AUGMENTED IMPEDANCE CONTROL: AN APPROACH TO IMPACT REDUCTION FOR KINEMATICALLY REDUNDANT MANIPULATORS

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Summary

Applications of robotics to manufacturing tasks, in addition to high-speed maneuvering in unconstrained space requires interaction with the environment, or with the workpiece being handled. For example, in robotic assembly tasks the robot contacts and manipulates workpieces on a routine basis. At the instant of contact, the manipulator undergoes an impact with the workpiece which creates an impulsive force at the end-effector that is propagated through the manipulator structure. If the magnitude of this impulsive force is large, it can have detrimental effects on the manipulator and the workpiece. Thus, in many cases, particularly when either the manipulator end-effector or the workpiece (or both) are fragile, the contact (or grasp) must be as gentle as possible fo ensure minimum impulsive force. Clearly, for these robotic applications it is important to have techniques for contact modeling and force control so that detrimental effects resulting from impact may be minimized.

In this paper, we consider end-effector/environment collisions which can be modeled as instantaneous phenomena where the impact occurs in an infinitesimally small period of time [1,2]. For collisions of this nature, it is well known [2] that the impact force is a function of the manipulator configuration at the instant of impact, the velocity before impact, and the stiffness of the environment. Thus, when the stiffness of the environment and the velocity before impact are given, we can reduce the impact force by

controlling the configuration of the manipulator. This fact shows that a redundant manipulator has an advantage over a nonredundant one is minimizing the impact force, because in general, it is capable of contacting a surface in an infinite number of configurations. Then, since different configurations have different attributes (such as effective mass, damping, and stiffness) in task space, it is obvious that by altering a configuration, we can modify the manipulator response during impact using appropriate hybrid or impedance control strategies. Therefore, in this paper, we consider the reduction of the effects of instantaneous collisions by considering recent advances in the analysis and design of control techniques in the area of redundant manipulators and impedance control [3].

The proposed utilization of redundancy is based on the configuration control approach [4]. The main advantage of this approach lies in the fact that it can incorporate easily any desired kinematic or dynamic objective function [5]. Here, we utilize redundancy to "soften" the impact force of the end-effector/environment collision. We assume that the manipulator task space trajectory is given and that the environment is stationary with a known stiffness. Within the framework of configuration control, the optimization of this objective function is converted into a tracking problem. In the proposed scheme, a dynamics-based optimization is performed within the redundant manipulator's control loop. The optimization is set up so as to yield the minimum impact configuration at each point of the trajectory in the neighborhood of a collision. This is a useful feature when the contact instant is not precisely known. It also has a potential application to recontact between a manipulator end-effector and its environment when there is a possible loss of contact during compliant motion.

To maintain stable contact after collision, we propose here a task-based impedance controller which is shown to overcome the after-collision rebound effects. As is well known [3], impedance control comprises a control system design philosophy where one attempts to regulate the dynamic behavior of the system with respect to its interaction with an environment. Thus, in the impedance control approach, the motion is controlled to respond according to a target impedance relation between the sensed contact force and the desired response. Clearly, the aim of this controller is to make the manipulator end-effector behave with some desired Cartesian (task space) mass, damping, and stiffness. In general, a Cartesian target impedance is specified as a second-order linear system with positive definite matrix coefficients of specified mass, damping, and stiffness. Note that by choosing these coefficient matrices appropriately, we can achieve various manipulation task objectives. For example, high stiffness is usually specified in directions where the environment is compliant and position accuracy is important, while low stiffness is specified in directions where the environment is stiff, or when small interaction forces must be maintained. Also, a large value for the damping matrix is specified when energy must be dissipated. Finally, the mass matrix is used to provide smoothing in the end-effector response due to external contact. The mass matrix is particularly important when the impedance controller is designed to control collision impact. Note that in this case, if the desired effective mass is chosen to be considerably larger than the mass of the actual manipulator, then one has to expect large impulsive forces. On the other hand, if the desired effective mass is chosen to be considerably smaller than the mass of the actual manipulator, then one can expect large oscillatory behavior which increases the rebound effects. In this paper, we use a "reduced-order" impedance controller where the desired effective mass is chosen to be equal to the natural manipulator inertia tensor as expressed in task space. An application of the reduced-order impedance controller in compliant motion (which is equivalent to stiffness control) can be found in [6]. In this paper, we use a reduced-order impedance controller to suppress the after collision rebound effects. Note that in the case of collision impact, stiffness control alone is not sufficient since the discontinuities of velocity and acceleration create large errors which affect the impulsive force. Consequently, in the proposed formulation, the reaction force includes static as well as dynamic terms. This formulation not only describes more accurately the impact force, it also provides the desired damping (e.g. critical damping) for the closed-loop characteristic equation of the system.

The proposed task-based augmented impedance control scheme controls directly the configuration variables so as to achieve smooth tracking of the desired reference trajectories while the additional task (impact minimization) is accomplished by optimizing the dynamics-based objective function. Our control system consists of two loops. The inner loop basically achieves feedback linearization of the manipulator's nonlinear dynamics. The outer loop performes trajectory tracking as well as dynamics-based optimization. Computer simulations have been carried out using a three-link planar robot manipulator. The results show that in the neighborhood of contact, the manipulator end-effector tracks a desired reference trajectory while achieving a configuration that gives minimum impact force.

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