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ROBUST CONTROL DESIGN OF A ROBOT ARM-AND-HAND SYSTEM USING ROBUST RIGHT COPRIME FACTORIZATION APPROACH

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Abstract. *This work focuses on robust nonlinear control design of a robot arm-and-hand system by using robust right coprime factorization (RRCF) approach. In detail, to control the precise endpoint position of robot arm and obtain the desired force using micro-hand according to the external environment or task involved, a double-loop feedback control architecture based on RRCF approach is proposed. In inner-loop feedback control scheme, to control the angular position of the robot arm, the operator controllers and the tracking controller are designed, and the robust stability and tracking conditions are derived based on RRCF approach. The stable inner-loop is considered as a right factorization, a new robust control scheme using RRCF approach is presented to control the micro-hand force, and the robust tracking conditions are also discussed. Finally, the effectiveness of the proposed control system is verified by simulation results.*
Keywords: Robot arm, Micro-hand, Robust right coprime factorization, Robust nonlinear control

1. Introduction.

The high quality and rapidity requirements in production systems of modern industrial plants demand a wide variety of dexterous robot arms [1]. As far as we know, the robot arm dynamics is highly nonlinear and difficult to model which limits the performance of model based control methods. In addition to these modelling errors, external disturbances are inevitable in real situations. These disturbances also degrade the control performance. Therefore, the controller should have a robust capability to achieve the desired motion under the above circumstances. Till now, robust analysis and output tracking problem in the development of dexterous robot arms still attract the researcher's attention due to the importance in real applications.

Some approaches, such as disturbance observer and approximation of model, have been proposed to develop controllers that are more robust so that their performance is not sensitive to modelling errors and robust control. However, the disturbance observer is usually designed based on the state space to compensate the disturbances. Due to high-dimensional state space in the complex robot arm system, it is difficult to obtain the desired performance. Therefore, how to eliminate and reduce the effect of uncertainties is still a challenge issue [2].

Moreover, when robot hands interact directly with humans, safety becomes a major consideration. Such machines must meet the essential requirements of safety, conveniency, versatility and adaptability to specific tasks. To satisfy these requirements, actuators should be safe, reliable, and light, and can be readily integrated in the system. Smart materials-based actuators have the following characteristics: large strain and stress induced electrically, light in weight, small and simple mechanisms, small electric consumption, and low drive voltage, etc., and have many applications in developments of miniature robots and biomedical devices [3]. Especially, soft actuators driven by pneumatic pressure are promising actuators for mechanical systems in medical, biological, agriculture, and welfare fields, because they can ensure high safety for fragile objects with low mechanical impedance. The soft pneumatic rubber actuator has typical advantages over the conventional electric actuators because of simple structures, high compliance, high-efficiency, and high power/weight ratio, and thus leads to many potential applications as an actuation component for mechanical systems in medical, human-support/human-care robots, micromanipulation, and inspection in narrow space. In spite of the high expectations and interests, the research in the field of pneumatic soft actuators is still in an early stage, and it requires radically new approaches for significant breakthroughs of morphological computation, nonlinear analysis and modelling, precise position and force control, etc.

Addressing the above problems, and also for the purpose of real application, an operator-based robust nonlinear control design for a robot arm by using robust right coprime factorization (RRCF) approach has been proposed in [3], and it is based on input output spaces. It is well known that RRCF approach has been a promising approach for analysis, design, stabilization and control of nonlinear system with disturbances and model uncertainties. Especially, the RRCF approach has attracted much attention due to its convenient in researching input-output stability problems of nonlinear system with uncertainties [4]. Moreover, the characteristics analysis and modelling of a miniature pneumatic curling soft (MPCS) actuator have been investigated in [5,6].

Motivated by the aforementioned challenges, this paper investigates the robust nonlinear control of a robot arm-and-hand system using RRCF approach. The micro-hand with three fingers made up of MPCS actuators is designed in the endpoint of the robot arm. For the proposed control scheme, the control system and controller design are analysed, and the robust stability and tracking performance are investigated. Finally, the realization of the control system is discussed, and the effectiveness of the proposed control scheme is verified by simulation results.

The outline of this paper is organized as follows. In Section 2, preliminaries and problem statement are described. Robust nonlinear control design for a robot arm with micro-hand is investigated in Section 3. The simulation and experimental results are shown in Section 4, and Section 5 is the conclusion.

2. Preliminaries and Problem Statement.

2.1. Robot arm.

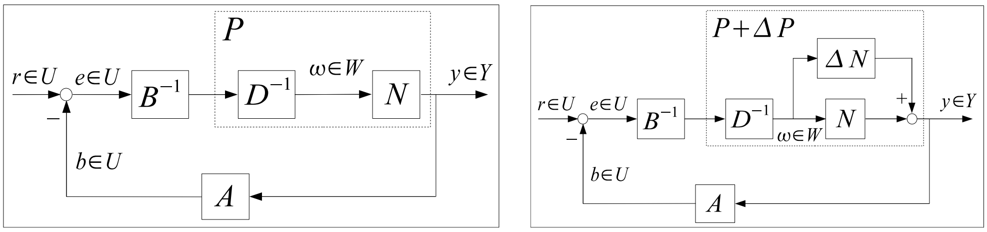
The two-link rigid robot arm dynamics in the horizontal plane is generally modeled by the following second-order nonlinear differential equation [1],

$$\mathbf{M}(\theta)\ddot{\theta} + \mathbf{H}\left(\dot{\theta}, \theta\right) = \tau \tag{1}$$

where, θ, $\dot{\theta}$, and $\ddot{\theta}$ denote angular position, velocity and acceleration vectors, respectively, and $\theta = (\theta_1, \theta_2)^T$, $\theta_i(t)$ $(i = 1, 2)$ is the joint angle of link i. $\tau = (\tau_1, \tau_2)^T$, $\tau_i(t)$ $(i = 1, 2)$ is the control input torque of link i. It is assumed that the first joint driving torque, τ_1, acts between the base and link 1, and that the second joint driving torque, τ_2, acts between links 1 and 2. $\mathbf{M}$ and $\mathbf{H}$ denote the inertial matrix (2×2) and Coriolis-Centrifugal force vector, respectively, and

$$\mathbf{M} = \begin{bmatrix} Z_1 + 2Z_2\cos\theta_2 & Z_3 + Z_2\cos\theta_2 \\ Z_3 + Z_2\cos\theta_2 & Z_3 \end{bmatrix}, \ \mathbf{H} = \begin{bmatrix} -Z_2\sin\theta_2\left(\dot{\theta}_2^{\ 2} + 2\dot{\theta}_1\dot{\theta}_2\right) \\ Z_2\dot{\theta}_1^{\ 2}\sin\theta_2 \end{bmatrix} \tag{2}$$

where, $Z_1 = m_1 l_{g1}^2 + m_2\left(l_1^2 + l_{g2}^2\right) + I_1 + I_2$, $Z_2 = m_2 l_1 l_{g2}$, $Z_3 = m_2 l_{g2}^2 + I_2$. m_i $(i = 1, 2)$ denotes the masses of link i, l_{gi} $(i = 1, 2)$ denotes the distance between joint i and the center of mass of link i, I_i denotes the moment of inertia of link i with respect to the



(a) (b)

Figure 1. RRCF-based feedback system: (a) without uncertainties, (b) with uncertainties

center of mass, and l_i ($i = 1, 2$) denotes the length of link i. Z_1, Z_2 and Z_3 are the structural parameters which denote the physical features of the robot arm.

2.2. **Operator-based robust right coprime factorization.** The operator based nonlinear feedback control systems are shown in Figure 1, where $\mathbf{U}$ and $\mathbf{Y}$ are used to denote the input space and output space of a given plant operator P, respectively, i.e., $P : \mathbf{U} \to \mathbf{Y}$. P is nominal plant, ΔP is unknown bounded uncertainties, and $P + \Delta P$ is the real plant. In the operator based control system shown in Figure 1, the right factorization, right coprime factorization, and RRCF were defined as follows, respectively.

Definition 2.1. *The given plant operator $P : \mathbf{U} \to \mathbf{Y}$ is said to have a* **right factorization**, *if there exist a linear space $\mathbf{W}$ and two stable operators $D : \mathbf{W} \to \mathbf{U}$ and $N : \mathbf{W} \to \mathbf{Y}$ such that $P = ND^{-1}$ where D is invertible. Such a factorization of P is denoted by (N, D) and $\mathbf{W}$ is called a quasi-state space of P. The factorization is said to be coprime, or P is said to have a* **right coprime factorization** *in Figure 1(a), if there exist two stable operators $A : \mathbf{Y} \to \mathbf{U}$ and $B : \mathbf{U} \to \mathbf{U}$, satisfying the Bezout identity*

$$AN + BD = T, \quad \text{for some } T \in u(W, U) \tag{3}$$

Generally speaking, for the corresponding control system with uncertainties, let the Bezout identity of the nominal process and the real process be $AN + BD = M \in u(W, U)$, $A(N + \Delta N) + BD = \tilde{M}$, respectively. If

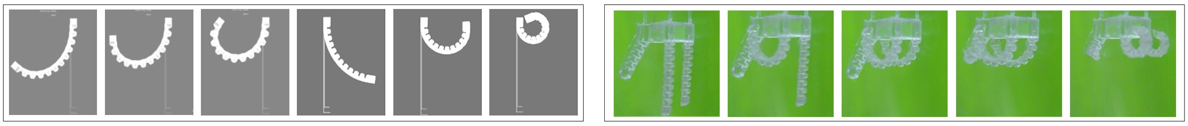
$$\|(A(N + \Delta N) - AN)M^{-1}\| < 1 \tag{4}$$

then the system shown in Figure 1(b) is BIBO stable, and is called **robust right coprime factorization**.

It is worth mentioning that the initial state should also be considered, that is, $AN(\omega_0, t_0) + BD(\omega_0, t_0) = M(\omega_0, t_0)$ should be satisfied. In this paper, $t_0 = 0$ and $\omega_0 = 0$ are selected.

2.3. **Soft micro-hand with three fingers.** Generally, mechanical systems consist of most of rigid components made from metallic materials and these rigid mechanisms strongly support industrial activities. On the other hand, soft actuators are key devices in soft mechanisms because they relate directly to contacting or manipulating such objects physically. In this paper, a typical MPCS actuator made from silicone rubber is used. It bends like a flexible micro-actuator but its structure is simpler than that of the flexible micro-actuator. It consists of one chamber and one air-supply tube and can generate curling motion in two directions under different positive and negative pressures. Figure 2(a) shows bidirectional motion of a MPCS actuator in different positive and negative pressures.

In this paper, three fingers of the soft micro-hand are fabricated by three MPCS actuators. Lengths of the three fingers are designed based on human fingers, namely, the first (thumb), the second (index) and the third (middle) fingers are 7.6mm, 11.2mm, 12.4mm, respectively. The second and third fingers are arranged in parallel, and the first finger is



(a) (b)

FIGURE 2. Motion demonstration: (a) MPCS actuator (b) micro-hand

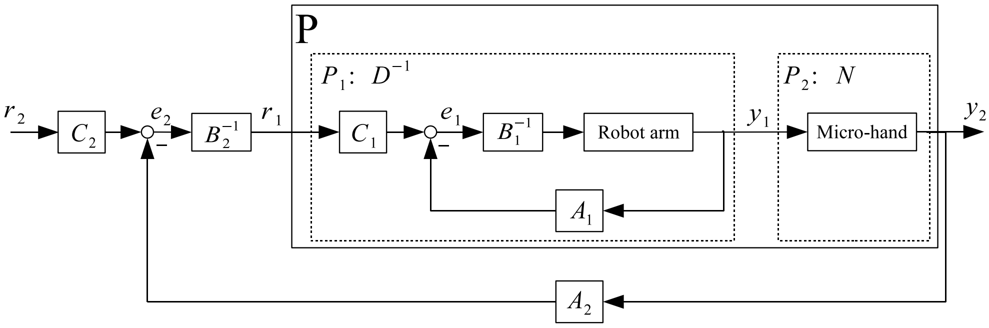


FIGURE 3. The proposed robust nonlinear tracking control system

set at an angle of 30° to the other two fingers. The developed soft micro-hand can be used to carry out handling demonstration tasks, such as opening and closing motions because the MPCS actuators can generate bidirectional bending, and experimental motions are shown in Figure 2(b).

2.4. **Problem statement.** The objective of this paper is to investigate the robust nonlinear control issue of a robot arm-and-hand system by using RRCF approach. We can control both the endpoint position of the robot arm and the force of each finger of the micro-hand to generate desired force to perform various actions. In the proposed control system, a new type of typical MPCS actuator which can generate bidirectional curling motions in two directions under different positive and negative pressures is used to build a micro-hand with three fingers. For the robot arm-and-hand system, factorizing this complex process and design operator controllers to guarantee the robust stability and perform output tracking are investigated, and the effectiveness verifications are also discussed.

3. **Robust Nonlinear Tracking Control System Design.** The proposed robust nonlinear tracking control system of the robot arm-and-hand system by using RRCF approach is shown in Figure 3, where the components, including the robot arm, the micro-hand with three fingers, the operator controllers A_1, B_1, A_2, B_2, and the operator tracking controllers C_1, C_2 are connected. $r_1 = (\theta_{1d}, \theta_{2d})$ and $y_1 = (\theta_1, \theta_2)$ are the reference inputs and the plant outputs of angular positions in the robot arm movement, respectively. $r_2 = (F_{1d}, F_{2d}, F_{3d})$ and $y_2 = (F_1, F_2, F_3)$ are the reference force inputs and outputs of three fingers, respectively. **For the inner-loop feedback control system, the controllers A_1, B_1, and C_1 are designed based on the former research results in [3].** In the following sections, the controllers A_2, B_2, and C_2 design, the system robustness analysis, and the tracking conditions analysis will be explained in detail.

Soft pneumatic actuators are generally known as pneumatic artificial muscles, and a number of geometric configurations have been developed over years. Essentially, in order to control precise force using the present MPCS actuator, the deformation of rubber in MPCS actuator caused by different pressure should be clear. However, it is difficult to predict the deformation of rubber in MPCS actuator by the pressure with high accuracy. That is to say, all areas of rubber of MPCS actuator cannot maintain the same shape and state perfectly during actual operations like fabrication and driving. In terms of this phenomenon, in this research, all areas of rubber are assumed to maintain the same shape and state perfectly during motions. Specifically, the model relationship between output force and input pressure is identified by experimental data.

The force that a MPCR actuator exerts depends on the pressure. For a MPCR actuator, the identified results show that the relationship between output force and input pressure is almost linear for positive and negative pressure, respectively. This paper defines a new model with uncertainties to describe the relationship between the force and input pressure,

$$\begin{aligned} y_2(t) &= P_2(u_2)(t) \\ &= \frac{1}{2}((\alpha_1+\Delta_1)(1+sgn(u_2(t)))u_2(t)+(\alpha_2+\Delta_2)(1-sgn(u_2(t)))u_2(t)) \end{aligned} \tag{5}$$

where $u_2(t)$ and $y_2(t)$ are the control pressure input and the force output, respectively. α_1 and α_2 are two identified constants, Δ_1 and Δ_2 are unknown and bounded uncertainties, and sgn$(\cdot)$ is a sign function.

For the micro-hand with three soft fingers in the presence of model uncertainties, the overall plant is defined as $\tilde{P}_2 = \left(\tilde{P}_{21}, \tilde{P}_{22}, \tilde{P}_{23}\right)$, which includes two parts, the nominal plant $P_2 = (P_{21}, P_{22}, P_{23})$ and the uncertain plant $\Delta P_2 = (\Delta P_{21}, \Delta P_{22}, \Delta P_{23})$, namely, $\tilde{P}_2 = P_2 + \Delta P_2$. The nominal plant P_2 and the overall plant $\tilde{P}_2$ are assumed to have right factorizations as $P_{2i} = N_{2i}D_{2i}^{-1}$ $(i = 1, 2, 3)$ and $\tilde{P}_{2i} = P_{2i} + \Delta P_{2i} = (N_{2i} + \Delta N_{2i})\, D_{2i}^{-1}$ $(i = 1, 2, 3)$, respectively, N_{2i}, ΔN_{2i}, and D_{2i} $(i = 1, 2, 3)$ are stable operators, D_{2i} is invertible, and ΔN_{2i} is unknown but the upper and lower boundaries are known. Obviously, there are no the coupling effects among the three fingers. For the soft micro-hand, the right factorizations D_2 and N_2 of the three fingers dynamics in (5) are shown as,

$$D_{2i}(\omega_2)(t) = \omega_2(t), \quad i = 1, 2, 3 \tag{6}$$

$$N_{2i}(\omega_2)(t) = \frac{1}{2}\left((1+sgn(\omega_2(t)))\alpha_{i1} + (1-sgn(\omega_2(t)))\alpha_{i2}\right)(\omega_2)(t), \quad i = 1, 2, 3 \tag{7}$$

where the operators D_{2i} and N_{2i} are stable, and D_{2i} is invertible, α_{i1} and α_{i2} $(i = 1, 2, 3)$ are the corresponding model parameters of the ith finger of the micro-hand.

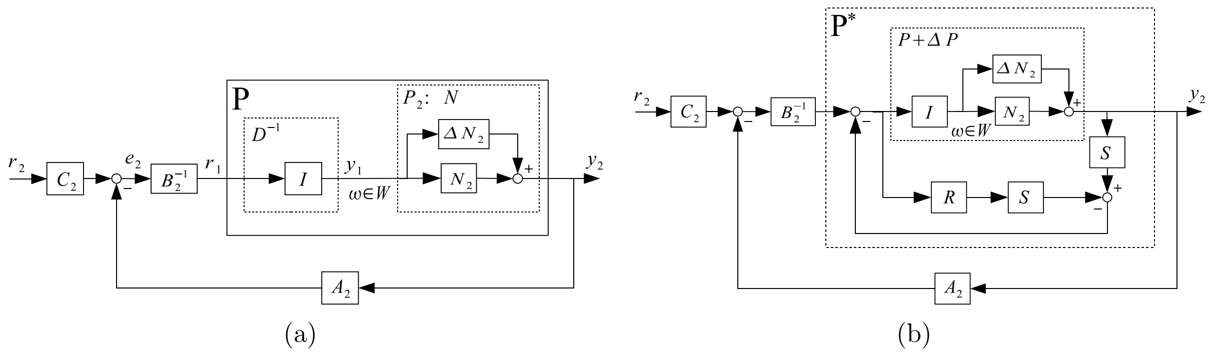


FIGURE 4. (a) The equivalent block diagram of Figure 3, (b) the proposed robust perfect tracking control scheme

Based on the above results, namely, the output y_1 tracks the reference input r_1, and the equivalent block diagram of Figure 3 is given in Figure 4(a). For the new equivalent plant P, the right factorizations N, ΔN, and D are defined as,

$$D_i(\omega)(t) = \omega(t), \quad i = 1, 2, 3 \tag{8}$$

$$N_i(\omega)(t) = \frac{1}{2}\left((1+sgn(\omega(t)))\alpha_{i1} + (1-sgn(\omega(t)))\alpha_{i2}\right)(\omega)(t), \quad i = 1, 2, 3 \tag{9}$$

$$\Delta N_i(\omega)(t) = \frac{1}{2}\left((1 + sgn(\omega(t)))\Delta_{i1} + (1 - sgn(\omega(t)))\Delta_{i2}\right)(\omega)(t), \quad i = 1, 2, 3 \tag{10}$$

where Δ_{i1} and Δ_{i2} ($i = 1, 2, 3$) are the corresponding model parameters of the ith finger of the micro-hand. The operator controller $A_2(y_2)(t)$ and $B_2^{-1}(e_2)(t)$ are defined as

$$A_2(y_2)(t) = \beta y_2(t) \tag{11}$$

$$B_2^{-1}(e_2)(t) = \frac{1}{2(1-\beta)}\left(\frac{1 + sgn(e_2(t))}{\alpha_1} + \frac{1 - sgn(e_2(t))}{\alpha_2}\right)e_2(t) \tag{12}$$

where β is the designed parameter, and $\beta \in (2, 3)$. Based on the defined right factorizations N and D, and the operator controllers A_2 and B_2, we have

$$A_{2i}N_i + B_{2i}D_i = \alpha_{1i}\omega(t) \text{ or } \alpha_{2i}\omega(t) \in u(W, U), \quad i = 1, 2, 3 \tag{13}$$

and $\alpha_{1i}\omega(t)$ or $\alpha_{2i}\omega(t)$ are unimodular operators. Moreover, because there are no coupling effects between the fingers,

$$A_{2i}(N_i + \Delta N_i) + B_{2i}D_i = (1 + \Delta_{i1})\omega_i(t) \text{ or } (1 + \Delta_{i2})\omega_i(t) \in u(W, U), \quad i = 1, 2, 3 \tag{14}$$

are also unimodular operators, and

$$\|A_{2i}(N_i + \Delta N_i) - A_{2i}N_i\| = \beta\Delta_{i1} \text{ or } \beta\Delta_{i2}, \quad i = 1, 2, 3 \tag{15}$$

where, Δ_{i1} and Δ_{i2} are identified based on the experimental data using model (5). We can make $\Delta_{i1} \ll 0.1$ and $\Delta_{i2} \ll 0.1$, or even less by improving the identification method. Moreover, since $\beta \in (2, 3)$, thus $\|A_{2i}\,(N_i + \Delta N_i) - A_{2i}N_i\| = \beta\Delta_{i1}$ or $\beta\Delta_{i2} < 1$, $i = 1, 2, 3$ is satisfied. Then, the BIBO stability of the nonlinear feedback control system with uncertainty shown in the feedback control part of Figure 4(a) is guaranteed.

Similarly, we can design the operator controller C_2 by using the proposed method in [3]. However, to further improve the tracking performance, a new robust tracking control scheme with uncertainties is designed for the robot arm with the micro-hand and is shown in Figure 4(b).

Lemma 3.1. *For the proposed robust perfect tracking control scheme with uncertainties shown in Figure 4(b), if*

$$S = N_2 \text{ and } RP = I \tag{16}$$

then the new equivalent plant $P^* = P$, and the effect of uncertainties is compensated, where, I is an identity operator [7]. Based on this lemma, for the proposed control scheme in Figure 4(b), the following theorem can be derived.

Theorem 3.1. *For the proposed robust nonlinear perfect tracking control scheme with uncertainties shown in Figure 4(b), if*

$$A_2N_2 + B_2 = T \in u(W, U) \text{ and } N_2T^{-1}C_2 = I \tag{17}$$

then the conditions of robust stability and perfect tracking can be guaranteed.

Proof: Based on the robust stability condition in (3), we find that the robust stability can be guaranteed if (17) is satisfied. According to the conditions in Lemma 3.1, namely, the equivalent $P^* = P$, then, $y_2(t) = N_2(\omega)(t) = N_2(A_2N_2 + B_2I)^{-1}C_2(r_2)(t) = N_2T^{-1}C_2(r_2)(t) = I(r_2)(t) = r_2(t)$, and the plant output $y_2(t)$ tracks the reference input $r_2(t)$.

Based on Theorem 3.1, the operator observers S and R are defined as

$$S(y_2)(t) = \frac{1}{2}\left((1 + sgn(y_2(t)))\alpha_1 + (1 - sgn(y_2(t)))\alpha_2\right)(y_2)(t), \quad i = 1, 2, 3 \tag{18}$$

$$R(u)(t) = \frac{1}{2}\left(\frac{1 + sgn(u(t))}{\alpha_1} + \frac{1 - sgn(u(t))}{\alpha_2}\right)(u)(t) \tag{19}$$

Based on the defined A_2, N_2, and B_2, $A_{2i}N_i + B_{2i} = \alpha_{1i}\omega(t)$ or $\alpha_{2i}\omega(t) \in u(W, U)$, $i = 1, 2, 3$ can be obtained. Moreover, the operator tracking controller C_2 is defined as

$$C_2(r_2)(t) = I(r_2)(t) \tag{20}$$

and, $N_2T^{-1}C_2 = I$ is obtained, the conditions of robust stability and perfect tracking can be guaranteed.

4. **Simulation.** To illustrate the effectiveness of proposed method, some simulation results are given in this section. For the robot arm, the physical and structural parameters are considered to be $l_1 = 0.29(\mathrm{m})$, $l_2 = 0.34(\mathrm{m})$, $Z_1 = 0.4507$, $Z_2 = 0.1575$, and $Z_3 = 0.1530$, respectively. So far, the nominal model of the robot arm was introduced. However, in real control, it is difficult to obtain the real values of l_i, l_{gi} and m_i, namely, the real value of structure parameters Z_i is unknown. So, in the simulation, the uncertainties of structural parameters of the robot arm are considered to be $Z_i = Z_i^* \pm \Delta Z_i^*$, $\Delta = 0.5$, where Z_i^* is assumed to be real value. Moreover, the disturbances are considered to be $\tau_d = 0.5 + 0.05 * \sin(100\pi t)$. The effect of structural uncertainties and disturbances is summarized into ΔN. In the simulation, the initial conditions are $\dot{\theta}(0) = \left(\dot{\theta}_1(0), \dot{\theta}_2(0)\right)^T = (0, 0)^T$ and $\ddot{\theta}(0) = \left(\ddot{\theta}_1(0), \ddot{\theta}_2(0)\right)^T = (0, 0)^T$. Here, a complicated desired trajectory $y_d = \frac{\tanh(20*(0.3-x_d)+0.7)+1}{4}$, $0 \le x_d \le 0.6$ and $y_d \ge 0$ is given,

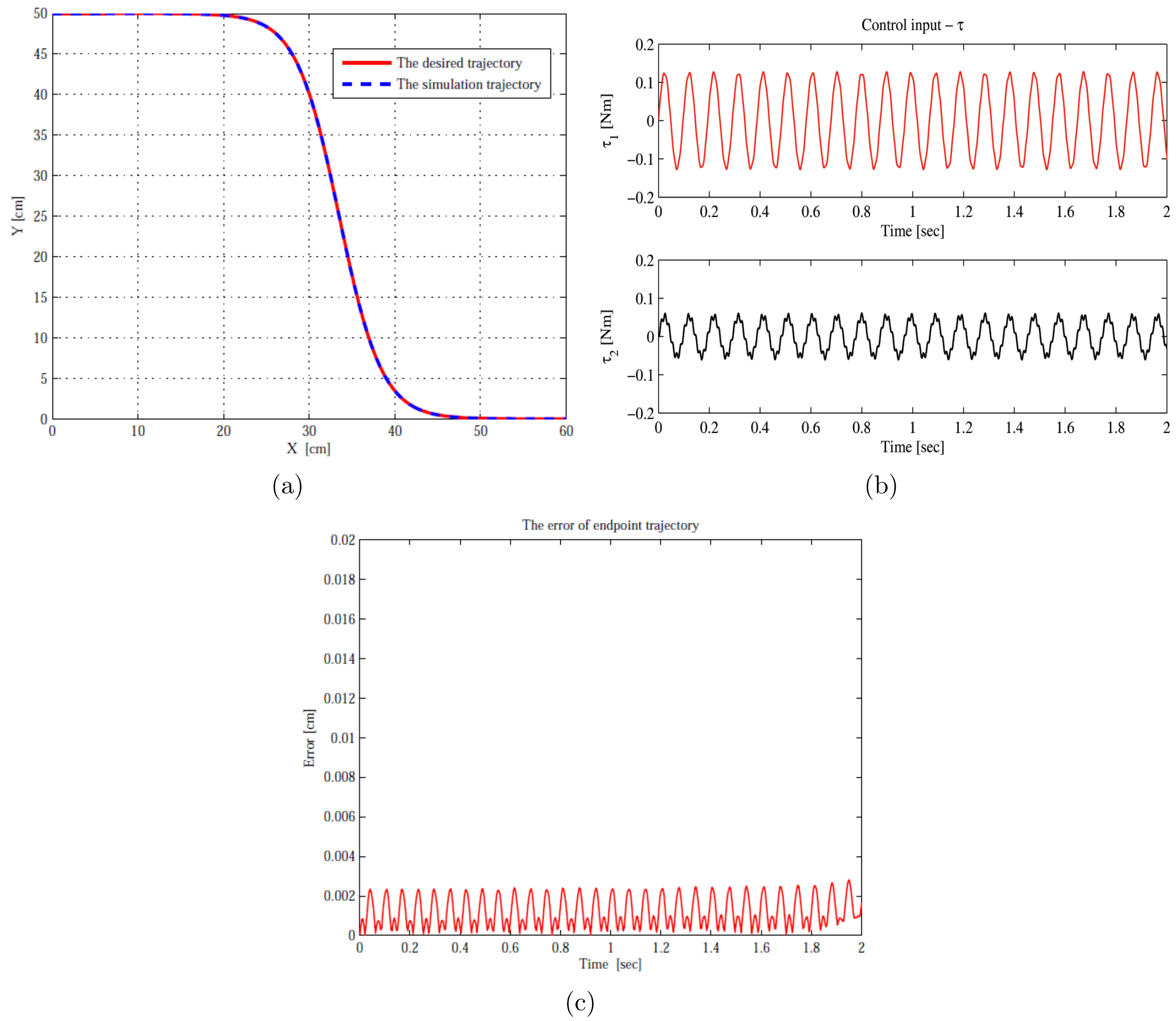


FIGURE 5. The simulation results of robot arm: (a) tracking, (b) control input, (c) error

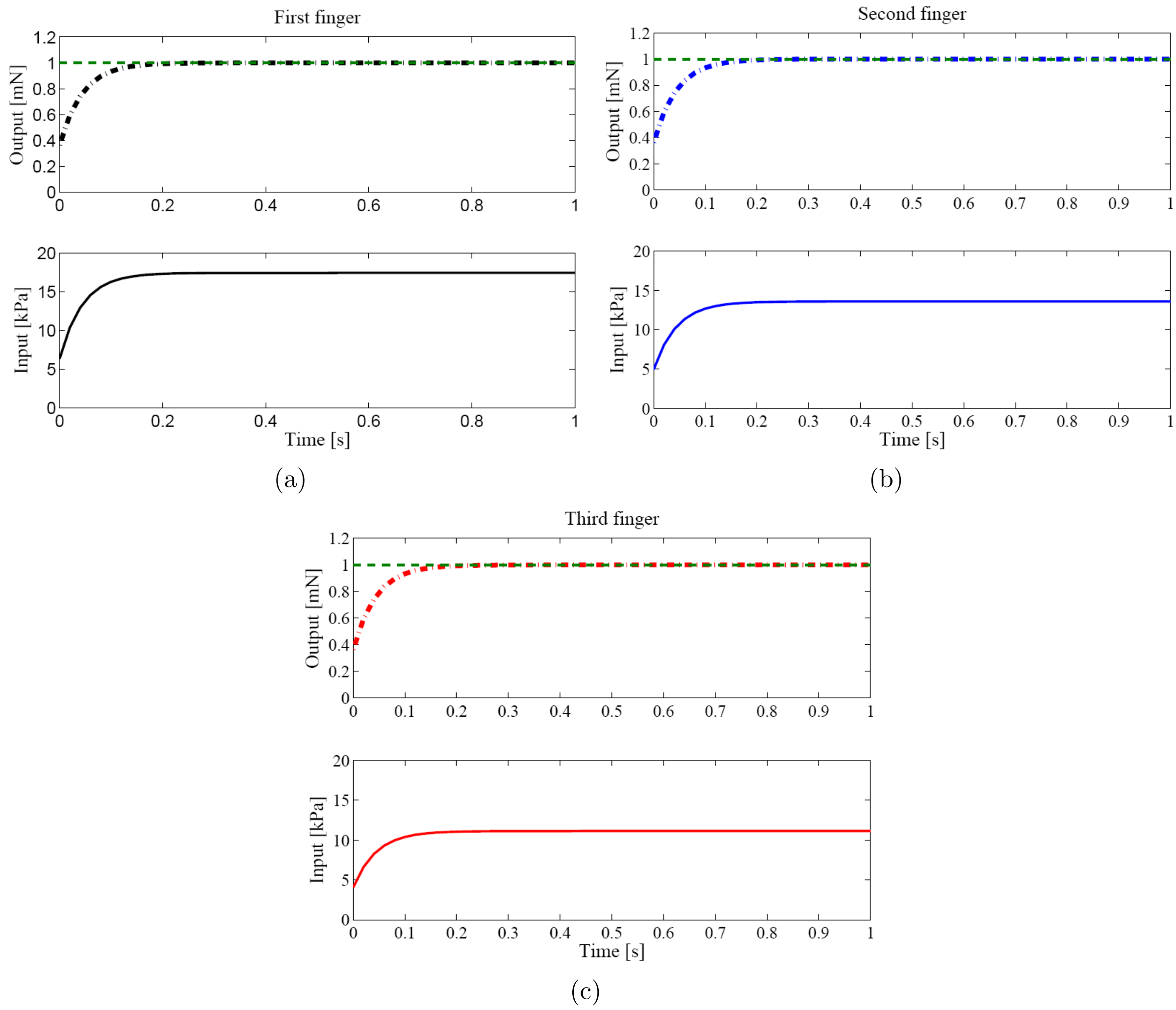


FIGURE 6. The force tracking results: (a) first finger, (b) second finger, (c) third finger

where, $\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$, and moves from the start position $(x_d, y_d) = (0, 0.5)(m)$ to the end position $(x_d, y_d) = (0.6, 0)(m)$. Figure 5(a) shows the tracking result of endpoint position based on the proposed method, Figure 5(b) shows the input torques τ_1, and τ_2, respectively, and the tracking error of endpoint trajectory is shown in Figure 5(c). From Figure 6, we can find that the simulated trajectory (x, y) tracks the desired trajectory (x_d, y_d), namely, y_1 can track r_1 in proposed control system shown in Figure 3.

Based on the former designed experimental setup in [5], the force characteristics of three MPCS actuators are measured, separately, where, the force response of every MPCS actuator is measured fifty times. In each time, a sequence of pressure values are monotonically form −16kPa to 40kPa, the step is 1kPa, and every pressure is held for 2 seconds to guarantee the actuator to reach the steady-state, which makes sure that the effects of others dynamics are eliminated or minimized. Based on the obtained fifty group data information of every actuator, the relationship between output force and input pressure of fingers in micro-hand consisting of first finger, second finger, and third finger are identified, respectively, and the identified model parameters of three fingers in (5) are: the first finger: $\alpha_{11} = 0.057468$, $\alpha_{12} = -0.034316$, the second finger: $\alpha_{21} = 0.073618$ and $\alpha_{22} = -0.043959$, and the third finger: $\alpha_{31} = 0.090054$, $\alpha_{32} = -0.053773$.

In the force control system simulation of three fingers in micro-hand, the model uncertainties of each MPCS actuator are considered to be $\alpha_{i1} = \alpha_{i1}^* + \Delta_{i1}$, $\Delta_{i1} = 0.02$

$(i = 1, 2, 3)$, and $\alpha_{i2} = \alpha_{i2}^* + \Delta_{i2}$, $\Delta_{i2} = 0.02$, where α_{i1}^* and α_{i2}^* $(i = 1, 2, 3)$ are assumed to be real value. Moreover, the disturbance is considered to be $u_{2d} = 0.02 + 0.02 * \sin(2\pi t)$. The effect of parameter uncertainties and disturbances can also be summarized into ΔN. Based on the structure of three fingers in micro-hand, the three output forces of fingers must be the same to guarantee the equilibrium when performing various actions. Based on the proposed method, the output force of endpoint in the three actuators, and control pressure input simulation results are shown in Figures 6(a), 6(b), and 6(c), respectively. From Figure 6, we can find that the simulation force can track the desired reference input, the robust stability is guaranteed, and the effectiveness of the proposed control system can be confirmed by simulation results.

5. **Conclusion.** This paper has focused on the robust nonlinear tracking control of a robot arm-and-hand by using RRCF approach, the endpoint position of the robot arm can be controlled, and the three fingers of the micro-hand can generate the desired force to perform various actions. In this paper, first, the robust nonlinear tracking control scheme was designed by using operator-based RRCF approach. Second, the realizable operator controllers, operator-based observers, and tracking controllers were built, and the tracking performances were analysed. Finally, some simulation results to illustrate the presented concepts were given. The future work will develop a new model of the MPCS actuator with comprehensive physics knowledge including physical system derivation and the hysteresis properties.

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