Human-Like Robot Arm Robust Nonlinear Control Using a Bio-inspired Controller with Uncertain Properties

Yiping Chang, Aihui Wang(✉), Shengjun Wen, and Wudai Liao

School of Electronic Information, Zhongyuan University of Technology,
Zhengzhou, China
`a.wang@zut.edu.cn`

Abstract. This work focuses on a nonlinear robust control of a human arm-like robot arm by using a bio-inspired method based human arm musculoskeletal characteristics, mainly consisting of multi-joint viscosity and multi-joint stiffness. The multi-joint viscosity and multi-joint stiffness are used in designing a bio-inspired operator controller, and the time-varying on estimated human arm multi-joint viscoelasticity (HAMV) data is fed to the designed controller in simulation. Using the designed control architecture, the sufficient robust stable conditions are derived in the presence of uncertainties of modelling and measurement errors, and the control output tracking performance is also realized.

Keywords: HMJA viscoelasticity · Bio-inspired controller · RRCF approach · Robot arm control

1 Introduction

In the last 60 years, the robot arms have always played the some roles of "replacing" and "confronting" the human being, and been mainly focused on industrial fields. However, with the evolution of technology, applications of robot rams research have been broadened taking interest in not only to aiding humans in repetitive tasks, but aiding them in our everyday lives, medical rehabilitation, and social services [1], and these robot arms have always been inspired by the human or animal bodies [2]. Because there are many potential and practical applications, some robots with human arm-inspired motion characteristics which can perform actions smoothly and dexterous as the human arms are still a hot research point in both academic and industrial fields [3,4].

During the last decade, the bio-inspired robot arms have become more and more agile like the human multi-joint arm (HMJA) by measuring or capturing the HMJA motion and converting it to motion of the robot arm [5,6]. Studies on control strategis imitating the movement principle of HMJAs can be considered in developing some bio-inspired robot arms as the humans can control their HMJAs flexibly and robustly. Many concepts that describe the motion principle

F. Cong et al. (Eds.): ISNN 2017, Part II, LNCS 10262, pp. 3–10, 2017.
DOI: 10.1007/978-3-319-59081-3_1

of HMJA have been applied in the robot arms control, for example equilibrium-point control hypothesis, cost functions, and electromyography (EMG) signal-based methods. The various given trajectories can be obtained by using the optimal principles of the above methods based the learned and obtained information pairs in advance. However, in order to generate multifarious movement mode to the same movement assignment, the information pairs are needed to achieve online control. This is difficult in practice.

Assuming that the HMJA has a model similar to a regular connected robot arm, the mechanical properties of the HMJA musculoskeletal system can be mainly modelled by using a called HMJA viscoelasticity [7,8]. The HMJA viscoelasticity includes the multi-joint stiffness and the multi-joint viscosity, which are regulated by the central nervous system (CNS) to make the HMJA can move Arbitrarily to the external different environments or various movements (see Fig. 1). The HMJA viscoelasticity has been widely used in diseases diagnosis, vehicle driving system, and rehabilitation training fields by measuring viscoelastic properties of HMJA [9]. Similarly, if the viscoelastic properties during HMJA can be adapted effectively in the robot arm control, many skillful strategies of the HMJA may be embed into the robot arm control.

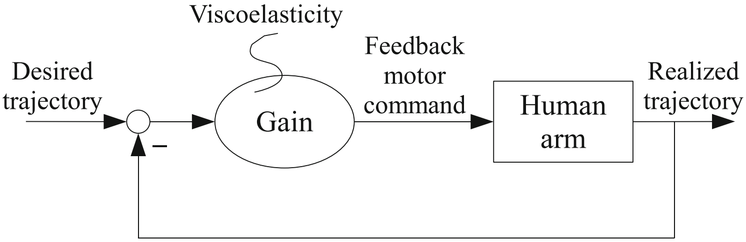


Fig. 1. A human motion control system

Moreover, there not only exist measurement errors from HMJA viscoelasticity estimating data, and but also the robot arms have highly nonlinear, disturbances and model uncertainties. Therefore, it is very difficult to achieve the robustness and output tracking performances. Address these issues, many approaches, such as, state or disturbance observer methods, Lyapunov-based methods, and cost function are used. However, the most existing approaches require that the controlled objects have the precise state space equations in designing a controller, whilst in many cases, the existing methods are used to obtain the approximation model based on a real system. To improve this question, and also for the practical application consideration, the operator-based robust right coprime factorisation (RRCF) approach [10] is becoming an effective and practicable method in linear or nonlinear control system analysis and design.

Addressing the existing challenges, the paper focus on a human-like robot arm robust nonlinear control using a bio-inspired controller with uncertain properties. We propose a new control approach that is inspired by the biological model of HMJA viscoelasticity. The bio-inspired controller is design by using HMJA viscoelastic properties, and there not only exist measurement uncertainties in HMJA viscoelasticity estimating. The objective is that the robot arm can perform a random wide variety of dexterous operations based on the remote motions by the human arm in unstructured environments. Addressing the designed control system, we will discuss the controller design, investigate the robustness and tracking performance.

2 Preliminaries

2.1 Robot Arm

The two-link robot arm dynamics can be modeled as [9],

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

where, θ is angular, and $\theta = (\theta_1, \theta_2)^T$, $\theta_i(t)$ (i = 1, 2) is the ith link joint angle. $\tau = (\tau_1, \tau_2)^T$, $\tau_i(t)$ is the ith link control input torque. $\mathbf{H}$ and $\mathbf{M}$ are the Coriolis-Centrifugal force vector and inertial matrix, and

$$\mathbf{M} = \begin{bmatrix} Z_1 + 2Z_2\cos\theta_2 & Z_3 + Z_2\cos\theta_2 \\ Z_3 + Z_2\cos\theta_2 & Z_3 \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} -Z_2\sin\theta_2(\dot{\theta_2}^2 + 2\dot{\theta}_1\dot{\theta}_2) \\ Z_2\dot{\theta_1}^2\sin\theta_2 \end{bmatrix} \tag{2}$$

where $Z_1 = m_1 l_{g1}^2 + m_2(l_1^2 + l_{g2}^2) + I_1 + I_2$, $Z_2 = m_2 l_1 l_{g2}$, and $Z_3 = m_2 l_{g2}^2 + I_2$ are the structural parameters.

2.2 Human Multi-joint Arm

Imitating the robot arm, the two-link HMJA dynamics can also be modeled,

$$\mathbf{M}_A(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{H}_A(\dot{\mathbf{q}}, \mathbf{q}) = \tau_A(\dot{\mathbf{q}}, \mathbf{q}, \mathbf{u}) \tag{3}$$

where, $\mathbf{q}$ is angular, and $\mathbf{q} = [\theta_s(t), \theta_e(t)]^T$, $\theta_s(t)$ is the shoulder joint angle and $\theta_e(t)$ is the elbow joint angle, the subscripts s and e denote the shoulder joint and the elbow joint, respectively. $\tau_A = [\tau_s, \tau_e]^T$ denote the multi-joint torque. $\mathbf{M}_A$ and $\mathbf{H}_A$ have the same definition and structure as $\mathbf{M}$ and $\mathbf{H}$ in (1).

From (3), we have,

$$\delta\tau_A = -\mathbf{R}_A(t)\delta\dot{\mathbf{q}} - \mathbf{K}_A(t)\delta\mathbf{q} + \frac{\partial\tau_A}{\partial\mathbf{u}}\delta\mathbf{u} \tag{4}$$

where, $\mathbf{R}_A(t)$ and $\mathbf{K}_A(t)$ represent human arm multi-joint viscosity and multi-joint stiffness, and

$$-\frac{\partial\tau_A}{\partial\dot{\mathbf{q}}} \equiv \mathbf{R}_A(t) = \begin{bmatrix} R_{A-ss} & R_{A-se} \\ R_{A-es} & R_{A-ee} \end{bmatrix}, \quad -\frac{\partial\tau_A}{\partial\mathbf{q}} \equiv \mathbf{K}_A(t) = \begin{bmatrix} K_{A-ss} & K_{A-se} \\ K_{A-es} & K_{A-ee} \end{bmatrix} \tag{5}$$

3 Control System Design and Analysis

The proposed control system based on HMJA viscoelastic properties is given in Fig. 2, where the component units, consisting of the robot arm dynamics $P+\Delta P$, the controller operator A, the bio-inspired controller operator B with measurement uncertainties ΔB, and the tracking controllers operator C are connected. $r = (\theta_{1d}, \theta_{2d})$ and $y = (\theta_1, \theta_2)$ are the control reference angular inputs and the plant control angular outputs.

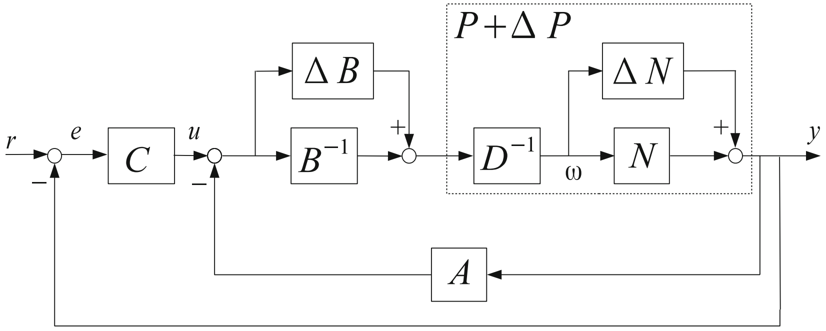


Fig. 2. The proposed robust nonlinear tracking control system

To control the robot arm joint angular, an robust nonlinear control architecture shown in Fig. 3 is designed firstly based operator-RRCF approach. For the robot arm dynamics with uncertainties, the operator model $\tilde{P} = (\tilde{P}_1, \tilde{P}_2)$, includes two parts, the nominal plant $P = (P_1, P_1)$ and the uncertain plant $\Delta P = (\Delta P_1, \Delta P_2)$, namely, $\tilde{P} = P + \Delta P$. The nominal plant P and the real plant $\tilde{P}$ are assumed to have right factorization as $P_i = N_i D_i^{-1}$ (i = 1, 2) and $\tilde{P}_i = P_i + \Delta P_i = (N_i + \Delta N_i) D_i^{-1}$ (i = 1, 2), respectively, N_i, ΔN_i, and D_i (i = 1, 2) are the stable operators, D_i is invertible, ΔN_i is unknown. Addressing the robot arm dynamic in (1), the right factorizations N_1 and D_1 can be modeled as

$$D_i(\omega)(t) = \mathbf{M}_i(\omega(t))\ddot{\omega}(t) + \mathbf{H}_i(\dot{\omega}(t), \omega(t)) \tag{6}$$

$$N_i(\omega)(t) = \omega(t) \tag{7}$$

For the proposed control architecture shown in Fig. 2, the controllers operator A, B, ΔB are designed controller operators to ensure the robustness and stability. B is a bio-inspired operator controller which is designed to obtain the expected motion mechanism of HMJA by using time-varying on estimating HMJA viscoelasticity. In order to satisfy that $T_i = A_i N_i + B_i D_i$ (i = 1, 2), the controller operator A is designed,

$$A(y)(t) = I(y)(t) \tag{8}$$

And the controller operator B is,

$$B^{-1}(s)(t) = -\mathbf{R}(t)\dot{e}_1(t) - \mathbf{K}(t)e_1(t) \tag{9}$$

here $\mathbf{R}(t)$, $\mathbf{K}(t)$ are the expected two-joint viscosity and two-joint stiffness, respectively, and which can be modelled and obtained by using the robot arm dynamic model, like Eqs. (4) and (5). Here, the two-joint viscosity $\mathbf{R}(t)$ and two-joint stiffness $\mathbf{K}(t)$ are replaced by the estimating viscoelasticity data $\mathbf{R}_A(t)$ and $\mathbf{K}_A(t)$ of a HMJA.

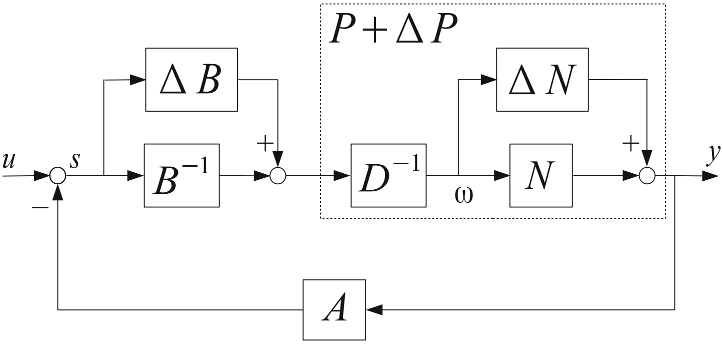


Fig. 3. The proposed robust control architecture

Based on the designed $N_i(\omega)(t)$, $D_i(\omega)(t)$, $A(y)(t)$ and $B^{-1}(s)(t)$, we can find

$$T_i = A_i N_i + B_i D_i = 2\omega(t) \tag{10}$$

is an unimodular operator. Addressing the designed control architecture in Fig. 2, if there does not exist measurement errors of HMJA viscoelasticity and conditon (10) is satisfied, and the robust stability is guaranteed [10]. However, there are the measurement errors or uncertainties of HMJA viscoelasticity, which usually can be described as ΔB. In order to ensure the system robustness and stability, a new condition related to ΔB is discussed.

Theorem 1. For the Fig. 3, the Bezout identity of the nominal model and the real model are $A_i N_i + B_i D_i = T_i \in u(W,U)$, $A_i(N_i + \Delta N_i) + (B_i + \Delta B_i)D_i = \hat{T}_i \in u(W,U)$, respectively. If

$$\left\| (\Delta N_i + \Delta B_i D_i) T_i^{-1} \right\| < 1, \quad i = 1,\ 2 \tag{11}$$

is satisfied, and the robustness and stability can be guaranteed.

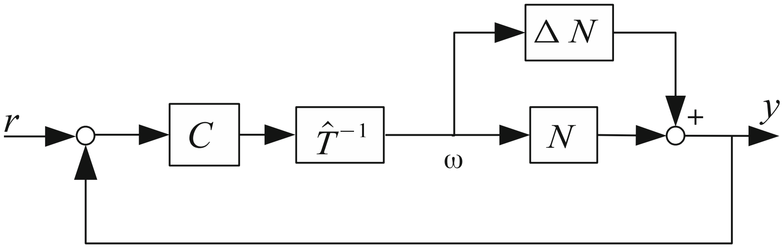


Fig. 4. The equivalent control architecture of Fig. 2

Based on the above condition (11), the robustness and stability can be guaranteed. However, the tracking performance does not be obtained. Based on the proposed conditions, the equivalent control architecture of Fig. 3 can be obtained and shown in Fig. 4. To obtained the control output tracking performance, an controller operator **C** is designed in the following condition, namely,

$$(N_i + \varDelta N_i)\hat{T}_i^{-1}\mathbf{C} = I \tag{12}$$

Namely, under (12), $N_i + \varDelta N_i + (B_i + \varDelta B_i)D_i = \hat{T}_i$ are unimodular operators, which implies that $y(t) = (N_i + \varDelta N_i)\ \hat{T}_i^{-1}\mathbf{C}r(t)$. Hence, the expected joint angular output y can track the given reference control input r under the condition $(N_i + \varDelta N_i)\hat{T}_i^{-1}\mathbf{C} = I$. However, because the $\varDelta N_i$ is unknown, and $\varDelta B_i$ has also uncertainties. Therefore, based on the condition of (12), we can not design directly the perfect tracking controller **C** in expected tracking control performance. SO, in the paper, we design a tracking controller C is to improve control tracking performance, it is,

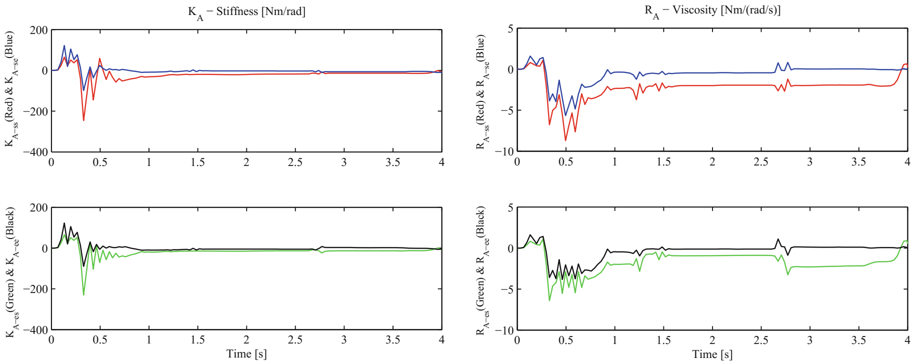
$$C = \varGamma_{\alpha i} e_i(t) + \varGamma_{\beta i} \int_0^t e_i(\tau) d\tau \tag{13}$$

where $\varGamma_{\alpha i},\ \varGamma_{\beta i})$ are the designed controller parameters.

4 Simulation Results

According to the presented HMJA viscoelasticity online estimating method in [11], the stiffness data and viscosity data of a multi-joint HMJA are measured in Fig. 5(a) and (b), where, the HMJA moves from the starting point $(x, y) =$ $[-41.7596, 33.8013]$ (cm) to the end point $(x, y) = [20.4489, 42.4762$ (cm).

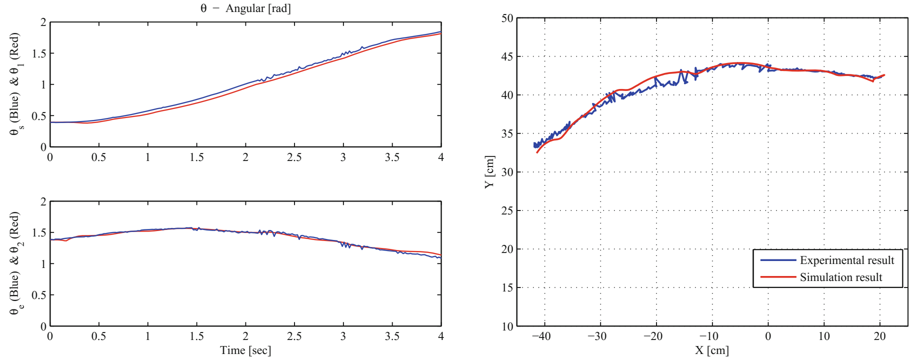
In control simulation, the controlled objet is assumed as a HMJA model, the expected movement trajectory is the above experimental path in estimating HMJA viscoelasticity. The measured HMJA multi-joint stiffness data and multi-joint viscosity data are fed to the controller operator B. The robot arm structural parameters uncertainties is to be $Z_i = Z_i^* + \varDelta Z_i$, $\varDelta = 0.05$, where Z_i^*



(a) (b)

Fig. 5. Measured experimental data: (a) Stiffness; (b) Viscoesity (Color figure online)

can be assumed to be real value. The unknown external disturbances are to be $\tau_d = 0.5 + 0.05 * sin(2\pi t)$. The effect of structural uncertainties and disturbances can be as ΔN. Moreover, the uncertainties of controller operator ΔB is be $\Delta B = \Delta B^* + \sigma \Delta B$, $\sigma = 0.05$, where ΔB^* can be assumed to be a real value. The control parameters are $K_{\alpha 1} = K_{\alpha 2} = 50$, and $K_{\beta 1} = K_{\beta 2} = 0.02$. Using the proposed architecture, the tracking simulation results consisting of joint angles movement and endpoint position motion of robot arm are shown in Fig. 6(a) and (b), respectively. From Fig. 6(a) and (b), the expected results can be achieved, namely robustness, stability, and tracking can be obtained.



(a) (b)

Fig. 6. Simulation results: (a) Angles; (b) Position (Color figure online)

5 Conclusions

This paper has investigated a robot arm robust nonlinear control by using a new bio-inspired method based on HMJA viscoelastic properties, the robot arm end-point position can be controlled by using the estimated online HMJA viscoelasticity. Based on operator-based RRCF theory, for the designed architecture, the sufficient conditions of robustness and stability were derived in the presence of coupling effects, and the control output tracking was also realized.

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