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Hard Contact Transition Control Laws : Three Different Approaches

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Abstract

In this paper, we consider on **hard** contact transition control strategies. Hard contact transition phase can be divided into two definitely different phases, *"Pre-Transition Phase"* and *"Transition Phase"*. Here we focus on the *"Pre-Transition Phase"* and we propose three control methods. First, we propose a novel controller named as *"Suppression Controller"* which is not only stable but also simple to implement. Second, we present passive damper named as *"Flexible-Damped Joint"* which is good solution in circumventing pre-transition phase. Third, we suggest a stable and simple controller which can maximize joint damping and minimize recontact velocity in flexible-damped joint. It is named as *"Joint Damping Controller"*.

1 Introduction

As the task of the robots becomes more complex, there increases the need of contact tasks, which inevitably brings contact transition period. The contact transition control can be divided into three categories : (1) Dealing with impacts during contact transience, (2) Preparing for impact in advance, and (3) Mixing different controller for optimization.

Through the literature survey, we found that the hard contact situation, *i.e.* high initial velocity with very stiff environment, was not focused on until now. Under hard contact situation, the transition phase can be divided into two definitely different phases as shown in Fig.1. We name the first phase as *"Pre-Transition Phase"* and second phase as *"Transition Phase"*. The pre-transition phase is important in two reasons. First, the maximum force peaks arise during pre-transition phase. Second, during the force peak, almost no closed loop can be constructed because of the very short time of contact. Now we propose three different methods for pre-transition phase control. First, we propose a novel controller named as *"Suppression Controller"*. Second, we present passive damper named as *"Flexible-Damped Joint"*. Third, we suggest a stable and simple controller which can maximize joint damping and decreasing recontact velocity in flexible-damped joint. It is named as *"Joint Damping Controller"* and can be used in flexible-damped joint only. Suppression controller as well as joint damping controller are not only stable but also simple to implement. So we need neither complex gain tuning which is needed in most explicit force controllers nor complex stability boundaries. This properties gives robustness to this controller, because it can be used in any unknown environment. Even unexpected collision, the controller can decide control parameters instantly from the first impact force data and pre-programed table, and it can successfully reach on transition phase. Once it reaches on transition phase, it converge to its steady-state exponentially[1].

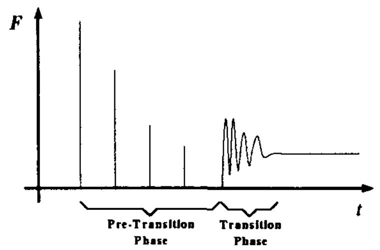


Fig. 1: Pre-transition phase and transition phase

2 Suppression Controller

In treating pre-transition phase, we concentrate on the position rebounds. The position rebound is shown in Fig.2(a) which collides with environment at time $t = t_0$. Pre-transition phase controller's final aim is to reach on transition phase which does not lose its contact again, as fast as possible. Now, pre-transition control problem becomes optimum problem which minimizes a performance index given as follows:

$$J = \frac{1}{2}(\dot{q}(t_f) - \dot{q}^*)^2 + \int_{t_0}^{t_f} dt, \qquad (1)$$

where $\dot{q}^*$ is optimal recontact velocity that the manipulator keep its contact[1]. In Eq.(1), first term, $\frac{1}{2}(\dot{q}(t_f) - \dot{q}^*)^2$, forces recontact velocity to the optimum velocity, $\dot{q}^*$, as closely as possible and second term, $\int_{t_0}^{t_f} dt$, brings minimum recontact time, *i.e.* minimum settling time.

2.1 Controller

Here we propose a novel control transition law which guarantees stability, simplicity and good enough optimum performance. We name it as ***suppression con-***

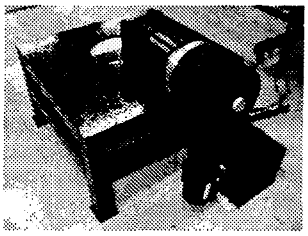


Fig. 2: POSTECH 1 DOF DD ARM

troller which is given in Eq.(2).

$$\tau_{in} = \begin{cases} \tau_{max} & \boldsymbol{F} = 0 \text{ and } \dot{q} > \dot{q}^* \\ \tau_d & \text{otherwise} \end{cases}, \qquad (2)$$

where τ_{max}, τ_d, $\boldsymbol{F}$ and $\dot{q}^*$ is maximum control input, desired control input, measured force and optimal recontact velocity, respectively. Here τ_d is desired control input to achieve desired force at steady-state, *i.e.* $\tau_d = \boldsymbol{J}^T\boldsymbol{F}_d$ where $\boldsymbol{J}$ is jacobian matrix and $\boldsymbol{F}_d$ is desired force. Now we will describe more on the suppression controller.

Case 1 $\tau_{in} = \tau_{max}$

The first condition $\boldsymbol{F} = 0$ informs that the manipulator is under position rebound. And the second condition, $\dot{q} > \dot{q}^*$, has two important meanings. First, it acts as a velocity dead band as shown in Fig.2(b). If By setting $\dot{q}^*$ as a dead band we can minimize performance index and we also can eliminates the ambiguity. Second, we can check the time when to change controller from pre-transition phase controller to transition phase controller. If it recontact with velocity $\dot{q}^*$ as shown in Fig.2(b) at $t = t_4$, it's rebounding velocity is less than $\dot{q}^*$,*i.e.* $\dot{q}(t_4^+) < \dot{q}^*$, because the coefficient of restitution is always less than unity. If force peak is detected under a velocity lower than $\dot{q}^*$, we have to substitute pre-transition controller with transition phase controller. This approach informs us exact time of substitution and this is the first discontinuous approach as far as the authors knowledge.

Case 2 $\tau_{in} = \tau_d$

Either $\boldsymbol{F} \neq 0$ or $\dot{q} \leq \dot{q}^*$, we simply push the manipulator with $\tau_{in} = \boldsymbol{J}^T\boldsymbol{F}_d$ as shown in Fig.2(c) from time t_1 to t_2. It does not destablize the system, because τ_{in} does not related to the state explicitly. This control action leads robot manipulator to establish recontact with environment. It's major merits lies on stability and simplicity. This controller do not use system state explicitly. So the system will never be destabilized and it will successfully recontact with environment. This controller is also very simple. With proper choice of $\dot{q}^*$, this controller can be used any

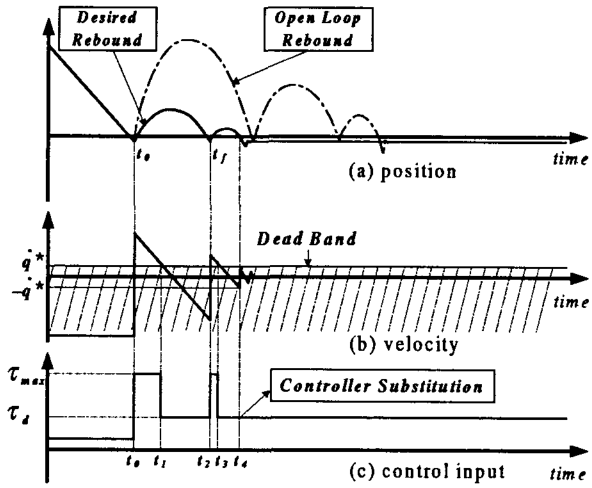
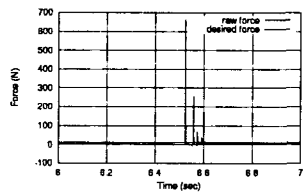
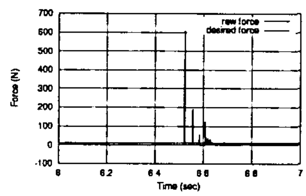


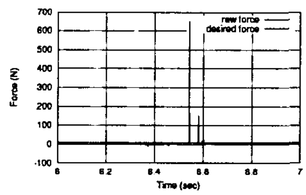
Fig. 3: Graphic description on suppression controller



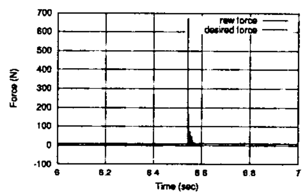
(a) Joint torque control



(b) Active damping



(c) PI force control



(d) Suppression control

Fig. 4: Experimental comparison results

unknown or unexpected impact phenomena which means robustness.

2.2 Comparative Study

Here we give comparative study with three other controllers. One is *joint torque control*. The other is *active damping* and another is *PI force control with velocity feedback*. Fig.3 shows its experimental results. In all cases, desired force was set as $10N$ with 0.3 m/s approaching velocity. Among these controllers, *suppression controller* shows the best result. The second and third force peak are also reduced greatly and it shows faster settling time than other controllers because position rebound is suppressed and recontact velocity $\dot{q}(t_f)$ is minimized.

3 Flexible-Damped Joint

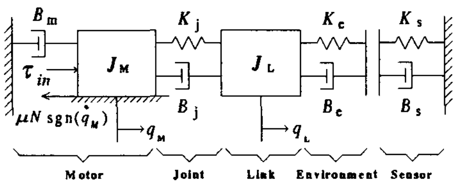


Fig. 5: Schematic diagram of flexible-damped joint

We designed "flexible-damped joint" as shown in Fig.4 and it's dynamic equations are given as follows:

$$\begin{aligned} &\boldsymbol{J}_M\ddot{\boldsymbol{q}}_M + \mu N \operatorname{sgn}(\dot{\boldsymbol{q}}_M) + B_m\dot{\boldsymbol{q}}_M \\ &\quad + K_j(\boldsymbol{q}_M - \boldsymbol{q}_L) + B_j(\dot{\boldsymbol{q}}_M - \dot{\boldsymbol{q}}_L) = \tau_{in} \qquad (3) \\ &\boldsymbol{J}_L\ddot{\boldsymbol{q}}_L + K_j(\boldsymbol{q}_L - \boldsymbol{q}_M) + B_j(\dot{\boldsymbol{q}}_L - \dot{\boldsymbol{q}}_M) = 0, \end{aligned}$$

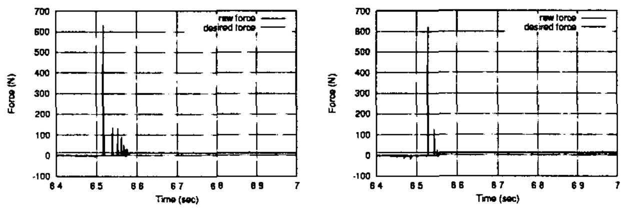
where $\boldsymbol{J}_M$, $\boldsymbol{J}_L$, K_j, B_j, $\boldsymbol{q}_M$ and $\boldsymbol{q}_L$ is motor inertia, link inertia, joint stiffness, joint damping, motor position and link position, respectively. Incremental encoder is attached between motor and link to sense the deflection of joint. The relative motion of link and motor induces passive damping.

3.1 Flexible-Damped Joint

As it is well known, damping is the most important and desirable factor in contact transition control. Damping is important to absorb impact energy as well as stabilize overall system. But there is certain limit to increase damping using controllers as it is well known. An[2] suggested passive compliance covering. But it can not sense the accurate end point position and also can not give good enough steady-state force. To overcome these problem, Y.H.Oh[3] developed passive damper. But this damper fixed on the ground which can not be used in earth-free manipulators.

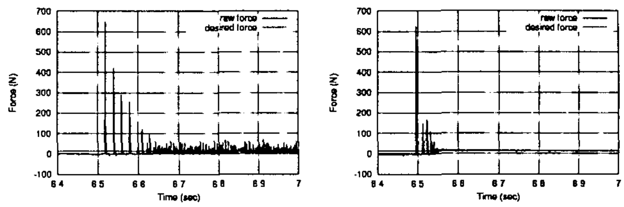
The flexible-damped joint, presented in Fig.4, can overcome all the problems given above. However, it's control performance is degraded, because of the non-collocation mode coming from joint flexibility. So we can say that this is a trade-off problem.

The effectiveness of this joint is experimented and the results are given in Fig.5 and Fig.6. The desired force was set as 15 N in both experiments. Fig.5 is joint torque controlled response. In case of flexible-damped joint, Fig.5(b), the settling time is shortened as well as third and forth rebounds suppressed greatly compared to rigid joint experiment, Fig.5(a). Fig.6 is results of PI force control with velocity feedback under same PI force and velocity feedback gain. In rigid case, Fig.6(a), it shows unsteady response, but in flexible-damped joint, Fig.6(b), it keeps it's stability as well as showing good performances. Consequently, we can conclude that flexible-damped joint is a good solution in minimizing pre-transition phase and achieving short settling time and stability.



(a) Rigid joint (b) Flexible-damped joint

Fig. 6: Response of joint torque control



(a) Rigid joint (b) Flexible-damped joint

Fig. 7: Response of PI force control with velocity feedback

4 Joint Damping Controller

4.1 Control Law

The proposed control law is given as follows:

$$\tau_{in} = \begin{cases} \tau_{max} = \kappa\tau_{min} & \text{if } \dot{\boldsymbol{q}}_M < 0 \\ -\tau_{min} & \text{if } \dot{\boldsymbol{q}}_M \geq 0 \end{cases} \qquad (4)$$

where τ_{max}, τ_{min} is user defined maximum and minimum control input. κ is a positive constant bigger than unity which has to be satisfied for recontact with environment.

4.2 Stability

After compensating friction terms in Eq.(3) we can choose Lyapunov candidate function as Eq(5) which is positive definite.

$$\boldsymbol{V} = \frac{K_j}{2}(\boldsymbol{q}_M - \boldsymbol{q}_L)^2 + \frac{1}{2}\boldsymbol{J}_M\dot{\boldsymbol{q}}_M^2 + \frac{1}{2}\boldsymbol{J}_L\dot{\boldsymbol{q}}_L^2 \qquad (5)$$

We can calculate derivative of Eq(5) as Eq(6).

$$\begin{aligned} \dot{\boldsymbol{V}} &= K_j\boldsymbol{q}_M\dot{\boldsymbol{q}}_M + K_j\boldsymbol{q}_L\dot{\boldsymbol{q}}_L - K_j\boldsymbol{q}_L\dot{\boldsymbol{q}}_M - K_j\dot{\boldsymbol{q}}_L\boldsymbol{q}_M \\ &\quad + \boldsymbol{J}_M\dot{\boldsymbol{q}}_M\ddot{\boldsymbol{q}}_M + \boldsymbol{J}_L\dot{\boldsymbol{q}}_L\ddot{\boldsymbol{q}}_L \\ &= K_j\boldsymbol{q}_M\dot{\boldsymbol{q}}_M + K_j\boldsymbol{q}_L\dot{\boldsymbol{q}}_L - K_j\boldsymbol{q}_L\dot{\boldsymbol{q}}_M - K_j\dot{\boldsymbol{q}}_L\boldsymbol{q}_M \\ &\quad + \boldsymbol{J}_M\dot{\boldsymbol{q}}_M(-\boldsymbol{J}_M^{-1})\{K_j(\boldsymbol{q}_M - \boldsymbol{q}_L) + B_j(\dot{\boldsymbol{q}}_M - \dot{\boldsymbol{q}}_L) - \tau_{in}\} \\ &\quad + \boldsymbol{J}_L\dot{\boldsymbol{q}}_L(-\boldsymbol{J}_L^{-1})\{K_j(\boldsymbol{q}_L - \boldsymbol{q}_M) + B_j(\dot{\boldsymbol{q}}_L - \dot{\boldsymbol{q}}_M)\} \\ &= -B_j(\dot{\boldsymbol{q}}_M - \dot{\boldsymbol{q}}_L)^2 + \dot{\boldsymbol{q}}_M\tau_{in} \end{aligned} \qquad (6)$$

By embedding Eqs.(4) into (6), we get Eq.(7) which proves it's stability that the states will not diverge.

$$\dot{V} = -B_j(\dot{q}_M + \dot{q}_L)^2 - \gamma \dot{q}_M \text{sgn}(\dot{q}_M) < 0, \quad (7)$$

where γ is either τ_{max} or τ_{min}.

Analysis

This controller is designed to maximize joint damping as well as minimizing recontact velocity. First, we can divide Eq.(4) into two equation as Eq.(8),(9).

$$\tau_{in} = \begin{cases} \tau_{max} & \text{if } \dot{q}_L < 0 \\ -\tau_{min} & \text{if } \dot{q}_L \geq 0 \end{cases} \text{ if sgn } (\dot{q}_M) = \text{sgn } (\dot{q}_L) \quad (8)$$

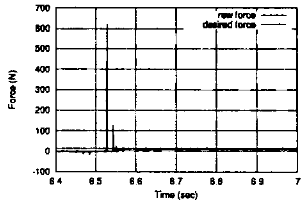
$$\tau_{in} = \begin{cases} \tau_{max} & \text{if } \dot{q}_M < 0 \\ -\tau_{min} & \text{if } \dot{q}_M \geq 0 \end{cases} \text{ if sgn } (\dot{q}_M) \neq \text{sgn } (\dot{q}_L) \quad (9)$$

1.**When sgn $(\dot{q}_L)$ = sgn $(\dot{q}_M)$** : Eq.(8) is the control law that is maximizing joint damping. As shown in Fig.4, the left direction is negative direction and vice versa. When link velocity $\dot{q}_L$ is negative then τ_{max} is exerted to the motor which forces motor velocity $\dot{q}_M$ to positive value. This action compresses passive damper which maximizes joint damping. And when $\dot{q}_L$ has positive value, $-\tau_{min}$ is exerted to the motor which forces motor velocity $\dot{q}_M$ to negative value. This action expands passive damper which is maximizing joint damping, too. These two actions maximizes joint damping and governed by Eq.(8).

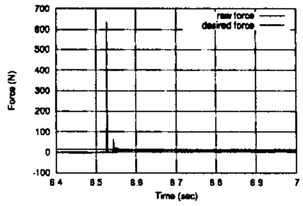
2. **When sgn $(\dot{q}_L) \neq$ sgn $(\dot{q}_M)$** : Eq.(9) is used for stability. Because there is joint stiffness in flexible-damped joint, it is basically non-collocated system. To prevent instability coming from non-collocation mode, we use Eq.(9) in addition to Eq.(8). Now we will focus on the fact that joint damping controller forces both $\dot{q}_M$ and $\dot{q}_L$ near to zero because $\boldsymbol{V}$= 0 means $\dot{q}_M = \dot{q}_L = 0$. It will decreases recontact velocity so that it reduces second and third peaks and shortens settling time.

4.3 Comparative Study

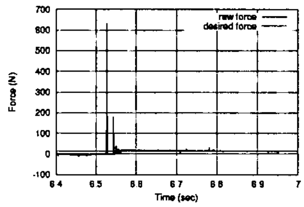
In Fig.7, the experimental results are compared with three other controllers which was used in section 2. By comparing those figures, we can validate the effectiveness of proposed controller. It's major merits lay on both stability and simplicity. Not like PI force controller or explicit force controller which is apt to be destablized according to the gain or environment, it's stability is already proved and it will not diverges at any situation.



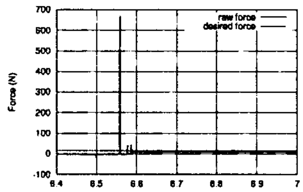
(a) Joint torque control



(b) Active damping control



(c) PI force control



(d) Joint Damping Controller

Fig. 8: Various controller comparison

5 Conclusion

In this paper, we considered on *hard* contact transition control strategies. We defined a new phase named as ***"pre-transition phase"***. We also proposed three control strategies for pre-transition phase control. First, we suggested ***suppression controller*** which is stable, simple and robust which can be implemented in general manipulator. It's performance is validated by comparative study. Second, we present passive damper named as ***"flexible-damped joint"***. It's effectiveness is validated by experiments. Third, we proposed a novel controller for ***"flexible-damped joint"*** which is named as ***"joint damping controller"***. This controller is stable and simple. It's performance is also validated by comparative study.

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