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Force and impact control for robot manipulators with unknown dynamics and disturbances

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Case Western Reserve University, 1994
FORCE AND IMPACT CONTROL FOR ROBOT MANIPULATORS
WITH UNKNOWN DYNAMICS AND DISTURBANCES

by

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Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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FORCE AND IMPACT CONTROL FOR ROBOT MANIPULATORS
WITH UNKNOWN DYNAMICS AND DISTURBANCES

Abstract

by

EUNJEONG LEE

In this dissertation, three problems have been primarily studied in the area of robot control: (1) characterization of robot nonlinear dynamics, (2) force control of robot manipulators with unknown dynamics and disturbances, and (3) nonlinear impact force control.

In order to identify the robot control problems, we studied the effects of plant dynamics, focusing on robot joint dynamics such as joint flexibility and friction. Extensive experimental studies have been done on robot transmissions. The experiments have included: transmission linearity, backlash, static and dynamic friction, and forward efficiency. In order to understand the influence of transmission properties on overall system performance, a comparative evaluation was performed on three competing transmission types: worm-gear drive, cone-drive and traction drive transmission. The results of experiments performed on worm-gear drive validated a load-dependent friction model, which was derived for feed-forward friction compensation in feedback control.
With understanding of how transmission nonlinearities influence closed-loop and controlled behavior, a new controller has been developed by combining Natural Admittance Control with Time Delay Control. The proposed nonlinear controller is not model based control. The only system parameter that must be estimated is inertia, rendering it easy to implement. It rejects unmodeled dynamics, nonlinearities, and disturbances without a difficult characterization process while preserving desired dynamics. The simulation results demonstrate not only good external disturbance rejection, robustness to parameter changes and insensitivity to noise, but also demonstrate good trajectory tracking providing good rejection of internal Coulomb friction.

For stabilization of a robot manipulator upon collision with a stiff environment, we proposed a novel impact force control strategy which is developed based on the observation of human interactive behavior. It uses a robust natural admittance/time-delay control with an added negative force feedback to absorb impact force and stabilize the system. During the impact phase, this control input alternates with zero control input when no environment force is sensed. Simulation results show that this simple bang-bang control approach produces a stable interaction with a very stiff environment and its performance is comparable to the other existing impact force control techniques.
To My Loving God
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- 1 Corinthians 15:10 -
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4.1 System Parameters
Chapter 1

Introduction

1.1 Statement of Purpose

This thesis addresses the dynamics and control of robots with dynamic interaction with the environment. The major objective of the robot manipulation is to achieve stable and commanded interaction with its environment. Many approaches have been developed to meet this challenge over the last years. There have been some successes, but certain limitations of interaction controllers still remain. One popular method is the "impedance control (Hogan, 1985)" method.

The primary goal of this thesis is to develop an interaction controller for robot manipulators by improving impedance control. This controller is intended to be implemented on any industrial manipulator with nonideal or nonlinear dynamics which is operating in a non-structured and changing environment. The performance will be verified by simulation.

The second goal is to design an impact controller which stabilizes robot manipulators upon collision with a stiff environment. A simple nonlinear strategy will
be devised incorporating sensed environment force. Its performance will be examined in simulation.

In developing control systems, it is essential to have a solid understanding of the dynamic characteristics of the systems to be controlled. A final goal of this work is to understand the dynamic characteristics of robot systems. The effects of plant dynamics on closed-loop performance will be studied in order to identify the robot control problems. Extensive experimental studies have been done on robot transmission.

1.2 Background

The controller to be developed in this work is based on impedance control. The purpose of this section is to provide a brief background of impedance control.

1.2.1 Impedance Control

In robot control system design, two approaches have been used in order to assure compliant motion for manipulators. The first method is aimed at regulating a system's output (e.g., force and position). Generally, the controller is assumed to minimize the error between a reference command vector and a desired output vector, subject to the electro-mechanical limitations of the physical hardware. Upon contact with the environment, this type of controller treats interaction forces as disturbances and attempts to reject them, thus causing more interaction forces and torques. It eventually leads to instability and hardware failure. However, when robots make
dynamic interaction with the environment, which is common in most robot applications such as manufacturing, the interaction forces should be accommodated rather than resisted (Kazerooni et al., 1986a). The system's response to its environment becomes important. Accordingly, the control objective should be to modify the dynamics of interaction between a system and an environment rather than merely control some vector of port variables such as positions, velocities and forces. This concept of control has been termed impedance control (Hogan, 1985). Impedance controllers are distinguished from those designed for manipulators that do not have dynamic interaction with environment. In this sense, impedance control is often referred to as interaction control. Impedance control provides an approach to understanding manipulation rather than a prescription for designing controllers. Impedance control changes the dynamic relationships among the interaction port variables, such as admittances and impedances, in such a way to achieve stable and desirable interaction behavior. Impedance control provides good performance and can guarantee stable interaction with arbitrary passive environment, if certain passivity criteria are satisfied.

Despite the desirable properties that impedance controllers offer, it is not always easy (or even possible) to implement a particular impedance or to maintain contact stability during contact tasks. A major reason for this is that real robots have various nonlinearities, such as actuator, transmission, link structure, and sensor dynamics. These nonlinearities include actuator saturation, stiction, Coulomb friction, backlash, torque ripple, and nonlinear spring characteristics in the transmission. Time delay with force feedback can also cause instability when in contact with a stiff environment (Colgate, 1988, Lawrence, 1988).

For the successful implementation of impedance control, a target impedance for a given task must be chosen so that the manipulator will be stable when interacting with
the environment. The proper choice of target dynamics is based on accurate knowledge of the robot dynamics. It is difficult to design a high-performance control system if the undesirable nonlinear dynamics are unmodeled. Even unmodeled linear dynamics, which can produce marginally stable behavior, jeopardize stability and make the controlled system exhibit poor robustness to parameter variations unless these lightly-damped poles are considered in the control design (Eppinger et al., 1992). Unmodeled high frequency dynamics are important above the frequency range of normal operation because the higher frequency structural modes can be excited by the unmodeled dynamics.

Contact stability can also be jeopardized by dynamic interaction between the robot and its environment. Contact dynamics change the performance of the robot dramatically. Eppinger and Seering have shown that the dynamic elements (modeled or not) separating the actuator and the sensor are most important in contact instability. These, in fact, limit high feedback gain in force control even though the robot is extensively modeled (Anderson, 1989, Eppinger et al., 1992).

In the remainder of the chapter, the stability of a manipulator interacting with its environment is discussed. The state-of-the-art designs and implementations of impedance control are studied, and compared with their limitations. The major problems which need to be addressed to improve the interaction performance are identified. The major contributions of this thesis are summarized.

1.2.2 Contact Stability

One of the important effects which may cause a manipulator to depart from ideal dynamic behavior is the interface dynamics between the manipulator and the
environment. Many researchers have studied the coupled stability property in the control of dynamically interacting systems. Three major techniques are used for nonlinear stability analysis: the small gain theorem (Kazeroni, 1989), passivity and dissipativeness (Colgate, 1988, Hogan, 1988), and Lyapunov theory (Fasse et al., 1989).

Hogan (1987,1988) has shown, based on physical systems theory, that a simple impedance controlled manipulator remains stable when coupled to an arbitrary passive environment. A simple impedance control is distinguished from nonlinear force-feedback impedance control in that it does not use force feedback in its implementation. Hogan used a rigid body model of the manipulator with ideal torque sources for actuators.

Kazeroni (1985, 1986ab) studied the stability of impedance controlled manipulators. He assumed that the environment was passive and linearizable. He did not establish the robustness of the coupled stability. He has shown that the stability robustness of a simple impedance controller is preserved when the environment contains active sources which do not depend on the state variables of the manipulator. However, his analysis was local because it was based on the assumption that the environment was linear or differentiable.

Wlassich (1986) implemented a nonlinear force-feedback impedance controller using a rigid-body model of the manipulator and an ideal actuator. His experimental results showed that there were ranges of impedance which did not demonstrate the robust coupled stability properties as predicted by Hogan in (Hogan, 1987).

Fasse (1987, Fasse et al., 1988) presented a Lyapunov function approach to analyze the robustness of coupled stability to modeling errors within a linear framework for the robot; a electromechanical actuator, drivetrain dynamics, and force transducer dynamics. The environment was assumed to be non-conservative allowing even non-
differentiable environmental nonlinearities. A weakness of his analysis lies in the fact that it provides only sufficient conditions.

Colgate (1988) derives a set of a necessary and sufficient conditions for coupled stability of linear-time-invariant multi-port systems using linear passivity analysis of network theory. He established quantitative design criteria which any implementations of impedance control must meet if it is to be successful.

Hogan (1988) shows that the coupled stability of the manipulator, interacting with a large class of stable environments, is guaranteed if the manipulator has the behavior of a simple impedance. His paper showed, using concepts from physical systems theory, that robust stability can be obtained by imposing appropriate structure on the dynamic behavior of a manipulator. The two key assumptions are: First, the environment is stable in isolation. Second, the behavior of the controlled system (i.e., desired endpoint impedance) as seen from the environment is that of a passive and dissipative system. It is unrealistic, however, to assume a strictly passive environment because many real environments contain active power sources and all motion is not damped in the environment. Another limitation is the restriction to passive and dissipative behavior because strict passivity can not be obtained without disabling the robot's ability to achieve a desired command.

Fasse et al. (1989) extended Hogan's analysis in (Hogan, 1987) to include a more general impedance controller using a Lyapunov approach. Assuming collocated sensors and actuators, the coupled stability of a simple impedance controller has been analyzed for robustness to some modelling errors: kinematic errors, joint friction, gravity, base dynamics and actuator transmission dynamics. However, the coupled stability analysis for a nonlinear force feedback impedance controller shows that a general impedance controller is not immune to modelling and implementation errors as is observed in (Wlassich, 1986, Fasse, 1987).
Anderson (1989) used the PHIDE subclass of Hilbert networks to model both the manipulator and the environment. His stability proof shows that the velocities of a manipulator using a passive force control law are asymptotically stable upon contact with an arbitrary, passive environment. His analysis, however, does not include the effects which cause manipulators to lose passivity.

Kazerooni et al. (1989, 1990, Waibel et al., 1991) present a nonlinear input-output stability analysis using the small gain theorem. They use unstructured models for the dynamic behavior of the robot and the environment focusing on the input-output relationships rather than the interaction dynamic structure. The stability conditions are described in terms of sensitivity functions. This approach allows the incorporation of the non-rigid-body dynamics in the analysis (i.e., sensor noises, structural compliance, external disturbances, parameter uncertainties, and actuator dynamics, etc.). It is shown that there must be some initial compliance either in the manipulator or in the environment to have stable manipulation. Two stability criteria are derived for a robot interacting with a finite-stiffness environment, with/without force feedback. The third stability criterion, for a robot contacting infinite-stiffness environment, shows that the gain of the force compensator must decrease as the gain of the trajectory compensator increases. Their stability analysis, though, provides only sufficient conditions and results in extremely conservative gains.

1.2.3 Recent Designs and Implementations of Impedance Control

Hogan (1985) presents an impedance controller using a rigid-body model and an ideal actuator as follows:
\[ I(\theta) \frac{d\omega}{dt} + C(\theta, \omega) + V(\omega) + S(\theta) = U + J'(\theta)F \]

where \( \theta \) and \( \omega \) are the generalized actuator angles and velocities respectively; \( I(\theta) \) is the configuration-dependent inertia tensor in actuator coordinates; \( C(\theta, \omega) \) is a vector of the inertial coupling forces such as centrifugal and Coriolis force; \( V(\omega) \) is a vector of the velocity-dependent forces such as viscous friction; \( S(\theta) \) is a vector of any position-dependent forces such as gravitational forces; \( U \) is a vector of actuator forces (or torques); \( J(\theta) \) is the position-dependent Jacobian of the kinematic transformation from joint velocities to end-point velocities; and \( F \) is a vector of the environment-imposed endpoint forces. Any actuator dynamics have been neglected.

The desired endpoint behavior can be generally described as follows:

\[ M \frac{dV}{dt} - B[Vd - V] - K[Xd - X] = F \]

where \( M \), \( B(\cdot) \) and \( K(\cdot) \) represent the inertia tensor in end-point coordinates, force/velocity relation and force/displacement relation, respectively; \( X(Xd) \) and \( V(Vd) \) represent the positions (desired positions) and the velocities (desired velocities) in end-point coordinates, respectively. The control torques can be derived by equating the actual acceleration and the target acceleration. After substitution, the complete control torque becomes:

\[
U = I(\theta)J^{-1}(\theta)M^{-1}K[Xd - L(\theta)] + S(\theta) \\
+ I(\theta)J^{-1}(\theta)M^{-1}B[Vd - J(\theta)\omega] + V(\omega) \\
+ I(\theta)J^{-1}(\theta)M^{-1}F - J'(\theta)F \\
- I(\theta)J^{-1}(\theta)G(\theta, \omega) + C(\theta, \omega)
\]
where
\[ G(\theta, \omega) = \left[ d\{J(\theta)\omega\} / d\theta\right] \omega \]

and the end-point coordinates are obtained from the actuator angles via the linkage kinematic transformation:

\[ \mathbf{X} = L(\theta) \]

The control law involves only the inverse Jacobian and does not require inverse kinematic equations.

Kazerooni (1985) was the first to study a non-ideal manipulator. He designed an impedance controller which includes the first-order decoupled actuator dynamics in a linearized manipulator model. His linearized plant model differs from that of Hogan's in that gravity is included and the joint damping is not included. According to physical system theory, stability can be obtained by imposing appropriate structure on the target dynamics of a manipulator. By the use of an eigenvector assignment technique, he chooses state-feedback and force-feedforward gains to match the eigenstructure of the manipulator to that of target dynamics. His design, however, fails to meet coupled stability criterion because the stability of the target dynamics is not enough to guarantee the coupled stability. The result shows that first-order actuator dynamics can cause significant difficulty in control even if it is included in the design procedure. The high-frequency unmodelled dynamics results in narrow closed-loop bandwidths of manipulation and a very conservative feedback gain.

Wlassich (1986) implemented a nonlinear force-feedback impedance control with a computed torque scheme assuming a rigid-body model of the manipulator and an
ideal actuator. His controller differs from Hogan's (Hogan, 1985) in that it uses a weighted pseudoinverse Jacobian instead of the Jacobian.

Anderson and Spong (1987) combine hybrid force/position control and impedance control. Non-idealities are not considered in the model. Their method allows for higher order target dynamics, even though second order target dynamics are used for simplification. The importance of the environment modelling is shown in the design of a control strategy. This method requires high computing power, making it not attractive for practical use.

Kazerooni (1987) presented the most general approach to the design and implementation of impedance control. His control architecture is two-nonlinear mappings - one (G) from an input-command trajectory vector to the manipulator position vector, and another (S) from a vector of external forces to the position - each subject to $L_p$ boundedness. The environment is also modeled as a nonlinear mapping (E). He modeled the robot and the environment in an unstructured form which accommodates all existing industrial robots. The transfer function matrix $H$ is a compensator to be designed and embodies the target impedance, at least at low frequency. However, a method for selecting $H$ or relating it to particular target dynamics is not addressed. His design allows for tracking the input command vector, as well as for compliance in the system. It generates electronic compliance for robot manipulators by altering its inherent dynamics. The global stability range of the manipulator and environment were derived based on the multivariable Nyquist theorem; the results were experimentally verified. His analysis shows that the bound for coupled stability is increased by the compliance in the robot or between the robot and the environment.

Spong (1987) combines an integral manifold nonlinear controller with an impedance controller for manipulators with joint flexibility. He uses second order
actuator dynamics. Using the ideas of singular perturbation and integral manifolds, he derives a reduced-order model of the manipulator which incorporates the effects of joint flexibility on the system. An impedance control has been designed for the rigid body model followed by a corrective control to compensate for the effects of flexibility. The inner loop is a nonlinear control which linearizes the system restricted to a suitable manifold in state space. The outer loop is a linear control using impedance control for rigid manipulators which can be designed independent of the nonlinear inner loop. The control has two parts: The slow control consisting of the impedance control plus the corrective control transforms the integral manifold into the rigid manifold. The fast control can be used if the manifold is not sufficiently attractive. However, practical implementation of this scheme remains questionable due to its extreme sensitivity to parameter changes and disturbances. The technique requires exact knowledge of many system parameters.

Goldenberg (1988) developed a controller which uses both force and impedance control. This approach can be applied to the nonlinear target dynamics although he uses ideal linearized models and second order target dynamics. It does not require interaction force measurement.

Hamilton (1988) extends Kazerooni's compliant motion control approach (1985, 1986ab) to assure global stability. He uses an ideal robot model without actuator dynamics and second order target dynamics. His approach may be extended to redundant manipulators.

Goldenberg, Anderson and Spong invert the robot impedance and replace it with the desired impedance. They assume that an inverse of the robot's impedance is possible assuming that cancellation occurs only at low frequencies. This approach may introduce nonminimum phase zeros thereby jeopardizing coupled stability. Kazerooni's second approach also tries to mask the robot's inherent dynamics by
implementing the target dynamics through feedback. Colgate (1988) concludes that the concept of replacing the inherent driving point impedance with a target impedance through the action of state and input feedback is incompatible with robust coupled stability of the closed-loop system because interactive behavior is achieved through a term which cannot be positive real. The effect of the positive force feedback proposed by Hogan (1985, 1987) and Wlassich (1986) is to enhance the inherent dynamics rather than mask and replace it. Their controllers show more robust interactive behavior. However, even for positive force feedback, the gain should be low so as to not generate nonminimum phase zeros.

Newman (1992a) designed a new control strategy (called Natural Admittance Control) by preserving Colgate's passivity criteria and avoiding suppression of the system's inherent dynamics. Under natural admittance control (NAC), the target dynamics is an admittance, $Y_{m}$, the uncontrolled actuator motion in response to applied endpoint forces. $Y_{m}$ is the maximum achievable admittance which can be obtained while satisfying the passivity criterion. Full state feedback is not required and the target dynamics are intentionally chosen to be representative of the system. Therefore, natural admittance control enhances the inherent dynamics rather than suppressing them. Implementation of natural admittance control is divided into two phases: First, it tries to achieve the maximum possible admittance, $Y_{m}$, with any force feedback scheme. In the second phase, natural admittance control is implemented to reject internal disturbances (such as Coulomb friction) with high gain. Natural Admittance Control has two major advantages: First, it guarantees stable contact with all passive environments because it is designed using the passivity criteria. It does not require any knowledge of the environment. Second, natural admittance control obtains an endpoint admittance which achieves optimal responsiveness and good rejection of internal disturbances with admittance amplification. Most force feedback controllers cannot
achieve good disturbance rejection because the passivity restriction allows only low gains.

Many problems need to be addressed to apply natural admittance control to a broad class of robot manipulators: for the case that the joint velocity and angle at motor port are not available and the case that there is significant amount of friction between the endpoint and the environment. It will be beneficial to design some transfer function (other than just a constant as shown in (Newman, 1992a) for the feedback compensator of $v_m$ (velocity at motor port). The feedback compensator for $v_e$ (velocity at force sensor location) needs to be designed to fully implement the natural admittance controller.

1.3 Contributions

The major contributions of this thesis may be summarized as follows:

- Experimental investigation of transmission dynamics which characterize the nonlinear dynamic effects of robot.

- The development of a interaction controller for the constrained robot manipulation. Advantages include:

  - The rejection of unmodeled dynamics and nonlinearities without a difficult and inaccurate characterization or estimation process which makes the manipulator achieve good command following.
- The rejection of unexpected disturbances and the robustness to environmental stiffness changes which allow the manipulator to achieve good interactive behavior in unstructured environments.

- The easy implementation which does not necessitate the estimation of system parameters, except inertia, because the controller is not model based control.

- The robustness to parameter changes and insensitivity to implementation noise which facilitates practical implementation.

- The development of an impact controller which stabilizes a robot manipulator upon collision with a stiff environment. The controller stabilizes the system by a simple nonlinear scheme which is inspired by human interactive behavior.

1.4 Summary of Remaining Chapters

Chapter 2 investigates dynamic characteristics of robot systems. The effects of plant dynamics on closed-loop system performance are studied, focusing on robot joint dynamics such as joint flexibility and friction. Experimental characterizations are performed on three competing transmission types.

With understanding of how transmission nonlinearities influence closed-loop and controlled behavior, a new controller is developed by combining Natural Admittance Control with Time Delay Control in Chapter 3. The development of
"natural admittance control" is described as a background. A system model is derived and the results are compared to natural admittance control by simulation. In chapter 4, a nonlinear impact controller is developed for contact transition from free space to constrained manipulation. A system model is described and the performance is compared with the performances of several existing approaches in simulation. In chapter 5, the results and contributions of the thesis are summarized. Related areas of research are explained and directions for future research are discussed.
Chapter 2

Robot Dynamics

2.1 Overview

In chapter 2, the effects of unmodeled dynamics on the robot performance and its contact stability are discussed in detail. A comparative evaluation is presented for two flexible dynamic effects which are important in robot control; the low-frequency dynamically collocated modes and higher-frequency dynamically noncollocated modes. Various robot joint dynamics are discussed with an experimental transmission characterization.

A rigid-body model is severely limited in its ability to represent real machine systems, which always include some form of flexibility. This flexibility becomes significant especially at high manipulation speeds, precision and/or large payload conditions. Examples of flexible elements in robot systems are: gear tooth bending, bearing mount compliance, link bending or torsion, mounting base compliance, bending of axis guides or ways, force sensor compliance, grasp compliance, and workpiece compliance. Note that some of these flexible elements are physically located between the actuator and sensor, while others not. Base and workpiece dynamics add dynamically collocated modes (where the actuator and sensor remain in phase), while
transmission and link flexibility cause dynamically noncolocated modes (where the actuator and sensor can vibrate out of phase).

Eppinger and Seering have shown that dynamic elements (modeled or not) that separate the actuator and sensor are most important for contact instability. These, in fact, limit high feedback gain in force control even though the robot is accurately modeled (Eppinger et al., 1992). In terms of the noncolocated dynamic elements, the points of the highest stress are the joints, and the resulting elastic deformation of the joints, either through deformation of the bearings or the gear teeth themselves, will introduce joint flexibility that has a greater significance for control system design than do the actual bending modes of the links, which can be of significantly higher frequency (30-60 Hz for the lowest resonance) than the resonant flexible modes of the joints (8-12 Hz). Therefore, joint flexible modes of robots with transmission systems exhibit a more pronounced effect on the system performance. In this context, robot joint dynamics will be discussed in detail. Transmission characteristics, including backlash, friction, transmission ratio, and efficiency are experimentally identified and their effects on transmission performance are observed.

2.2 Dynamically Noncolocated Modes

Noncolocation means that the actuator and sensor do not reside at the same physical location, but are separated by dynamic elements. Dynamically noncolocated modes are flexible modes in which the actuator and sensor response is out of phase. Even though an actuator and sensor have noncolocated physical placement on the structure, they can introduce dynamically colocated modes where the actuator and sensor responses are in phase.
In the case of a robot, the actuators are generally located at the joints and the force sensor is near the end-effector, separated from the actuators by transmission dynamics and structural dynamics of the link. The transmission and link dynamically couple the actuator to the end point. With any flexibility in either the transmission or the link, there will be frequencies above which the actuator and end point velocities will not only be different, but out of phase. This effect, noncolocation, was first discussed by Gevarter in the context of controlling flexible vehicles. A root locus plot showed that there were unstable modes in the noncolocated closed loop system (Gevarter, 1970). Dynamically noncolocated modes are usually modeled by strictly proper rational functions and at resonance can contribute 180 degrees of phase lag limiting the achievable bandwidth.

When the sensors and actuators are noncolocated, the control system must account for the presence of many vibration modes. Modal damping ratios and vibration frequencies must be known accurately or identified continually, because the controller will invariably destabilize some of the high frequency modes even when the plant is known, so that the typically low values of inherent damping will limit achievable performance greatly. However, the fundamental performance limitation is represented by the frequency of the lowest mode in which the actuator and sensor move opposite in phase (from their rigid-body mode motion). All of the other modes are less important. The designer must pay particular attention to increasing the frequency of these dynamically noncolocated flexible modes. The resonance only needs to be increased beyond the open-loop phase crossover of the rigid-body model.

In the case of noncolocation, any controlled flexible system may be extremely sensitive to the actual values of system parameters because "pole-zero flipping" can occur when parameters vary (while colocated systems always have alternating poles and zeros even when parameters vary greatly). Therefore, quite sophisticated
techniques are needed to achieve fast, stable and robust control. Noncolocated control is often recommended, in spite of its disadvantages, to achieve high performance with precision in the presence of modeling uncertainty or tip disturbance.

2.3 Dynamically Colocated Modes

Dynamically colocated modes are flexible modes in which the actuator and sensor move together (in phase) despite their noncolocated physical placement on the structure. Gevarter (1970) showed that colocation does not guarantee stable closed loop control. Even if the actuator and sensor are physically colocated, there can still be modes in which the actuator output and the sensor signal are out of phase, while for the rigid-body mode, they are in phase. It depends on what is being measured and where the actuator/sensor pair is placed on the structure.

The base and workpiece dynamics contribute dynamically colocated modes which do not severely affect the system performance. In contrast with the link and transmission compliance, the base compliance is less detrimental to the bandwidth of the closed loop system. The phase dip contributed by the base dynamics would not cause instability if the rigid-body system has sufficient phase margin to keep the total phase above -180 degrees. Also, if the base mode is sufficiently damped, then the pair of poles will lie very close to the pair of zeros, and this phase dip is hardly even noticeable. The base mode is dynamically colocated, since the base resonance does not cause the actuator and sensor to vibrate opposite in phase. The workpiece dynamics have very little effect on stability or bandwidth.

Colocated control is robust to parameter changes since colocated systems always have alternating poles and zeros even when the parameters vary greatly. The
important conclusion about collocated dynamics is that they have very little effect on the overall response of the system, however they do affect the response over a small range of frequency. This phenomenon is quite similar to the contribution of a second-order lead filter.

2.4 Robot Nonlinearity

In robot systems many sofisticated controllers do not achieve the desired performance due to the inherent nonlinear dynamics and digital sampling. These nonlinearities are mainly present in the actuator and drive systems that most robots employ for mechanical advantage. The actuators are electro-mechanical devices which are usually modelled as pure torque sources or as dynamic first-order lags. The first-order lag representation of actuators is only an approximation. However, in many practical implementations actuator dynamics are represented by low-pass filters. In this section, we focus on the nonlinear drive system dynamics for robot manipulators.

Recent experimental work provides convincing evidence that joint elasticity is the dominant source of compliance in most current manipulator designs. Good et al. (1985) observed experimentally the torsional elasticity in the drive system. Yang and Donath (1988) have shown that the joint flexibility can have significant effects on the deflection of flexible arms. This joint elasticity may limit the speed and dynamic accuracy achievable by control algorithms that are designed assuming perfect rigidity at the joints. In addition to joint elasticity, the problem of controlling high-precision, high-speed robots in a wide range of configuration calls for accurate modeling of the significant nonlinearities.
Among joint dynamics, transmission dynamics are a major source of motion disturbance and prospective instability in feedback. Mechanical transmissions are an essential part of many electro-mechanical drive systems allowing the use of smaller and lighter actuators to produce larger torques. Transmissions, however, contain several nonlinearities such as stiction, Coulomb friction, backlash, torque ripple (Salisbury et al., 1988), and nonlinear hardening spring characteristics (Sweet et al., 1984, Good et al., 1985). Stiction can cause limit cycling; Coulomb friction, which can extend system stability by absorbing oscillation energy, may lead to input-dependent instability and an actuator limit cycle (Kubo et al., 1986, Townsend et al., 1987). Gearing backlash may lead to instability in closed loop control systems (Tustin, 1947) but may be mechanically reduced, though at the cost of increased Coulomb friction and stiction (Yang and Tomizuka, 1988). These nonlinearities not only limit performance in precise positioning tasks but also make high performance force control more difficult.

These undesirable, nonlinear effects can be minimized either by the mechanical system design or masked by the controller design. Direct-drive robots have been developed to avoid mechanical backlash and friction by eliminating transmissions altogether (Asada et al., 1984). However, this design suffers from the ability to only handle small payloads. Special attention has also been given to the selection of appropriate transmission elements (Jacobsen et al., 1986, Salisbury et al., 1988). Feed-forward friction compensation has been developed to mask robot joint friction (Hollar et al., 1985). Feedback techniques (Salisbury, 1980, Wu et al., 1980, Kubo et al., 1986, Gogoussis, 1987, Townsend et al., 1987) and feedback/feedforward techniques (Handlykken et al., 1980, Walrath, 1984) have also been used.
2.5 Experimental Characterization of Transmission Dynamics

Mechanical transmissions are an essential component of most electro-mechanical systems. However, transmission dynamics are a major source of motion disturbance and prospective instability in feedback. In a wide variety of applications, from high-performance web tension and velocity control to robot position and force control, transmission dynamics can be a limiting factor in achieving the desired performance.

In this section, a detailed comparative evaluation is presented for three transmission types: a worm-gear drive (worm gear), a cone-drive, and a traction-drive. Measurements performed include: transmission linearity and backlash. For a worm-gear drive, viscous and Coulomb friction (Dohring et al., 1993) and forward and reverse efficiency are measured. Nonlinear hardening spring characteristics of the transmission and the closed-loop properties of the transmissions should be further investigated.

In this experiment, three commercial transmissions were investigated:

- a Dodge model 5350 Tiegear, 10:1 ratio, worm-gear drive transmission, rated at 1671 in-lb output torque, 1750 rpm, 5.1 Hp

- a Textron Cone Drive model H030A769-2, 8:1 ratio, cone-drive transmission, rated at 4.48 Hp, 1750 rpm

- a Mitsubishi model TRDB80H6.3RB, 6.3:1 traction-drive transmission,
2.5.1 Friction

In robot joint dynamics, transmission friction is often the major source of nonlinearity. To compensate for this nonlinearity feed-forward compensation is often added to the control algorithm, requiring an accurate friction model. While an exact friction model is essential to real-time friction compensation, little effort has been given to the study of friction behavior in robotic transmissions. Recent experimental evidence has suggested that the friction in robot joints is load dependent. It has been shown that an apparent position dependence of the friction in a General Electric GP132 manipulator is actually due to the varying gravity-load (Ballou, 1990). Coulomb-like friction caused in a cable transmission was observed to be proportional to the square of the torque load (Townsend et al., 1987). Recently, there has been some effort to mathematically describe friction behavior in a robot transmission. The analytical dependency of friction on load in a robot joint using a harmonic drive or a worm gear transmission has been explicitly examined without experimental verification (Gogoussis et al., 1988, Vossoughi et al., 1988). Load-dependent friction in screw drives has also been discussed as in (Dupont, 1990). This section presents the experimental characterization of friction in worm gear drives along with a discussion of how well the data fits a simple load-dependent friction model.
2.5.1.A. Friction Model

Worm gear transmissions have been used in robotic systems to avoid backdrivability (Vossoughi et al., 1988). A worm gear set consists of a worm (pinion) and a worm gear. The worm is a screw-like member whose teeth wrap around the pitch cylinder. The face of a worm gear is made concave to fit the curvature of the worm providing a line contact for a single-enveloping gear set. (A double-enveloping gear set generates an area contact between the gears.) The shafts of the gears do not intersect and are usually orthogonal. Because of its kinematic structure and contact properties, the following bidirectional wedge model is proposed (Dohring et al., 1993). The model is obtained by "unwinding" the worm into a ramp and uses a single "tooth" from the worm gear to form a slot. The mechanism is now planar as shown in figure 2.1.

![Diagram](image)

Figure 2.1 Planar mechanism (taken from (Dohring et al., 1993))
In figure 2.1, $M_1$ and $M_2$ are the masses of links one and two, respectively. $F$ and $v$ are forces and velocities, respectively. Force and velocity directions of positive ports 1 and 2 are the same as the positive directions of $x$ and $y$. The angle $0 < \phi < \pi / 4$ determines the transmission ratio as $R = 1 / \tan(\phi)$. Under steady-state conditions, the dynamic equations of the model are described as follows.

For positive velocity,

$$F_1R = -F_2 \frac{1 + \mu R}{1 - \mu R} \tag{3.1}$$

For negative velocity,

$$F_1R = -F_2 \frac{1 - \mu R}{1 + \mu R} \tag{3.2}$$

The sliding friction force at a surface is proportional to the normal force $F_N$ with coefficient of friction $\mu$.

$$F_f = \mu F_N \text{sgn}(v_1) = \mu F_N \text{sgn}(v_2) \tag{3.3}$$

Detailed derivation can be found in (Dohring et al., 1993).
2.5.1.B Apparatus

The experimental test platform for friction measurement is given below. The test stand consists of a computer control and data acquisition station, two rotating torque transducers and associated electronics, two DC servo motors with integral resolvers, a traction-drive transmission and a transmission to be tested, a mechanical brake, mechanical mounts for each component, mechanical flexible couplings for each component, associated computer I/O hardware and software, and the test bench for mounting the hardware. Analog torque signals were generated using Himmelstein strain-gauge amplifiers.

![Diagram of experimental setup](image)

Figure 2.2 Experimental setup (friction measurement)
The major components of the apparatus for these experiments are shown in figure 2.2, and the objective is to measure the port velocities, positions, and forces. The setup consists of a mechanical chain containing, in order from the high speed port (port 1) of the worm gear transmission, a D.C. servo motor with integral resolver, a reactionless rotating torque transducer, the worm gear transmission, a second torque transducer, a traction drive transmission transmission ratio of 29:1 and a second D.C. servo motor with resolver. Each element was coupled to the next by a Thomas miniature flexible disc coupling which has a high torsional stiffness about the shaft axis while providing compliance in all five remaining degrees of freedom. Input (high speed port) shaft torque transducer is Himmelstein model MCRT 2402T, 50 in-lbf range, non-contact rotating torque transducer with rated 0.1% linearity. Output (low speed port) torque transducer is Himmelstein model MCRT 2402T, 350 in-lbf range, non-contact rotating torque transducer.

2.5.1.C. Data Acquisition

The raw data was collected after a calibration procedure. Calibrations were done with the two torque transducers as well as with the analog-to-digital converters and the strain-guage amplifiers. The two torque transducers were calibrated relative to each other. They were connected in series and a load was applied. After collecting data from both sensors, the scale factor is computed to establish the relationship between the two outputs.

For friction measurements, the high speed side motor (motor 1) was used as a controlled velocity source while the low speed side motor (motor 2) and traction drive
combination was used as a controlled load source. The input shaft is driven by a servo
motor via a proportinal and integral velocity controller. Velocities $\omega_i$ and $\omega_o$ at the
shafts of the worm gear transmission were obtained from the motor resolver outputs.
Steady-state port torques $\tau_i$ and $\tau_o$ were measured by the reactionless torque
transducers for a sequence of controlled values of $\omega_i$ at several regulated negative load
torques $\tau_o$. For both torque transducers, the strain-gauge amplifier low-pass filter
frequency was 1 Hz and the analog data was sampled by 12-bit analog-to-digital
converters with a 1 kHz sampling frequency and averaged over 15,000 samples for
each data point.

2.5.1.D. Data Analysis

Figure 2.3 shows input-shaft friction data corresponding to an unloved output
shaft. It shows Coulomb friction as well as linear viscous friction. The Coulomb
friction is measured to be approximately 1Nm. The raw data is shown in figure 2.4 for
values of $\tau_i$ of -3.7, -7.4, -11.2 and -14.8 Newton-meters. The data was reduced by
finding the best fit lines for input torque vs. velocity at each of the load torque values.
The zero velocity intercepts represent $\tau_i$ reflected to port 1 plus the friction at
impending motion. Figure 2.5 shows the best fit with $\mu = 0.0240$. The friction torque
seen at port 1 is plotted versus the regulated load at port 2 for both positive and negative
power flows in figure 2.6 and shows clearly that $\tau_o$ contains a load-dependent friction
component for both positive and negative steady-state power flow. It is also evident
from the graph that there is a constant Coulomb component of the friction torque at port
1 even for zero load at port 2. The raw data also shows that there is a linear viscous
term as well.
Figure 2.3 Input friction

Figure 2.4 Raw data
Figure 2.5 Torque 1 vs. torque 2

Figure 2.6 Friction torque 1 vs. torque 2
The value of $\mu = 0.0240$ is consistent with the backdrivability criterion that requires $\mu < 1/R = 0.1$. It is also a believable value based on published values for lubricated (Shigley et al., 1983) motion considering that the coefficient of friction may vary from 20% to 100% or more because of cleanliness, surface finish, pressure, materials, and velocity. It was noticed that a better fit could be obtained on each load line separately. This leads to a difference in the values of $\mu$ for forward and reverse power flow and may be attributable to additional terms not in our model such as a load-dependent bearing friction, gear tooth bending at slow gear speeds, or other physical effects. For positive power flow these other friction losses are amplified. Under negative power flow conditions, the additional friction terms are attenuated. It is probably not attributable to effects directly related to the velocity reversal.

2.5.2 Efficiency

In this section, efficiency of the worm gear drive is measured as a function of velocity and torque.

2.5.2.A Apparatus

The experimental test platform for efficiency measurement is as below. The test stand consists of a computer control and data acquisition station (VME cage and SPARC station), a 10,000 lb-in torque transducer with a AM502 amplifier which is connected to a A/D converter, 350 lb-in torque transducer and associated A/D
converter, two DC servo motors with integral resolvers, a 10kw traction-drive transmission and a 300w traction drive transmission, a transmission to be tested, a mechanical brake, mechanical mounts for each component, mechanical flexible couplings for each component, associated computer I/O hardware and software and the test bench for mounting the hardware. Analog torque signals were generated using a Himmelstein strain-gauge amplifiers. The DC servo motors are connected to power amplifiers and D/A converters, and the resolvers are connected to resolver-to-digital converters. These converters were connected to the VME cage and SPARC station for data collection.

The major components of the setup consists of a mechanical chain containing, in order from the high speed (input) port of the worm gear transmission, a D.C. servo motor with integral resolver, a 300w traction drive transmission (transmission ratio of 23.23;1), a 350 lb-in reactionless rotating torque transducer, the worm gear transmission, a 10,000 lb-in torque transducer, a 10kw traction drive transmission (transmission ratio of 29:1) which is used as a regulated load and a second D.C. servo motor with resolver. Each element is coupled to the next via a Thomas miniature flexible disc coupling.

2.5.2.B Data Acquisition

Measurements are limited up to approximately 1kw of power input due to limitation of power amplifier capacity. Data are collected while the output torque is regulated at a certain value and the input velocity is incremented between -80 rad/sec and 80 rad/sec. To obtain accurate steady-state load torque through a range of input velocities, the output DC servo motor is controlled by a proportional plus integral
torque controller based on the measurement of the worm gear drive output torque. The input velocity is also regulated by a proportional plus integral velocity controller. The velocity started from zero, increasing in fixed incremental steps to 80 rad/sec, then decreasing in the same fixed decremental steps to -80 rad/sec, and increasing again in the same manner to zero. A computer program was written to collect and average data during steady-state conditions and to wait until steady-state is reached after each new velocity command. For both torque transducers, the strain-gauge amplifier low-pass filter frequency was at 1 Hz and the analog data was sampled by 12-bit analog-to-digital converters operating at a 1 kHz sampling frequency and averaged over 10,000 samples for each data point.

2.5.2.C Data Analysis

Experimental data shown in figures 2.7 and 2.8 show the torques for the input velocities under four different load conditions. Figure 2.8 proves that the commanded torque level is achieved and figure 2.7 shows the required input torques for the prescribed loads. Efficiency measurements are shown in figures 2.9 and 2.10. Hysteresis is observed in both graphs. The highest efficiency was approximately 70%. It is observed that higher efficiency is achieved with increased load condition (Newman, 1993). It suggests that as load (or power transfer) increases, the percentage of Coulomb friction decreases, thus increasing efficiency. Therefore, it is believed that the power loss is mainly due to Coulomb friction rather than viscous friction. Negative power flows occur when the input velocities are negative and the output loads are positive. At negative input velocities, the transmission can be regarded as a speed increaser rather than a speed reducer since the loaded high-torque (low-speed) shaft acts
as a power source and the velocity controller at the low-torque (high-speed) shaft acts as a brake sinking power. In other words, the servo motor of the load acts as a power source, while the drive motor at the high-speed (input) shaft acts as a power sink. This is not common in transmission measurements since a transmission output shaft is seldom regulated to have a specific load by a drive motor which is an active torque source. However, such negative power flow is experienced when torque or velocity reverses in these systems. Figure 2.9 shows that the ability of the transmission to absorb power flows in the backward direction is not good. It explains the fact that the worm gear transmission is essentially used for position controlled devices due to its poor backdrivability. Reverse power flow efficiency is noticeably low and it becomes negative at low output loads. The efficiency at near zero velocity is not included since the regulated incremental velocities cannot be achieved and are not continuous. Figure 2.10 shows the efficiency near zero input velocity. It shows that friction decreases as velocity increases from zero and after it reaches to a certain value friction increases again. This phenomenon matches with the experimental observation by Armstrong (1988).
Figure 2.7 Input torque

Figure 2.8 Output torque
Figure 2.9 Efficiency

Figure 2.10 Efficiency at 10 Nm load
2.3.3 Backlash

The backlash effect is difficult to analyze and control in a feedback loop. Backlash is a source of position errors in many robotic systems and produces more errors as transmissions wear out. Backlash becomes important when the motor inertia is relatively large compared to the load inertia (Tustin, 1947). Generally, the backlash effect is small compared to other nonlinear effects in robot systems.

2.5.3.A Apparatus

The experimental test platform for backlash and transmission linearity measurement is given below. The test stand consists of a computer control and data acquisition station, a transmission to be tested, two high-precision optical encoders and associated computer I/O hardware and software, and the test bench for mounting the hardware. For measurement of transmission linearity and backlash, the major components of the apparatus are the transmission and two high-resolution optical incremental encoders. The encoders were coupled to the input and output shafts of each of the transmissions via Thomas miniature flexible disc coupling. The shaft sensors used were BEI series 143 optical incremental encoders, which provided 360,000 counts per revolution.
2.5.3.B. Data Acquisition

The encoder measures the drive shaft position while it is rotated manually. It was rotated forward, backward, forward and backward to display backlash effectively. Input and output angles were recorded while the encoders were sampled at a high rate.

2.5.3.C. Data Analysis

Transmission backlash is shown in figure 2.11. It is shown that hysteresis exists in backlash. A worm gear drive exhibit significant backlash while the traction drive exhibits none. The backlash of the traction drive could not be measured with the high-precision optical encoders which have 0.001 deg resolution. The rollers of the traction drive are preloaded and accordingly contact is not lost, providing zero backlash. The worm gear has a backlash of 0.27 deg. It seems to result from backlash and compliance of the input-shaft thrust bearing rather than by the gear. The cone drive has a backlash of 0.065 deg relative to the output shaft position. The worm gear drive has roughly four times more backlash than the cone drive.
(2.11.a) Traction drive backlash

(2.11.b) Cone drive backlash
(2.11.c) Worm gear backlash

Figure 2.11 Transmission Backlash
2.5.4. Transmission Linearity

Characterization of transmission linearity is important in the study of robot dynamics since the nonlinear effect called torque ripple depends on it. Torque ripple is highly dependent on the dynamics of the transmission, the degree of internal transmission preload, and the amount of transmitted load (Schempf et al., 1993). In geared transmissions the transmission ratio is determined by the relative numbers of gear teeth. However, the condition of gears vary over the course of cycles since mechanical wear develops due to incorrect machining and assembly during the manufacturing process. Such degradation of the gear teeth can generate cyclic accelerations of the transmission input and output, and thus generates a torque ripple (Newman, 1993). This torque ripple appears in the form of position ripple. To reduce such undesirable nonlinear torque disturbances, transmission linearity should be maximized. In this section, a characterization of transmission linearity is described.

2.5.4.A Data Acquisition

The experimental setup for measurement of transmission linearity is same as the backlash measurement. The input and output shaft positions were collected from the optical incremental encoders with the 0.001 deg resolution which are coupled to the input and output shafts of the transmissions. The data were sampled while the input shaft of the transmission is rotated in one direction slowly by hand. This quasi-static rotation alleviates undesirable effects like backlash. From the collected data, the ratio of input to output position increments is calculated for every one degree of output rotation.
This measurement technique is evaluated by using the same technique for a very stiff solid shaft which has unity transmission ratio. The technique is verified to have 0.1% accuracy.

2.5.4.B Data Analysis

Transmission linearity is demonstrated well in figure 2.12. The transmission ratio of the worm gear is 10 with the 0.8 % maximum variation of ratio. The transmission ratio of the cone drive is 8 with the 1.0 % maximum variation of ratio. The transmission ratio of the traction drive is 6.29 with the 0.5 % maximum variation of ratio. The traction drive has the lowest nonlinearity and the worm gear drive shows higher frequency variation.
(2.12.a) Worm gear incremental transmission ratio

(2.12.b) Cone drive incremental transmission ratio
(2.12.c) Traction drive incremental transmission ratio

Figure 2.12 Transmission Linearity
Chapter 3

An Interaction Control through Time Delay for Robot Manipulators with Unknown Dynamics and Disturbances

3.1 Background

A decade has passed since Hogan (1985) proposed impedance control as an approach to achieve stable and desirable interaction behavior with an arbitrary passive environment. Impedance control changes the dynamic relations among the interaction port variables, such as admittances and impedances, in such a way to provide good performance and to guarantee stable interaction.

Many researchers have studied impedance control of dynamically interacting systems since Hogan. Kazerooni (1985) was the first to study a non-ideal manipulator. By the use of an eigenvector assignment technique, he selects state-feedback and force-feedforward gains to match the eigen structure of the manipulator to that of the target dynamics. His design fails to meet the coupled stability criterion and the high-frequency unmodeled dynamics results in a narrow closed-loop bandwidth and a very conservative feedback gain. The result shows that first-order actuator dynamics can cause significant difficulty in control even if it is included in the design procedure.
Wlassich (1986) implemented a nonlinear force-feedback impedance control. His experimental results show that there are ranges of impedance which do not demonstrate the robust coupled stability properties as predicted in (Hogan, 1987).

Anderson and Spong (1987) combined hybrid force/position control and impedance control. The importance of the environment modeling is shown in the design of a control strategy. Their methods require significant computing power, making it not attractive for practical use.

Kazerooni (1987) presented the most general approach to impedance control by using two nonlinear mappings. His design generates a desired compliance for robot manipulators by altering their inherent dynamics.

Spong (1987) combined impedance control and an integral manifold nonlinear control scheme for a manipulator with joint flexibility. An impedance control has been designed for the rigid body model followed by a corrective control to compensate for the effects of flexibility. This scheme is sensitive to parameter uncertainty.

Goldenberg (1988) developed a controller which uses both force and impedance control without requiring an environment force measurement. This approach can be applied to the nonlinear target dynamics.

It is noteworthy that Anderson, Spong and Goldenberg inverted the robot impedance and replaced it with the desired dynamics. Kazerooni’s second approach also tries to mask the robot’s inherent dynamics and implement the target dynamics through feedback. Colgate (1988) concludes that the concept of replacing the inherent impedance with a target impedance through the action of state and input feedback is incompatible with robust coupled stability of the closed-loop system since they try to implement interactive behavior through the term which cannot be positive real.

Newman (1992a) proposed a new control approach, called Natural Admittance Control (NAC), by avoiding supression of the system’s inherent dynamics and
preserving Colgate's passivity criteria. Under natural admittance control, the target dynamics are chosen to be representative of the system, thus enhancing the inherent dynamics rather than suppressing them. Natural admittance control obtains optimal endpoint admittance and good rejection of internal disturbances. The advantages of NAC over the other existing force control schemes have been verified through simulation and experiments (Newman, 1992ab, Glosser, 1992).

Despite the desirable properties that the natural admittance control offers, the performance is still limited during contact tasks. A major reason for this is that robots have various nonlinearities inherent in their actuator, transmission, link structure, and sensor dynamics. These nonlinearities include actuator saturation, stiction, Coulomb friction, backlash, torque ripple, and nonlinear spring characteristics in the transmission (Dohring et al., 1993). Time delay in force feedback loop can also cause instability when contact is made with a stiff surface (Colgate, 1988, Lawrence, 1988). Another important effect which may cause the manipulator to depart from the ideal dynamic behavior is the interface dynamics between the manipulator and the environment.

In order to account for these effects, in general, feedforward compensation techniques have been applied. Friction models are developed and nonlinearities are characterized. However, this process is complicated and system dependent (Dohring et al., 1993). Better compensation can be achieved by a simpler estimation technique that evaluates a function representing the effect of uncertainties. Youcef-Toumi proposed a Time Delay Control (TDC) for such a purpose (Youcef-Toumi et al., 1989, 1990). It uses recent past observation of the system's response and the control input to directly estimate the unknown dynamics and unexpected disturbances. Even though this approach resulted in satisfactory performance with a position controller, to our knowledge, time delay control has never been applied to interaction (force) control. In this chapter, time delay control is applied to natural admittance control to achieve a
high-performance control system. The improved performance is demonstrated in
simulation in the presence of Coulomb friction for constrained manipulation.

3.2 Natural Admittance Control

In this section, the development of natural admittance control is explained. The
problems which need be addressed to improve its performance are identified.

3.2.1. Admittance: Force Control Performance Measure

In the operation of robot manipulators, a force controller is used to respond
quickly to environment forces by rapidly changing the robot’s state while a position
controller is used to regulate a fixed position by rejecting environmental forces as
disturbances. Therefore, the commonly adopted measures of controller performance
such as bandwidth, overshoot and etc. are not adequate enough to measure the
performance of a interaction controller which is designed to achieve some desired
interaction dynamics. As a proper measure of the effectiveness of the system, the
mechanical admittance is proposed (Newman, 1992). The mechanical admittance (also
called mechanical driving-point mobility (Hixson, 1976) ), $Y$, is

$$ Y = \frac{v}{F} $$

(3.1)

where $F$ is the sensed contact force at the point of interaction and $v$ is the velocity of
the controlled system at the point of interaction. To achieve a fast motion response to
contact force upon contact with an environment, the mechanical admittance should be increased. However, it cannot be increased without bound due to stability constraints. The controlled system should remain stable while accomplishing the specified contact tasks. A contact stability criterion is derived by Colgate for the system dynamically interacting with its environment (Colgate, 1988). He shows (Colgate, 1988):

"A linear time invariant n-port will be stable when coupled to an arbitrary passive environment iff it has the driving point impedance of a passive system."

In other words, the controlled system should present a passive driving point admittance to an arbitrary passive environment to assure coupled stability. Colgate and Newman show separately that the maximum target admittance which does not violate the passivity constraint is:

$$y = \frac{I}{M_x s}$$  \hspace{1cm} (3.2)

which is the high-frequency asymptote of the natural end-point admittance $Y_n$, where $M_x$ is the end-point mass (Colgate, 1988, Newman, 1992). Thus, the achieved admittance should not exceed in magnitude the inertia of end point mass and it should not introduce more than $\pm 90.$ degree in phase according to stability criterion. Under natural admittance control (NAC), the target dynamics to be achieved are explicitly chosen to be the natural system dynamics. Therefore, the natural admittance control tries to approach this driving-point admittance at high frequencies, while it emulates the
desired stiffness $K_{des}$ and damping $B_{des}$ at low-frequencies to achieve better interactive behavior. The resulting target admittance is:

$$Y_{des} = \frac{I}{(K_{des}/s) + B_{des} + (1/Y_{ss})} < \frac{I}{M_s s} \quad (3.3)$$

### 3.2.2 Natural Admittance Control

Consider an arbitrary linear two-port system where actuator forces $F_m$ are exerted on the motor port which moves at a velocity of $v_m$ and interaction forces $F_s$ are imposed on the system by the environment on the sensor port which moves at a velocity of $v_s$. For this two-port system, there exist open-loop admittance transfer functions which map velocity to force as follows:

$$
\begin{bmatrix}
  v_s \\
  v_m
\end{bmatrix}
= 
\begin{bmatrix}
  Y_{ss} & Y_{sm} \\
  Y_{ms} & Y_{mm}
\end{bmatrix}
\begin{bmatrix}
  F_s \\
  F_m
\end{bmatrix}
\quad (3.4)
$$

After exerting a general control law of the form:

$$F_m = G_f F_s - G_s v_m + F_f \quad (3.5)$$

the closed-loop admittance, $Y_s$, of the controlled system becomes:

$$Y_s = Y_{ss} + Y_{sm} \frac{G_f - G_s Y_{ss}}{1 + G_s Y_{mm}} \quad (3.6)$$
where:

\( G_* \): a causal velocity feedback compensator
\( G_f \): a causal force feedback compensator
\( F_f \): feedforward or friction forces exerted on the actuator
\( Y_{ss} \): natural admittance of the system without control
\( Y_{sm} \): motion of the force sensor in response to actuator forces
\( Y_{na} \): uncontrolled actuator motion in response to applied endpoint forces
\( Y_{na} \): motion of the actuator in response to actuator forces

Likewise, the dynamic response to feedforward or friction forces, \( F_f \), becomes:

\[
Y_f = \frac{Y_{sm}}{1 + G_* Y_{na}}
\]  

(3.7)

This equation also describes the sensitivity of the end point to feedforward or friction forces applied at the actuator. To achieve high performance in the presence of internal disturbances such as transmission friction or motor brush friction, these undesirable effects should be rejected by minimizing the sensitivity, \( Y_f \). At the same time, \( G_* \) and \( G_f \) should be selected to increase \( Y_s \) while preserving passivity condition. The two conditions are satisfied by setting:

\[
G_f = G_* Y_{na}
\]  

(3.8)

This makes the controlled system admittance, \( Y_s \), same as the open-loop natural admittance of the system, \( Y_{ss} \), which is passive. Thus, a passive \( Y_s \) can be guaranteed.

The complete form of the natural admittance control law becomes:
\[ F_m = G_v (F_s Y_{na} - v_m) + F_f \]  \hspace{1cm} (3.9)

Since \( Y_s = Y_{na} \), the target dynamics of equation (3.3) becomes:

\[ Y_{des} = \frac{1}{(K_{des} / s) + B_{des} + (1 / Y_{na})} = \frac{1}{(K_{des} / s) + B_{des} + \frac{1}{M_s s}} \]  \hspace{1cm} (3.10)

The simplest form of natural admittance control which achieves the target dynamics of equation (3.10) can be described as follows:

\[ F = G_v (v_{cmd} - v) + \left( \frac{1}{s} K_{des} + B_{des} \right) (v_{des} - v) \]

where

\[ v_{cmd} = \frac{F_s + (K_{des} / s + B_{des}) (v_{des} - v)}{M_s s} \]  \hspace{1cm} (3.11)

\( v \) represents the velocity at the motor port. In NAC, the sensed environment force \( F_s \) is fed back as a velocity command to mask undesirable dynamic effects such as friction. Thus, natural admittance control achieves the maximum passive responsiveness to sensed forces and has good disturbance rejection properties (Newman, 1992ab). However, NAC does not guarantee the convergence of closed loop behavior to the desired trajectory.
3.2.3 Limitations

Natural admittance control law of the form of $F_m = G_i(F_i Y_{m} - v_m) + F_f$ is similar to servo-masking, which is suggested by Colgate as one systematic procedure for the design an interaction controller (Colgate, 1988). This approach is called "servo-masking" since it masks undesirable dynamic effects in the plant model contributed by the actuator and transmission, without attempting to mask and replace the entire impedance. With this technique, the target impedance can be achieved at all frequencies if it is selected sufficiently similar to the actual plant model. However, servo masking generally requires full state feedback and the measurements of interaction port variables, which are not usually available in many industrial robots. It also does not guarantee the convergence of closed loop behavior to the desired performance. It is essential to the success of this approach that the target model is selected sufficiently close to the actual system dynamics. Natural admittance control does select the natural system dynamics as target dynamics and does not require full state feedback. However, like servo-masking, it does not guarantee zero convergence error.

Under natural admittance control, inevitable modelling uncertainties arise in both the controller derivation and its implementation process. From examination of equation (3.6), it is found that a good open loop plant model needs to be obtained, either analytically or experimentally. In the experimental process, significant error can be introduced in the cross admittance model since it is obtained by data fitting. Also, in the derivation of the passivity constraint on the target admittance, internal dynamics between the force sensor and the actuator are postulated which may not describe the actual system dynamics accurately. Errors may be introduced if the commanded
actuator force is used in the cross admittance instead of the measured actuator force since the transmission and motor dynamics can make them different. Modeling uncertainty also includes any unmodeled nonlinearity and any parameter variations. This problem can be solved by using a feedforward compensator, which does not affect stability but does affect the transient response and the equilibrium state. Newman includes a feedforward term, $F_f$, to account for Coulomb friction and other disturbances (Newman, 1992b). However, this process is complicated, tedious and system dependent (Dohring et al., 1993).

Better compensation may be achieved by a simpler estimation technique that evaluates a function representing the effect of uncertainties. Youcef-Toumi proposed a time delay control (TDC) for such a purpose (Youcef-Toumi et al., 1989, 1990). It uses a recent past observation of the system's response and the control input to directly estimate the unknown dynamics and unexpected disturbances at any given instant through time delay. The controller updates its observation every sampling period and uses this information to counteract the unknown dynamics and disturbances simultaneously. Then the desired dynamics is inserted into the plant.

In the next section, time delay control will be introduced and combined with natural admittance control to achieve better interaction behavior.

### 3.3 Design of Natural Admittance/Time Delay Control

In this section, a brief description of time delay control is presented along with its control laws. The design of a hybrid NAC/TDC control is developed.
Consider a single-input single-output single DOF robotic system which can be described by the nonlinear dynamic equation:

\[ \ddot{x}(t) = f(x, \dot{x}, t) + h(x, \dot{x}, t) + b(x, \dot{x}, t)u(t) + d(t) \]  

(3.12)

where \( x \), \( \dot{x} \) and \( \ddot{x} \) are states, \( u(t) \) is a control input, \( b(x, \dot{x}, t) \) is a control distribution term, \( d(t) \) represents unknown disturbance, and \( f(x, \dot{x}, t) \) and \( h(x, \dot{x}, t) \) represent known and unknown nonlinear dynamics of the system, respectively. The variable \( t \) represents time. \( h(x, \dot{x}, t) \) includes inertial coupling terms such as Coriolis and centrifugal forces, actuator saturation and stiction, and Coulomb friction and nonlinear spring characteristics in the transmission. The system output is the variable \( x \) and the reference model for \( x \) is defined by:

\[ \ddot{x}_r(t) = c_r x_r(t) + a_r \dot{x}_r(t) + b_r r(t) \]  

(3.13)

where \( x_r(t) \), \( \dot{x}_r(t) \) and \( \ddot{x}_r(t) \) are model states, \( r(t) \) is a reference input and \( c_r \), \( a_r \) and \( b_r \) are known constants. The error is defined as:

\[ e = (x_r - x) + (\dot{x}_r - \dot{x}) \]  

(3.14)

The objective is to stabilize the error with the desired error dynamics:

\[ \dot{e} = Ke \]  

(3.15)

where \( K \) is a constant matrix. By combining equations (3.12) through (3.15), the control input \( u \) becomes:
\[ u(t) = (1 / b(x, \dot{x}, t))[a_r \dot{x}(t) + b_r r(t) - h(x, \dot{x}, t) - d(t) - f(x, \dot{x}, t) - K_p(x_r - x) - K_v(\dot{x}_r - \dot{x})] \] (3.16)

where \( K_p \) and \( K_v \) are error feedback gains. If the time delay \( L \) is sufficiently small, the effect of the unknown terms \( h(x, \dot{x}, t) + d(t) \) at the present time \( t \) can be estimated by:

\[ \hat{h}(x, \dot{x}, t) + \hat{d}(t) \equiv \ddot{x}(t - L) - f(x, \dot{x}, t - L) - b(x, \dot{x}, t - L)u(t - L) \] (3.17)

\( b \) is set equal to a constant and we assume that no information is available on the nonlinear dynamics, i.e. \( f \) is unknown. Then, the time delay control law is derived by substituting equation (3.17) into equation (3.16).

\[ u(t) = u(t - L) + (1 / b)[-\ddot{x}(t - L) - K_p(x_r - x) - K_v(\dot{x}_r - \dot{x}) + c_r \dot{x}(t) + a_r \dot{x}(t) + b_r r(t)] \] (3.18)

In this particular time delay control law, the delayed control action term and the delayed acceleration term try to compensate for the nonlinear dynamics and disturbances, while the desired reference model is followed by adjusting the error dynamics.

Now, let us examine the structure of the natural admittance control law in the time domain.

\[ u(t) = G_v(\dot{x}_{\text{cmd}} - \dot{x}) + K_{\text{des}}(x_{\text{des}} - x) + B_{\text{des}}(\ddot{x}_{\text{des}} - \dot{x}) \] (3.19)

where
\[
\dot{x}_{\text{cmd}} = \frac{F_x + K_{\text{des}}(x_{\text{des}} - x) + B_{\text{des}}(\dot{x}_{\text{des}} - \dot{x})}{M_x} dt
\]

Notice that the first term of natural admittance control law can be regarded as a reference model in the time delay control law. If we set:

\[
a_r = b_r = G_v, \\
r(t) = \dot{x}_{\text{cmd}}(t),
\]

the desired dynamics in the natural admittance control is essentially an error dynamics in time delay control. The NAC/TDC control law has the form

\[
u(t) = u(t - L) + (1/b)[-\ddot{x}(t - L) + G_v(\dot{x}_{\text{cmd}} - \dot{x}) \\
+ c_x x + K_{\text{des}}(x_{\text{des}} - x) + B_{\text{des}}(\dot{x}_{\text{des}} - \dot{x})]
\]

NAC/TDC control achieves the optimal responsiveness and provides good trajectory following since the nonlinear effects and disturbances are attenuated by a direct estimation technique. In order to implement the control law only one system parameter, the mass, needs to be estimated.

### 3.4 Simulation

In this section, we compare the simulated performance of a manipulator under the natural admittance control law to the simulated results under the NAC/TDC control law. The system is a robot manipulator dynamically interacting with its environment.
Unknown Coulomb friction is included in the system model since it is a major source of contact instability.

3.4.1 The Model: Constrained Manipulation

![Schematic of Two-Mass Model](image)

Figure. 3.1 Schematic of Two-Mass Model

Let us consider the dynamics of a robot arm in contact with the environment as shown in figure 3.1. The robot is described as a simple two-mass model coupled to its environment which has stiffness $Ks$ and damping $Bs$. through the force sensor. The stiffness $Kms$ and the damping $Bms$ between the motor mass $Mm$ and the end-point mass represent the transmission or link flexibility, and define the frequency and damping of the robot's first mode. The viscous damper $Bm$ describes the rigid body mode of the actuator. The control input $F$ is directly exerted on the actuator mass.
Coulomb friction $F_c$ is acting on mass $M_m$. This is the same modeling approach used by other researchers (Colgate, 1988, Newman, 1992a, Eppinger et al., 1992).

The equations of motion describing the response of the model to its control input are:

$$M_m\ddot{x}_m = F - K_{nu}(x_m - x_s) - B_{nu}(\dot{x}_m - \dot{x}_s) - B_m\dot{x}_m + F_c$$  \hspace{1cm} (3.22)

$$M_s\ddot{x}_s = K_{nu}(x_m - x_s) + B_{nu}(\dot{x}_m - \dot{x}_s) - (K_s x_s + B_s \dot{x}_s)$$  \hspace{1cm} (3.23)

Environment force $F_s$ is given by the last two terms of equation (3.23). The values of the system parameters are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>$M_m$</th>
<th>1 kg</th>
<th>$B_s$</th>
<th>10 N sec/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s$</td>
<td>1 kg</td>
<td>$K_{ms}$</td>
<td>2K N/m</td>
</tr>
<tr>
<td>$B_{ms}$</td>
<td>80 N sec/m</td>
<td>$K_s$</td>
<td>10K N/m</td>
</tr>
<tr>
<td>$B_m$</td>
<td>0 N sec/m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The undamped natural frequency of the system is approximately 10 Hz, which is the first resonance of typical industrial robots.

3.4.2 Simulation

The controllers used for the simulations are in equation (3.19) and equation (3.21) where its states denotes the states at the motor port. The acceleration signal is given by the following backward difference approximation with delay time $L=1$ msec.:
\[ \ddot{x}(t-L) \equiv \dot{x}(t) - \dot{x}(t-L) / L \] (3.24)

The objective is to follow a desired trajectory \(0.02 \sin t\) m with desired velocity of \(0.02 \cos t\) m/sec in the presence of a 100N Coulomb friction force. The control parameters are adjusted to be \(K_{\text{det}}=6,000 / \text{sec}^2\), \(B_{\text{det}}=200 / \text{sec}\), \(G_{\text{v}}=1000 / \text{sec}\) for NAC and \(G_c=0.01 / \text{sec}\) and \(1/b=1.7 \text{N sec}^2 / \text{m}\) for NAC/TDC. \(c_r\) is set to be 0. for this simulation, but this term helps to stabilize the system. \(M_{\text{det}}\) is set to the true plant value to preserve passivity. Simulations were done in a Sun workstation with an integration step size of 1 m second. Same simulation results are obtained with an integration step size (1 ms) shorter than the sampling interval (2 ms). This model is used to observe control performance such as disturbance rejection property, robustness to parameter change, insensitivity to the sensor noise and to observe the performance with different environments.

### 3.4.2.A Disturbance Rejection

The more robots are expected to perform a variety of tasks autonomously, the more likely it is that robots will be challenged by unexpected disturbances from unstructured environments. A robot should be able to execute tasks successfully regardless of disturbances and at the same time the disturbance forces should be handled in such a way as not to damage the mechanical hardware of the robot. This section demonstrates that NAC/TDC has remarkable disturbance rejection capability.

To evaluate its disturbance rejection property, a step disturbance of 500N is applied at \(t = 2\) sec. As shown in figures 3.2 through 3.4, NAC has about a 40 percent
steady state position error even with no disturbances applied while NAC/TDC has less than a 2 percent error. NAC shows a large steady state error even with excessive control action while the manipulator under NAC/TDC follows the desired trajectory very closely, with a 4 percent steady state position error. The deterioration of the response of the NAC/TDC under the sudden disturbance is negligible. However, figure 3.4 shows that there are actual changes in the positions, control inputs and contact forces. The remarkable disturbance rejection ability of NAC/TDC control can be explained by its low control gains. Compare the gains of NAC/TDC ($G_c=0.01/sec$, $1/b=1.7\,N\,sec^2/m$) to the gain of NAC ($G_c=1000/sec$). This low NAC/TDC gain results in almost no change in control action despite the unexpected 500N external disturbance. The large spike in the NAC/TDC control input difference (figure 3.4) is caused by the change of velocity direction since NAC/TDC introduces a direct acceleration term into its control action.
Figure 3.2 System response under NAC: disturbance rejection property
(Xdes-desired trajectory, 1-without disturbance, 2-with disturbance)
Figure 3.2 System response under NAC: disturbance rejection property
(1-without disturbance, 2-with disturbance)
Figure 3.3  System response under NAC/TDC: disturbance rejection property 
(1-without disturbance, 2-with disturbance)
Figure 3.3 System response under NAC/TDC: disturbance rejection property
(1-without disturbance, 2-with disturbance)
Figure 3.4 System response under NAC/TDC: disturbance rejection property
(1-without disturbance, 2-with disturbance,
Xm- position of Mm, F-control input, Fs-contact force)
Figure 3.4 System response under NAC/TDC: disturbance rejection property
(1-without disturbance, 2-with disturbance, Xs - position of Ms)
3.4.2.B Robustness to Environmental Change

Manipulation requires the manipulator to dynamically interact with the object being manipulated. However, in many robot applications, knowledge about the environment is often not provided beforehand and the manipulator is still expected to stably interact with a broad range of environments. Kazerooni shows via the small gain theorem that a lower feedback gain should be selected to achieve stable interaction with a stiffer environment (1987). His analysis gives a stringent stability criterion since it uses the small gain theorem. NAC is designed based on a passivity criterion and works well with stiffer environments without changing control gains as long as they are within the passivity limit. One of the advantages of using NAC is that it works well with all passive environments while many varieties of conventional force controllers perform well only with a particular environment. This advantage is further enhanced through time delay.

We simulated the controller performance with a 10 times stiffer environment without changing the control parameters. It was shown in figure 3.5 that both controllers make stable contact and NAC/TDC is shown to be more robust to environmental stiffness changes. NAC/TDC follows the commanded trajectory almost perfectly while NAC follows the trajectory with approximately 10 percent error.
Figure 3.5 System response: robustness to Environmental Change
(1-NAC, 2-NAC with stiffer environment,
3-NAC/TDC, 4-NAC/TDC with stiffer environment)
Figure 3.5 System response: robustness to Environmental Change
(1-NAC, 2-NAC with stiffer environment,
3-NAC/TDC, 4-NAC/TDC with stiffer environment)
3.4.2.C  Insensitivity to Noise

In a practical implementation, the manipulator state and contact force information are corrupted by tachometer noise and force sensor measurement noise. Generally, noise is observed to be up to 15 to 20 percent for tachometers and around 10 percent for high performance force sensors. Such a situation is simulated by applying white Gaussian noise to tachometer velocity signals and sensed force signals (figures 3.6 and 3.7). 20 percent noise-power-to-signal-power ratio (standard deviation $\sigma = 0.009\text{m/sec}$ for NAC and $\sigma = 0.006\text{m/sec}$ for NAC/TDC) is applied to velocity signals and 10 percent noise-power-to-signal-power ratio ( $\sigma = 10.286\text{N}$ for NAC and $\sigma = 7.603\text{N}$ for NAC/TDC) is applied to sensed force signals. After limiting actuator torque between $\pm 500\text{N}$ for NAC/TDC, better trajectory tracking is achieved with NAC/TDC. This actuation limit can be the actual actuator saturation limit or it can be set lower than the actual value to prevent hardware failure. As shown in figure 3.7, the influence of noise on trajectory following is negligible with NAC/TDC. The endpoint mass does not break contact and chattering is not observed. If proper sensors are selected, the servo-motors work as low pass filters reducing the noise effect. In a practical implementation, the measurement signals need to be prefiltered by anti-aliasing filters to limit the high frequency components (Youcef-Toumi et al., 1992).
Figure 3.6 System response under NAC: insensitivity to measurement noise
(1-without noise, 2-with noise,
Xm-position of Mm, F-control input, Fs-contact force)
Figure 3.6 System response under NAC: insensitivity to measurement noise (1-without noise, 2-with noise, Xs-position of Ms)
Figure 3.7 System response under NAC/TDC: insensitivity to measurement noise
(1-without noise, 2-with noise,
Xm-position of Mm, F-control input, Fs-contact force)
Figure 3.7 System response under NAC/TDC: insensitivity to measurement noise
(1-without noise, 2-with noise, Xs - position of Ms)
3.4.2.D Robustness to Parameter Uncertainty

In any modeling process, modeling errors occur. Modeling uncertainties can be introduced through the order of the system model (high frequency unmodeled dynamics), through unmodeled nonlinearities and by the uncertainty and variation of the parameters in the modeled dynamics. In robots, most parameter uncertainties arise from joint flexibility and nonlinear Coulomb friction and stiction. Joint flexibility arises from nonlinear stiffening spring characteristics of drive systems, such as gears, belts, bearings, tendons, etc. Friction is hard to characterize or model especially at low velocities. The system parameters also vary due to mechanical wear of parts and operating conditions, such as temperature and humidity. When robots pick up or carry objects, the end point mass can change significantly. Thus, robustness to parameter variations is an essential feature in the controller for robots which actively interact with its workpiece.

In this simulation, we examine the robustness of the controllers with respect to parameter errors. In NAC, the mass should be overestimated and the damping should be underestimated to preserve passivity of the closed loop system. Figure 3.8 shows the results with 25 percent overestimation of mass and 25 percent underestimation of damping and stiffness. Under NAC/TDC, the trajectory following is not degraded with 25 percent parameter change, while NAC performance is degraded. Analysis is necessary to find the allowable bound of parameter uncertainty for stable NAC/TDC operation.
Figure 3.8 System response: robustness to parameter change
(1-NAC, 2-NAC with parameter change,
3-NAC/TDC, 4-NAC/TDC with parameter change)
Figure 3.8 System response: robustness to parameter change
(1-NAC, 2-NAC with parameter change, 3-NAC/TDC, 4-NAC/TDC with parameter change)
3.5 Summary

A new approach to the interaction control of systems with unknown dynamics has been developed by combining Natural Admittance Control with Time Delay Control. The proposed nonlinear controller is not model based control. Although the gains depend upon system dynamics, detailed knowledge of the system is not required. The only system parameter that must be estimated is inertia, rendering it easy to implement. It rejects unmodeled dynamics, nonlinearities, and disturbances without a difficult characterization process while preserving desired dynamics. The simulation results demonstrate not only good external and internal disturbance rejection, robustness to parameter changes and insensitivity to noise, but also demonstrate good trajectory following providing good rejection of internal Coulomb friction. Due to its robustness to parameter uncertainty and its good disturbance rejection property, NAC/TDC will be particularly useful for mobile robots and for the manipulation under large payload changes and the tasks in unstructured environment.

Future work includes the experimental verification of NAC/TDC performance. Contact stability issues need to be further investigated via analysis or experiment. The methods should be devised in order to implement NAC/TDC on the systems with non-negligible time delay in the force feedback control loops.
Chapter 4

A Nonlinear Bang-Bang Impact Force Control Inspired by Human Interactive Behavior

4.1 Introduction

As technology develops, robots are expected to perform more sophisticated and diversified tasks. In general, such tasks involve active interaction with an unknown or changing environment, and this requires making and breaking contact with the workpieces frequently. When robots move from free-space to constrained motion, impact generally occurs and the ability to achieve stable and smooth contact transition becomes crucial for successful manipulation. In contrast to its importance, however, not many research works have been done in the area of impact control. One main reason may be the difficulties involved in contact discontinuity. In this chapter, an impact force controller is developed based on observations of human interactive behavior and its validity is verified through simulations.

The most general approach to impact control is the method proposed by Khatib and Burdick (1986), which involves maximum damping action proportional to the contact velocity. This may perform well with soft environments. Upon collision with
stiff environments, however, damping action alone is not sufficient to damp out the oscillations with high frequencies and small amplitudes.

Hogan (1987) implemented impedance control for tasks involving contact transition and achieved stability against a stiff environment without discontinuous control action.

Quian and De Schutter (1992) developed an active linear and nonlinear damping approach. Active damping is obtained using the derivative of the contact force. This method is particularly useful in case of stiff contact, because the velocity signal can be smaller than the resolution of the tachometer.

Hyde and Cutkosky (1993) developed an input command preshaping control. Unlike the above methods, input command preshaping sends a feedforward command to suppress vibration. Based on the results of frequency identification tests, shaping sequences are generated for the dominant low and secondary lowest frequency modes of the impact response and used as a feedforward input to the control loop. Including a compliant component between the force sensor and the environment, they demonstrated experimentally that all these methods can result in stable and smooth contact transition with properly chosen gains.

Marth et al. (1993) used an event based motion planning method to deal with the problem of impact. Upon detection of a contact event, the position controller switches to the explicit force controller. Later, they (1994) introduced a more sophisticated event based approach to impact control. With this algorithm, manipulators are expected to approach the constraining surface with a limited velocity.

Volpe and Khosla (1992, 1993ab) showed that impedance control is successful in maintaining stability and contact upon impact by employing negative force feedback. The negative force feedback directly negates the impact force by passively accepting it rather than aggressively exerting control input to reject it as a disturbance. However,
this method is not recommended for tracking force commands because the negative force feedback control cannot exert a sufficient control input to move the system to the desired force level.

Youcef-Toumi and Gutz (1989, 1994) used integral force compensation with velocity feedback to reject impacts and achieve better force tracking. Their results show that performance improves with decreasing approach velocity and with increasing the dimensionless ratio of force command to approach velocity. However, the idea of using integral action for impact control is not recommended because integrator wind-up is likely to occur due to the loss of contact and this can cause severe hopping on the surface. Volpe and Khosla (1993a) observed that experiments with a direct-drive robot arm exhibited very oscillatory response during impact.

Xu et al. (1994) proposed a nonlinear PD control for force and transient contact control. They designed a nonlinear gain function assuming the preservation of contact continuity, which is not a realistic assumption for impact phenomenon. The design process also requires estimation of the flexible robot model, which is rather complicated. This technique involves force derivative. The performance of this method can be better judged with a higher approach velocity than presented in their paper (1.2 mm/sec).

Oh et al. (1994) designed a passive damper for force and impact control. Akella et al. (1991) designed passive compliant fingertips containing electro-rheological fluids and actively controlled the damping characteristics to reduce oscillations after impact.

The impact controller proposed in this chapter actively mimics human interactive behavior to achieve stable and desirable contact. In the next section, the dynamics of human interaction will be described and the rationale behind the proposed bang-bang impact control will be explained.
4.2 The Dynamics of Interaction

Consider a man trying to establish a desired dynamic interaction with a stiff environment. If he happens to hit the stiff wall with a nonzero approach velocity and excites vibration both on himself and the wall, he would not recklessly push the wall back to settle the vibration. If the environment is soft, he may obtain his goal by exerting a large force to reject the induced vibrations. In the case of a stiff environment, however, this strategy might be futile because of high frequency vibrations of the wall or the large reaction forces. A wise person would rather try to achieve his objective by cautiously establishing stable contact first, then gradually working toward the desired state. When a human pushes on an object, a reactive force is felt during contact. If more force is used to compensate for the reaction force, this kind of interaction behavior can easily destabilize the human/environment system.

In order to establish stable contact and reach the desired state, instead, it may be necessary to exert behavior opposite to that of the environment (Hogan, 1987). To make a peaceful resolution in conflict situations, humans often compromise, while still attempting to achieve their desired goal. Using compromise and negotiation process, both parties can reach a satisfactory outcome. Likewise, when a robot senses the environment(reaction) force during contact transition, it must exert control action in such a manner to achieve the desired dynamics while absorbing the interaction forces. One approach is to use negative force feedback (Volpe, 1992, 1993ab). Negative force feedback generates a mitigated control action because a certain amount of the environment force is subtracted from the control action to absorb the environment force. On the contrary, positive force feedback raises control action to confront the
environment force. The next moment after impact, the manipulator does not usually sense the environment force because it loses contact due to bouncing on the surface. At that moment, it should not exert any control action not to introduce any further impact vibrations. A series of bang-bang control action should be taken until the transient response is damped out. After steady state is attained, other controller can be used to drive the system to the desired state.

4.3 Nonlinear Bang-Bang Impact Control

Using the observation given in the last section, a nonlinear bang-bang impact controller is designed. During free-space motion, a natural-admittance/time-delay control with negative force feedback is used. Upon impact, the negative force feedback helps to minimize impact force. When the contact is broken due to bouncing, no control input is applied. This bang-bang control approach repeats until steady state is attained. Negative force feedback gains provide a very stable system and are very effective for impact control. However, they must not be used after the impact transient because poor steady state accuracy results from the use of negative feedback gains. Negative force feedback cannot be used for tracking input force commands because the response of the system approaches zero as the force feedback gain approaches -1 (Volpe, 1992, 1993ab). It cannot generate a control input which is large enough to move the system to the desired force level. Other force control strategies must be used after the impact phase is over. In this work, natural-admittance/time-delay control, integral position control and natural admittance control are applied. The resulting control strategy is summarized as follows.
1) In unconstrained motion - NAC/TDC with negative force feedback:

\[ u(t) = u(t - L) + (1/b)[-\ddot{x}(t - L) + G_v(\dot{x}_{cmd} - \dot{x}) + c_x x + K_{des}(x_{des} - x) + B_{des}(\dot{x}_{des} - \dot{x})] - F_s \]  \hspace{2cm} (4.1)

where

\[ \dot{x}_{cmd} = \left[ \frac{F_s + K_{des}(x_{des} - x) + B_{des}(\ddot{x}_{des} - \dot{x})}{M_s} \right] dt \]  \hspace{2cm} (4.2)

2) In contact transition:

If \( F_s > 0 \), equations (4.1) and (4.2)

If \( F_s = 0 \), \( u(t) = 0 \)  \hspace{2cm} (4.3)

3) In steady state - interaction control:

a) NAC/TDC:

\[ u(t) = u(t - L) + (1/b)[-\ddot{x}(t - L) + G_v(\dot{x}_{cmd} - \dot{x}) + c_x x + K_{des}(x_{des} - x) + B_{des}(\dot{x}_{des} - \dot{x})] \]  \hspace{2cm} (4.4)

b) Integral position control (IPC):

\[ u(t) = K_i \int (x_{des} - x) dt \]  \hspace{2cm} (4.5)
This nonlinear bang-bang impact controller deals with the notorious contact discontinuity problem by discontinuous on-off control action which matches the state of the contact continuity. After steady state, any stable force controller can be used according to the task required.

4.4 The Model

![Figure. 4.1 Schematic of three-mass model](image)

A three mass model (figure 4.1) is introduced to model contact transition when contact occurs with a non-zero approach velocity. This model is as same as the one used for constrained manipulation (figure 3.1) except that the environment mass $M_e$ is added to the same robot and sensor dynamics to observe the impact phenomena. It is assumed that the duration of impulse is short and a common impact force is applied
both to the manipulator and the environment. When the manipulator is not in contact with the environment, the equations of motion for the system become:

\[ M_m \ddot{x}_m = F_m - K_{ms}(x_m - x_s) - B_{ms}(\dot{x}_m - \dot{x}_s) - B_m\dot{x}_m + F_c \quad (4.6) \]

\[ M_x \ddot{x}_s = K_{ms}(x_m - x_s) + B_{ms}(\dot{x}_m - \dot{x}_s) \quad (4.7) \]

\[ M_e \ddot{\epsilon}_e = -K_{x_e}x_e - B_x\dot{\epsilon}_e \quad (4.8) \]

Upon impact, the amount of energy loss is given by the coefficient of restitution \( e \). The velocities after collision can be obtained from the principle of conservation of momentum. Since the duration of the impulse is assumed short, the impact force \( F_i \) assumed constant over the interval and the impulse can be modeled as follows:

\[ \int_{t_i}^{t_f} F_i \, dt \equiv F_i \Delta t = M_s (\dot{x}_s' - \dot{x}_s) \quad (4.9) \]

where the prime denotes the state after collision.

The system is governed by the following equations of motion, until the manipulator is out of contact with the environment again:

\[ M_m \ddot{x}_m = F_m - K_{ms}(x_m - x_s) - B_{ms}(\dot{x}_m - \dot{x}_s) - B_m\dot{x}_m + F_c \quad (4.10) \]

\[ (M_s + M_e) \ddot{x}_s = K_{ms}(x_m - x_s) + B_{ms}(\dot{x}_m - \dot{x}_s) - K_s x_s - B_x\dot{x}_s \quad (4.11) \]

The values of the system parameters are summarized in Table 4.1.
The undamped natural frequency of the system is approximately 10 Hz, which is the first resonance of most industrial robots. The environment is chosen to be lightly damped and stiff to resemble the worst environment for force control.

| \( M_m \) | 1 kg | \( B_s \) | 10 N sec/m |
| \( M_s \) | 1 kg | \( K_{ns} \) | 2K N/m |
| \( M_e \) | 1 kg | \( K_s \) | 1M N/m |
| \( B_m \) | 0 N sec/m | \( e \) | 0.6 |
| \( B_{mx} \) | 80 N sec/m | \( F_c \) | 100 N |

### 4.5 Simulation

The controllers used for the simulations are in equations (4.1)-(4.3) for fre-space motion and impact, and equations (4.4)-(4.5) for steady state constrained manipulation where its states denotes the states at the motor port. The performance of the proposed bang-bang impact controller is compared with the natural admittance controller. Natural admittance control used in this simulation has the form:

\[
u(t) = K_{des}(x_{des} - x) + B_{des}(\dot{x}_{des} - \dot{x}) + G_v(\dot{x}_{cmd} - \dot{x})
\]

where

\[
\dot{x}_{cmd} = \frac{F_s + K_{des}(x_{des} - x) + B_{des}(\dot{x}_{des} - \dot{x})}{M_s}\quad dt
\]

The acceleration signal is given by the following backward difference approximation with delay time \( L=1 \) msec.:
\[ \ddot{x}(t - L) \equiv \frac{\dot{x}(t) - \dot{x}(t - L)}{L} \]  

(4.13)

The objective is to drive the robot 0.015 m with desired velocity of 0.01 m/sec, i.e., 0.012 m in free space and 0.003 m after contact with the environment, in the presence of a 100 N Coulomb friction force. Simulations were done using a Sun workstation with a sampling interval of 1 m second and an integration step size of 0.02 m second. Force sensor measurement delay is incorporated in the system by delaying the force signal by 10 m seconds. This model is used to observe time responses such as settling time, peak impact force, overshoot and the rejection of impact disturbances and to observe the control performance with different environments.

4.5.1 Bang-Bang Impact Control and Impedance Control

In this section, the control performance of the impact bang-bang control and impedance control are compared. Integral control for position is used after the transient response dies out. Natural admittance control is used as an impedance control because it is known to be a stable realization of impedance control.

For impact/integral position control, the control parameters are adjusted to be \( K_{\text{des}} = 10,000 / \text{sec}^2 \), \( B_{\text{des}} = 2,000 / \text{sec} \), \( G_c = 0.01 / \text{sec} \) and \( 1/b = 0.1 \text{ N sec}^2 / \text{m} \) for NAC/TDC with negative force feedback. \( c \) helps to stabilize the system and is set to be 130 / \text{sec}^2 for this simulation. \( K_i = 5,000 \text{ N} / (\text{m} \cdot \text{sec}) \) is chosen for integral position control. For NAC control, the control parameters are set to be \( K_{\text{des}} = 5,000 / \text{sec}^2 \), \( B_{\text{des}} = 4,800 / \text{sec} \), and \( G_c = 1 / \text{sec} \).
The system responses for bang-bang impact control/integral position control are shown in figure 4.2. The impact force vibration damps out within 0.127 seconds after the impact occurs. The maximum impact force is about 2.6 N while the steady state contact force is about 1.4 N. The robot contacts the environment with an approach velocity of 0.025 m/sec and the position reaches steady state about 0.125 seconds after contact with the environment with a steady state position error of about 15 percent. No position overshoot is observed.

With increased $K_{\text{da}}$, impact forces are increased while steady state position errors are decreased. High $K_{\text{da}}$ achieves fast rise time in position trajectory tracking and fast settling time of contact forces. With increased $B_{\text{da}}$, steady state position errors are increased while impact forces are decreased. High $B_{\text{da}}$ achieves slow rise time in position trajectory tracking and slow settling time of contact forces. The control parameters must be carefully tuned to best handle the required tasks.

The system responses under NAC are compared with impact/integral position control in figure 4.2. The steady state position error is about 3 percent with no overshoot, but it has very slow rise time. The maximum impact force is 1.5 N, approximately a half of impact/integral position control. However, Control input undergoes severe jumps and the vibration dies out 9.5 seconds after impact. It is shown through simulation that even the best tuned control gains cannot make NAC achieve successful impact control against very stiff environment.
Figure 4.2 System response under impact/integral position control and NAC control
(solid: NAC, dashed: impact/integral position control)
Figure 4.2 System response under impact/integral position control and NAC control (solid: NAC, dashed: impact/integral position control)
Figure 4.2 System response under impact/integral position control and NAC control
(solid: NAC, dashed: impact/integral position control)
4.5.2 Impact/TDC and Impact/Integral Position Control

For impact/integral position control and impact/TDC control, the control parameters are selected to be the same as for bang-bang impact control in the above section.

Figure 4.3 demonstrates the system responses. The impact force vibration damps out within 0.127 seconds for IPC and 0.2 seconds for TDC after impact occurs. After collision, the control input jumps between about 100 N and zero a few times until it reaches the steady state. The steady state contact force is about 1.4 N for IPC and about 10.4 N for TDC. These fast settling times and small impact forces are comparable to or better than those of other existing impact control techniques (Hyde et al., 1993, Volpe and Khosla, 1992, 1993ab, Marth et al., 1993, 1994, Xu et al., 1994). The position reaches steady state about 0.125 seconds after contact with the environment for IPC and about 1.75 seconds for TDC. The steady state position error is about 15 percent for both controllers. In order to achieve better position trajectory tracking, TDC control gains must be readjusted after steady state is reached.

It is observed through simulation that integral position control cannot constantly exert large contact forces because the position command cannot issue forces sufficient enough to push hard environments in a stable manner. Accordingly, it can move only a short distance against the environmental surface. If the manipulator is commanded to travel a short distance after contact with the environment, the steady state position error will be small. However, if the manipulator is given a command to move a long distance after contact to create large contact forces, it will suffer from large steady state
position errors. It fits best tasks requiring contact with the surface without exerting a large force.
Figure 4.3 System response under impact/TDC and impact/integral position control
Figure 4.3 System response under impact/TDC and impact/integral position control
Figure 4.3 System response under impact/TDC and impact/integral position control
4.5.3 Simulation with High Approach Velocity

The proposed impact/integral position controller is simulated with different desired dynamics to investigate the control performance with higher approach velocity.

The objective is to drive the robot 0.05m with desired velocity of 0.05m/sec, i.e., 0.047m in free space and 0.003m after contact with the environment, in the presence of a 100N Coulomb friction force. The control parameters are adjusted to be $K_{des}=1,000/\text{sec}^2$, $B_{des}=400/\text{sec}$, $G_r=0.01/\text{sec}$ and $l/b=0.1\text{N sec}^2/\text{m}$ for NAC/TDC with negative force feedback. $c_r$ is set to be $130/\text{sec}^2$. $K_i=500\text{N/(m \cdot sec)}$ is chosen for integral position control.

Figure 4.4 shows the control performance when the robot collides with an environment with an approach velocity of 0.075 m/sec, which is three times faster than the former case. The impact force vibration damps out within approximately 0.2 seconds after impact occurs. Compare the settling time of impact force, 0.125 seconds, with approach velocity of 0.025 m/sec. The control input makes big jumps after impact, but does not deteriorate the trajectory following. The maximum impact force reaches about 19.3 N while steady state contact force is about 3.3 N. The position reaches steady state about 0.02 seconds after contact with environment with a steady state position error of about 4 percent. No position overshoot is observed. The overall steady state position error is significantly decreased because the traveling distance after collision is small portion of the entire trajectory.

This simulation proves that the proposed bang-bang impact control is capable of controlling impacts with high approach velocity. The full potential of this controller is to be further investigated.
Figure 4.4 System response under impact/integral position control with high approach velocity
Figure 4.4 System response under impact/integral position control with high approach velocity
4.6 Summary and Suggestions for Future Work

A nonlinear bang-bang impact controller is developed based on the observation of human interactive behavior. It uses a robust natural admittance/time-delay control with an added negative force feedback to absorb impact force and stabilize the system. This control input alternates with zero control input when no environment force is sensed due to loss of contact. This alternation of control action repeats until impact transient is over and steady state is established. The simple control algorithm settles the notorious contact discontinuity problem with an unique discontinuous control action which matches with the state of the contact continuity.

The proposed impact control performance is observed to be superior to impedance controller via simulation. After steady state is reached, an integral position control and a natural admittance/time-delay control are used. It is shown that the integral position control performs better than NAC/TDC. However, it is observed that IPC cannot constantly exert large contact forces which are required for certain manufacturing processes such as deburring. It reaffirms the fact that position control is not suitable for constrained manipulation.

For better performance, the control gains of NAC/TDC must be changed after an impact transient. The method of gain scheduling after steady state is to be further investigated. The use of other force control techniques after impact transient must also be studied.

The performance of the proposed bang-bang impact controller must be further compared with the various existing impact control techniques in order to fully evaluate its attributes and shortcomings. Future work also includes the experimental verification of the proposed control method.
Chapter 5

Conclusions

5.1 Summary

In this dissertation, three problems have been primarily studied in the area of robot control: (1) characterization of robot nonlinear dynamics, (2) force control of robot manipulators with unknown dynamics and disturbances, and (3) nonlinear impact force control.

In developing control systems, it is essential to have a solid understanding of the dynamic characteristics of the systems to be controlled. In order to identify the robot control problems, we studied the effects of plant dynamics, focusing on robot joint dynamics such as joint flexibility and friction. Extensive experimental studies have been done on robot transmissions. The experiments have included: transmission linearity, backlash, static and dynamic friction, and forward efficiency. In order to understand the influence of transmission properties on overall system performance, a comparative evaluation was performed on three competing transmission types: worm-gear drive, cone-drive and traction drive transmission. The results of experiments performed on worm-gear drive validated a load-dependent friction model, which was derived for feed-forward friction compensation in feedback control.
With understanding of how transmission nonlinearities influence closed-loop and controlled behavior, a new controller has been developed by combining Natural Admittance Control with Time Delay Control. The proposed nonlinear controller is not model based control. Although the gains depend upon system dynamics, detailed knowledge of the system is not required. The only system parameter that must be estimated is inertia, rendering it easy to implement. It rejects unmodeled dynamics, nonlinearities, and disturbances without a difficult characterization process while preserving desired dynamics. The simulation results demonstrate not only good external disturbance rejection, robustness to parameter changes and insensitivity to noise, but also demonstrate good trajectory tracking providing good rejection of internal Coulomb friction.

For stabilization of a robot manipulator upon collision with a stiff environment, we proposed a novel impact force control strategy which is developed based on the observation of human interactive behavior. It uses a robust natural admittance /time-delay control with an added negative force feedback to absorb impact force and stabilize the system. During the impact phase, this control input alternates with zero control input when no environment force is sensed. Simulation results show that this simple bang-bang control approach produces a stable interaction with a very stiff environment and its performance is comparable to the other existing impact force control techniques.

5.2 Related Areas of Research and Future Work

This thesis work can be related to broadly three areas of research: space telerobotics, manufacturing, and control of electro-mechanical systems/ intelligent control.
Space Telerobotics

Kinematics, Dynamics, and Control

Telerobotics presents very difficult challenges due to its unique dynamics and control problems. In the area of dynamics and control of flexible spacecraft and space-based manipulators, the understanding of robot dynamics gained in this thesis will help to address the problems related to noncollocated sensors and actuators and to study dynamics and control of multibody/robotic systems. The proposed force and impact control strategies can be used for impact minimization and stable manipulation during interaction between free-flying robots and objects in space. The control laws will prove useful in space operation because the control law is robust with varying-stiffness environment and has a very good disturbance rejection property.

Teleoperation, Time Delay and Autonomy

In space teleoperation, for movements involving contact and assembly, predictor display does not seem to help much, but accommodation by compliance or impedance seems to be adequate (Sheridan, 1984). Force-reflective telemanipulated systems with compliance control capabilities have been known to be promising for telemanipulation and the key research focus has been on force feedback and time delay amelioration/exploitation. In this thesis, we developed a force controller which exploits time delay. This research enhances the understanding of the time delay effect in the
force feedback loop and may suggest a new possibility of exploiting or compensating for time delay in teleoperation.

**Design of Space Flight Systems**

The experimental study of robot hardware will help to develop space robot systems and to modify the components of mechanical structures for control. Since all robot systems contain the same basic mechanical components, it is hoped that designers will find these experimental results useful when they are faced with the problem of selecting the components and control method, so that they can do so in a unified manner.

**Manufacturing Systems: Haptic Interfaces for Environment and Teleoperator Systems**

Most telerobotics technology is a dual-use technology, since telemanipulation technology developed for space robotic systems can also be employed in remote manufacturing systems and to robot systems in hazardous environments. Control of master-slave manipulators and force feedback (Anderson et al., 1992) will be a main research area focusing on the man-machine interface. It is hoped that the control performance of the proposed force controller exploiting time delay will give an interesting perspective to see the effect of time delay as a benefit rather than a disadvantage.
Control of Electro-Mechanical Systems and Intelligent Control

Future engineering systems will be more complex and accordingly will present many difficult and complicated problems. For example, a design which is beneficial from the perspective of mechanical design may prove detrimental from the perspective of control system design (Sharon, 1989). Future research focus must be on unifying control systems design with mechanical systems design. In performing complicated tasks, a single control strategy may prove to be insufficient to meet the complexity of the task and varying operating conditions. In order to achieve the best performance, it may be necessary to mix various control techniques with the aid of artificial intelligence concepts (intelligent control).

In robot applications, the success of robot control is measured by the degree to which robots can imitate the human ability to handle a specific task. It implies that robots must learn how to handle the task from a human and adopt his way if possible. This philosophy underlies the design of the proposed impact force control. In order to enhance the capacity of robots' service for human welfare, engineers must study human interaction dynamics such as voluntary control, reflexes, and dynamics of the musculoskeletal system (Mussa-Ivaldi et al., 1985) and observe human interactive behavior. Robust interaction and high performance can be achieved by synergistic use of mechanical design, control, learning from human interaction dynamics and behavior, and adopting human intelligence to handle situations in autonomy. This unified approach will lead to exciting new advances in these fields.
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