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Contact Force Control of Robot Hand using VSS

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Abstract : The motion of an workpiece to be manipulated is determined by the forces applied to the workpiece. During the contact between the robot hand and the workpiece, impulsive forces may dominate all other forces, and determine the ultimate success or failure of a task. Therefore, one of the important problems in the robot hands is the control of the initial impact force. In this paper, the problem of the force control of robot hand under system with contact force is presented. The principle of energy can be applied in the modelling of the impact force. In order to achieve stable contact and avoid bounces and vibrations, VSS is adopted in the design of the contact force controller. Some simulations are carried out for a pushing operation to control the contact force.

1. Introduction

Robot manipulators perform tasks in two ways : by moving freely in the work space, and by dynamically interacting with an environment under constraints. In the trajectory control case, a manipulator is controlled to follow a path in its work space without any interactions with the environment. In the force control, a manipulator interacts with the environment while the controller attempts to maintain a force trajectory [1].

However, the general-purpose manipulator may be used for moving workpieces, moving levers and knobs, assembling parts etc. In all these operations, the manipulator must come into physical contact with the workpiece before the desired force and movement can be made on it. When the manipulator makes this control, a collision and generally impact force which is impulsive force with high peak, occurs in transition between the no-interaction and interaction situation [2]. This impact can produce instability or poor control performance after contacting with the environment.The control of maximum impact force becomes much more crucial in the case of robot hand handling fragile workpieces.

Research work on contact dynamics and contact force control appears to be scant in comparison to works on trajectory and force control of robot manipulator. Recently though, the contact force problem associated with impact were studied in [3,4,5]. The derivation is given for the maximum impact force for a general two-body collision in [3]. The resulting model, which is based on the energy transfer during collision. The impact and force control was investigated in [4]. The study improves force tracking and reject impacts by using an integral force compensation with velocity feedback. The changing method of control mode is reported in [5]. When the desired contact force is obtained, the mode is switched from position mode to force mode.

In this paper, we propose the VSS (Variable Structure Systems) force controller in order to achieve stable contact and avoid bounces and vibrations. Here, the contact force is considered as disturbances. VSS controller with sliding mode has strong robustness on feedback stability against parametric variations and disturbances. It is hoped that this controller will achieve stable force control.

In this paper, we also present an impact force equation for a general two-body collision problem using energy principle. The equation of the impact force utilizes the kinetic energy, the strain energy stored in the elastic bodies, and the energy lost due to structural damping.

Some simulations are carried out for a pushing operation of the robot hand to control the contact force.

2. Contact Force Equation

The contact force, which will be denoted by F_c, depends on the impact. When a robot hand first makes contact an environment, the impulsive impact forces act for a short times. Generally, an elastic collision between bodies can be illustrated in two stages. The instant of just before the collision and the point of maximum elastic deformation of the bodies during the collision. At the start of the collision, a finger with mass m_f has a velocity of v_f, and an workpiece, with mass m_w has a velocity v_w. There is no deformation on the bodies at this point. However, at certain point during the collision, there is maximum elastic deformation on the workpiece. At the point of maximum elastic deformation, both the finger and the workpiece move with the same speed v_a.

A model representing a robot hand colliding with a workpiece is shown in Figure 1, which is equivalent to one half oscillation of a lumped parameter spring-mass-damper system.

The principle of energy analysis following [3] is used to model the impact force in this paper. The loss in the kinetic energy, during the period from the start of a collision to the point of the maximum deformation δ_{max}, is transformed into strain energy stored in the elastic region of contact and into energy loss due to structural damping in the bodies. Since the strain energy and energy dissipation from structural damping during a collision dictate the maximum impact force, the maximum impact force can be determined using the following equation.

$$\Delta KE = SE + LE \tag{1}$$

where, ΔKE is the change in the kinetic energy, SE is the gain in strain energy and LE is the energy loss due to structural damping during the period of the collision.

The change in the kinetic energy during the collision can be expressed as follows :

$$\Delta KE = \frac{1}{2}[(m_f v_f^2 + m_w v_w^2 - \frac{(m_f v_f + m_w v_w)^2}{m_f + m_w}] \tag{2}$$

The gain in strain energy can be obtained by integrating the contact force F_c from the start of the collision to the point where the maximum deformation is reached.

$$SE = \int_0^{\delta_{max}} F_c \, dx \tag{3}$$

In equation (3), F_c is given by kx, where k is the spring stiffness and x denotes the deflection of a workpiece.

The energy loss due to structural damping can be found by integrating of the maximum deformation with respect to the body deflection x.

$$LE = \int_0^{\delta_{max}} F_d \, dx \tag{4}$$

In equation (4), F_d is given by $C_{eff} v_{fw}$, where v_{fw} is relative velocity of the finger with respect to the workpiece and C_{eff} is the effective damping coefficient that corresponds to the relative velocity .

When two bodies collide squarely in a plane, there is a linear relationship between the contact force F_c and the body deflection x. The maximum contact force $F_{c(max)}$ for the case of linear deformation can be obtained by equation (2), (3), and (4) as follows:

$$F_{c(max)} = \sqrt{\frac{b^2}{4a^2} + \frac{\Delta KE}{a}} - \frac{b}{2a} \tag{5}$$

$$a = \frac{1}{2k_{eff}}, \qquad b = 0.03\sqrt{\frac{m_{eff}}{k_{eff}}}\, v_{fw}$$

where, k_{eff} is the effective linear stiffness of two bodies, m_{eff} is the effective mass that is deforming during the collision and can be expressed as

$$m_{eff} = \frac{m_f v_f^2 + m_w v_w^2 - (m_f v_f + m_w v_w)^2/(m_f + m_w)}{v_{fw}^2} \tag{6}$$

3. Dynamic Model of Contact Tasks

In this paper, one dimensional pushing operation for realizing stable force control is employed as a model with impulsive contact force. To simplify the model, the robot hand and actuator are considered as rigid bodies with no vibrational modes. Figure 2 shows the model of robot hand system.

From this model, the following dynamical equations are derived.

$$m_a \ddot{x}_a = F - k_a x_a - b_a \dot{x}_a - k_f(x_a - x_f) - b_f(\dot{x}_a - \dot{x}_f) \tag{7}$$

$$m_f \ddot{x}_f = k_f(x_a - x_f) + b_f(\dot{x}_a - \dot{x}_f) - k_s(x_f - x_s) - b_s(\dot{x}_f - \dot{x}_s) \tag{8}$$

$$m_s \ddot{x}_s = k_s(x_f - x_s) + b_s(\dot{x}_f - \dot{x}_s) - F_c \tag{9}$$

$$m_w \ddot{x}_w = F_c - k_w x_w - b_w \dot{x}_w \tag{10}$$

In the above equations,

m_a : Mass of the actuator
k_a : Equivalent stiffness of the actuator
b_a : Equivalent damping coefficient of the actuator
m_f : Mass of robot hand
k_f : Equivalent stiffness of the robot hand
b_f : Equivalent damping coefficient of the robot hand
m_s : Mass of the force sensor
k_s : Equivalent stiffness of the force sensor
b_s : Equivalent damping coefficient of the force sensor
m_w : Effective moving mass of the workpiece
k_w : Equivalent stiffness of the workpiece
b_w : Equivalent damping coefficient of the workpiece

And F_c is impulsive contact force which is obtained by equation (5).

The state and output equations will now have the usual form :

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t) + \mathbf{F_c} \tag{11}$$

$$y(t) = \mathbf{C}\mathbf{x}(t) \tag{12}$$

For the case of contact force control , the state vector is given by

$$\mathbf{x} = \begin{bmatrix} \text{Actuator position} \\ \text{Actuator velocity} \\ \text{Hand position} \\ \text{Hand velocity} \\ \text{Tip position} \\ \text{Tip velocity} \\ \text{Workpiece position} \\ \text{Workpiece velocity} \end{bmatrix}$$

so that

$$\mathbf{x}(t) = [x_a(t)\ \dot{x}_a(t)\ x_f(t)\ \dot{x}_f(t)\ x_s(t)\ \dot{x}_s(t)\ x_w(t)\ \dot{x}_w(t)]^T$$

The **A**, **B**, and **C** matrices and vector $\mathbf{F_c}$ are given by

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{k_a+k_f}{m_a} & -\frac{b_a+b_f}{m_a} & \frac{k_f}{m_a} & \frac{b_f}{m_a} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{k_f}{m_f} & \frac{b_f}{m_f} & -\frac{k_f+k_s}{m_f} & -\frac{b_f+b_s}{m_f} & \frac{k_s}{m_f} & \frac{b_s}{m_f} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{k_s}{m_s} & \frac{b_s}{m_s} & -\frac{k_s}{m_s} & -\frac{b_s}{m_s} & 0 & c \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{k_w}{m_w} & -\frac{b_w}{m_w} \end{bmatrix}$$

$$\mathbf{B} = \left[0\ \frac{1}{m_w}\ 0\ 0\ 0\ 0\ 0\ 0\right]^T$$

$$\mathbf{C} = [0\ 0\ k_s\ b_s\ -k_s\ -b_s\ 0\ 0]$$

$$\mathbf{F_c} = \left[0\ 0\ 0\ 0\ 0\ -\frac{F_c}{m_s}\ 0\ \frac{F_c}{m_w}\right]^T$$

In the output equation (12), the output variable y(t) is the contact force which is the force across the force sensor.

4. VSS Approach to Control System Design

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 workpieces

4.1 Sliding Mode control

We first briefly summarized the basic concepts of sliding mode control. Sliding mode control is characterized by discontinuous control which changes structures on reaching a set of predetermined switching surfaces in the state space [6] [7]. Here a general type is considered, and represented by

$$\dot{\mathbf{x}}(t) = \mathbf{f}(x,t) + \mathbf{B}(x,t)u(t) \tag{13}$$

where $\mathbf{x}(t), \mathbf{f}(x,t) \in R^n$, $u(t) \in R^n$, $\mathbf{B} \in R^{n\times n}$.

The control input has the form of

$$u_i(x,t) = \begin{cases} u_i^+(x,t) & \text{if } s_i(x) > 0 \\ u_i^-(x,t) & \text{if } s_i(x) < 0 \end{cases} \tag{14}$$

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

$$s = \sum_{i=1}^{m} c_i x_i \tag{15}$$

$$c_i = \text{const}, \qquad c_m = 1$$

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 ith hypersurface is

$$\lim s_i(x)\dot{s}_i(t) < 0 \tag{16}$$

In the sliding mode, the system satisfies the equation

$$s_i(x) = 0 \quad \text{and} \quad \dot{s}_i(x) = 0 \tag{17}$$

Equation (16) 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 Design of Force Controller

In this section, we will design the VSS force controller based on the above mentioned sliding mode. Figure 3 depicts the block diagram of the VSS force control system of robot hand.

Consider again system (11) and (12)

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t) + \mathbf{F}_c \tag{18}$$

$$y(t) = \mathbf{C}\mathbf{x}(t) \tag{19}$$

where u(t) is the control input, y(t) is the force output, and $\mathbf{x}(t)$ is the state vector. These are already defined in the previous section 3. In the above equation matrix **A** is not exactly known because parameters k_w and b_w are uaually unknown, but the imprecision $|A|$ is upper bounded by a known parameter.

$$k_{w(min)} \le k_w \le k_{w(max)}$$

$$b_{w(min)} \le b_w \le b_{w(max)} \tag{20}$$

And $\mathbf{F}_c$ represents impulsive contact force with disturbances. It is unknown but bounded in absolute value which is obtained by equation (5).

The control problem is to pick up u(t) as a function of the measured x(t) so as to have

$$e(t) = y_d(t) - y(t) \tag{21}$$

go to zero, where y_d is the desired output. The VSS force controller is designed by using sliding mode.

Here, the following sliding switching surface is selected:

$$s = ce(t) + \dot{e}(t), \quad c > 0 \tag{22}$$

The control input u(t) is composed of nonlinear compensation and sliding mode term as follows

$$u(t) = u_{eq}(t) + \Delta u(t) \tag{23}$$

where, $u_{eq}(t)$ is equivalent control input when $\dot{s} = 0$. From equations (18) and (22), the equivalent control input $u_{eq}(t)$ is obtained. And sliding mode term $\Delta u(t)$ is chosen as follows :

$$\Delta u(t) = \phi_i x_i + \delta \mathrm{sgn}(s), \quad i = 1, \cdots, 8 \tag{24}$$

From the existence condition of sliding mode $s\dot{s} < 0$, each coefficients of equation (24) must be chosen to satisfy the following inequalities.

$$\phi_i = \begin{cases} \phi_i^+ & \text{if } sx_i > 0 \\ \phi_i^- & \text{if } sx_i < 0 \end{cases}, \qquad \delta > 0 \tag{25}$$

5. Simulation Result

In order to examine the performance of the proposed VSS force controller, some simulations are carried out for the one dimensional pushing system which is modeled with impulsive contact force. The simulation sequence of contact force control is as follows : (a) approach a robot hand to the workpiece with constant velocity, (b) apply impact force with high peak to the system with disturbance as soon as the robot hand come into contact with workpiece [Figure 4 (a)].

Figure 4(b) shows the time response of controlled contact force performance. The simulation result is very good in spite of impact force with high pick during the transition between the no-interaction and interaction situation. However, a small overshoot occur during the transient. It will be removed by redesigning the VSS controller.

6. Conclusion

In this paper, the contact force control of robot hand under system with impact is investigated by using the variable structure systems. A simple energy analysis is used to model the impact. According to the simulation result, the proposed VSS force controller is shown to give the force control good performance and impact rejection characteristics.

In future, we will conduct experimental tests by using the proposed method.

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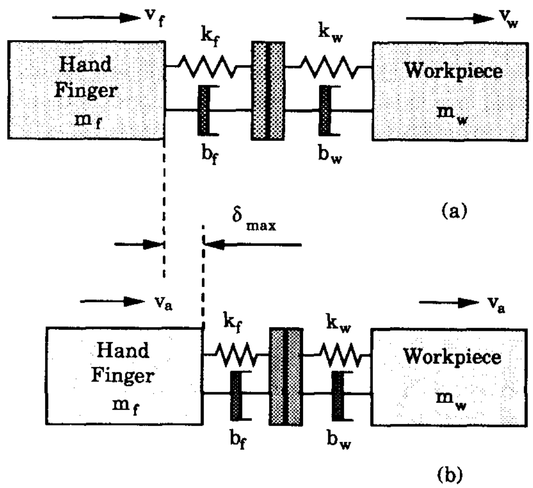

Figure 1. A model of robot hand colliding with a workpiece
(a) Just before collision, Deformation = 0
(b) During collision at the maximum deformation, Deformation = δ_{max}

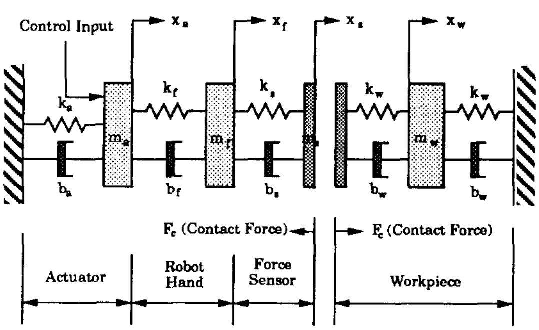

Figure 2. Dynamical model of robot hand for contact tasks

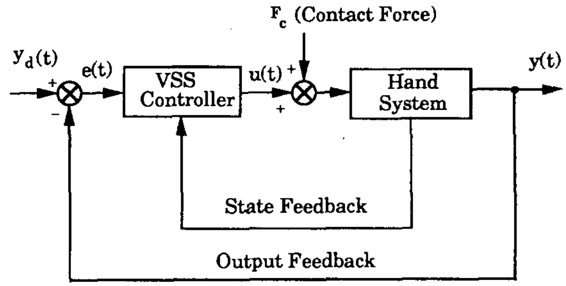

Figure 3. Block diagram of VSS force controller

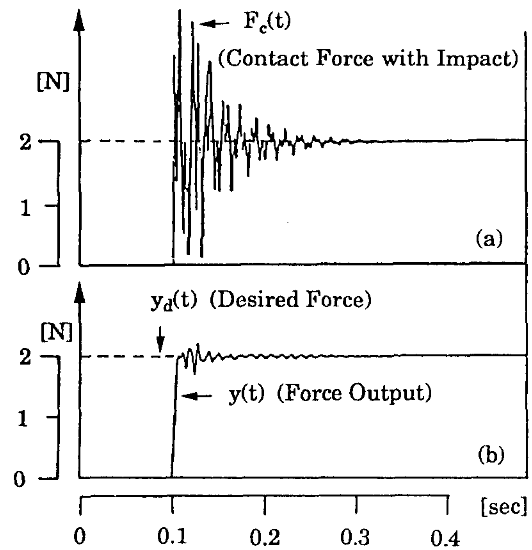

Figure 4. Simulation result for pushing operation of robot hand
(a) Contact force with impact
(b) Time response of contact force