'88 추계학술대회

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GRASPING FORCE CONTROL OF ROBOT HAND

* Kwee-Bo Sim, Hideki Hashimoto, and Fumio Harashima

Institute of Industrial Science
University of Tokyo
7-22-1, Roppongi, Minato-ku, Tokyo 106, JAPAN

Abstract : In this paper, a grasping force control of robot hand is presented with consideration of workpiece dynamics. It is difficult to control a manipulator without the knowledge of its dynamics, because its handling with unknown workpiece may bring about overshoots and vibrations. Then it is necessary to adjust control gains according to the handling workpieces in order to achieve good control performances. The authors propose a new control strategy which uses adaptive observer and VSS (Variable Structure System) controller to subdue these overshoots and vibrations. Some simulations of the proposed method are carried out for a grasping system to control the grasping force to various workpieces, whose dynamics cannot be known in advance.

1. Introduction

Robot arm perform tasks in two ways : by moving freely in the work space, and by dynamically interacting with the environment under constraints. Position control is appropriate when motions of robots are unconstrained. However, when a robot arm comes into contact with the environment, for example, in assembly tasks, position control may not results in the desired performance. If the stiffness of the end effector or of the environment is high, it may even not be possible to carry out the task. Force control is then introduced to provide robot arm with compliance.

Various force control methods have been proposed in the literature [1]. Among them are the stiffness control, the damping control, hybrid position and force control, and the explicit force control. These methods generally based on kinematic considerations were developed within the framework of the joint coordinate spaces. None of these control systems pay attention to the characteristics of workpieces. Recently, the necessity of the impedance control has been reported for the force control of robot arm with interaction to the working environment [2], but it is inadequate to control actual systems which have unknown parameters. Thereby, the adaptability and the applicability of robotic system are still limited.

In order to cope with the above problems, this paper proposes a new control strategy in which dynamic characteristics of workpieces are taken into account by using adaptive observer and VSS controller. Firstly, the unknown parameters are estimated by using a adaptive observer, then the control gain of controller is updated according to the those estimated workpiece parameters. To obtain the desired control performances such as no vibrational and no overshoot, VSS is adopted in the design of the controller. VSS with sliding mode has strong robustness on feedback stability against parametric variations and disturbances. It is hoped that this method will achieve stable force control over a wide range of workpiece stiffness.

2. Modelling of the system with workpiece dynamics

One dimensional grasping problem for realizing stable force control is employed as a model with consideration of the workpiece dynamics. The robot arm and gripper are considered as rigid bodies with no vibrational modes. However, for force loop of the gripper, it is observed that vibration, depending upon the characteristics of the workpiece, is exhibited in dynamics behavior. The robot system, i.e., robot and gripper with workpiece, is modelled as shown in Figure 1. Here, both the gripper and the workpiece are assumed to move symmetrically so that the center of the gripper is always on the center of the workpiece. Thus, translational motion of the gripper and the workpiece can be neglected. The gripper of robot is modelled as a mass with a damper. The mass, m_r, represents the effective moving mass of the robot arm. The viscous damper, b_r, is chosen to give the appropriate rigid-body mode to the unattached robot. While structural damping is very low, b_r includes the linearized effects of all other damping in the robot. The sensor has stiffness k_s and damping coefficient b_s. The workpiece is also considered by introducing a spring and a damper with parameters k_ω and b_ω respectively. The mass, m_ω, represents the effective moving mass.

From this model, the following dynamical equations are derived.

$$m_r\ddot{x}_r(t)+b_r\dot{x}_r(t)+b_s\{\dot{x}_r(t)-\dot{x}_\omega(t)\}+k_s\{x_r(t)-x_\omega(t)\} = \frac{n}{r}T_l(t) \qquad (1)$$

$$m_\omega\ddot{x}_\omega(t)+b_\omega\dot{x}_\omega(t)+k_\omega x_\omega(t)-b_s\{\dot{x}_r(t)-\dot{x}_\omega(t)\}-k_s\{x_r(t)-x_\omega(t)\} = 0 \qquad (2)$$

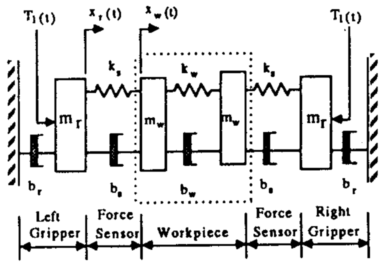

Fig. 1 Gripper model including workpiece dynamics

The relationship between the actuator and robot hand is as follows :

$$A_m u(t) = V(t) \quad (3)$$

$$L_a \dot{i}_a(t) + R_a i_a(t) + k_e \dot{\theta}_m(t) = V(t) \quad (4)$$

$$T_m(t) = k_t \theta_m(t) \quad (5)$$

$$J_m \ddot{\theta}_m(t) + B_m \dot{\theta}_m(t) = T_m(t) - T_l(t), \quad (6)$$

$$\theta_m(t) = \frac{n}{r} x_r(t) \quad (7)$$

where
- A_m : Amplifier gain
- G_m : Gain of the DC servo motor
- J_m : Inertia moment of the servo motor
- B_m : Friction coefficient of the motor
- R_a : Armature resistance of the motor
- L_a : Armature Inductance of the motor
- k_e : Constant of the counter electric power
- k_t : Torque constant of the motor
- r : Radius of the pinion gear in robot hand
- n : Gear reduction rate
- $u(t)$: Input Voltage
- $V(t)$: Motor Input voltage
- $T_l(t)$: Load Torque
- $T_m(t)$: Generated torque
- $i_a(t)$: Armature current
- $\theta_m(t)$: Rotational angle of the motor
- $x_r(t)$: Moving distance of the robot hand

Then the state equation and output equation can be expressed as follows :

$$\dot{x}_p(t) = A_p x_p(t) + B_p u(t) \quad (8)$$

$$y_p(t) = C_p^T x_p(t) \quad (9)$$

where $x_p(t)$ is $[x_r(t)\ x_\omega(t)\ \dot{x}_r(t)\ \dot{x}_\omega(t)]^T$,

$$A_p = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ a_1 & a_2 & a_3 & a_4 \\ a_5 & a_6 & a_7 & a_8 \end{bmatrix} \quad B_p = \begin{bmatrix} 0 \\ 0 \\ b \\ 0 \end{bmatrix} \quad C_p = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix}$$

$$a_0 = n^2 J_m + r^2 m_r, \quad a_1 = -r^2 k_s / a_0, \quad a_2 = r^2 k_s / a_0,$$

$$a_3 = -\{n^2 k_e k_t + r^2 R_a (b_r + b_s)\} / (R_a a_0), \quad a_4 = r^2 b_r / a_0,$$

$$a_5 = k_s / m_\omega, \quad a_6 = -(k_s + k_\omega)/m_\omega, \quad a_7 = b_s / m_\omega,$$

$$a_8 = -(b_s + b_\omega)/m_\omega, \quad b = A_m r n k_t / R_a a_0,$$

$$c_1 = k_s, \quad c_2 = -k_s, \quad c_3 = b_s, \quad c_4 = -b_s.$$

In this system, the state variables $x_r(t)$ and $x_\omega(t)$ are the position of the gripper and the position of the workpiece respectively. The variable $x_\omega(t)$ is unmeasurable and parameters k_ω and b_ω are usually unknown, but with some known ranges ($k_{\omega min} \le k_\omega \le k_{\omega max}, b_{\omega min} \le b_\omega \le b_{\omega max}$).

In the output equation (9), the output variable $y_p(t)$ is the contact force which is the force $F_r(t)$ across the force sensor, and given by

$$F_r(t) = k_s\{x_r(t) - x_\omega(t)\} + b_s\{\dot{x}_r(t) - \dot{x}_\omega(t)\} \quad (10)$$

3. Identification of parameters for the unknown workpieces

In order to obtain the desired control performance, it is necessary to observe the unknown states and identify all the unknown parameters. The adaptive algorithm used here is one as described by [3].

Since the system described by equations (8) and (9) is completely observable and controllable, then it can easily be represented in the following form:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \\ \dot{x}_4(t) \end{bmatrix} = \left[\begin{array}{c|ccc} \bar{a}_1 & 1 & 1 & 1 \\ \hline \bar{a}_2 & & & \\ \bar{a}_3 & & \Lambda & \\ \bar{a}_4 & & & \end{array}\right] \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \end{bmatrix} + \begin{bmatrix} \bar{b}_1 \\ \bar{b}_2 \\ \bar{b}_3 \\ \bar{b}_4 \end{bmatrix} u(t) \quad (11)$$

$$y(t) = [1\ 0\ 0\ 0] x_i(t) = x_1(t) \quad (12)$$

where Λ is a 3×3 diagonal matrix with arbitrary but known constant and negative diagonal elements $-\lambda_i$, i=2,3,4 ($\lambda_i > 0$, $\lambda_i \ne \lambda_j$, for $i \ne j$), and $\bar{a}_i$ and $\bar{b}_i$ (i=1,2,3,4) are unknown parameters to be identified.

Now consider a model with a form similar to (11) and its parameters $\hat{a}(t) = \{\hat{a}_1(t), \hat{a}_2(t), \hat{a}_3(t), \hat{a}_4(t)\}^T$ and $\hat{b}(t) = \{\hat{b}_1(t), \hat{b}_2(t), \hat{b}_3(t), \hat{b}_4(t)\}^T$ will be adjusted adaptively in order to match those of the system as $t \to \infty$.

$$\begin{bmatrix} \dot{\hat{x}}_1(t) \\ \dot{\hat{x}}_2(t) \\ \dot{\hat{x}}_3(t) \\ \dot{\hat{x}}_4(t) \end{bmatrix} = \begin{bmatrix} \hat{a}_1(t) & 1 & 1 & 1 \\ \hat{a}_2(t) & -\lambda_2 & 0 & 0 \\ \hat{a}_3(t) & 0 & -\lambda_3 & 0 \\ \hat{a}_4(t) & 0 & 0 & -\lambda_4 \end{bmatrix} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \\ \hat{x}_4(t) \end{bmatrix} + \begin{bmatrix} \hat{b}_1(t) \\ \hat{b}_2(t) \\ \hat{b}_3(t) \\ \hat{b}_4(t) \end{bmatrix} u(t) + \begin{bmatrix} \{\hat{a}_1(t) + \lambda_1(t)\} x_1(t) \\ \rho_2(t) \\ \rho_3(t) \\ \rho_4(t) \end{bmatrix} \quad (13)$$

where ρ_i (i=2,3,4) are signals which are added to assure the stability in overall adaptive scheme and will be defined later in (16).

Subtracting (11) from (13) will give the equation of the state error $e(t) = \hat{x}(t) - x(t)$:

$$\begin{bmatrix} \dot{e}_1(t) \\ \dot{e}_2(t) \\ \dot{e}_3(t) \\ \dot{e}_4(t) \end{bmatrix} = \begin{bmatrix} -\lambda_1 & 1 & 1 & 1 \\ 0 & -\lambda_2 & 0 & 0 \\ 0 & 0 & -\lambda_3 & 0 \\ 0 & 0 & 0 & -\lambda_4 \end{bmatrix} \begin{bmatrix} e_1(t) \\ e_2(t) \\ e_3(t) \\ e_4(t) \end{bmatrix} + \begin{bmatrix} \phi_1(t) \\ \phi_2(t) \\ \phi_3(t) \\ \phi_4(t) \end{bmatrix} x_1(t) + \begin{bmatrix} \varphi_1(t) \\ \varphi_2(t) \\ \varphi_3(t) \\ \varphi_4(t) \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ \rho_2(t) \\ \rho_3(t) \\ \rho_4(t) \end{bmatrix} \quad (14)$$

where $\phi_i(t) = \hat{\bar{a}}_i(t) - \bar{a}_i(t)$ and $\varphi_i(t) = \hat{\bar{b}}_i(t) - \bar{b}_i(t)$ (with i= 1,2,3,4) are the parameter errors between the system (11) and the model (13).

It is now desirable to find adaptive updating equations for the parameters vectors $\hat{\bar{a}}_i(t)$ and $\hat{\bar{b}}_i(t)$ so that as $t \to \infty$, $\hat{\bar{a}}_i(t) \to \bar{a}_i$, $\hat{\bar{b}}_i(t) \to \bar{b}_i$ and $e(t)=\hat{x}(t)-x(t) \to 0$.

Note that, with $\dot{\phi}(t)$ and $\dot{\varphi}(t)$ given by equation (20), the auxiliary signal $\rho(t)$ can be constructed by using only physically realizable filters and the signals $x_1(t)$ and $u(t)$. If signals $v_i(t)$ and $w_i(t)$ (with i=2,3,4) are defined as those generated by first-order filters :

$$\dot{v}_i(t) + \lambda_i v_i(t) = x_1(t), \qquad \dot{w}_i(t) + \lambda_i w_i(t) = u(t), \qquad (15)$$

then $\rho(t)=[\rho_2(t), \rho_3(t), \rho_4(t)]^T$ can be rewritten as following form :

$$\rho_i(t) = \phi_i(t)v_i(t) + \dot{\varphi}_i(t)w_i(t) \qquad (16)$$

Error $\mathbf{e}(t)$ can be obtained by substituting (16) into (14), i.e.,

$$\dot{e}_i(t) = -\lambda_i e_i(t) + \phi_i x_1(t) + \varphi_i u(t) + \rho_i(t) \qquad (17)$$

and then integrate equation (17), it gives

$$e_i(t) = \phi_i(t)v_i(t) + \varphi_i(t)w_i(t) + \exp(-\lambda_i t)e_i(t_0) \qquad (18)$$

Finally, substituting $e_i(t)$ into the first equation of (14) yields

$$\dot{e}_1(t) = -\lambda_1 e_1(t)+\phi^T(t)v(t)+\varphi^T(t)w(t)+\sum_{i=2}^{4} \exp(-\lambda_i t)e_i(t_0) \qquad (19)$$

where, $v(t)=[y(t), v_2(t), v_3(t), v_4(t)]$, $w(t)=[u(t), w_2(t), w_3(t), w_4(t)]$, and $e_i(t_0)$ is the initial error $e_i(t)$ at the time t_0.

If we choose the adaptive law as follows :

$$\dot{\hat{\bar{a}}}_i(t) = \dot{\phi}_i(t) = -\Gamma_{yi}v(t)e_1(t), \qquad \dot{\hat{\bar{b}}}_i(t) = \dot{\varphi}_i(t) = -\Gamma_{ui}w(t)e_1(t) \qquad (20)$$

then it gives $e_1(t) \to 0$ as $t \to \infty$ when control input u(t) contains at least 4 distinct frequencies. Therefore, we can get the unmeasurable states and all the unknown parameters of the system.

$$\lim_{t\to\infty} \hat{\bar{a}}_i(t) = \bar{a}_i \quad \lim_{t\to\infty} \hat{\bar{b}}_i(t) = \bar{b}_i \quad \lim_{t\to\infty} \hat{x}_i(t) = x_i \qquad (21)$$

4. VSS approach to control system design

The indexes of our control strategy are listed as follows :

(1) Fast response and no overshoot
(2) No steady state error
(3) Robustness of stability in closed loop
(4) Grasping operation without vibration
(5) Reduce the chattering phenomenon

In the force control system, it is necessary to perform the desired tasks without any overshoots and vibrations. Specially, overshoots should be avoided when the robot hand comes in contact with fragile work pieces, such as electronic chips, light bulbs, glass etc. And since the robot hand must handle various workpieces, especially robust performances are required in the robot force control system.

4.1 Sliding Mode control

Prior to the design of the VSS force controller, this section describes the basic idea of sliding mode control based on VSS. Sliding mode control is characterized by discontinuous control which changes structures on reaching a set of predetermined switching surfaces in the state space[4]. Here a general type is considered, and represented by

$$\dot{x}(t) = f(x,t) + B(x,t)u(t) \qquad (22)$$

where $x(t)$, $f(x,t) \in R^n$, $u(t) \in R^n$, $B \in R^{n\times n}$.
The control input has the form of

$$u_i(x,t) = \begin{cases} u_i^+(x,t) & \text{if } s_i(x)>0 \\ u_i^-(x,t) & \text{if } s_i(x)<0 \end{cases} \qquad (23)$$

where $u_i(t)$ is the ith component of u(t), and $s_i(x)=0$ is the ith component of the *m* switching hypersurfaces

$$s = \sum_{i=1}^{m} c_i x_i, \quad c_i=\text{const}, \ c_m=1 \qquad (24)$$

in the state space. The above system with discontinuous control is termed as a variable structure system, since the feedback control structure is switched alternatively according to the state of the system.

Sliding mode occurs on the switching surface $s_i(x)=0$ when all of trajectories move towards to the switching surface. Then the state slides and remains on the surface $s_i(x)=0$. The condition for sliding mode to exist on the *i*th hypersurface is

$$\lim s_i(x)\dot{s}_i(t) < 0 \qquad (25)$$

In the sliding mode, the system satisfies the equation

$$s_i(x) = 0 \quad \text{and} \quad \dot{s}_i(x) = 0 \qquad (26)$$

Equation (26) yields the motion which is described by the switching surface, thus, the trajectories of the predetermined hypersurface. The system in the sliding mode is completely robust, that is, independent of the parameter variations and external disturbances.

4.2 Switching Surface and Controller

The VSS force controller is designed by using the parameters and states estimated by the adaptive observer. Figure 2 depicts a VSS force control system of robot hand based on the above mentioned sliding mode. Here, the following switching line is selected :

$$s = c\int e_o(t)dt + e_o(t) \qquad (27)$$

where $e_o(t)=y_d(t)-y(t)$, y_d is the desired reference force, and c>0.

The control input u(t) is of the form, that means, estimated value term $u_{eq}(t)$ and sliding mode term $\Delta u(t)$ are related as follows :

$$u(t) = u_{eq}(t)+\Delta u(t) \tag{28}$$

where $u_{eq}(t)$ is equivalent control input when $s=0$ and $\dot{s}=0$. From $\dot{s}=0$,

$$u(t) = \frac{1}{\hat{b}_1}\{ce_o(t)-\hat{a}_1x_1(t)-\hat{x}_2(t)-\hat{x}_3(t)-\hat{x}_4(t)\} \tag{29}$$

where $\hat{a}_1$ and $\hat{b}_1$ are identified parameters by the adaptive observer, and $\hat{x}_i(t)$ $(i=2,3,4)$ are estimated state variables.

Sliding mode term $\Delta u(t)$ is chosen as follows:

$$\Delta u(t) = \psi_1x_1(t)+\psi_2\hat{x}_2(t)+\psi_3\hat{x}_3(t)+\psi_4\hat{x}_4(t)+\psi_5e_o(t)+k_f\mathrm{sgn}(s) \tag{30}$$

From above equations, it gives

$$s\dot{s} = s_{11}sx_1(t)+s_{12}s\hat{x}_2(t)+s_{13}s\hat{x}_3(t)+s_{14}s\hat{x}_4(t)+s_{15}se_o(t)+s_{16}|s| \tag{31}$$

where s_{1i} $(i=1,\cdots,6)$ are coefficients which contain the unknown workpiece parameters. From the existence condition of sliding mode (25), each coefficient of equation (30) must be chosen to satisfy following inequalities and then the force control system will satisfy the existence condition.

$$\psi_1 = \begin{cases}\psi_1^+ & \text{if } sx_1(t)>0\\ \psi_1^- & \text{if } sx_1(t)<0\end{cases},\quad \psi_2 = \begin{cases}\psi_2^+ & \text{if } s\hat{x}_2(t)>0\\ \psi_2^- & \text{if } s\hat{x}_2(t)<0\end{cases}$$

$$\psi_3 = \begin{cases}\psi_3^+ & \text{if } s\hat{x}_3(t)>0\\ \psi_3^- & \text{if } s\hat{x}_3(t)<0\end{cases},\quad \psi_4 = \begin{cases}\psi_4^+ & \text{if } s\hat{x}_4(t)>0\\ \psi_4^- & \text{if } s\hat{x}_4(t)<0\end{cases}$$

$$\psi_5 = \begin{cases}\psi_4^+ & \text{if } se_o(t)>0\\ \psi_4^- & \text{if } se_o(t)<0\end{cases},\quad k_f>0 \tag{32}$$

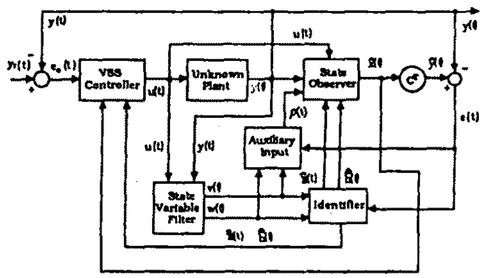

Fig. 2 Block diagram of VSS force control system using adaptive observer

5. Simulation results

In order to examine the performance of the proposed force control system, computer simulations have been carried out. The varying range of unknown parameters k_ω and b_ω are assumed as follows:

$$100[N/m] \le k_\omega[N/m] \le 10000[N/m]$$

$$100[N\text{-}m/sec] \le b_\omega[N\text{-}m/sec] \le 1000[N\text{-}m/sec]$$

In this paper, both soft and hard workpieces are chosen as simulation objects which have the spring constant 500[N/m] and 5000[N/m] respectively. Figure 3 shows the results of the VSS force controller without the adaptive observer. In here, the grasping can be performed without oscillations and overshoot to both the workpieces, but the undesirable chattering phenomenon of control input becomes violent. On the contrary, figure 4 shows the simulation results by applying the proposed method. The grasping operations can be performed without any oscillations and overshoot and also no chattering phenomenon to both the workpieces. Therefore it verified that the proposed method can improve the performance of the force control of robot manipulator.

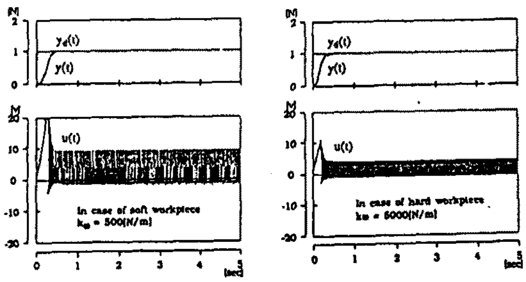

Fig. 3 Simulation result of force control with VSS controller without adaptive observer

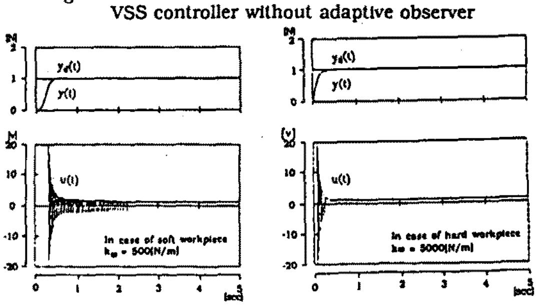

Fig. 4 Simulation result of force control with VSS controller with adaptive observer

6. Conclusion

The force control method using the adaptive observer and sliding mode is proposed for the robotic manipulator system with consideration of characteristics of workpiece dynamics. The proposed method was very effective throughout the simulations of the grasping force. Furthermore, the proposed method can adapt to changes of the workpiece characteristics and can improve the adaptability much better than the conventional force control method.

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