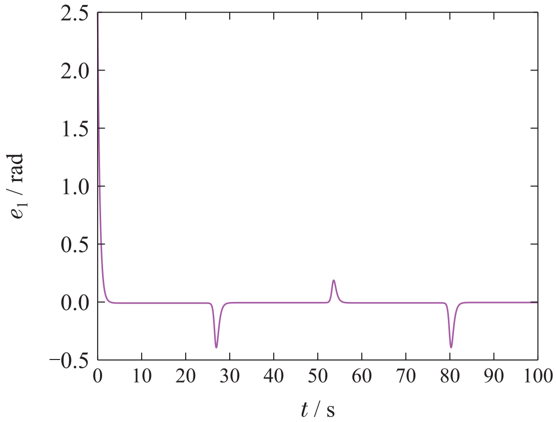

Fig. 12 The tracking control error e_1

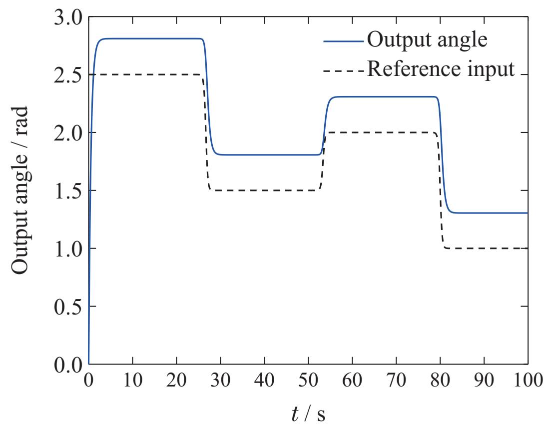

Fig. 13 The position tracking by RRCF

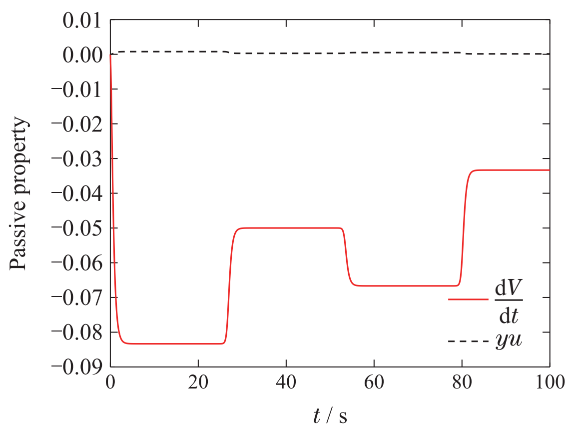

Fig. 14 Passivity performance

5 Conclusion and future work

In this paper, using operator-based RRCF, the robustness and passivity of the micro-hand system are guaranteed by designing the improved robust controllers. Then, the tracking controller is designed in combination with the dual Bezout identity, which make the influence of the disturbance of the system as small as possible under the premise of ensuring the stability of the system, and makes the system have perfect tracking performance.

Due to the nature of rubber tube, there will be time-delay and hysteresis in the process of inflating, which will not be ignored in our future research work.

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作者简介:

步 妮 博士, 目前研究方向为软体机器手系统设计、非线性系统控制与设计, E-mail: bunihan@qust.edu.cn;

李小永 硕士研究生, 目前研究方向为非线性系统控制与设计, E-mail: lxy357515790@163.com;

张玉义 硕士研究生, 目前研究方向为非线性系统控制与设计, E-mail: qustzyy@163.com.