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Microprocessor—Based Trajectory Control of Robot Manipulator Using Adaptive Sliding Mode

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Abstract: This paper demonstrates the approach of implementing the adaptive sliding mode control algorithm on a two—link revolute joint manipulator. Experiment results show the validity of accurate tracking capability and robust performance of the system.

Key words: computer control; sliding mode; robot; parameter estimation

1 Introduction

The development of modern industrial manipulator calls for robustness of performance with regard to variable payloads, torque disturbances, parameter uncertainties and other specifications. Therein, the tracking of desired trajectory (trajectory control) is an important field of control problems that has been considered by many investigators. Variable structure control of robot manipulators as an approach to solve the trajectory control problem has attracted intense research interests [1]. Many variable structure controllers have been proposed in the literature, but most of them only give the theoretical analysis and computer simulations. However, the ultimate justification for value and applicability of an algorithm lies in its actual hardware implementation. Based on this perspective, this paper proposes an adaptive sliding mode robot control algorithm. Using a single—board Motorola MC68000 microprocessor, the proposed algorithm was implemented on a two revolute joint manipulator.

2 Adaptive Sliding Mode Controller

In the absence of friction or other disturbances the dynamics of a n—link rigid manipulator can be written as

$$M(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) = u. \tag{1}$$

where q is the $n\times 1$ vector of joint displacements, u is the $n\times 1$ vector of applied joint torques, $M(q)$ is the $n\times n$ symmetric positive definite manipulator inertial matrix, $B(q,\dot{q})\dot{q}$ is the $n\times 1$ vector of centripetal and Coriolis torques, and $G(q)$ is $n\times 1$ vector of gravitational torques.

Two simplifying properties should be noted about this dynamic structure [2]. First, the two matrices M and B are not independent. Specifically, given a proper definition of B, the matrix $\dot{M}$

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$-2B$ is skew—symmetric. The second important property is that the individual terms on the left side of (1), and therefore the whole dynamics, are linear in terms of a suitably selected set of robot and load parameters.

The controller design problem is as follows: Given the desired trajectory $q_d(t)$ and $\dot{q}_d(t)$, and choose the sliding surface $s=0$, and with some or all manipulator parameters being not exactly known, derive a control law for the actuator torques and an estimation law for the unknown parameters such that the manipulator tracking errors $\tilde{q}(t)=q(t)-q_d(t)$ are forced to slide along the sliding surface $s=0$, thus guaranteeing asymptotic convergence of the tracking after an initial adaptation process.

The sliding surface is defined as

$$s = C(q(t) - q_d(t)) + (\dot{q}(t) - \dot{q}_d(t)). \tag{2}$$

where $C=\mathrm{diag}(c_1\cdots c_n), c_i>0, i=1\cdots n$.

Let a be a m—dimensional vector containing the unknown elements in the suitably selected set of equivalent dynamic parameters. Let $\hat{a}$ be its estimate, and let $\hat{M}, \hat{B}$, and $\hat{G}$ be the matrices obtained from the matrices M, B, and G by substituting the estimated $\hat{a}$ for actual a.

Suppose the overall feedback control law to be implemented has the following form:

$$u(t) = \tilde{u}_{eq}(t) + \Delta u(t). \tag{3}$$

where $u_{eq}(t)$ is the equivalent control [3], $\tilde{u}_{eq}(t)$ is its estimation and the expression is

$$\tilde{u}_{eq}(t) = -(\hat{M}C - \hat{B})\dot{q}(t) + \hat{M}C\dot{q}_d(t) + \hat{G} + \hat{M}\ddot{q}_d(t) \tag{4}$$

and $\hat{M}(q), \hat{B}(q,\dot{q})$ and $\hat{G}(q)$ are respectively the estimated values of $M(q)$, $B(q,q)$ and $G(q)$. $\Delta u(t)$ is sliding torque and taken as

$$\Delta u(t) = -K\mathrm{sgn}(s). \tag{5}$$

where $K=\mathrm{diag}(k_1\cdots k_n)$; $\mathrm{sgn}(s)^T=(\mathrm{sgn}(s_1)\cdots\mathrm{sgn}(s_n))$ and will be determined in the following. Note that $u_{eq}(t)$ is equal to the average value of $u(t)$ which maintains the tracking errors on the sliding surface $s=0$, and the role of $\Delta u(t)$ acts to overcome the effects of the uncertainties and nonlinearities and bend the entire system trajectory toward the sliding surface until sliding mode occures.

The linear parametrizability of the dynamics enables us to write

$$(\tilde{M}C - \tilde{B})\dot{q}(t) - \tilde{M}C\dot{q}_d(t) - \tilde{G} - \tilde{M}\ddot{q}_d(t) = Y(q,\dot{q},\dot{q}_d,\ddot{q}_d)\tilde{a}. \tag{6}$$

where $\tilde{a}=\hat{a}-a$ is the parameter estimation error, $Y(q,\dot{q},\dot{q}_d,\ddot{q}_d)$ is a $n\times m$ matrix independent of the dynamic parameters.

The adaptive sliding mode controller and adaptation law becomes

$$u(t) = -Y(q,\dot{q},\dot{q}_d,\ddot{q}_d)\hat{a} + \Delta u(t). \tag{7}$$

$$\Delta u_i(t) = -\left(\sum_{j=1}^{n} f_{ij}|s_j| + \delta_i\right)sgn(s_i), \qquad i = 1,\cdots n.$$

$$\dot{\hat{a}} = -P^{-1}Y^T s. \tag{8}$$

Where P is an uniformly positive definite matrix, and f_{ij} is function satisfying $|B_{ij}|<f_{ij}$. The above control and adaptation laws are globally asymptotically stable and guarantee zero tracking

errors. It can be proved with the Lyapunov function

$$V = s^T M(q)s + \tilde{a}^T P \tilde{a} \tag{9}$$

and strict mathematical proof of such results is detailed in [4].

Remark 1 In sliding mode, the resulting system equation is

$$\dot{\tilde{q}}(t) = - C\tilde{q}(t). \tag{10}$$

Equation (10) represents n uncoupled first order linear system and the system only depends on the parameter C. Clearly, the robustness to the uncertainties of the system is guaranteed.

Remark 2 Since the control law (7) is discontinuous across sliding surface, such a control law leads to control chattering. This can be remedied by approximating these discontinuous control laws by continuous ones inside the boundary layer [5]. To do this, we replace sgn (s) by sat (s/φ), φ is the boundary layer thickness. This leads to tracking to within a guaranteed precision.

3 Real—Time Implementation

To demonstrate the validity of proposed robust algorithm (7) and (8), a real—time implementation of the control strategy was developed for only two degrees—of—freedom out of a self—built 5—axis manipulator. Since a robotic manipulator must have at least three degrees—of—freedom in order to move to an arbitrary point in space, two degrees—of—freedom, however, are sufficient to examine the validity of the control strategy.

The controlled two—link manipulator is shown in Fig. 1. A dc servomotor is mounted on each joint which is driven through gear drives (1:60). The computer controller is a Motorola MC68000 16—bit single—board microprocessor runing at 8 MHz. The SBM provides voltages to the robot motors through 12—bit D/A converters. The manipulator angular positions were fed back to the microprocessor from encoders mounted at the motor shafts. The encoder outputs were converted into a count representing angular positions and read by the microprocessor through a 16—bit parallel port.

Software for implementing the control algorithm was developed in PASCAL programming language togather with MC68000 Assembly language. The impetus for using PASCAL was primarily due to the availabity of a PASCAL compiler for MC68000 and the complexity of the control strategy. Inasmuch as the SBM does not have a floating point processor, all floating point arithmetic operations are performed in software and therefore significant performance bottleneck is caused. Thus the choice of sample time is restricted, and the sample interval cannot be chosen to be small enough. Hence in this situation, the desired trajectory to be tracked may not be planned too fast and the switching frequency which should be ideally infinite is limited by the microprocessor speed.

The dynamics of the two—link manipulator including actuators are described in

$$\begin{vmatrix} \alpha + \beta + 2\eta\cos\theta_2 + I_1 + h_{11}/h_{31} & \eta\cos\theta_2 + \beta \\ \eta\cos\theta_2 + \beta & \beta + h_{12}/h_{32} \end{vmatrix} \begin{vmatrix} \theta_1 \\ \theta_2 \end{vmatrix}$$

$$+\begin{vmatrix} -\eta\dot{\theta}_2\sin\theta_2 - (\dot{\theta}_1+\dot{\theta}_2)\eta\sin\theta_2 \\ \eta\dot{\theta}_1\sin\theta_2 \quad 0 \end{vmatrix}\begin{vmatrix}\dot{\theta}_1\\ \theta_2\end{vmatrix}$$

$$+\begin{vmatrix}\alpha\cos\theta_1+\eta\cos(\theta_1+\theta_2)\\ \eta\cos(\theta_1+\theta_2)\end{vmatrix}\frac{g}{l_1}=\begin{vmatrix}u_1\\ u_2\end{vmatrix}-\begin{vmatrix}h_{21}/h_{31}\\ h_{22}/h_{32}\end{vmatrix}^T\begin{vmatrix}\dot{\theta}_1\\ \dot{\theta}_2\end{vmatrix}.$$

where $h_{ij}(i=1,2,3;j=1,2)$, I_1 and l_1 are known constants, g is the acceleration of gravity, three unknown parameters α, β and η are functions of unknown physical parameters of the manipulator, u_i is the input of actuators. The known constants and parameters are as follows:

$$h_{11}=0.042;\quad h_{12}=0.033;\quad h_{21}=3.5$$
$$h_{22}=3.04;\quad h_{31}=0.027;\quad h_{32}=0.016$$
$$I_1=-0.38;\quad l_1=0.36;\quad c_1=c_2=2;$$
$$\alpha=2.43;\quad \beta=0.5;\quad \eta=0.3;\quad r(P=rI)=30$$
$$\delta_1=9;\quad \delta_2=2;\quad \varphi_1=0.05;\quad \varphi_2=0.05$$

The desired trajectories are illustrated in Fig. 2. A removable 2.3 kg load was placed at the end of the manipulator. Test runs were made both with and without this load. Changes in the load were not accounted for in the controller in order to test the robustness of the controller. The controller was run at sample interval of 0.015s. This is the maximum effective rate at which the controller can run.

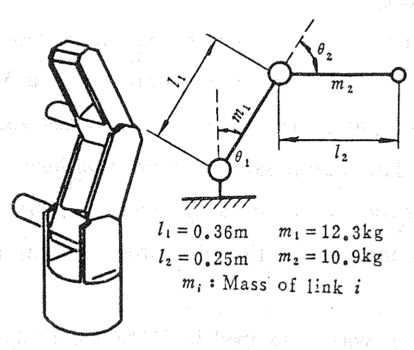

Fig. 1 Two—linkage manipulator

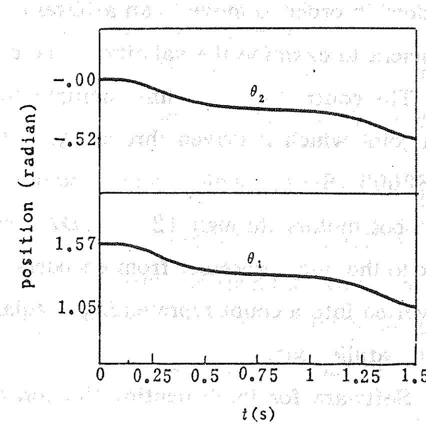

Fig. 2 Desired trajectory

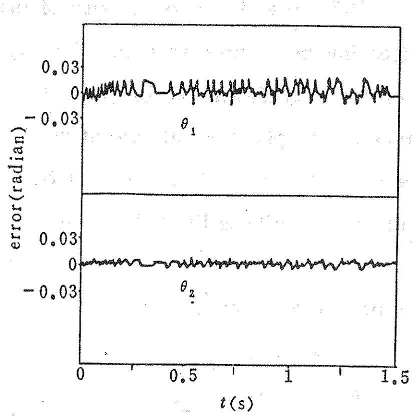

Fig. 3 Tracking error

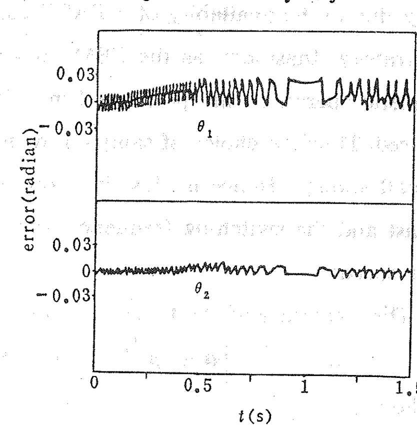

Fig. 4 Tracking error for unloaded system

System time responses were obtained from actual measurement and stored in the SBM, displayed on a CRT and recorded. The trajectory tracking errors for the manoeuver described above with the load attached are shown in Fig. 3. Since $s(0)=0$ and sliding mode occures immediately, there are no transient periods in the error responses. Fig. 4 shows the joint angle tracking errors with the load removed from the end of link 2. The slightly large tracking error in joint 1 compared with joint 2 is due to the larger gear backlashes in joint 1. Thus, it is confirmed that validity of this adaptive sliding controller is explicit for the purpose of trajectory tracking in the presence of uncertainties and nonlinearities of the system.

4 Conclusion

The experimental result demonstrates that the adaptive sliding mode controller achieves good tracking accuracy for high—speed operations in the presence of parametric uncertainties such as handling a varying payload, and the computational requirements of the algorithm are within the capabilities of the microprocessor.

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机械手轨迹控制在自适应滑动模下的微机实现

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摘要：本文针对具有两个回转关节的机械手，实现了自适应滑动模控制方法. 试验结果证实了系统的良好跟踪性能和鲁棒性能.

关键词：计算机控制；滑动模；机器人；参数估计