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Design of a Teleoperation Controller for an Underwater Manipulator

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Abstract

A robust teleoperation controller design method for an underwater manipulator is proposed considering the master and the underwater slave separately. To achieve transparency and stability for a teleoperation of an underwater manipulator in unknown environments with time-varying uncertainties such as added mass, buoyancy, hydraulic drag and friction effect, an adaptive sliding mode control scheme is proposed for robust position tracking control of slave manipulator. To guarantee a force transparency in the master side, disturbance observer is used as a local controller for compensating a friction and coupled nonlinear dynamic effects of the master manipulator. Numerical simulations are performed to demonstrate the transparency and robustness of the proposed controller.

1. Introduction

Underwater robotic manipulators, mounted on remotely operated vehicles (ROVs), have an important role to play in shallow or deep water missions for marine science, oil and gas survey, exploration and military applications [1,2].

The manipulators are usually operated in a master slave configuration by an operator on the surface vessel. The movement of the small master arm is replicated by the large slave arm forming a spatially correspondent system. However, in the underwater, the operator's perception from the video camera has poor quality and it degrades performance dramatically about the operations such as debris removal are performed.

With such a poor vision, force reflection can give the operator comfort and confident underwater work capability. However, in underwater manipulator systems, the bilateral force reflecting control structure usually shows limited position force tracking performance and control stability problem due to unknown underwater environments with uncertainties such as added mass, buoyancy, hydraulic drag and friction effect.

To achieve transparency for teleoperation in unknown environments, classes of adaptive bilateral control schemes have been suggested in [3,4,5]. However, the validity of the adaptive control scheme is based on the assumption that the system and environment parameters are constant and there is no time-varying external disturbance. Thus, the adaptive bilateral control schemes are not suitable to the underwater manipulator system, which has time-varying uncertainties. To deal with the teleoperation systems, which have time-varying parameters and external disturbances, teleoperation control schemes based on the sliding mode control strategy have been addressed in [6,7]. In the sliding mode control design, however, the bounds of uncertainties and external disturbances are also assumed to be available. However, in underwater manipulator systems, the bound on the uncertainties may not be easily obtained. Thus, new control architecture is needed for the teleoperation of underwater manipulator systems whose parameters are composed of a large, fixed component and a small, bounded uncertain component.

In this paper, a robust teleoperation controller is proposed based on the position-force architecture. Adaptive sliding mode control scheme is proposed for robust position tracking control of an underwater manipulator in unknown environments (large fixed components) with time-varying uncertainties (small bounded components). The proposed adaptive sliding mode control law combines the merits of adaptive control of Slotine and Li [9] and sliding mode control of Su and Leung [10] to obtain the best of both approaches. Adaptive controller estimate the large fixed uncertain parameters and sliding mode control compensate the small bounded uncertainties, in an adaptive manner. The Similar approach has been proposed by Chong [8] for the tracking problem of a single robotic manipulator. In addition, a disturbance observer is used as a local controller of the master to improve the force transmission capability. By removing friction and coupled nonlinear dynamics of the master manipulator, force transparency can be guaranteed.

2. Teleoperation System for an Underwater Manipulation

Fig. 1 shows the master/slave system for an underwater manipulation, where x_m and x_s means the displacements of the master and slave arm respectively. f_m denotes the force that the operator applies to the master arm, and f_s denotes the force that the slave arm applies to the object. The force f_s is measured by the force/torque sensor, which is attached at the end of underwater manipulator. f_{ex} denotes external disturbances which exist under the sea.

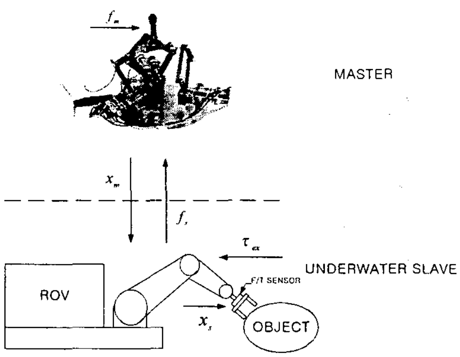

Fig. 1 Master/Underwater slave schematic diagram

To achieve a transparency, displacement of the underwater manipulator (x_s) should track the master position command (x_m), even though there exist unknown external disturbances, and f_m should be equal to the measured force at the slave side (f_s).

If added mass, buoyancy, hydraulic drag and friction are added on the underwater manipulator dynamics, dynamic equation of an underwater manipulator which has n joints, is as follows:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(q,\dot{q}) + D(q,\dot{q}) = \tau_s - J_s^T f_s \quad (1)$$

where $q \in R^{n\times 1}$ is the joint angular position, $H(q) \in R^{n\times n}$ is the symmetric positive-definite inertia matrix which includes added mass terms, $C(q,\dot{q}) \in R^{n\times n}$ denotes the coriolis, centrifugal forces which include added mass terms, $G(q) \in R^{n\times 1}$ represents the gravity forces which include buoyancy effects, $F(q,\dot{q}) \in R^{n\times 1}$ is the friction terms which is increased by sealing the joint, $D(q,\dot{q}) \in R^{n\times 1}$ is the hydraulic drag forces which caused by the relative velocity of manipulator to ocean current and waves, $\tau_s \in R^{n\times 1}$ is the vector of applied joint torques which are actually control inputs, $J_s \in R^{n\times n}$ is the Jacobian matrix of slave manipulator and $f_s \in R^{n\times 1}$ denotes the force that the slave arm applies to the object.

The dynamics of the environment are assumed to be second-order models

$$M_e \ddot{x}_e + D_e \dot{x}_e + K_e x_e = f_s - f_{ex}^* \quad (2)$$

where M_e, D_e and K_e are 6×6 positive-definite matrices associated with inertia, damping and stiffness, respectively. x_e is the displacement of the environment including deformation. f_{ex}^* denotes the exogenous force/moment generated by the environment. However, environment is considered as a passive system, thus, $f_{ex}^* = 0$. Note that, x_e is equivalent to x_s, when the manipulator doing the works in contact with the environments.

From (1) and (2), the dynamics of the slave robot incorporating the environment is written as:

$$(\Pi^T M \Pi)\ddot{x}_s + (\Pi^T B \Pi + \Pi^T M \dot{\Pi})\dot{x}_s + \Pi^T g = J_s^{-T}\tau_s \quad (3)$$

where

$$\Pi = \begin{bmatrix} J_s^{-1} \\ I_6 \end{bmatrix}, \quad M = \begin{bmatrix} H & 0 \\ 0 & M_e \end{bmatrix}, \quad B = \begin{bmatrix} C & 0 \\ 0 & 0_6 \end{bmatrix},$$

$$g = \begin{bmatrix} G + F + D & 0 \\ 0 & D_e \dot{x}_s + K_e x_s \end{bmatrix}.$$

3. Adaptive Sliding Mode Controller for an Underwater Manipulator

A robust tracking controller for an underwater manipulator is proposed based on the adaptive sliding mode control strategy.

We assume that the bounded uncertainties of the underwater manipulators are of the form

$$H = H_0 + \Delta H \quad (4)$$

$$C = C_0 + \Delta C \quad (5)$$

$$G = G_0 + \Delta G \quad (6)$$

these uncertainties caused by the added mass and buoyancy effects. Substituting the expressions (4)-(6) into the dynamics (3) give rise to

$$(\Pi^T M_0 \Pi)\ddot{x}_s + (\Pi^T B_0 \Pi + \Pi^T M_0 \dot{\Pi})\dot{x}_s + \Pi^T g_0 = J_s^{-T}\tau_s + J_s^{-T}\rho \quad (7)$$

where

$$M_0 = \begin{bmatrix} H_0 & 0 \\ 0 & M_e \end{bmatrix}, \quad B_0 = \begin{bmatrix} C_0 & 0 \\ 0 & 0_6 \end{bmatrix},$$

$$g_0 = \begin{bmatrix} G_0 & 0 \\ 0 & D_e \dot{x}_s + K_e x_s \end{bmatrix},$$

with

$$\rho = -\Delta H \ddot{q} - \Delta C \dot{q} - \Delta G - F - D \quad (8)$$

representing all the uncertain terms. When $\rho = 0$, we call the dynamics as the 'nominal dynamics' of the underwater manipulator incorporating the environment. $M > 0$ and C is skew symmetric.

Some mild assumptions are made prior to further discussion. These assumptions are usually satisfied in practices.

Assumptions

1. The matrix H is bounded and invertible, i.e., for some arbitrary constant γ^h

$$\|H(q)\| < \gamma^h, \tag{9}$$

and H^{-1} exists.

2. The vector $B(q,\dot{q})$ and $G(q)$ satisfy

$$\|C(q,\dot{q})\dot{q}\| < \gamma_0^c + \gamma_1^c\|q\| + \gamma_2^c\|\dot{q}\|^2 \tag{10}$$

$$\|G(q)\| < \gamma_0^g + \gamma_1^g\|q\|. \tag{11}$$

3. Generally, viscous and Coulomb friction forces may be modeled as $F_v\dot{q} + F_c\, sgn(\dot{q})$. Therefore, friction effect satisfy

$$\|F\| < \gamma_0^f + \gamma_1^f\|q\| + \gamma_2^f\|\dot{q}\|^2. \tag{12}$$

4. The hydraulic drag forces cab be bounded as

$$\|D\| < \gamma_0^d + \gamma_1^d\|q\| + \gamma_2^d\|\dot{q}\|^2, \tag{13}$$

where $\gamma^h, \gamma_0^c, \gamma_1^c, \gamma_2^c, \gamma_0^g, \gamma_1^g, \gamma_0^f, \gamma_1^f, \gamma_2^f, \gamma_0^d, \gamma_1^d$ and γ_2^d are positive constants.

5. the form of the control input vector τ_s is chosen such that the norm of the control input vector τ_s satisfies the following inequality:

$$\|\tau_s\| < \lambda_0 + \lambda_1\|q\| + \lambda_2\|\dot{q}\|^2, \tag{14}$$

where λ_0, λ_1 and λ_2 are arbitrary positive numbers.

With the mild assumptions, the following lemma is derived which will be very useful for later derivation of the robust adaptive controller for underwater manipulators.

If the above assumptions are satisfied, then the uncertainty term ρ satisfies

$$\|\rho\| < b_0 + b_1\|q\| + b_2\|\dot{q}\|^2, \tag{15}$$

where b_0, b_1 and b_2 are positive constants.

The parameters of the dynamics of an underwater manipulator incorporating the environment are composed of large, fixed components such as manipulator parameters and environment parameters, and small, bounded uncertain components such as added mass, buoyancy, friction and hydraulic drag forces.

In order to achieve transparency for teleoperation of underwater manipulator, a class of indirect adaptive sliding mode bilateral control scheme is developed based on the adaptive sliding mode control.

To analyze the convergence of the sliding function to the sliding surface, let the sliding function be

$$\varphi = \dot{e} + \Lambda e = x_s - \dot{x}_r \tag{16}$$

where $\dot{x}_r = \dot{x}_m - \Lambda e$, and x_m is the desired trajectory command coming from the master, while Λ is a positive constant matrix.

Assume that there exists a vector $\alpha \in R^{m \times 1}$ with components depending on the manipulator and environment parameters (masses, moments of inertia, etc.), such that

$$M_0 \frac{d}{dt}(\Pi \cdot \dot{x}_r) + B_0 \cdot \Pi \cdot x_r + g_0 = \Phi_r \cdot \alpha \tag{17}$$

where $\Phi \in R^{n \times m}$ is called a regressor matrix [9].

The control torque and the update laws given below, ensure convergence of the sliding function to the sliding surface:

$$\tau_s = J_s^T(\Pi^T \cdot \Phi_r \cdot \hat{\alpha} + K_d\varphi + \tau_d), \tag{18}$$

$$\tau_d = \frac{\hat{\eta}_1\varphi + \hat{\eta}_2\|q\|\varphi + \hat{\eta}_3\|\dot{q}\|^2\varphi}{\|\varphi\|}, \tag{19}$$

update laws

$$\dot{\hat{\alpha}} = \Gamma(\Phi_r^T \cdot \Pi \cdot \varphi + W^T \cdot \Pi \cdot E_w), \tag{20}$$

$$\dot{\hat{\eta}}_1 = \Omega_1\|\varphi\|, \tag{21}$$

$$\dot{\hat{\eta}}_2 = \Omega_2\|q\| \cdot \|\varphi\| \tag{22}$$

$$\dot{\hat{\eta}}_3 = \Omega_3\|\dot{q}\|^2 \cdot \|\varphi\| \tag{23}$$

where W is the filtered version of Φ, the regressor matrix. As a result,

$$W(x_s, \dot{x}_s) = \frac{\lambda_f}{s + \lambda_f}[\Phi(x_s, \dot{x}_s, \ddot{x}_s)], \tag{24}$$

and E_W is the filtered prediction error of the filtered input τ_{sw} as follows:

$$E_W = J_s^{-T}\tau_{sw} - \Pi^T W\hat{\alpha} \tag{25}$$

K_d and Γ are constant positive definite matrices, and Ω_1, Ω_2 and Ω_3 are the positive learning constants for η_1, η_2 and η_3.

To analyze the convergence of the sliding function to the sliding surface, the Lyapunov candidate

$$V = \frac{1}{2}\left[\begin{array}{l}(\Pi\varphi)^T \cdot M_0 \cdot (\Pi\varphi) + \tilde{\alpha}^T \Gamma^{-1}\tilde{\alpha} + \frac{(\eta_1 - \hat{\eta}_1)^2}{\Omega_1} \\ + \frac{(\eta_2 - \hat{\eta}_2)^2}{\Omega_2} + \frac{(\eta_3 - \hat{\eta}_3)^2}{\Omega_3}\end{array}\right] \tag{26}$$

is chosen. Where $\tilde{\alpha} = \alpha - \hat{\alpha}$. Using the equations (7) ~ (25), the following is obtained.

$$\dot{V} \le -\varphi^T \cdot K_d \cdot \varphi - \tilde{\alpha}^T \cdot W^T \cdot \Pi \cdot \Pi^T \cdot W \cdot \tilde{\alpha} \tag{27}$$

Therefore, the dynamic system defined by (7) ~ (25) satisfies the convergence of the sliding function to the sliding surface $(\varphi = 0)$. That is, the underwater manipulator can track the master position commands with robustness.

4. Disturbance observer for Master Hand Controller

A control structure known as a disturbance observer has been used to improve the robustness and to simplify both force and position robotic control algorithms [11,12,13]. The effectiveness of a disturbance observer is investigated for achieving the transparency.

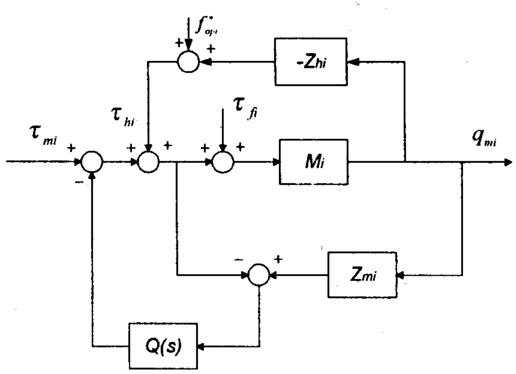

Fig. 2 Structure of disturbance observer for the master

Fig. 2 shows a structure of the disturbance observer for the ith axis of the master. In Fig. 2, M_i is the master plant, Z_{mi} is the desired master impedance and Z_{hi} is the human impedance. $Q(s)$ is a low-pass filter which is employed to realize Z_{mi} and to reduce the effect of measurement noise.

The disturbance observer loop shown in Fig. 2 is used to enforce a robust linear input/output behavior of the master by canceling disturbances and plant/model mismatch. This can be seen by looking at the transfer functions from the master input (τ_{mi}), disturbance (τ_{fi}) and human intention force (f^{*}_{opi}) to the output of the master, q_{mi}.

$$q_{mi} = G_{fq}\tau_{fi}(s) + G_{\tau q}\tau_{mi}(s) + G_{hq}f^{*}_{opi}(s) \tag{28}$$

where

$$G_{fq} = \frac{M_i(1-Q)}{M_i Z_{hi} + 1 + Q(M_i Z_{mi} - 1)}, \tag{29}$$

$$G_{\tau q} = \frac{M_i}{M_i Z_{hi} + 1 + Q(M_i Z_{mi} - 1)}, \tag{30}$$

$$G_{hq} = \frac{M_i}{M_i Z_{hi} + 1 + Q(M_i Z_{mi} - 1)}, \tag{31}$$

suppose $Q(s)$ is a low pass filter with the steady state gain of 1. In this case, evaluating the transfer function in the low frequency range $(Q(s) \approx 1)$ gives: $G_{fq}(s) \approx 0$, $G_{\tau q}(s) \approx 1/(Z_{hi} + Z_{mi})$ and $G_{hq}(s) \approx 1/(Z_{hi} + Z_{mi})$. This indicates that low frequency disturbances are canceled and plant/model mismatch is compensated for command signals of the low frequency range. This work used a 3rd order binomial low-pass filter as shown in (32).

$$Q(s) = \frac{3\left(\tau_c s + \frac{1}{3}\right)}{(\tau_c s + 1)^3} \tag{32}$$

Finally, in the low frequency range, the master system can be expressed as follows:

$$\tau_{hi} = Z_{mi} q_{mi} - \tau_{mi} \tag{33}$$

Therefore, the master system becomes uncoupled linear dynamic system by removing friction and coupled nonlinear dynamics with the disturbance observer.

5. Adaptive Transparency

In Section 3, the robust tracking control of the underwater manipulator, regardless of the role of the master and the operator, has been studied. In Section 4, the force control of the master is addressed. In this section, the application of the adaptive sliding mode controller for the slave and the disturbance observer for the master have been combined and the total system controller has been analyzed. The control and adaptation laws for this system are governed by (18) ~ (23). Now, consider the general block diagram of a teleoperation system, which is expanded to the multi-DOF case and include local force feedback presented in Fig. 3. C_1, C_2, C_3, C_4, C_m and C_s provide feed-forward and feedback signals to control the system bilaterally. $\dot{x}_m$ and $\dot{x}_s$ are the velocities of the operator's hand and of the slave end-effector. $f_{op}^{*}, f_h, f_s, f_{ex}^{*}$ are the intention force generated by the operator, the force applied to the master by the operator, the force exerted by the slave to the environment and the exogenous force generated at the environment, respectively.

If the control input of the master, τ_{mi} in (33) is given as

$$\tau_{mi} = \hat{Z}_{mi} q_{mi} - \sum_{j=1}^{n} (J_m^T)_{ji} f_{si}, \quad (34)$$

the force, f_{hi} can be represented as follows:

$$\sum_{j=1}^{n} (J_m^T)_{ji} f_{hi} = (Z_{mi} - \hat{Z}_{mi}) q_{mi} + \sum_{j=1}^{n} (J_m^T)_{ji} f_{si} \quad (35)$$

where Z_{mi} is the known desired master impedance. If $\hat{Z}_{mi}$ can be taken as Z_{mi}, operator can feel the force, f_{si} exactly. However, the first order estimation of Z_{mi} is used as the $\hat{Z}_{mi}$ to avoid the use of the acceleration measure. Then, the force transparency ($f_{hi} = f_{si}$) is guaranteed only in the low frequency.

C_1 and C_s are determined by the adaptive sliding mode control strategy utilized at the slave, and C_2, C_5 and C_m are obtained by applying the disturbance observer based force control (34) for the master. Since no local force feedback is provided at the slave, $C_6 = 0$, and $C_3 = C_4 = 0$.

To shows the meaning of the proposed teleoperation scheme, the controller is analyzed about 1-DOF master/slave system. Each gain is gives as follows:

$$C_1 = (\hat{m}_s + \hat{m}_e)s + (\hat{b}_s + \hat{b}_e) + \hat{C}, \quad (36)$$

$$C_s = \hat{C} - \frac{\hat{k}_e}{s}, \quad (37)$$

$$C_2 = 1, \quad (38)$$

$$C_3 = C_4 = 0, \quad (39)$$

$$C_m = -\hat{Z}_m, \quad (40)$$

$$\hat{C} = (\hat{m}_s + \hat{m}_e)K_d + \Lambda + \frac{K_d(\hat{b}_s + \hat{b}_s + \Lambda)}{s}, \quad (41)$$

where $\hat{m}_s, \hat{m}_e, \hat{b}_s, \hat{b}_e, \hat{k}_e$ are the estimated slave mass, environment mass, slave damping, environment damping and environment stiffness parameters.

Assume that the parameter uncertainties are completely compensated by parameter adaptation and the disturbance observer. Then, by inserting the proposed adaptive controller, (36) ~ (41) to the two-port hybrid model [14], the master and slave closed-loop dynamics can be expressed as follows:

$$f_h = J_m^{-T}(Z_m - \hat{Z}_m)q_m + f_s \quad (42)$$

$$\left((m_s + m_e)s + (b_s + b_e) + \hat{C} + \left(\frac{k_e - \hat{k}_e}{s}\right)\right)\dot{x}_s = -(\hat{m}_t s + \hat{b}_t + \hat{C})\dot{x}_m \quad (43)$$

If $\hat{Z}_m = Z_m$ and $\hat{m}_s, \hat{m}_e, \hat{b}_s, \hat{b}_e, \hat{k}_e$ converge to their true values, then eventually transparency is achieved.

6. Numerical Simulation Results

Consider the system with

$$Z_m = 2s + 0.2\,(Ns/m)$$
$$Z_s = (2 + m_{ad})s + 0.2 - d\,(Ns/m),$$
$$Z_{op} = s + 50 + 2000/s(Ns/m)$$
$$Z_e = 50 + 1000/s(Ns/m),$$

where added mass, $m_{ad} = 5(1 - cos(2\pi t))$ and disturbance, $d = 30\,cos(2\pi t)$. The operator's hand force f_h^{*} is given as $f_{op}^{*} = 200\left(1 - cos\left(\frac{\pi}{2}t\right)\right) + 50\left(sin\left(\pi\left(\frac{\pi}{4}t\right) + sin\left(\frac{\pi}{8}t\right)\right)\right)$.

Assuming the system to be initially at rest and choosing $\Lambda = 70$, $K_d = 100$, $\Gamma = diag[2, 20, 2000]$, $\Omega_1 = 100$, $\Omega_2 = 200$, $\Omega_3 = 200$ and $\lambda_f = 100$.

Free Motion

The underwater manipulator tracks the position commands from the master without contact the environments. Fig. 4 shows the robust position/force tracking performance of the underwater manipulator, even though time-varying uncertainties exist. There is no interaction force with an environment, but operator feels master impedance at high frequency, which could not be canceled with (40).

Continuous Contact

The underwater manipulator is touching the surface of a fairly soft object characterized by Z_e. The force input f_h^{*} is applied at the master side to make the slave press against the object without losing the contact. Fig. 5 shows the robust position/force tracking performance in continuous contact motion.

Intermittent Contact

The slave start at $x_s = 0$ moving towards the same object located at $x_s = 0.1$. About $1sec$ after, the underwater manipulator contacts the object and the slave moves with contact continuously until it detaches from the object. Similar to the continuous contact simulation, the proposed teleoperation controller shows robust position/force tracking performance in Fig. 5.

7. Conclusions

A robust teleoperation controller design method for an underwater manipulator is presented by treating the master and the underwater slave separately. By using an adaptive sliding mode control scheme for robust position tracking control of slave manipulator, transparency and stability is obtained for a teleoperation of underwater manipulator in unknown environments, even though there exist time-varying uncertainties. Disturbance observer is used as a local controller to gives a force transparency in the master side. Numerical simulations have shown excellent position and force tracking performance. Therefore, it can be said that the transparency of the underwater manipulator system has been obtained.

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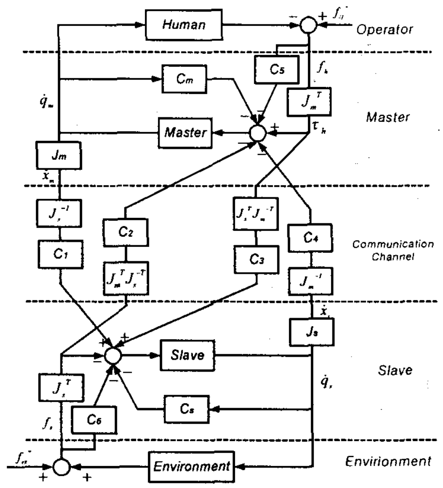

Figure 3 General block diagram of a bilateral controlled system

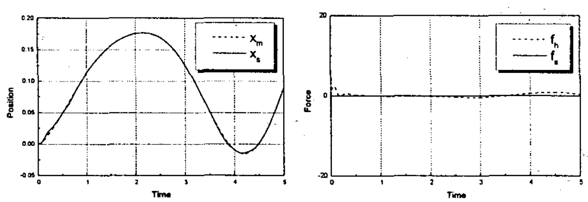

Fig. 4 Free motion simulation

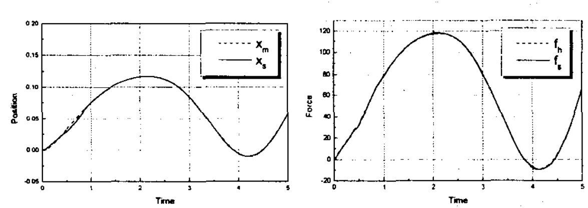

Fig. 5 Continuous contact simulation

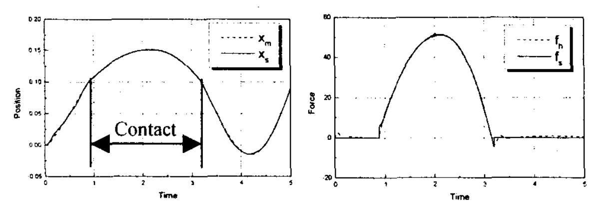

Fig. 6 Intermittent contact simulation