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Designing a Robust Control Scheme for Robotic Systems with an Adaptive Observer

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ABSTRACT

This paper introduces a robust task-space control scheme for a robotic system with an adaptive observer. The proposed approach does not require the availability of the system states and an adaptive observer is developed to estimate the state variables. These estimated states are then used in the control scheme. First, the dynamic model of a robot is derived. Next, an observer-based robust control scheme is designed to compensate the uncertainties occurring in the control system. Moreover, upper bound of the lumped uncertainty is essential in the design of the robust controller. However, the upper bound of the lumped uncertainty is difficult to obtain in practical applications. Therefore, an adaptive law is derived to adapt the value of the lumped uncertainty, and an adaptive observer-based robust task-space controller is obtained. In this paper, we proved that the proposed adaptive observer-based controller can guarantee that the task-space tracking error and also the observation error converge to zero. To demonstrate the effectiveness of the proposed method, simulation results are illustrated in this paper.

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1. INTRODUCTION

In recent years, robotic systems have been increasingly implemented for many engineering applications [1-6]. Robust control of nonlinear systems has been the focus of many researchers to confront the uncertainties including parametric uncertainty, unmodeled dynamics and external disturbances [7, 8]. Since the lumped uncertainty is unknown in practical application, the upper bound of the lumped uncertainty is difficult to determine. Hence, an adaptive law is proposed to adapt the value of the lumped uncertainty in this paper.

In robotic systems, an encoder that gives very precise measurements can be used for providing the controllers with the position feedbacks. Also, the velocity signals are often sensed by using a velocity tachometer, which is expensive and may be contaminated by noise [9]. Hence, it is essential to design an observer to estimate the velocity signals precisely. Therefore, in this paper, a robust control scheme for robotic systems with an adaptive observer is proposed.

The control signal utilizes the estimated states derived from the observer and is designed using voltage control strategy. In this strategy, on the contrary of torque control strategy, actuator dynamics have not been excluded. In other words, instead of the applied torques to the robot joints, motor voltages are computed by the control law [10]. In comparison with the observer-controller structure developed in literature [11], the proposed method is superior due to the model-free observer. The methods presented in literature [12-17] require all the states of the system to be available for measurement, whereas the proposed approach does not require the availability of the states and utilizes an adaptive observer to estimate the system states. Unlike the robust control approaches in literature [18-20], the proposed method has an advantage that does not need the upper bound of the lumped uncertainty.

The rest of this paper is organized as follows. Section 2 states the robotic problem formulation. Section 3 focuses on the design of a robust control scheme with an adaptive observer. Section 4 presents the stability analysis. One example is illustrated in Section 5 to show the effectiveness of the proposed method. Conclusions are drawn in section 6.

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2. PROBLEM FORMULATION

The dynamics of electrically driven robot manipulator is given by Spong et al. [21]

$$D(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=\tau_l \tag{1}$$

$$J_m r^{-1}\ddot{q}+B_m r^{-1}\dot{q}+r\tau_l=K_m I_a \tag{2}$$

$$RI_a+L\dot{I}_a+K_m r^{-1}\dot{q}+\varphi=v(t) \tag{3}$$

The details are completely explained in literature [22]. Substitution of τ_l from Equation (1) into Equation (2) yields:

$$\begin{aligned}&\bar{D}(q)\ddot{q}+\bar{C}(q,\dot{q})\dot{q}+\bar{G}(q)=K_m I_a\\&\bar{D}(q)=J_m r^{-1}+rD(q)\\&\bar{C}(q,\dot{q})=B_m r^{-1}+rC(q,\dot{q})\\&\bar{G}(q)=rG(q)\end{aligned} \tag{4}$$

Substituting I_a from Equation (3) into Equation (4) results in:

$$\begin{aligned}&\bar{D}(q)\ddot{q}+\left(\bar{C}(q,\dot{q})+K_m R^{-1}K_m r^{-1}\right)\dot{q}+\bar{G}(q)+\\&K_m R^{-1}L\dot{I}_a+K_m R^{-1}\varphi=K_m R^{-1}V\end{aligned} \tag{5}$$

Suppose that h is the N-dimensional vector of the end-effector's position and orientation in the task space. The Jacobian matrix $J(q)$ relates the joint-space velocity vector $\dot{q}$ to the task-space velocity vector $\dot{h}$ as $\dot{h}=J(q)\dot{q}$. Consequently, $\ddot{h}$ is given by $\ddot{h}=J(q)\ddot{q}+\dot{J}(q)\dot{q}$. Substitution of $\dot{q}$ and $\ddot{q}$ into Equation (5), yields:

$$\begin{aligned}&\bar{D}(q)J^{-1}(q)\ddot{h}+[\bar{C}(q,\dot{q})+K_m R^{-1}K_m r^{-1}-\\&\bar{D}(q)J^{-1}(q)\dot{J}(q)]J^{-1}(q)\dot{h}+\bar{G}(q)+\\&K_m R^{-1}L\dot{I}_a+K_m R^{-1}\varphi=K_m R^{-1}V\end{aligned} \tag{6}$$

In order to represent Equation (6) in the task-space, $J(q)^{-T}$ is multiplied to both sides. As a result, we have

$$\begin{aligned}&J^{-T}\bar{D}(q)J^{-1}(q)\ddot{h}+J^{-T}[\bar{C}(q,\dot{q})+K_m R^{-1}K_m r^{-1}-\\&\bar{D}(q)J^{-1}(q)\dot{J}(q)]J^{-1}(q)\dot{h}+J^{-T}[\bar{G}(q)+\\&K_m R^{-1}L\dot{I}_a+K_m R^{-1}\varphi]=J^{-T}K_m R^{-1}V\end{aligned} \tag{7}$$

Now, Equation (7) can be rewritten as follows:

$$\begin{aligned}&M(h)\ddot{h}+N(h,\dot{h})\dot{h}+H(h)=u(t)\\&M(h)=J(q)^{-T}\bar{D}(q)J(q)^{-1}\\&N(h,\dot{h})=J(q)^{-T}[\bar{C}(q,\dot{q})+K_m R^{-1}K_m r^{-1}-\\&\bar{D}(q)J^{-1}(q)\dot{J}(q)]J(q)^{-1}\\&H(h)=J(q)^{-T}[\bar{G}(q)+K_m R^{-1}L\dot{I}_a+K_m R^{-1}\varphi]\\&u(t)=J(q)^{-T}K_m R^{-1}v(t)\end{aligned} \tag{8}$$

Using state space representation, Equation (8) is given as follows:

$$\dot{x}=Ax+Bu(t)+B\delta(t),\ y=Cx \tag{9}$$

where

$$\begin{aligned}&x=[h\quad \dot{h}]^T\ ,\ A=\begin{bmatrix}0&I\\0&0\end{bmatrix}\ ,\ B=\begin{bmatrix}0\\I\end{bmatrix}\ ,\ C=[I\quad 0]\\&\delta(t)=(M(h)^{-1}-I)u(t)-M(h)^{-1}(N(h,\dot{h})\dot{h}+H(h))\end{aligned} \tag{10}$$

such that x is a $2n\times 1$ state vector, y is a $n\times 1$ output vector, 0 and I are the $n\times n$ zero and identity matrices and $\delta(t)$ is the lumped uncertainty, respectively. The control law calculates the signal $u(t)$. Then, the voltage signal is obtained by $v(t)=\hat{R}\hat{K}_m^{-1}\hat{J}(q)^T u(t)$ in which $\hat{R}$, $\hat{K}_m$ and $\hat{J}(q)$ are nominal values.

3. DESIGN OF A ROBUST CONTROL SCHEME WITH AN ADAPTIVE OBSERVER

The tracking error can be defined as $e=x-x_d$. Thus, $x=e+x_d$. Substitution of x into Equation (9) yields:

$$\dot{e}=Ae+Ax_d-\dot{x}_d+B(u+\delta) \tag{11}$$

It is easy to show that $-Ax_d-B\ddot{x}_{d1}=-\dot{x}_d$. Thus, Equation (11) can be rewritten as follows:

$$\dot{e}=Ae+B(u+\delta-\ddot{x}_{d1}) \tag{12}$$

Define $A_c=A-Bk_c^T$. Consequently, $A=A_c+Bk_c^T$. As a result, Equation (12) is rewritten as follows:

$$\dot{e}=A_c e+B(k_c^T e+u+\delta-\ddot{x}_{d1}) \tag{13}$$

Now, the proposed observer is defined as follows:

$$\dot{\hat{x}}=A\hat{x}+k_o(y-C\hat{x})+B(\hat{\delta}+u-u_r) \tag{14}$$

In which u_r is the robust control term which will be determined in next section. The estimated tracking error can be defined as $\hat{e} = \hat{x} - x_d$. Now, the proposed control law is defined as follows:

$$u = -\hat{\delta} + \ddot{x}_{d1} - k_c^T \hat{e} + u_r \tag{15}$$

Substitution of Equation (15) into Equation (14) yields:

$$\dot{\hat{x}} = A\hat{x} + k_o(y - C\hat{x}) + B(\ddot{x}_{d1} - k_c^T \hat{e}) \tag{16}$$

After substitution of $\hat{x} = \hat{e} + x_d$ into Equation (16) and some simple manipulations, Equation (16) is given by

$$\dot{\hat{x}} - Ax_d - B\ddot{x}_{d1} = A_c\hat{e} + k_o C(x - \hat{x}) \tag{17}$$

It is easy to show that $-Ax_d - B\ddot{x}_{d1} = -\dot{x}_d$. Thus, (17) can be rewritten as follows:

$$\dot{\hat{e}} = A_c\hat{e} + k_o C(x - \hat{x}) \tag{18}$$

The observation error can be defined as $\tilde{e} = e - \hat{e} = x - x_d - (\hat{x} - x_d) = x - \hat{x}$. As a result, Equation (18) is given by

$$\dot{\hat{e}} = A_c\hat{e} + k_o C\tilde{e} \tag{19}$$

Taking the time derivative of $\tilde{e} = e - \hat{e}$ and using Equations (13), (15) and (19), we have

$$\dot{\tilde{e}} = \dot{e} - \dot{\hat{e}} = (A - k_o C)\tilde{e} + B(-\hat{\delta} + u_r + \delta) \tag{20}$$

Then , Equation (20) can be written as follows:

$$\dot{\tilde{e}} = A_o\tilde{e} + Bw \tag{21}$$

where $A_o = A - k_o C$. Now, define the augmented error vector as $E_a = \begin{bmatrix}\hat{e} & \tilde{e}\end{bmatrix}^T$. Using Equations (19) and (21), $\dot{E}$ is given by

$$\dot{E}_a = A_a E_a + B_a w, E_1 = C_a E_a \tag{22}$$

$$A_a = \begin{bmatrix} A_c & k_o C \\ 0 & A_o \end{bmatrix}, B_a = \begin{bmatrix} 0 \\ B \end{bmatrix}, C_a = \begin{bmatrix} C & C \end{bmatrix}, \quad w = \delta - \hat{\delta} + u_r, \tilde{\delta} = \delta - \hat{\delta} \tag{23}$$

Since the sampling interval in the experiment is short enough as compared with the variation of δ, the term δ is also assumed to be a constant during the estimation (i.e. $\tilde{\delta} = \delta - \hat{\delta} \rightarrow \dot{\tilde{\delta}} = -\dot{\hat{\delta}}$) [23, 24].

4. STABILITY ANALYSIS

Consider the Lyapunov function candidate as follows:

$$V = \frac{1}{2} E_a{}^T P E_a + \frac{1}{2\gamma} \tilde{\delta}^T \tilde{\delta} \tag{24}$$

where P is a symmetric positive definite matrix satisfying Kalman–Yakubovich (KY) lemma. In other words, based on KY lemma [25], there exist P and Q such that

$$A_a{}^T P + PA_a = -Q, B_a{}^T P = C_a \tag{25}$$

Taking the time derivative of Equation (24) yields:

$$\dot{V} = \frac{1}{2}\dot{E}_a{}^T P E_a + \frac{1}{2} E_a{}^T P \dot{E}_a - \frac{1}{\gamma} \tilde{\delta}^T \dot{\hat{\delta}} \tag{26}$$

By substituting Equations (22) and (25) into Equation (26), we can write as follows:

$$\begin{aligned} \dot{V} &= \frac{1}{2}(A_a E_a + B_a w)^T P E_a + \frac{1}{2} E_a{}^T P (A_a E_a + B_a w) \\ &- \frac{1}{\gamma} \tilde{\delta}^T \dot{\hat{\delta}} = \frac{1}{2}(E_a{}^T A_a{}^T + w^T B_a{}^T) P E_a + \\ &\frac{1}{2} E_a{}^T P (A_a E_a + B_a w) - \frac{1}{\gamma} \tilde{\delta}^T \dot{\hat{\delta}} = \\ &\frac{1}{2} E_a{}^T (A_a{}^T P + PA_a) E_a + \frac{1}{2} w^T B_a{}^T P E_a \\ &+ \frac{1}{2} E_a{}^T P B_a w - \frac{1}{\gamma} \tilde{\delta}^T \dot{\hat{\delta}} = \\ &\frac{-1}{2} E_a{}^T Q E_a + w^T B_a{}^T P E_a - \frac{1}{\gamma} \tilde{\delta}^T \dot{\hat{\delta}} \end{aligned} \tag{27}$$

Using w defined in Equation (23) we have

$$\dot{V} = \frac{-1}{2} E_a{}^T Q E_a + (\tilde{\delta} + u_r)^T B_a{}^T P E_a - \frac{1}{\gamma} \tilde{\delta}^T \dot{\hat{\delta}} \tag{28}$$

The adaptation law can be proposed as follows:

$$\dot{\hat{\delta}} = \gamma B_a{}^T P E_a \tag{29}$$

Then, Equation (28) can be written as follows:

$$\dot{V} = \frac{-1}{2} E_a{}^T Q E_a + (u_r)^T B_a{}^T P E_a \tag{30}$$

Robust control term can be proposed as follows:

$$u_r = -k B_a{}^T P E_a \tag{31}$$

Using Equations (30), (31) leads to

$$\dot{V} = \frac{-1}{2} E_a{}^T Q E_a - k \left\| B_a{}^T P E_a \right\|^2 \tag{32}$$

Thus, it has been guaranteed that $\dot{V} \le 0$. By using Barbalat's lemma [25, 26], it can be shown the task-space tracking error $\hat{e}$ and the observation error $\tilde{e}$ asymptotically converge to zero.

5. SIMULATION RESULTS

The control signal Equation (15) and the observer Equation (14) are simulated on an articulated robot manipulator driven by permanent magnet dc motors. The Denavit-Hartenberg (DH) parameters of the manipulator are given in Table 1 [27]. The parameters of motors are given as $R = 1.26$, $K_m = 0.26$, $J_m = 0.0002$, $B_m = 0.001$, $L = 0.001$ and $r = 0.01$. The parameters of robotic system are given in literature [28]. A symbolic representation of the manipulator is illustrated in Figure 1. The maximum voltage of each motor is set to $u_{\max} = 40$ V. The desired trajectory in the task-space is defined as follows:

$$x_d = \begin{bmatrix} x_{d1} \\ x_{d2} \end{bmatrix} = \begin{bmatrix} h_d \\ \dot{h}_d \end{bmatrix}, \quad h_d = \begin{bmatrix} 0.85 - 0.10\cos(\frac{\pi t}{3}) \\ 0.75 - 0.06\sin(\frac{\pi t}{3}) \\ 0 \end{bmatrix} \qquad (33)$$

The matrix k_c^T is calculated using $k_c = place(A, B, [-3.1 \ \ -3.2 \ \ -3.3 \ \ -3.4 \ \ -3.5 \ \ -3.6])$ and The matrix k_o is calculated via $k_o = place(A^T, C^T, [-31 \ \ -32 \ \ -33 \ \ -34 \ \ -35 \ \ -36])$. The parameters γ and k have been set to 4000 and 10, respectively.

TABLE 1. The DH parameters of the articulated manipulator

Link	θ	d	a	α
1	θ_1	d_1	0	$\pi/2$
2	θ_2	0	a_2	0
3	θ_3	0	a_3	0

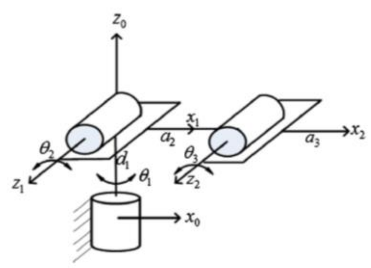

Figure 1. Symbolic representation of the articulated manipulator

The external disturbance is a step function with amplitude 2V which is applied to all motors at t = 3s. The voltage signal is obtained by $v(t) = \hat{R}\hat{K}_m^{-1}\hat{J}(q)^T u(t)$. It has been assumed that $\hat{R} = 0.8R$, $\hat{K}_m = 0.8K_m$ and $\hat{J}(q) = 0.8J(q)$. Figures 2 and 3 depict the tracking performances of the proposed scheme which are satisfactory. Meanwhile, voltage signals are presented in Figure 4. As shown in this figure, motor voltages are smooth and without any chattering. The observation performances of the proposed scheme are shown in Figures 5-7. These figures show that the adaptive observer can generate the estimated state very fast and correct.

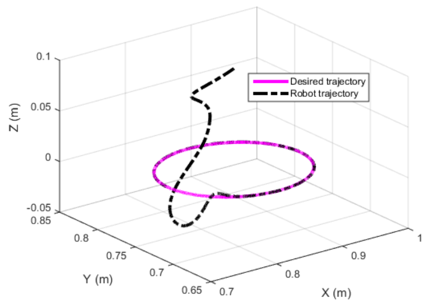

Figure 2. The desired and actual trajectories in the X-Y-Z plane

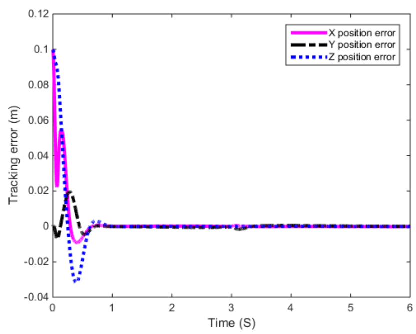

Figure 3. The task-space tracking errors

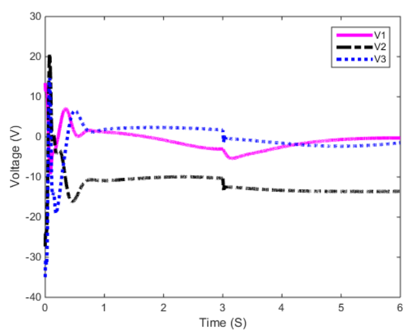

Figure 4. The control efforts

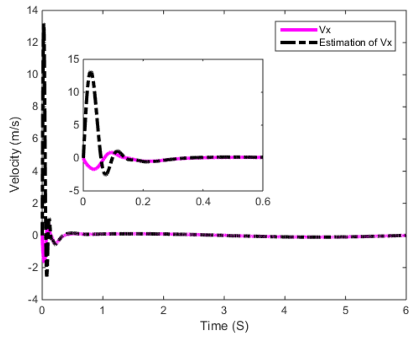

Figure 5. Comparison of velocity along the X axis and its estimation

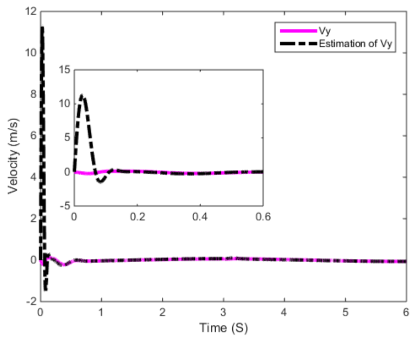

Figure 6. Comparison of velocity along the Y axis and its estimation

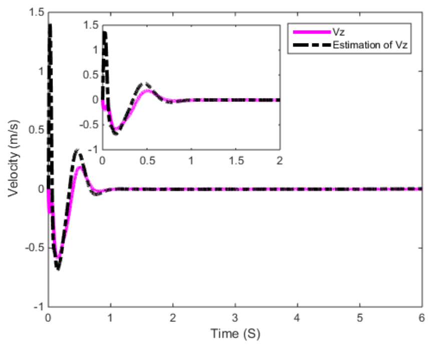

Figure 7. Comparison of velocity along the Z axis and its estimation

As a result, Simulation results show that the proposed method is able to control system with effective performance in the presence of unknown uncertainties. To improve the controller performance, optimization algorithms [29-34] can be applied.

6. CONCLUSION

This paper has introduced a robust control scheme for a robotic system with a simple adaptive observer. First, the dynamic model of a robot was introduced. Then, a robust control scheme with a simple adaptive observer was designed. However, the upper bound of the lumped uncertainty is essential in the design of the proposed scheme. To relax the requirement for the upper bound of the lumped uncertainty, an observer-based robust controller with an adaptive mechanism to adapt the lumped uncertainty was proposed. Finally, the effectiveness of the proposed scheme was confirmed by the simulation results.

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Designing a Robust Control Scheme for Robotic Systems with an Adaptive Observer

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چکیده

این مقاله یک روش کنترل فضای کار مقاوم برای یک سیستم رباتیک با یک رویتگر تطبیقی معرفی می‌کند. روش پیشنهادی نیازی به دسترسی به حالات سیستم ندارد و یک رویتگر تطبیقی برای تخمین متغیر های حالت طراحی می‌شود. سپس این حالات تخمینی در روش کنترل استفاده می‌شوند. ابتدا، مدل دینامیکی یک ربات بدست می آید. در مرحله بعد، یک روش کنترل مقاوم مبتنی بر رویتگر برای جبران عدم قطعیت های موجود در سیستم کنترل طراحی می‌شود. علاوه بر این، بدست آوردن باند بالایی عدم قطعیت مجتمع در کاربرد های عملی مشکل است. بنابراین، یک قانون تطبیقی برای تطبیق مقدار عدم قطعیت مجتمع بدست می آید، و یک کنترل کننده فضای کار مقاوم مبتنی بر رویتگر تطبیقی نتیجه می شود. در این مقاله، ما اثبات می‌کنیم که کنترل کننده مبتنی بر رویتگر تطبیقی پیشنهادی، می تواند تضمین کند که خطای ردگیری فضای کار و همچنین خطای رویتگر به صفر همگرا می‌شوند. برای نشان دادن کارامدی روش پیشنهادی، نتایج شبیه سازی در این مقاله نشان داده می‌شوند.

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