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A Compliant Contact Control Strategy for Robot Manipulators with Unknown Environment

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Abstract

This paper proposes a new compliant contact control strategy for the robot manipulators accidentally interacting with an unknown environment.

The main features of the proposed method are summarized as follows: First, each entry in the diagonal stiffness matrix corresponding to the task coordinate in Cartesian space is adaptively adjusted during contact along the corresponding axis based on the contact force with its environment. Second, it can be used for both unconstrained and constrained motions without any switching mechanism which often causes undesirable instability and/or vibrational motion of the end effector. Third, the adjusted stiffness gains are automatically recovered to initially specified stiffness gains when the task is changed from constrained motion to unconstrained motion. The simulation results show the effectiveness of the proposed method by employing a two-link direct drive manipulator interacting with an unknown environment.

1 Introduction

The nature of interaction between a robot and its environment can be categorized in two classes. The first one concerns the noncontact or unconstrained motion in the free work space, where any relevant environmental interference does not exerted on the robot. In contrast to these tasks, many complex advanced robotic applications such as assembly and machining require the manipulator to be mechanically coupled to other objects. These tasks are referred to as essential contact or constrained tasks because they include phases where the robot's end-effector must come into contact with objects in its environment, produce certain forces upon them, and move along their surfaces. A possible contact motion could be obtained after a phase transition from unconstrained motion to constrained motion. For phase transitions, following motion types can be usually observed: approach, contact motion and possible bouncing if contact failed to be maintained after impact. The robot must successfully manage such motion phases. Therefore, compliant contact control, concerned with the control of a manipulator in contact with its environment, is very important for both robot manipulator and environment or object [1]. For example, in a robotic assembly task whose objective is combining a number of individual parts into one completed device, the parts must be quickly assembled avoiding damage to either the individual parts of the device. To successfully complete this constrained task, the manipulator must develop compliant motion where the interaction force/torque along the constrained direction is accommodated rather than resisted.

By the way, it is known that a position servo is infinitely stiff and is appropriate when the manipulator is following a given trajectory in the free space. It will reject all force disturbances acting on the system. However, when a contact is made between the end-effector and the environment, high stiffness of the end-effector or the environment can make the manipulator be failed to maintain the contact. Small variations in relative positions due to either inaccuracy in position information or errors in position servo can produce undesirable large contact forces. An ideal force servo will exhibit zero stiffness and be able to maintain the desired force. However, force servos can not be useful for trajectory following due to sensitive positional variation even for a small external force disturbance.

In order to handle the interaction of a robot manipulator with the environment, many researchers have been studied in the field of the compliant motion control of robot manipulators. The hybrid position/force control approach [2, 3] is based on an orthogonal decomposition of the task space. In this scheme, it is pointed that control axes should be determined before the task begins, and the control performance may unstable due to the switching mechanism. Inner/outer control [4] achieves regulation of a desired contact force thanks to the closure of an outer force feedback loop around the inner position feedback loop. Parallel control combines the inherent robustness of the former with the force control capabilty of the latter; a force feedback loop is devised in parallel to a position feedback loop, while the control structure guarantees dominance of the force action over the position action along the constrained task directions [5, 6]. It is known that the common feature of all the above parallel control schemes is the possibility of regulating the contact force to a desired value without using explicit information on the constrained and unconstrained task directions, but the schemes doesn't adapt for the typical uncertainty on the contact stiffness.

In recent, in view of servo gain control, a position error based stiffness gain control approach has been studied in [11]. The method has some considerable points as follows: 1) It is assumed that exact trajectory control must be accomplished in Cartesian space since the contact is detected by position error. 2) The algorithm has not recovery procedure which is reset the temporal stiffness of robot manipulator into the initialized stiffness when the task space of robot manipulator is changed from the constrained space to free space. Therefore, the tracking performance of robot manipulator in the free space after contacting with the environment is degraded than the performance without contacting with the environment. And a parallel control scheme with stiffness adaptation related to force/position tracking has been developed in [7]. The method is useful for regulating contact force on the constrained space. But it also doesn't solve the second problem of the above descriptions. Accordingly, two methods are not effective as a unified stiffness gain control method.

Now, a new unified compliant contact control method is proposed in this paper. This method has an adaptive stiffness function for a successful motion of robot manipulator at both constrained and unconstrained space. The stiffness of robot manipulator is adjusted by an exponential function based on the contact force with environment. There are several features such as: simple, no need of any switching mechanism, applicable for soft touching and grasping of robot hand.

2 Robot Dynamics and Stiffness Control

When an n degrees-of-freedom robot manipulator contacts its environment, the robot or environment will deform and a reaction force at the end-effector will be transmitted into each joint. If F is a reaction force at the end-effector in Cartesian coordinate, then the dynamic equation takes the form,

$$\tau = M(q)\ddot{q} + H(q,\dot{q}) + G(q) + J(q)^T F, \tag{1}$$

where q, $\dot{q}$ and $\ddot{q}$ are $n \times 1$ vectors of joint positions, velocities, and accelerations, respectively. τ is the $n \times 1$ vector of joint torques supplied by the actuator. $M(q)$ is the $n \times n$ symmetric positive definite inertia matrix and $H(q,\dot{q})$ is the $n \times 1$ vector of centripetal and Coriolis forces. $G(q)$ is the $n \times 1$ vector of gravity. $J(q)$ is the $n \times n$ Jacobian matrix, relating joint velocities to task space velocities.

From the basic stiffness formulation in the Salisbury's work [10], the joint stiffness matrix K_q is obtained by

$$K_q = J^T K_c J, \tag{2}$$

where K_c denotes a desired $n \times n$ stiffness matrix in Cartesian space. For stiffness control [10], the control input is given by

$$\begin{aligned}\tau = K_q(q_d - q) + K_d(\dot{q}_d - \dot{q}) + K_f(K_q(q_d - q)\\ -J^T F) + G(q)\end{aligned} \tag{3}$$

where q_d and $\dot{q}_d$ are $n \times 1$ vectors of desired joint positions and velocities, respectively, K_d is the velocity damping matrix, and K_f is the force feedback gain matrix.

In stiffness control, it is confirmed that the stiffness of the end-effector can be transmitted into the joint stiffness by using linear spring model. By the way, this method keeps constant servo gains determined by the initially given Cartesian stiffness, and so the robot or environment in contact motion may be obtained serious damage if the servo gains are large. Now, it is pointed out that the robot manipulator contacts with an unexpected environment more compliantly if the stiffness of end-effector can be changeable as some adaptive mechanism.

3 Stiffness Adaptation

In this paper, the control input for compliant contact control of a robot manipulator is given by

$$\tau = K_q(\cdot)(q_d - q) + K_d(\dot{q}_d - \dot{q}) + G(q), \tag{4}$$

where q_d and $\dot{q}_d$ are $n \times 1$ vectors of desired joint positions and velocities, respectively. $K_q(\cdot)$ is a nonlinear joint stiffness matrix given by the proposed stiffness adaptation method, and K_d is the velocity damping matrix.

Now, we propose a new nonlinear stiffness adaptation method in (4) to replace the constant Cartesian stiffness as follows:

$$K_q(\cdot) = J^T K_c(\cdot) J,$$

where

$$K_c(\cdot) = \begin{pmatrix} K_{cx} e^{-s_x |F_{cx}|} & 0 \\ 0 & K_{cy} e^{-s_y |F_{cy}|} \end{pmatrix} \tag{5}$$

K_{cx} and K_{cy} are chosen to be positive constants with which the asymptotic stability is ensured in unconstrained motions. The slopes, s_x and s_y, in (5) are positive and play the role of determining the decreasing rate. F_c is the 2×1 contact force vector of the end-effector of robot manipulator.

Several points can be addressed for the proposed method. First, since each entry of the stiffness gain matrix K_c corresponds to the task coordinate in Cartesian space and decreases during contact only along the corresponding axes, the proposed method can be considered to be self-adjusting the pre-specified desired stiffness matrix for the given task. Second, this method has no switching mechanism which often causes undesired vibrational motions of the end effector. And so, the proposed method can be effectively used for both unconstrained and constrained motion. Third, the adjusted stiffness gains are automatically recovered into initially specified stiffness gains when the robot manipulator gets to the free space from the constrained environment. Another advantage of the method is that it can be applicable for complex and somewhat unspecified robotic tasks such as assembly, machining, or remote handling in unstructured environment, soft touching and grasping of robot hand during contact with environment or object.

4 Implementation and Results

4.1 Task Planning

To confirm the effectiveness of the proposed contact control method we define a compliant contact task of a two link robot interacting with an unknown environment in Figure 1, and consist a control block diagram for compliant motion of the robot manipulator as shown in Figure 2.

In this implementation, the task is given to follow a circular trajectory partially contacting hard environment with $K_e = 240000\ N/m$, where K_e is the stiffness of environment, in the xy-plane. To do so, a virtual desired path to be followed is intentionally given to be inside the surface of the environment.

For the manipulator, $l_1 = l_2 = 0.25\ m$ and $M_1 = M_2 = 1.0\ kg$, where l_i and M_i are the length and the mass of link. The center of mass is assumed to be at the mid point of the link. The manipulator starts from the point $A(0.16, 0.16)$ on the dotted circle with $0.05\ m$ diameters in Figure 1 and then turns around clockwise during 5 secs. The motion planning of the end-effector is performed by the velocity profile as shown in Figure 3. This makes it possible for the real trajectory planner to generate desired motion commands through the given path. The task spaces are changed in turn from free space to contact space, continuously.

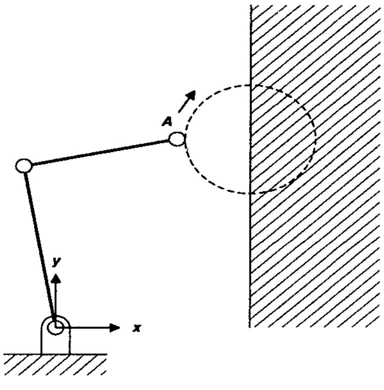


Figure 1: A compliant contact task of two link robot interacting with an unknown environment

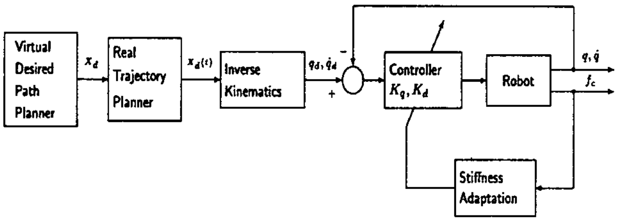


Figure 2: The block diagram for compliant contact control.

4.2 Simulation Results

The first simulation is to present the performance of a conventional stiffness control law. In fact, this is equal to the case of setting *slope* $= 0$ at the proposed method. The simulation results are shown in Figure 4, where the trajectory following state and the reflecting contact force are illustrated. The actual trajectory tracked the given trajectory well in the free space, but

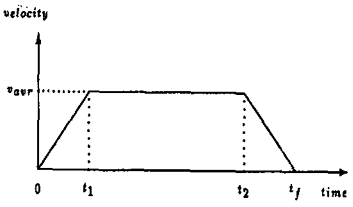


Figure 3: The velocity profile for the real trajectory planner.

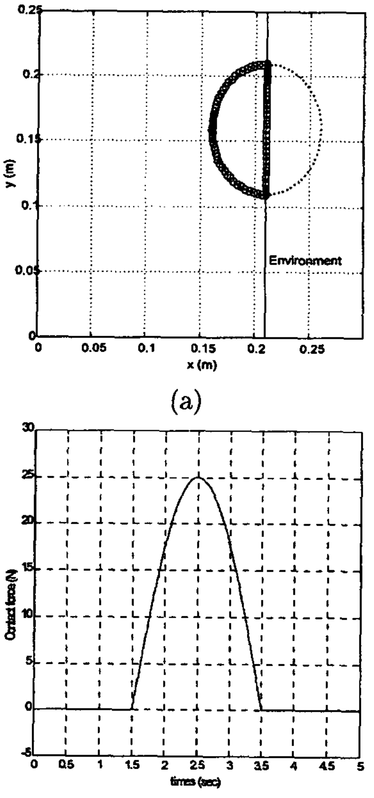
in the constrained space even though the desired position trajectory is located inside the surface, the actual position of end-effector remains on the surface due to the infinitely stiff environment, where contact force is generated.

Following simulations are performed by using the proposed method. The trajecory profiles and reflecting contact forces with different slopes are presented in Figure. 5 and 6, respectively.

In the results, we can confirm that the trajectory profiles are nearly the same in all cases, but the contact force in case of using the adaptive stiffness method is less than that of the conventional stiffness method. And if the slope becomes larger, then the contact force is gone more lower. This means that the proposed method can be applicable for soft touching when the robot manipulator contacts with unexpected environment. Figure 7 shows that the compliances of the end-effector of robot manipulator were adjusted by the different slope of the propose method. Therefore, we can get the compliant contact capability by adopting the proposed method in constrained motion.

The proposed method is very useful for the compliant contact control. For example, it is applicable to the soft touching and grasping of robot hand contacting with environment or object. The method is very simple and intuitively available to humanoid robot system. By the way, the slope doesn't go to infinite because the manipulator may be fall into unstable state such as sticking and separating continuously. So, it is additionally needed a method to select the range of an appropriate slope as some indices. Finally, the robot system with the proposed method can perform the given contact task more compliantly in comparing to the case of using the conventional stiffness control.

5 Concluding Remarks

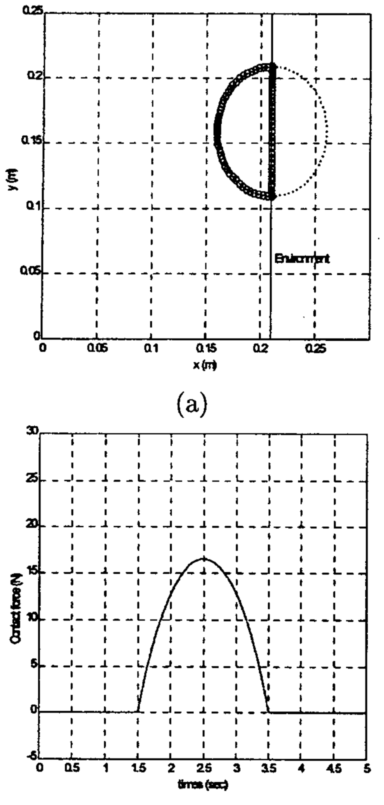


(a)

(b)

Figure 4: Actual performance on the task when the conventional stiffness control was used. The path of the end-point is shown on (a): desired path(dot) and actual path(circle). The history of contact force is shown on (b).

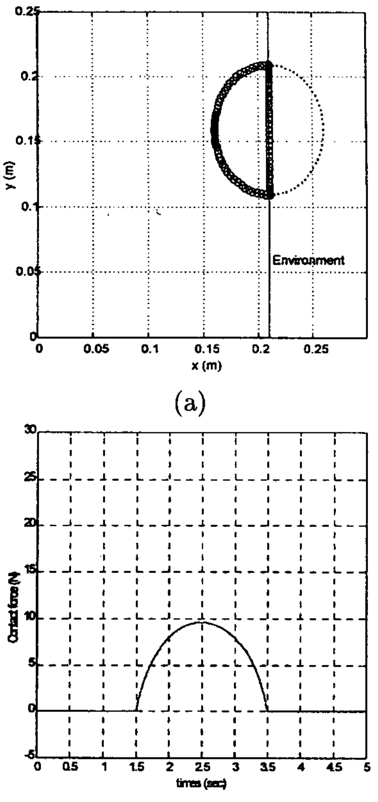
A new compliant contact control strategy was proposed for the robot manipulators accidentally interacting with its unknown environment. The stiffness of robot manipulator is adaptively adjusted based on the contact force with its environment. The proposed method was shown by simulations to work satisfactorily for a compliance control task, where we used a two link robot manipulator. By adopting this method, the contact force of the end-effector interacting with environment can be reduced in comparing to the conventional stiffness control. This means the robot system can perform the given contact task more compliantly. There are valuable features such as: simple, no need any switching mechanism and so available for both constrained and unconstrained space, and applicable for soft touching and grasping of robot hand. Accordingly, it can be employed for compliant control of humanoid robot system. It will be confirmed the effectiveness of the method by experiments and also performed the stability analysis in future.



(a)

(b)

Figure 5: Actual performance on the task when adaptive stiffness was used(slope=0.025). The path of the end-point is shown on (a): desired path(dot) and actual path(circle). The history of contact force is shown on (b).



(a)

(b)

Figure 6: Actual performance on the task when adaptive stiffness was used(slope=0.10). The path of the end-point is shown on (a): desired path(dot) and actual path(circle). The history of contact force is shown on (b).

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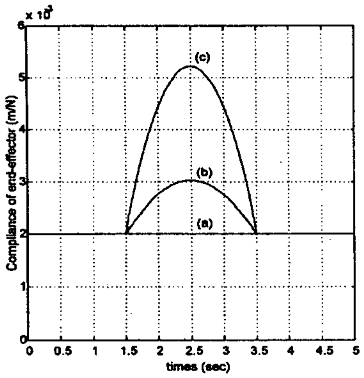

Figure 7: The compliance effect of the end-effector as the slope of the proposed stiffness function.
(a) slope = 0.0, (b) slope = 0.025, (c) slope = 0.10

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