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A Model-Free Robust Control Approach for Robot Manipulator

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Abstract**—**A model-free robust control (MFRC) approach is proposed for position control of robot manipulators in the state space. The control approach is verified analytically to be robust subject to uncertainties including external disturbances, unmodeled dynamics, and parametric uncertainties. There is a high flexibility to work on different systems including actuators by the use of the proposed control approach. The proposed control approach can guarantee the robustness of control system. A PUMA 560 robot driven by geared permanent magnet dc motors is simulated. The simulation results show a satisfactory performance for control system under technical specifications.

Keywords**—**Model-free, robust control, position control, PUMA 560.

I. INTRODUCTION

MOTION control of robot manipulators has been studied using various approaches, such as PID [1], feed forward [2], adaptive [3], sliding mode [4], neural networks [5], and fuzzy control [6]. The proportional–integral–derivative (PID) controller is very simple and does not require any knowledge of the robot dynamics. However, successful application of this model-free simple controller usually requires manual parameter retuning before being transferred to the process under control. Moreover, it requires very large actuation to achieve a precise control, which is not practical.

The control problem becomes hypersensitive when faster trajectories (motions along specified paths at high speeds) are demanded, which among these, laser cutting of thin films, arc welding, and glue dispensing can be mentioned. The main reason of this sensitivity refers to dynamic problems arising from high velocities. Therefore, robot's performance degrades quickly as speed increases. To avoid this, model-based control techniques are usually used that require precise knowledge of the mathematical model of the manipulator [7], [8]. However, uncertainties such as system parameter variations, external disturbance, friction force, and unmodeled dynamics, influence the prior-designed control characteristic. Then the performance of model-based control techniques in high speed operations is severely affected by these uncertainties [9]-[11]. So, design of a controller that solves the above problems has become the subject of many researches over the last decade.

For instance, due to difficulties arising from dynamic modeling and control of flexible link manipulators, a class of non-model-based position controller is proposed for a planer multi-link flexible robot [13]. In this approach, controller design and stability proof are independent from system dynamics. But this approach requires exact dynamic equations of a single-link flexible beam and system energy equations for control strategy. In [14] a model-free controller for a single-link flexible smart material robot is introduced which considers model uncertainties and/or model truncations. But it does not include the effects of external disturbances. [15] studies the same for multi-link smart-material robots including the problems resulting from presence of external disturbances.

Moreover, many researches on neural networks have been performed to provide model-free learning controllers for a class of nonlinear systems [16]–[20]. [16] has proposed the dynamic backpropagation algorithm for identification and control, employing the multilayer perceptron (MLP). [18] has considered the MLP in the adaptive control feedback and linearizable minimum-phase plants represented by an input–output model. In [19] dynamic identifier is analyzed to perform identification with the MLP and a dynamic state feedback controller is constructed. [20] has proposed robot controller based on neural networks. Also, a robust neural network output feedback scheme is proposed for motion control of robot manipulators needless of measuring joint velocities in which, a model-free neural network controller is utilized to control the robot manipulator [21]. [22] has studied a fuzzy logic controller to control wheeled mobile robots in a robot soccer game in which a heuristic fuzzy logic controller has been designed based on a model-free approach.

Also, a model free robust neural-fuzzy-network control approach is implemented to achieve high-precision joint position control of a two-link robot manipulator including actuator dynamics [23]. However, it must be noted that the structure of an MLP is complicated and its learning speed is generally low. Therefore, RBFN techniques, which are mathematically tractable, eliminate low learning speed of MLP [24]. The connectionist structure of a neural network provides powerful abilities, such as adaptive learning, parallelism, fault tolerance and generalization to the fuzzy controller. However, these control methods require predefined and fixed fuzzy rules or NN structure, which reduce the flexibility and numerical processing capability of the

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controller. More importantly, they result in redundant or inefficient computation and so it is very difficult to guarantee the stability and robustness of neural network control systems. Therefore, the recent works on the field of model-free approaches indicates necessity of most researches in this context [25]-[30].

This paper attempts to address a model-free robust control (MFRC) scheme for a six degrees of freedom robotic manipulator using linear state feedback, needless of model-based control strategies. The proposed approach obviates difficulties mentioned above, considering external disturbances and dynamic modeling error. A considerable point for tracking problem in state space is the use of actuators' free-model in control law design.

II. Dynamic Model of Actuators

The PUMA560 has six degrees of freedom. The motors of robot are designed in two different sizes. The large one is used to drive the first three major joints, and the small one is used to drive the last three minor joints [31], [32]. We first consider the familiar differential equations of motion which describe DC motors driving an n degrees of freedom robot. These equations are given by

$$J_{m_i} L_i \dddot{\theta} + (J_{m_i} R_i + L_i B_{m_i})\ddot{\theta}_i + (R_i B_{m_i} + K_{m_i} K_{b_i})\dot{\theta} = r_i K_{m_i} v_i - r_i^2 \left(R_i \tau_{l_i} + L_i \frac{d\tau_{l_i}}{dt}\right) \tag{1}$$

Selection of position, velocity and acceleration as state variables in a state vector $\mathbf{x}_i = \begin{bmatrix} \theta_i & \dot{\theta}_i & \ddot{\theta}_i \end{bmatrix}^T$ leads to a set of third-order state apace equations with armature voltages as inputs, that given by

$$\dot{\mathbf{x}}_i = \mathbf{A}_i \mathbf{x}_i + \quad \mathbf{u}_i + \sigma_i \tag{2}$$

where A_i, B_i, and σ_i matrices define as

$$A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & \dfrac{-\left(R_i B_{m_i} + K_{m_i} K_{b_i}\right)}{J_{m_i} L_i} & \dfrac{-\left(J_{m_i} R_i + L_i B_{m_i}\right)}{J_{mi} L_i} \end{bmatrix} \tag{3}$$

,

$$B_i = \begin{bmatrix} 0 \\ 0 \\ \dfrac{r_i K_{mi}}{J_{mi} L_i} \end{bmatrix}$$

$$\sigma_i = -\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \frac{r_i^2 \left(R_i \tau_{li} + L_i \dot{\tau}_{l_i}\right)}{J_{mi} L_i} \tag{4}$$

where $\dot{\theta}_i$ is load angular velocity, ν_i is the motor voltage, τ_{li} is the torque load, L_i is the armature inductance, R_i is the armature resistance, K_{bi} is the back emf constant, Km is the torque constant, J_{mi} is the moment of inertia, B_{mi} is the damping coefficient, σ_i is external disturbance and **r** is the gear ratio.

We consider equations of motion of robot links. The behavior of a rigid n-link robot manipulator is considered and expressed in the following Lagrange form:

$$M(q)\ddot{q} + C\left(q,\dot{q}\right)\dot{q} + G\left(q\right) = \tau_l \tag{5}$$

where $\dot{q}, \ddot{q} \in R^n$ are the joint velocity and acceleration vectors, respectively. $M(q) \in R^{n\times n}$ denotes the inertia matrix, $C(q,\dot{q}) \in R^{n\times n}$ expresses the matrix of centripetal and Coriolis forces, $G(q) \in R^{n\times 1}$ is the gravity vector.

III. Design of Model- Free Robust Control

Suppose that state space equation form, for i'th joint motor of robot manipulator is given by

$$\dot{\mathbf{x}}_i = \mathbf{A}_i \mathbf{x}_i + \quad \mathbf{u}_i + \mathbf{d}_i \tag{6}$$

$$\mathbf{y}_i = \mathbf{c}_i \mathbf{x}_i \tag{7}$$

where $\mathbf{u_i}$ is defined as

$$\mathbf{u}_i = -\mathbf{k}_i \mathbf{x}_i + k_{0,i} \mathbf{r}_i \tag{8}$$

$\mathbf{x_i}$ is the state vector, $\mathbf{y_i}$ is the output vector of the i'th coordinate, $\mathbf{k_i}$ and $\mathbf{k_{0,i}}$ are the design parameters for pole placement, $\mathbf{d_i}$ is the vector of uncertainty and $\mathbf{r_i}$ is the robustifying control input. The $\mathbf{A_i}$, $\mathbf{B_i}$, $\mathbf{c_i}$ matrices and $\mathbf{x_i}$, $\mathbf{d_i}$ vectors defined as follows:

$$A_i = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \tag{9}$$

$$B_i = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{10}$$

$$c_i = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{11}$$

$$\mathbf{x} = \begin{bmatrix} x_{1,i} \\ x_{2,i} \end{bmatrix} = \begin{bmatrix} \theta_i \\ \dot{\theta}_i \end{bmatrix} \tag{12}$$

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$$\mathrm{d}_i = \begin{bmatrix} 0 \\ \eta \end{bmatrix} \tag{13}$$

where η including modeling error and external disturbances. It must be noted that, here we assume information of actuators are not available and are considered as modeling error. Also, suppose that state space form of actuators obtained as a two-order equation, while, complete model of actuators are used for simulation. Substituting Equation (8) into (6) leads to:

$$\dot{\mathbf{x}}_i = \left(\mathbf{A}_i - \mathbf{B}_i\mathbf{k}_i\right)\mathbf{x}_i + \quad k_{0,i}\mathbf{r}_i + \mathbf{d}_i \tag{14}$$

We develop an algorithm to adjust $\mathbf{r_i}$ such that system will become asymptotically stable in spite of external disturbances and modeling error. To this end, we suppose that the desired closed loop state equations of i-th coordinate are given by:

$$\dot{\mathbf{x}}_i^d = \left(\mathbf{A}_i - \mathbf{B}_i\mathbf{k}_i\right)\mathbf{x}_i^d + \quad k_{0,i}\mathbf{r}_i^d \tag{15}$$

$$\mathbf{y}_i^d = \mathbf{c}_i\mathbf{x}_i^d \tag{16}$$

where $\mathbf{r_i^d}$ and $\mathbf{y_i^d}$ are the reference trajectory and desired output for the i-th coordinate in joint space, respectively. The coefficient vector $\mathbf{k_i}$ is determined such that, $\mathbf{y_i^d}$ closely follow $\mathbf{r_i^d}$. Subtracting (15) from (14) and (16) from (7), will obtain the tracking error equations as follows:

$$\dot{\mathbf{e}}_i = \left(\mathbf{A}_i - \mathbf{B}_i\mathbf{k}_i\right)\mathbf{e}_i + \mathbf{B}_i k_{0,i}\mathbf{v}_i + \mathbf{d}_i \qquad i=1,\ldots,n \tag{17}$$

$$\zeta_i = \mathbf{c}_i\mathbf{e}_i \tag{18}$$

where:

$$\zeta_i = \mathbf{y}_i - \mathbf{y}_i^d \tag{19}$$

$$\mathbf{e}_i = \mathbf{x}_i - \mathbf{x}_i^d \tag{20}$$

$$\mathbf{v}_i = \mathbf{r}_i - \mathbf{r}_i^d \tag{21}$$

With attention to linear system properties and taking time derivatives of both sides of (17), we arrive at

$$\mathbf{e}_i^{(p+1)} - \sum_{j=1}^{p} b_j\mathbf{e}_i^{(p-j+1)} = \left(\mathbf{A}_i - \mathbf{B}_i\mathbf{k}_i\right)\left\{\mathbf{e}_i^{(p)} - \sum_{j=1}^{p} b_j\mathbf{e}_i^{(p-j)}\right\}$$
$$+\mathbf{B}_i k_{0,i}\left\{\mathbf{v}_i^{(p)} - \sum_{j=1}^{p} b_j v_i^{(p-j)}\right\} + \left\{\mathbf{d_i}^{(p)} - \sum_{j=1}^{p} b_j\mathbf{d_i}^{(p-j)}\right\} \tag{22}$$

We assume $\mathbf{d_i}$ can be modeled by a p-order ordinary differential equation as follows [33], that the order p of this differential equation reflects the dynamic structure of $\mathbf{d}_i$:

$$\mathbf{d_i}^{(p)} = \sum_{j=1}^{p} b_j\mathbf{d_i}^{(p-j)} \tag{23}$$

We define a control law as follows.

$$\mathbf{v}_i^{(p)} - \sum_{j=1}^{p} b_j v_i^{(p-j)} = -\sum_{j=1}^{p}\mu_{j,i}\zeta_i^{(p-j)}$$
$$-\mu_{0,i}\left(\mathbf{e_i}^{(p)} - \sum_{j=1}^{p}\mathbf{b_j e_i}^{(p-j)}\right) \tag{24}$$

Whereas ζi is a function of tracking error ei, therefore $\mathbf{v_i}$ depends on the tracking error only and finally it ensures that the tracking error $\mathbf{e_i}$ ($\zeta_\mathbf{i}$) approaches zero asymptotically.

Substituting (24) into (22) and using (23) we will have

$$\mathbf{e}_i^{(p+1)} - \sum_{j=1}^{p} b_j\mathbf{e}_i^{(p-j+1)} = -\mathbf{B}_i k_{0,i}\mathbf{c}_i \sum \mu \quad \mathbf{e}_i^{(p-j)}$$
$$+\left(\mathbf{A}_i - \mathbf{B}_i\mathbf{k}_i - \mathbf{B}_i k_{0,i}\mu_{0,i}\right)\left\{\mathbf{e}_i^{(p)} - \sum_{j=1}^{p} b_j\mathbf{e}_i^{(p-j)}\right\} \tag{25}$$

The final step is to adjust the linear control input in (8) to account for the effects of modeling errors and external disturbance as follows

$$r_i = r \quad + v_i \tag{26}$$

Therefore two sets of closed-loop system poles must be decided:

1)Inner linear control part: to place closed loop poles in desired places and so control the output yi to follow the reference input ri.

2)Outer linear control part: to place closed-loop poles of equation (25) in desired places to suppress effects of uncertainties (modeling errors or disturbances).

According to [34], good tracking accuracy can be achieved with relatively low uncertainty model error (p=1 or 2). To this The proposed control scheme is illustrated in Fig. 1.

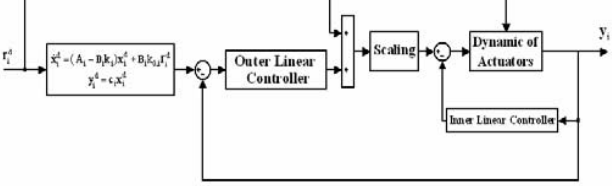

Fig. 1 Model-Free Robust control scheme

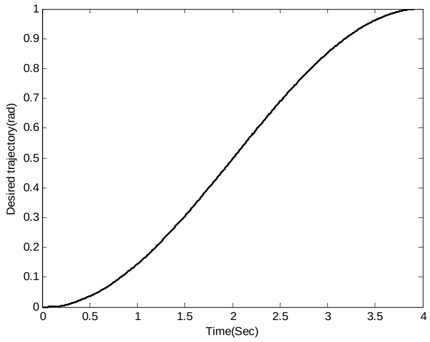

Fig. 2 The desired trajectory

end we can select the poles of equation (25) further to the left of the imaginary axis in the complex s plane than the inner control loop closed-loop poles.

IV. Simulation Results

We define specifications of the permanent magnet dc motors by Table I [32]. The parameters of PUMA560 robot that used in simulation are given by [31]. The major steps of the proposed algorithm for MFRC design can be described as follows:

A. Design a Smooth Desired Trajectory for Tracking

The desired trajectory that proposed to simulation is given by:

$$q_d = -a\cos(\frac{\pi}{T}t) + a, \quad t \geq 0 \tag{27}$$

It starts at zero with a velocity of zero and will finish at time T sec with a velocity of zero. It must be noted that, the trajectory has been started in where the joint angle has positioned. This yields a zero initial tracking error, which is a significant factor to reduce the tracking error. Here we set $a = 0.5rad$, and $T = 1\sec$ shown in Fig. 2.

B. Planning inner control loop to achieve tracking, using of pole placement.

Following the procedures described in section III, the step 1) is done by choosing the K state feedback vector as follows It must be noted that, the complete model of permanent magnet dc motors have been used for simulation, but incomplete state space form of them have been used for control law design.

TABLE I
The Motor Specifications

	R Ω	L H	J_m $kg.m^2$	B_m Nm.s/rad	K_m Nm/A
1	*2.1*	*0.0048*	*200e-6*	*1.48e-3*	*0.189*
2	*2.1*	*0.0048*	*200e-6*	*0.817e-3*	*0.219*
3	*2.1*	*0.0048*	*200e-6*	*1.38e-3*	*0.202*
4	*6.7*	*0.0039*	*33e-6*	*71.2e-6*	*0.075*
5	*6.7*	*0.0039*	*33e-6*	*82.6e-6*	*0.066*
6	*6.7*	*0.0039*	*33e-6*	*36.7e-6*	*0.066*

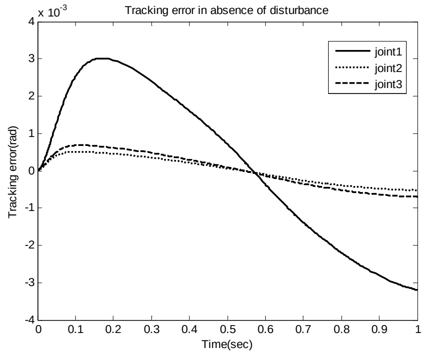

Fig. 3 Tracking error in the absence of disturbances

K_i=[*20225 50*] i=1, 2, …, 6

C. Modeling of Uncertainty by a p-order Differential Equation

Set the uncertainty equation to zero and finally getting b_j. In this step, if we choose p=1 for the uncertainty and set the uncertainty equation to zero, i.e.

$$d_i^{(1)} = b_1 d_i = 0 \tag{28}$$

Then

$$d_i = \text{arbitrary constant (a step function)} \tag{29}$$

$$b_1 = 0 \tag{30}$$

D. Outer Control Law Design

Definition of outer control law and suitable selection of closed loop poles for equation (25). On the basis of which that expressed in above, Fig. 3 depicts tracking error of all joints in the absence of disturbances. In this manner the motors voltage are given by Fig. 4. We wish to present that this scheme is robust subject to uncertainties (load torque, modeling error and external disturbances). In the case of applying external load torques on the motors shaft, such as Fig. 5, tracking error is also bounded. It is shown that the tracking error is limited

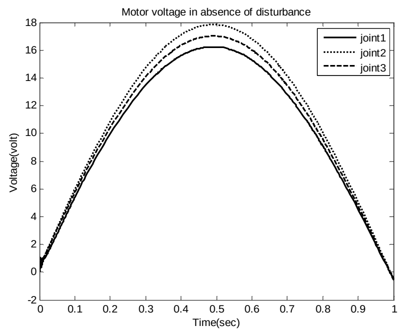

Fig. 4 Voltages of motors in the absence of disturbances

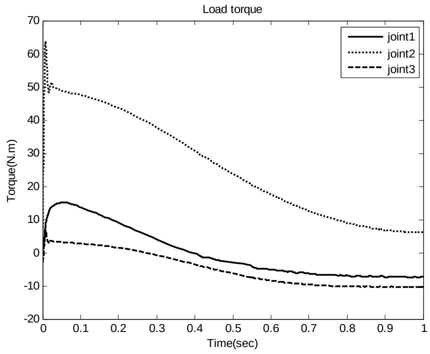

Fig. 5 Load torques

under about 0.003 rad that is acceptable due to mechanical resolution. The result has been shown in Fig. 6. It must be noted that the load torque for 3 second joint is at most zeros because there are no distortion in wrist center. The technical limits such as voltage limit, current limit, torque limit and control signal are considered in Figs. 7 and 8. They show motors voltage and control signal of actuators, respectively. They confirm good operation of actuators. In the other word, the control signals obtain a robust control. A gear ratio of 0.02 is used in this simulation to provide the operation requirements. As a test of robustness we forced a given disturbance on system as

$$dis = 75Sin\left(17.43t\right) + 37.5Sin\left(39.3t\right) + 37.5Sin\left(10.83t\right) - 22.5 \quad (31)$$

where dis is the disturbance. The tracking error, shown by Fig. 9, is bounded and so the proposed approach leads to asymptotic stability. Finally the technical limits such as motor voltages as shown in Fig. 10. Simulation results show that the robot can be effectively controlled and is robust subject to uncertainties based on using a free model controller.

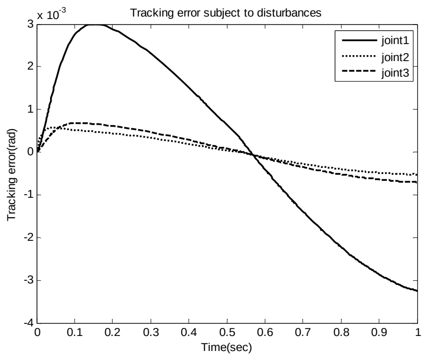

Fig. 6 Tracking error subject to disturbances

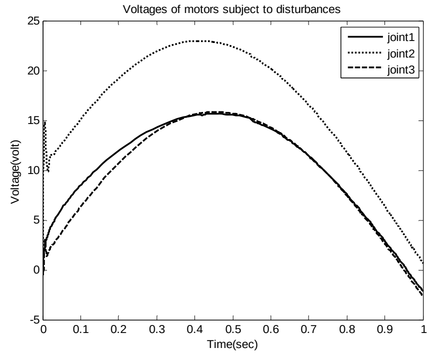

Fig. 7 Voltages of motor subject to disturbances

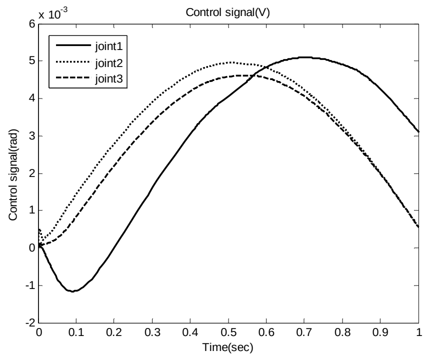

Fig. 8 Control signal

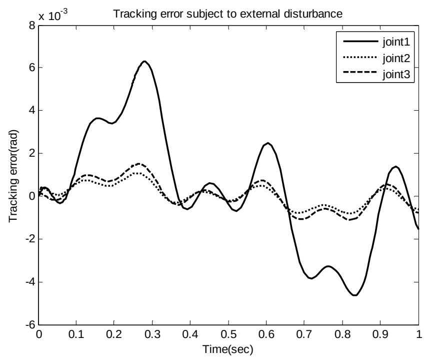

Fig. 9 Tracking error subject to external disturbances

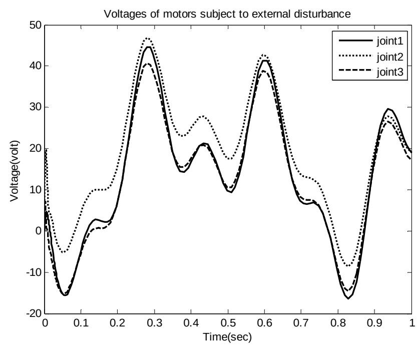

Fig. 10 Voltages of motors subject to external disturbances

V. Conclusion

Many modern control techniques have been designed to control of robot manipulator. However control performance is often degraded due to the existence of modeling errors and external disturbances. The use of a model-free robust control approach for trajectory tracking of PUMA560 robot was developed in this paper. The controller design was based on state feedback theory and needless to model-based control techniques and any information about dynamic modeling. Simulation results have shown a good performance of the controller to track the desired trajectory.

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