Force Control in Cooperative Space Robot through a Virtual Foundation

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ABSTRACT

Space robots perform tasks requiring mechanical interactions with environments or compliant objects, encounter force and motion constraint leading to tracking errors and uncontrolled forces at their end effectors. Using compliant finger, humans easily manipulate fragile and flexible objects without letting them to slip or crush. During the dynamic interactions, there exists a demand for the accurate control of forces at an upper limiting value or a lower limiting value. This paper presents a methodology for lower limit force control during manipulation of a rigid body by two cooperative space robots.

1.0 Introduction

An ideal approach to force control of robotic system is by impedance modulation strategy. The impedance of the system at an interaction port is defined as the ratio between the output effort and the input flow. For applications demanding high trajectory tracking accuracy, the robotic systems are programmed to have high impedance at the end-effector. This leads to poor accommodation of external disturbances during interaction, and hence control of interaction forces is difficult. However, it is desired to have a balance of both the characteristics, i.e., good trajectory robustness, and accommodation to environment interaction forces or torques. This is achieved by controlling the impedance appropriately instead of controlling the position or the force separately. The use of passive degree of freedom (DOF) in controller domain for control of interaction forces between robot tip and environment has been shown in literature [1]. This passive DOF was termed as virtual foundation. The use of virtual foundation to control the interaction force between space robot tip and environment is illustrated in literature [2]. The dynamics and modeling of space robots is discussed in literature [3-6]. Researchers have investigated the coordinative adaptive control [7] problem of two-space robot holding a common object on the basis of virtual decomposition. The design optimization and development of cooperative microrobots [8] are done by microstereophotolithography, actuated by shape memory alloy (SMA) wire micrometer. The concept of force control through virtual dissipative foundation [9] for the cooperative manipulation of compliant object with the existence of system damping to quench the self excited oscillations of the body has been discussed in literature. Hybrid Position/ force control of two cooperative flexible manipulators working in 3D Space is studied in [10].

In present work two single DOF cooperative space robots are considered. These cooperative space robots manipulate a floating rigid object of unknown mass over a prescribed trajectory. A bond graph [11] model of a cooperative space robot has been developed. It then extends the impedance control methodology shown in [2] for the cooperative space robot. When two cooperative space robots manipulate a rigid object, interaction forces are developed between the robot tip and the object due to the acceleration of the object. During this manipulation minimum gripping force is maintained by impedance control to prevent the object from slipping. Simulation studies have been carried out to validate the modelling. The bond graph modeling, and simulation is performed using SYMBOLS2000 [12], a bond graph modelling software.

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2.0 Theory of Virtual Foundation

In a robotic system sometimes additional DOF are incorporated in the manipulator (like a flexible foundation) for specific purposes. If these additional DOF are suitably designed and incorporated, they can be made to provide a desired accommodation of the external disturbing forces that arise during interaction. Let us consider a single DOF ground robot on flexible foundation, interacting with environment as shown in Fig.1. The foundation compensation is so designed that its impedance can be modulated to limit the forces of interaction. The bond graph for the system is shown in Fig.2. The controller consists of two subparts. First part has an effort-to-effort amplifier and a velocity feedback device. The second part is in computational domain. In this figure f_{ref} is the reference velocity command and $F_{dis}(t)$ is the foundation disturbance force. To incorporate the foundation disturbances in the inertial coordinates, the foundation velocity is sensed and feedback to the controller. A flow-activated transformer between the bonds 13 and 14 with modulus α shows the feedback compensation.

The transfer function between the output flow $f_{rob}(s)$ (i.e. the motion of the end-effector) and the input effort $e_{env}(s)$ (by the environment on the robot), represents the admittance $Y_{rob}(s)$ of the robotic system at the interaction port. The impedance $Z_{rob}(s)$ is the inverse of the admittance. From the bond graph shown in Fig. 2, the admittance at the interaction port can be derived as,

$$Y_{rob}(s)=\frac{1}{Z_{rob}(s)}=\frac{f_{rob}(s)}{e_{env}(s)}=\frac{f_1(s)}{e_{20}(s)}\frac{R(s)[1+\mu_H(1-\alpha)F(s)C(s)]}{1+\mu_H C(s)R(s)+\mu_H(1-\alpha)F(s)C(s)} \quad (1)$$

Here $R(s)=1/(m_p s)$ is transfer function of the robot, $C(s)=(M_c s^2+R_c s+K_c)/s$ is transfer function of the controller, and $F(s)=s/(M_f s^2+R_f s+K_f)$ is transfer function of the foundation. The effect of α, on the impedance or stiffness of the robot can be observed at the interaction port by studying response of the system to a constant environmental effort E.

Let $e_{env}(t)=E$, so $e_{env}(s)=E/s$.

End-effector displacement $X_{rob}(t)$ is obtained as the integral of its velocity $f_{rob}(t)$. Hence from Eq.(1)

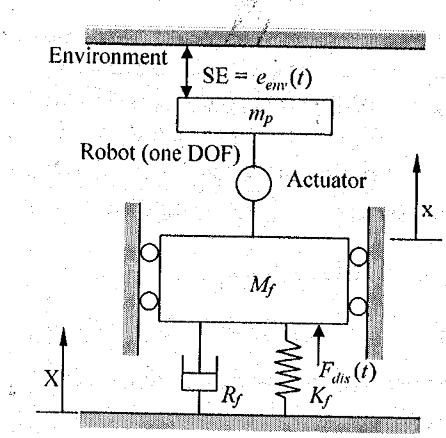

Figure 1: Single DOF robot on flexible foundation

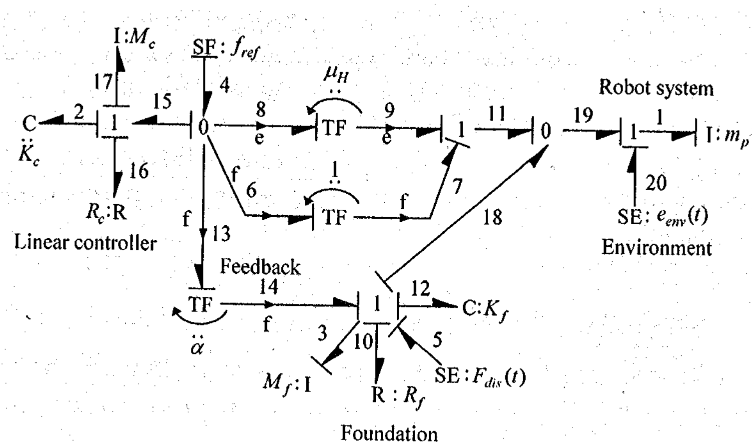

Figure 2: Bond graph of a single DOF robot on flexible foundation interacting with environment

$$\frac{sX_{rob}(s)}{(E/s)}=\frac{R(s)[1+\mu_H(1-\alpha)F(s)C(s)]}{1+\mu_H C(s)R(s)+\mu_H(1-\alpha)F(s)C(s)} \quad (2)$$

substituting the values of $R(s)$, $F(s)$ and $C(s)$, and using the final value theorem, the steady state response of the function $X_{rob}(s)/E$ can be obtained as,

$$\lim_{s\to 0}\left(\frac{sX_{rob}(s)}{E}\right)=\frac{1}{K_{rob}}=\frac{1}{\mu_H K_c}+\frac{(1-\alpha)}{K_f} \quad (3)$$

Here K_{rob} is termed as driving point stiffness of the robotic system since it is determined at the interaction port. From Eq. (3) two important conclusions can be inferred as

(i) When $\alpha = 1$, (i.e. full foundation compensation) $K_{rob} = \mu_H K_c$

If $\mu_H >> 1$, K_{rob} will be very high and manipulator will not accommodate any interaction force thus fulfilling the requirement of robust trajectory controller.

(ii) When $\alpha < 1$, and $\mu_H >> 1$, $K_{rob} \cong K_f/(1-\alpha)$.

i.e., α can be used to change the impedance or stiffness behavior of the robotic system at the interaction port, so as to accommodate forces from the environment. One can similarly carryout the exercise for damping and inertance to see the effects of the compensation gain.

Thus it is concluded that the impedance of the robotic system at the end-effector is dependent on the compensation gain α to the controller, which is characteristic of the flexible foundation. However force control using actual foundation is not a good proposition. Therefore an equivalent controller can be devised with its foundation moved into the controller domain. Impedance controller with foundation moved to controller domain is useful for having an entirely software controlled impedance behavior at the end-effector of the robotic system. This controller is developed through a system based bond graph approach, where certain transformations are performed among the various junction structures in the multi energy domain preserving the output impedance characteristic of the robotic system. An alternative bond graph representation of the controller manipulator interface junction structure with foundation moved into controller domain is shown in Fig. 3. The equivalence of two cases (i.e. Fig. 2 and Fig. 3) can be concluded by observing the power variables which are same at the plant port, environment port, controller port, and foundation port. From the bond graph shown in Fig. 3, the admittance of the robotic system at the interaction port can be derived from the state space equations as

$$Y_{rob}(s)=\frac{1}{Z_{rob}(s)}=\frac{f_{rob}(s)}{e_{env}(s)}=\frac{f_1}{e_{20}'}=\frac{R(s)[1+\beta_H(1-\alpha)F(s)C(s)]}{1+\mu_H C(s)R(s)+\beta_H(1-\alpha)F(s)C(s)} \quad (4)$$

Comparing the admittances given by Eqs. (1) and (4) we can see that the transformation from the foundation in physical domain to the foundation in controller domain is effected by replacing $\mu_H(1-\alpha)$ by $\beta_H(1-\alpha)$. Here β_H is a high gain parameter, which is equal to the high feed forward gain. The driving point stiffness $K_{rob}(s)$ of the robotic system at the interface with the environment for a constant environmental effort (E) can also be derived as,

$$\frac{1}{K_{rob}(s)}=\frac{1}{\mu_H K_C}+\frac{\beta_H(1-\alpha)}{\mu_H K_f} \quad (5)$$

Now, When, $\alpha < 1$, and $\mu_H, \beta_H >> 1$, $K_{rob}(\alpha) \cong \mu_H K_f / \beta_H(1-\alpha)$ (6)

When $\alpha < 1$, and $\mu_H, \beta_H >> 1$, $K_{rob}(\alpha) = \mu_H K_C$. (7)

In this case the additional DOF (foundation) is in the controller domain, and hence referred as virtual foundation. During accommodation of environmental interaction force, or during trajectory control, the end-effector flow will be compensated by the flow of the virtual foundation residing in the computational domain of the controller. Here, Hogan's [13] basic idea of conceiving a physical paradigm and realizing them in the controller domain is utilized. Such controllers can be realized either in active electronic circuit made from operational amplifiers, or from digital control system implementation. However, the virtual foundation in the controller domain need not necessarily be actual physical circuits or devices. It may be

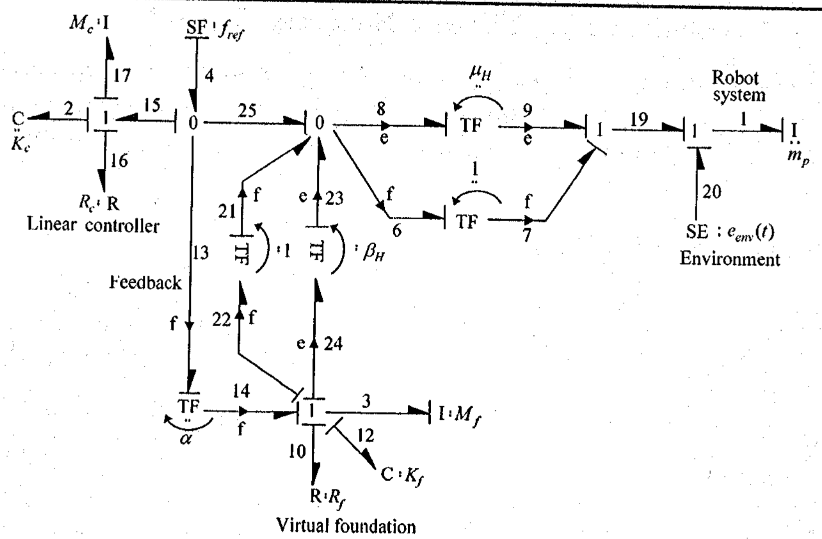

Figure 3: Bond graph of single DOF robot with flexible foundation in controller domain

in the form of equations residing in the control computer and representing the state of the control system equivalent. It will have the effect of the real system due to the equivalences established in the manner described.

3.0 Modelling of Cooperative Space Robot

The modelling strategy adopted here is known as double foundation approach. It basically consists of three stages.

STAGE I: Modelling of Space Robot

Translation DOF ground robot on a flexible foundation is considered. This flexible foundation is replaced by space vehicle carrying the space robot. To nullify the effect of the motion of space vehicle on the tip velocity of the space robot, the base velocity of space robot is fed back to the controller.

STAGE II: Modelling of ground robot on flexible foundation

A ground robot on flexible foundation is modelled. To incorporate foundation disturbances into workshop coordinate the foundation velocity is sensed and feedback to controller. Now the foundation is moved into the computational part of controller domain in order to make entirely software controlled impedance behaviour at the end-effector of the robotic system as discussed in section 2.0.

STAGE III: Modelling of Impedance Controller

The features of stage I appended to the ground robot with virtual foundation will result in a space robot with virtual foundation. The compensation gain of the virtual foundation in controller domain can be used to modulate the impedance at the interaction point between the space robot tip and environment.

Figure 4 shows the line sketch of two cooperative single DOF space robots manipulating a rigid body of mass M_b. The bond graph for this system is shown in Fig. 5.

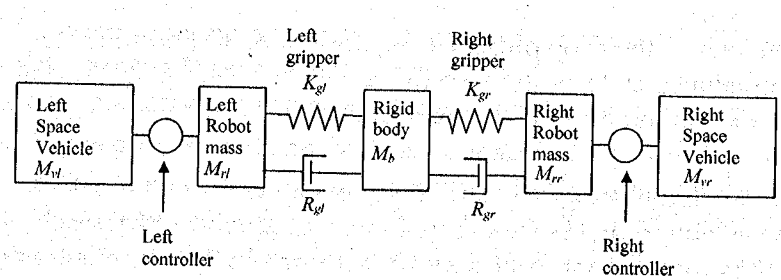

Figure 4: Schematic diagram of one DOF two cooperative space robot holding a rigid body

3. 1 Adaptive Gain Modulation and Amnesia Recovery Control

Kumar [1], and Mohan Kumar [9] achieved modulation of virtual foundation compensation gain g through a heuristic expression involving actual and limiting forces. For the gain modulation of the space robot the heuristic expression used by them is used here. The heuristic expression for gain modulation is given by

$$\gamma(F, F_{\lim}, t) = 1 - swi(F(t), F_{\lim})[K_{Ini} + K_{GP} * F_d + K_{GI} * Y(t)] \qquad (8)$$

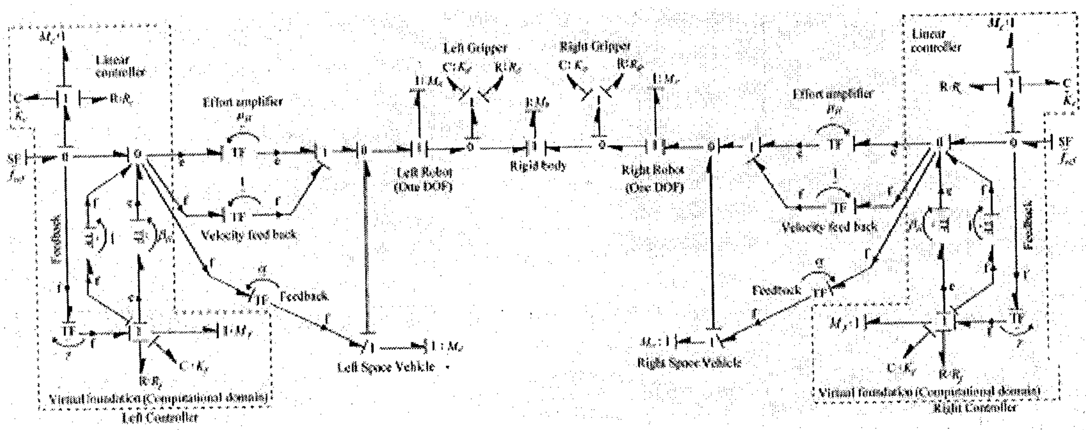

Figure 5: Bond graph model of one DOF two cooperative space robot holding a rigid body

Where *F (t)* is the actual contact force obtained from force sensor; $F_{\lim}$ is the limiting value of the force specified and $F_d = (F(t) - F_{\lim})$. The *swi* defines the switch function in SYMBOL2000 as

$swi(F(t), F_{\lim}) = 1, for\ F(t) \geq F_{\lim}$, (i.e., if $\gamma < 1$, impedance controller works in force control mode.) $swi(F(t), F_{\lim}) = 0, for\ F(t) < F_{\lim}$ (i.e., if $\gamma = 1$, impedance controller works in trajectory control mode).

Also in Eq.(8), K_{Ini} is constant, K_{GP} is a proportional gain term, K_{GI} is an integral gain term. The term *Y (t)* is given by

$$Y(t) = swi(F(t), F_{\lim}) * e^{-\tau t} \int_{t_i}^{t} e^{\tau \xi}(F(\xi) - F_{\lim}) d\xi \ . \qquad (9)$$

Here τ is a gain relaxation term and t_i is the time when force control is initiated. The expression *Y (t)* integrates the difference in the interaction force and the force limit to smoothen any sharp change in variation of impedance.

When the end effector does not have interaction with rigid body, the end effector follows the command in both velocity and position. At this condition, a high impedance state exists. During the interaction phase, when the force reaches its bound value, the end effector motion gets arrested, and yielding of the foundation compensates for the command motion. Due to yielding of the foundation, impedance is reduced to a lower value. This leads to a difference between the reference trajectory position and the actual manipulator position. When the interaction phase is over, the compensation gain γ is switched to 1 by Eq. (8) restoring the high impedance state of the system so that the end effector continues to follow the reference trajectory with a lag in the position (i.e. amnesia) of the end effector with respect to reference trajectory. The amnesia is removed in a two-stage process. In the first stage the controller records the loss in positional information of the trajectory during accommodation to interaction force. This information is recorded through the time integral of positional error. In the second stage the above recorded information is supplied to the trajectory controller by augmenting it to reference velocity during the non-interaction phase. Mathematically, error recording is done by a function like

$$Y(t)=e^{-\tau_e t}\int_{ts}^{t} e^{\tau_e \xi}(Y_{ref}-Y_{\xi})d\xi \tag{10}$$

where Y_{ref} is reference position and Y_{ξ} is the actual position, τ_e is time constant and t_s is the start of trajectory calibration following an interaction. The augmented trajectory command to reference input velocity is given by

$$SFc = Ge * Y(t)\ . \tag{11}$$

Here G_e is gain proportional to residual position error = $(Y_{ref} - Y_{\xi})$. The gain factor Ge and the relaxation terms τ_e controls the recovery of amnesia.

4.0 Simulation and Results

Table 1 shows the parameters and their values considered for simulation. Mass of rigid body, M_b = 1 Kg is assumed. The body is gripped to a minimum gripping force of 10 N by providing equal and opposite command velocities to the robots. The velocities given to both the robots is $V_C = A*(1\text{-}\cos(2\pi(t-t_o)))$, where t is the instantaneous time and to is time at the start of body motion. Figure 6(a) and (b) shows the simulation results for the left and right robot. It is seen from the figures that the minimum specified force of 10 N is maintained by the grippers on the rigid body.

Table 1: Parameters and Values Used for Simulation for left & right robot

Parameter	Values
Gripper	$K_{gl}=K_{gr}$ = 1000 N/m, $R_{gl}=R_{gr}$ =100 N/(m/s)
Controller	Mc =10 Kg, K_c = 500 N/m, R_c = 5 N/(m/s)
Virtual foundation	M_f = 1 Kg, K_f = 10 N/m, R_f = 200 N/(m/s)
Mass of robot	$M_{rl} = M_{rr}$ = 1 Kg
Amplitude of reference velocities	A_1 = 10 m/s, A_2 = -10 m/s
Mass of space vehicle base	$M_{vl} = M_{vr}$ =10 Kg
Minimum gripping force	$F_{lim\_L} = F_{lim\_R}$ = 10 N
Feed forward gains	μ_H =300, β_H=300
Gain modulation	$K_{ini\_L} = K_{ini\_R}$ = 0, K_{GP_L} = K_{GP_R} = 0.5, K_{GI_L} = K_{GI_R} = 0.1
Force error integration	K_τ = 100 N/m, R_τ = 80 N/(m/s)
Amnesia removal	K_e = 10.00 N/m, R_e = 6.00 N/(m/s)
Gain used for correcting reference trajectory to remove amnesia	G_a=600.00

5.0 Conclusions

The concept of force control through virtual foundation is best fitted for the cooperative manipulation of rigid mass. From the simulation results, it is seen that the minimum prescribed gripping force is maintained by the controller thus avoiding the body to slip. The work on control of the upper limit force by gripper is in progress. The multi DOF cooperative space robot modeling will be of more interest as cooperative space robots can be used in handling of floating unwanted objects in space.

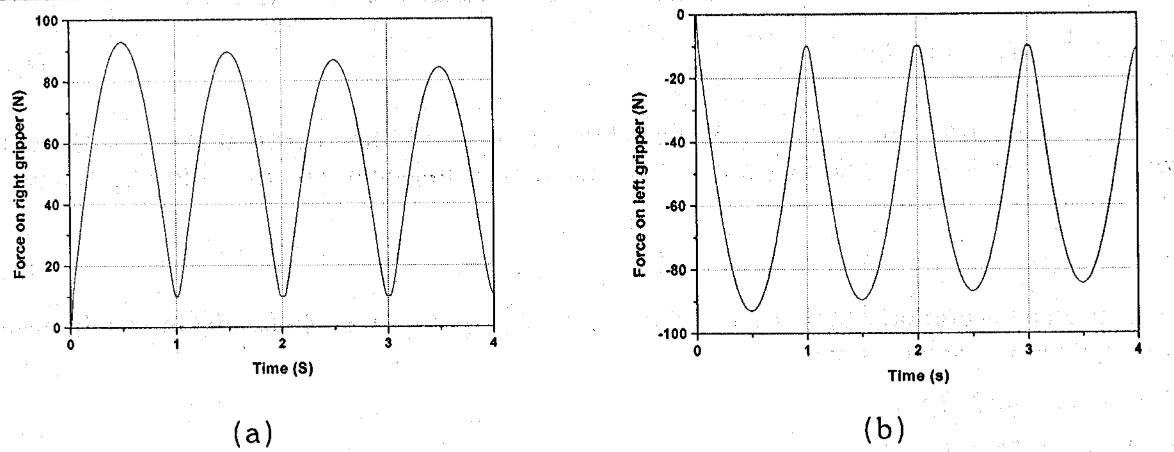

Figure 6: (a) Plot of force by right gripper on rigid body. (b) Plot of force by left gripper on rigid body.

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