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A Study on the Model Following Adaptive Control System of Industrial Robotic Manipulatior for Factory Automation

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Abstract

Adaptive control system has evolved as an attempt to avoid degradation of the dynamic performance of a control system when environmental variations occurs.

While the feedback control system is oriented toward the elimination of the effect of state perturbations, the adaptive control system is oriented toward the elimination of the effect of structural perturbation, upon the performances of the control system.

The model reference adaptive controller is utilized in velocity loop controller for positioning and tracking is designed based on the linear decoupled dynamics.

1. Introduction

Currently, the design of high performance robotic control systems, involving model reference adaptive control algorithms for space-based robotic mechanisms is of much interest. Robotic manipulators are multi-dimedsional, flexible geometry, programmable mechanical systems, which make them ideally suited for applications in a flexible automation environment. However their dynamics are inherentry nonlinear; eg. the inertia characteristics of manipulator depend on its configuration as well as the payload. As a consequence, linear feedback controllers are not able to realize the manipulator's full potential for speed and accuracy. It is generally agreed that dynamics of the spatial manipulator elements can be described by a set of coupled nonlinear second order differential equations. Physically, the coupling term represents gravitational torques, which depend on positions of the joints, reaction torques, due to accelerations of other joints, Coriolis and centrifugal torques The significance of these interaction torques depends on the physical parameters of the manipulator and the load it carries the comtrol system design is obviously complicated by the nonlinear character of the manipulator dynamics.

The approach followed in the present paper is based on adaptive model following control systems technique and hyperstability theory but it does with the assumption that the process is characterized by a linear model remaining time invariant during the adaptation process. the procedure, proposed in (24) for designing adaptation law for a class of time varying nonlinear plants, is simple and systemic and lead to a control law with a particular adaptation mechanism that assure global asymptotic stability.

The design of adaptive model following control does not require accurate modeling ; it is sufficient to know only the bound of the model parameter.

In this paper, we present a new scheme for the adaptive control of mechanical manipulators without using joint accelerations along with a proof of convergence and simulations. The new scheme does not require the measurement of joint acclerations and needs less computations.

2 . Dynamic model

The dynamic equation of an n-degree of freedom mechanical manipulator is expressed by applying Lagrange equation:

$$\frac{d}{dt}\frac{\partial k}{\partial \dot{\theta}_i} - \frac{\partial k}{\partial \theta_i} = G_i(\theta)+M(t),\ i=1,2...n \qquad (1)$$

where θ_i represents the relative angular position between the links at ith joint, k is the kinetic energy, $G(\theta)$ represents gravitational torques which depend on position of the links, $M(t)$ are input torque applied at the various joints.

For a rigid-body model of mechanical system, the kinetic energy can be expressed as:

$$k = \frac{1}{2}\sum_i\sum_j b_{ij}(\theta)\dot{\theta}_i\dot{\theta}_j,\quad \theta^T = [\theta_1, \theta_2, \ldots \theta_n]^T, \qquad (2)$$

where the coefficients b are the elements of the symetric square matrix, $B(\theta)$ is b (θ) and alway positive definite.

From equation(1), the manipulator dynamic model can be derived in the form:

$$M(t)=B(\theta(t))\ddot{\theta}(t)+H(\theta(t),\dot{\theta}(t))+G(\theta(t)), \qquad (3)$$

Where, $\theta(t)$ is joint variables, $M(t)$ is the nx1 vector of torque acting on the joints, $\dot{\theta}(t)$ is joint velocities, $B(\theta)$ is the nxn matrix of inertia, $H(\theta,\dot{\theta})$: coriolis and centrifugal torques, $G(\theta)$: the kx1 vector of gravitational torques.

Mainly, the objective of AMFC system is to assure that the genealized state error vector tends toward zero when the plant parameters differ from their nominal values for the input vector function.

It is convinent to rewrite equation(3), in terms of state variables to apply AMFC to the manipulator control.

Assuming that the joint angles and angular velocities are meausurable, the natural choice of state variables for a manipulator with n-degree of freedom is the following:

$$x(t) = \begin{pmatrix} x_{p_i} \\ x_{p_{i+k}} \end{pmatrix} = \begin{pmatrix} \theta_i \\ \dot{\theta}_i \end{pmatrix} \qquad i=1,2,...k \qquad (4)$$

Therefore, The state equation for the manipulator is expressed in the form:

$$\dot{x}_p = A_p(x_p)\cdot x_p + B_p(x_p)\cdot U_p \qquad (5)$$

where,

$$x_p^T = [\theta_i,\ \dot{\theta}_i]^T, \qquad U_p = M(t),$$

$$A_p(X_p) = \begin{pmatrix} 0 & I_k \\ \bar{B}_p(\theta)G(\theta), & -\bar{B}_p(\theta)c(\theta)z(\theta) \end{pmatrix}$$

$$B_p(X_p) = \begin{pmatrix} 0 \\ B^{-1}(\theta) \end{pmatrix}$$

$$G(\theta)=G'(\theta)\begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_k \end{pmatrix}, \qquad \bar{B}_p(\theta) = B_p^{-1}(\theta),$$

$$C(\theta,\dot{\theta})=C(\theta)\begin{pmatrix} \dot{\theta}_1\dot{\theta}_1 \\ \dot{\theta}_1\dot{\theta}_2 \\ \vdots \\ \dot{\theta}_k\dot{\theta}_k \end{pmatrix}$$

and I is the ixi identity matrix.

3. The Design of Adaptive Model Following Control System.

Adaptive model following control system is an extension of linear control system for the case where the parameters of the plant are poorly known or vary during operation. Mainly, the objective of AMFC system is to assure that genealized state error vector tend to zero when the plant parameters differ from their nominal values for any peciwise input vector function

3.1 Selection of Reference Model

The first step in the design of adaptation mechanism is the choice of reference model. In order to obtain from the nonlinear, coupled manipulator system well behaved linear uncoupled characteristics we choose a reference model described, for each degree of freedom, by a linear, second order, time invariant differential equation. With this choice the desire d performance characteristics may be specified with a minimum of parameters, simulataneously achieving a great reduction of the computation burden on the control computer.

The linear, second order differential equation for each degree freedom is written as:

$$\ddot{X}_{Mi} + a_{1i}\dot{X}_{Mi} + a_{0i}X_{Mi} = U_{Mi},\ i=1,2,...k; \qquad (6)$$

therefore, the reference model equation is expressed as:

$$\dot{X}_M = A_M X_M + B_M U_M ;\quad X_M \in R^{2k},\ U_M \in R^k. \qquad (7)$$

where,

$$A_M = \begin{pmatrix} 0 & I_k \\ \Lambda_0 & \Lambda_1 \end{pmatrix}, \qquad B_M = \begin{pmatrix} 0 \\ I_k \end{pmatrix}$$

with $\Lambda_0 = -\operatorname{diag}(a_{0i})$, $\Lambda_1 = -\operatorname{diag}(a_{1i})$,

$a_{0i} > 0, \quad a_{1i} > 0.$

3.2 Adaptation Law and stability analysis of AMFC System

With the choice of the reference model structure condition for perfect model following is always satisfied whichever are the values of the manipulator and reference model parameters.

The mechanical manipulator is described by equation(5). Referring to the block diagram of fig.1, the generate state error $e \triangleq X_M - X_p$ and $V = De$.

Therefore, the manipulator input is chosen as:

$$u_p = \phi(v, x_p, t) - \psi(v, u_M, t)\, u_M + k_u u_M \quad (8)$$

where ϕ and ψ are matrics generated by the adaptation mechanism and k_u and k_p are usual feedback and feedfoard blocks.

We know that, in order to assure the adaptation, the following structure conditions must be satisfied:

$$\begin{aligned} &(I - B_p B_p^{+})(A_M - A_p) = 0 , \\ &(I - B_p B_p^{+}) B_M = 0 , \end{aligned} \qquad \forall\ X, t \qquad (9)$$

where A_M, A_p are (nxm)matrics and B_p,B_M are nxm matrics and $B_p = (B_p^T B_p)^{-1} B_p^T$ is the Penrose pseudoinverse of B_p. Reffering to the block diagram of fig.1, by combination equation(5),(6),(8) and assuming that the structure conditions(8) for the perfect model following are satisfied, we can write the AMFC equation in terms of the genearized state error as follows:

$$\dot{e} = A_M e + \begin{pmatrix} 0 \\ I \end{pmatrix} w_1 \qquad (10)$$

$$V = De$$

$$\begin{aligned} w_1 = -w = \bar{B}_p\left[B_p(A_M - A_p) + k_p - \phi\right] X_p \\ + B_p\left[B_p B_M - k_u - \psi\right] U_M \end{aligned} \qquad (11)$$

Equation(10),(11) suggest the equivalent representation of AMFC system, i.e., as a linear time invariant system connected with a nonlinear time varying block in the feedback path.

The necessary and sufficient conditions assuring the asypmtotic hyperstability of the system shown in fig.1 are following:

(i) the nonlinear time-varying block in the feedback path satisfies the intecral inequality:

$$\int_0^t v^T w \, d\tau \geq - r_0^2 , \quad \forall\ t \geq 0 \quad (12)$$

(ii). the transfer matrix of the time invariant linear block is strictly positive real:

$$Z(s) = D(sI - A)^{-1} \begin{pmatrix} 0 \\ I \end{pmatrix} \qquad (13)$$

The first condition can be satisfied by using the unit-vector adaptation law;i.e, by choosing:

$$\Phi(v, x_p, t) = q \frac{v}{\|v\|} (\operatorname{sgn} x_p), \quad (14)$$

$$\psi(v, u_M, t) = p \frac{v}{\|v\|} (\operatorname{sgn} u_M), \quad (15)$$

where,

$(\operatorname{sgn} x_p) = (\operatorname{sgn} x_p, \ldots\ldots \operatorname{sgn} x_p)$,

$\|v\| = (v^T v)^{1/2}$,

$$p \geq \|\bar{B}_p B_p^{+} B_M - \bar{B}_p k_u\| \cdot \|\bar{B}_p^{-1}\| \qquad (16)$$

$$q \geq \|\bar{B}_p B_p^{+} (A_M - A_p) + \bar{B}_p k_p\| \cdot \|\bar{B}_p^{-1}\| \qquad (17)$$

The inequality(12) may be rewritten as:

$$\int_0^t v^T(\bar{B}_p \phi - \bar{B}_p B_p^{+}(A_M - A_p) + \bar{B}_p k_p)\, d\tau + \int_0^t v^T(\bar{B}_p \psi - \bar{B}_p B_p^{+} B_M - \bar{B}_p k_u)\, d\tau \geq - r_0^2 , \ \forall\ t \geq 0. \qquad (18)$$

The choices (14)-(15)with p and q satisfying the inequalities (16),(17) leads to non-negative integrands in (18), therefore the inequality is satisfied with r = 0. Then, the unit-vector adaptation laws (16)-(17) assure the global convergence.

The second condition is satisfied by choosing:

$$D = (\, 0 \mid I \,) P \qquad (19)$$

where P is positive definite matrix solution of the Lyapunov equation

$$A_M^T + P A_M = - H \qquad (20)$$

with H symmetric positive definite matrix and A a stable matrix.

4. Simulation

In this paper, simulation study has been performed to investigate the effectiness of robotic manipulator adaptive control design via hyperstability as proposed for nonlinear time varying plants.

A manipulator with three degrees of freedom is considered with the following set of parameters: m_1 = 30kg, m_2 = 18.6kg, l_1 = l_2 = 0.6m, where m_i, l_i denote the mass and the length of the ith link. Actuators were assumed with no power limitation. The simulation runs has been carried out with reference to a desired trajectry given by a 1.8m straightly line in the cartestian space with a trapezoidal velocity law(fig.2) With the aim to study the effect of adaptive controller, preliminary the exact model input u_M, which eliminates tracking errors as regards the model state variables, has been computed. In a first set of simulations the manipulator response to an input with velocity law(a) was evaluated. The responses of reference model, which have not tracking error, are shown fig.3. The response of manipulator control system are vitually identical to the response of the reference model, which implies that the decoupling adaptive controller achieves its objective successfully. In fig.5 tracking errors are shown: $\$_1$ is the distance of end point of manipulator from the straight line on which the desire trajectory lies and $\$_2$ is the spatial delay along the direction of the trajectory. such errors ought to be theoretically zero, since the reference model and the manipulator have the same initial conditions on the state; but it must be taken into account that, whereas the adaptive control procedure has been developed for the continuous time system, actually the simulated systen is a sampled data system as the simulation work witha sampling period equal to 0.1ms, so that the errors are to be ascribe to the sampling effects. It must be noted that such errors are in any case very small, as shown(fig.5). The assumption that the torque value u can be changed instantaneously, while assures the stability of the adaptive system, is impractical owing to actuator dynamics. In order to evaluate the effects due to actuator dynamics a second set of simulation runs has been performed by introducing first order filter between each controller output u_P and the corresponding manipulator input torque.

The filters are characterized by the transfer functions 1/(1+sT), T=0.01sec. Fig .5 and fig.7 show the tracking error response and driving torques developed; note that the torque ripple is reduced but the tracking characteristics remain satisfactory. In fact the adaptation algorithm achieves its objectives successfully also if the reference model order is different from plant order. Finally, the responses of the manipulator control system have been evaluated when 5kg payload is considered. Reference model response and manipulator response are indistinguishable, which implies that the system is insentive to payload variations, i.e., to parameter variations. Correspondingly to the previous desired trajectory with the faster velocity law(b), in fig.2(b), a second set of simulation runs has been worked out assuming the actuators with no dynamics and no power limitations. the tracking errors, shown in fig.7, are still satisfactory, whereas higher torques are required. These simulation runs have been worked out in order to show that, as the unit vector adaptation law can be considered momeryless, the tracking characteristics of the robotic manipulator are affected mainly by the power ratings of the actuators only in part by the controller implementation. In this study,the reference model has been chosen for each linkage, with a_{0i} = 1.6 and a_{1i}=2.8, quite near manipulator linearized model in the neighborhood of its stable ecuilibrium position, taking into account the effect of $a_{0i}$and a_{1i}on the decaying speed of genealized error. This choice leads to a slow step response, but the system performance is better evaluated by considerating the trajectory tracking error, i.e. the distance manipulator end point from the trajectory imposed in the task oriented space, where performances and dynamical specification about the desired motion usually given. By choosing a 0.5sec time constant for each component of the state error the H matrix has been chosen. The value of H matrix has been chosen in order to give adequate gains to the linear compensator.

5. Conclusion

In this paper, an adaptive model following control method for robotic manipulators was presented, and the design of adaptive model following control system via hyperstability has been developed. It has used the unit vector type as adaptation law that the solution on line of differential equations is not required in the implimentation. It is simple and effective in design, and the class of reference model is sufficiently large and includes uncoupled models for each linkage.

By proposed technique, the global stability and the insensitivity to parameteric variations alwaysassured. And the significant results thus achievable were evidenced by a computer simulatiom of the adaptive control of a robotic manipulator with three degrees of freedom. The adapted nonlinear coupled manipulator dynamics show wellbehaved linear uncoupled characteristrics. It is recognized that an adaptive controller of the type suggested produces a discontinuous process forcing signal similar to a pulse amplitude modulated signal. The effects of such signals on the plant hardware should be taking into account. At any rate, it has been shown that the tracking characteristrics remain satisfactory and the torque ripple by considering the actuator dynamics.

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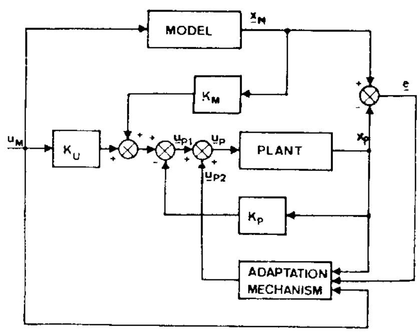

Fig.1 Dolck Diagram of Adaptive Control System.

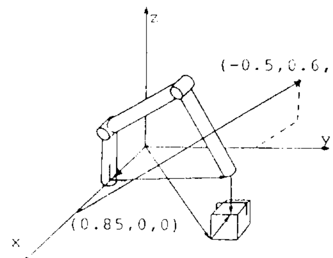

Fig.2(a) Manipulator trajectory

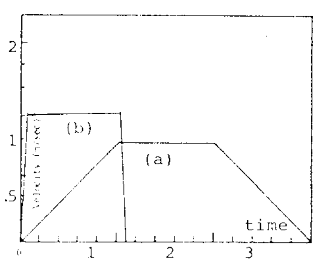

Fig.2(b) Velocity law of manipulator

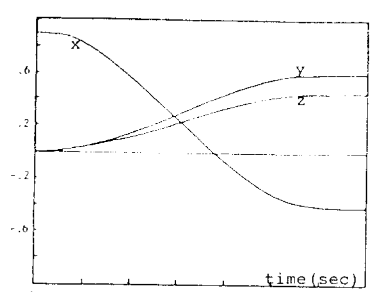

Fig.3 The response of reference model controlled manipulator corresponding to desired motion.

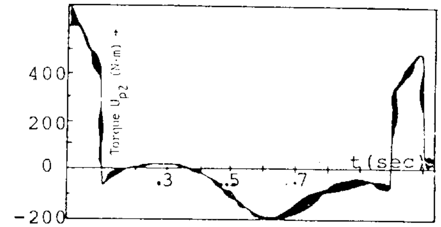

Fig.4 Torque developed at second manipulator joint corresponring to velocity law.

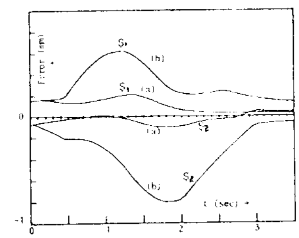

Fig.5 Trajectory tracking error.

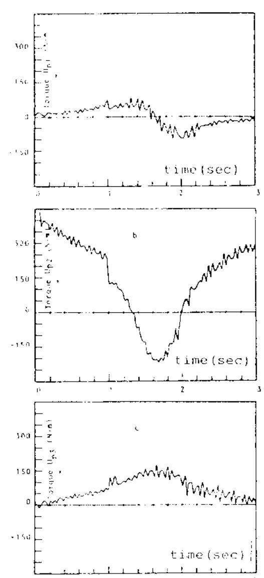

Fig.6 Torques developed at manipulator joint in presence of actuator dynamics

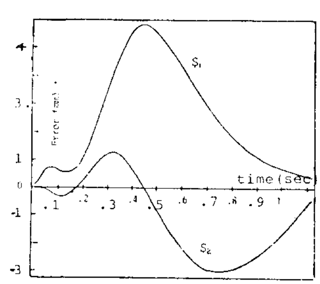

Fig.7 Tracking errors corresponding to velocity law(b)