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EXPERIMENTAL EVALUATION OF CONTROL STRATEGIES FOR ROBOTIC CONTACT TASKS

by

Nitish Kumar Mandal
B.E., University Of Madras, Madras, India May, 1989

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Applied Science

in the School
of
Engineering Science

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APPROVAL

Name: Nitish Kumar Mandal

Degree: Master of Applied Science

Title of thesis: EXPERIMENTAL EVALUATION OF CONTROL STRATEGIES FOR ROBOTIC CONTACT TASKS

Examining Committee: Dr. Jacques Vaisey, Chairman

Dr. Shahram Payandeh
Senior Supervisor

Dr. John Bird
Supervisor

Dr. Kamal Gupta
External Examiner

Date Approved: August 20th, 1993
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"Experimental Evaluation of Control Strategies for Robotic Contact Task"

Author:

Nitish Mandal
(name)

August 20, 1993
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ABSTRACT

In this thesis, we study the contact instability problem encountered in robotic manipulators while trying to make contact with an environment, such as grasping or pushing against objects, and propose a unified control strategy capable of achieving a stable contact against both stiff and compliant environments. We split the problem into the three distinct stages of the contact task. In the first stage, free-space motion, the robot is approaching the environment. In the second stage, we study post-contact force regulation, and, in the third, impact, the transition from the first stage to the second. We make experimental comparison of the control schemes that may be used for the three stages. In free-space motion, the criteria for a controller is a good trajectory tracking response, with a low absolute tracking error. During impact, the manipulator should not lose contact with the environment, as well as not exert high impulsive forces on the environment, and in the post-impact phase, the robot should have a fast force trajectory tracking. The best strategies for the above stages are experimentally determined and then combined into a single unified controller that can achieve stable contact as well as a fast force trajectory tracking response for surfaces of variable stiffnesses. This control scheme does not require a \textit{apriori} knowledge of the environment's stiffness, and is able to estimate the environmental stiffness and tune gains accordingly so as to achieve the best response. We also experimentally compare the use of such a scheme with impedance control, another method proposed in the literature for robotic contact task control.
DEDICATION

To the Creator, who in Her infinite ways, made this both possible and enjoyable, and to all Her subtle lessons that are not documented here.
I would like to express my sincerest appreciation and gratitude to my senior supervisor Dr. Shahram Payandeh for suggesting the research area, and his patience, guidance and encouragement throughout my study. I would also like to thank Drs. Jacques Vaisey, John Bird, and Kamal Gupta for serving on the committee.

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Special thanks go to my parents, and the Sahaja Yogis of Vancouver for their encouragement and guidance.

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<td>CT</td>
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<td>Feedforward torque scheme</td>
</tr>
<tr>
<td>RFFD</td>
<td>Reduced Feedforward torque scheme</td>
</tr>
<tr>
<td>PD</td>
<td>Proportional Derivative Controller</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative Controller</td>
</tr>
<tr>
<td>P</td>
<td>Proportional Controller</td>
</tr>
<tr>
<td>I</td>
<td>Integral Controller</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral Controller</td>
</tr>
<tr>
<td>DD</td>
<td>Direct Drive</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree Of Freedom</td>
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## Nomenclature

- $k_{sc}$: Combined stiffness of the sensor and environment
- $T_s$: Sampling time
- $M(\theta)$: The position dependant manipulator inertia matrix
- $\dot{M}(\theta)$: The modelled position dependant manipulator inertia matrix
- $V(\theta, \dot{\theta})$: Vector of coriolis terms
- $\dot{V}(\theta, \dot{\theta})$: The modelled vector of coriolis terms
- $G(\theta)$: Position dependant gravity matrix
- $\dot{G}(\theta)$: The modelled position dependant gravity matrix
- $\tau$: Torque
- $\theta_d$: Desired position reference
- $\dot{\theta}_d$: Desired velocity reference
- $\ddot{\theta}_d$: Desired acceleration reference
- $k_p$: Position Gain
- $k_v$: Velocity Gain
- $u$: Commanded acceleration
- $E$: Error vector
- $J$: Manipulator Jacobian
- $M$: Constant diagonal approximation to the modelled position dependant manipulator inertia matrix
- $k_i$: Integral gain
- $f_{ref}$: Reference force value
- $f_c$: Contact force
- $J^T$: Jacobian Transpose
- $J^{-1}$: Jacobian inverse
- $J^{-T}$: Jacobian inverse Transpose
- $k_{pf}$: Proportional force gain
- $k_{df}$: Derivative force gain
- $k_{fi}$: Integral force gain
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<td>$k_d$</td>
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<tr>
<td>$k_c$</td>
<td>Stiffness of compliant material</td>
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<td>$F_c$</td>
<td>Contact force</td>
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<tr>
<td>$F_{ref}$</td>
<td>Reference force</td>
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<tr>
<td>$T_f$</td>
<td>Force sensor sampling time</td>
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<td>$v_a$</td>
<td>Approach velocity to the environment</td>
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<td>$x_m$</td>
<td>Measured X position</td>
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<td>$\dot{x}_m$</td>
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<tr>
<td>$j$</td>
<td>Modelled impact impulse magnitude</td>
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</tr>
<tr>
<td>$m_r$</td>
<td>Manipulator mass</td>
</tr>
<tr>
<td>$m_e$</td>
<td>Environment mass</td>
</tr>
<tr>
<td>$e$</td>
<td>Coefficient of restitution</td>
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<td>$\Delta_i$</td>
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CHAPTER 1

INTRODUCTION

The history of industrial automation is characterized by periods of rapid change in popular methods. Either as a cause, or perhaps, an effect, such periods of change in automation techniques seem closely tied to world economics. Use of industrial robots, which became identifiable as a unique device in the 60's along with CAD systems and CAM systems, characterize the latest trends in automation of the manufacturing process.

Industrial robots are now beginning to revolutionize industry. These robots do not look or behave like humans, but they do the work of humans. Robots are particularly useful in a wide variety of industrial applications such as material handling, painting, welding, inspection and assembly. Even more impressive however, is the perspective that robots may bring to the factory of the future. Current research efforts focus on creating smart robots that can “see, hear, feel and make decisions”.

Over the years, a number of definitions for a robot have been proposed. However,
as robotic technology continues to evolve, any definition proposed may need to be refined and updated before long. For the purpose of material presented here, the following definition is used.

"A robot is a software-controllable mechanical device that uses sensors to guide one or more end effectors through programmed motions in a workspace in order to manipulate physical objects."

Contrary to popular notions about robots in science fiction literature (see, for instance, Asimov, 1950), today's industrial robots are not androids built to impersonate humans. Indeed, most are not even capable of self-locomotion. However, many of today's robots are anthropomorphic in the sense that they are patterned after the human arm. Consequently, industrial robots are often referred to as robotic arms or, more generally, as robotic manipulators. In this thesis, the word robot and manipulator have been used interchangeably.

Applying robots to contact tasks is one of the challenges of developing robot technology. Contact tasks are those in which the robot grasps or pushes on its workpiece. They make up a large proportion of the tasks to which robots could be applied. Examples of such tasks include the handling of fragile payloads, the insertion and removal of parts and deburring and machining. Yet, ironically, to date most of the successful applications of robots are to tasks in which the robot stays clear of the workpiece. Spray-painting is one example; the robot brings the spray gun through a complex path in space, but (if it is working correctly) never touches the workpiece. Seam-welding is another example; the robot end-effector tracks the seam, but never touches it. Even in those applications where the robot does contact the workpiece, as in material handling tasks, it generally does so without precise control of the way it
interacts with the object.

A major problem in such an interaction is contact instability. A robot system is stable if it does not produce any unbounded output while executing tasks which are within it's specifications. Thus contact instability is the unstable behavior of the robot when it interacts with an environment. Contact instability is particularly severe when the robot has to interact with rigid environments.

Due to contact instability, even apparently simple contact tasks (wiping a surface for example) prove to be surprisingly difficult. Robot control systems which perform stably during free movements can break into unstable oscillation upon contact with a surface. Despite the substantial research effort which has been directed at controlling the force exerted by a robot, attempts to use sensory feedback (e.g. from a wrist force sensor) for this purpose have been thwarted by this problem of contact instability. Indeed, in his review, Whitney[1] identifies this as one of the major challenges of developing robot technology.

1.1 Research Objectives

The objective of this research is to identify the main issues involved in successful impact and post-impact force control of robotic manipulators against environments of varying stiffnesses, and evolve a scheme that ensures a stable contact with the environment, irrespective of the environment's stiffness. The criteria of stability for contact tasks in this thesis is that the manipulator not lose contact with its environment once contact is established. The unified method of contact force control is also compared to another scheme proposed in the literature.
1.2 Thesis Overview

The thesis is divided into 8 chapters and 1 appendix as follows. Chapter Two, entitled "background and Overview", presents a brief literature survey of the issues involved in the contact instability problem, and the motivation for the thesis. Chapter Three discusses the hardware used for the experimental evaluation. Chapter Four, entitled "Free-space motion" evaluates the schemes for free-space motion. Chapter Five, entitled "Post-contact Force control" addresses the issues involved with post contact force control, and identifies a control strategy well suited for the purpose. In chapter Six, "The Impact Stage" the issues relating to achieving a stable impact are identified, as well as a control strategy suitable for the impact and subsequent post-impact force control is identified. Chapter Seven, "A Unified Control Strategy For Contact Tasks" develops a unified controller that is capable of handling the three stages effectively, regardless of the environment's stiffness, and achieves a fast response. This method is also compared to another method proposed in the literature for robotic contact task control. Finally, Chapter Eight, "Conclusion and Future Work", presents the conclusions of this thesis, and makes suggestions for future research work. The appendix provides additional details not found in the main text.

1.3 Contributions of this thesis

Our contributions to the understanding of the robotic contact task problem in this thesis have been the following:

1) Experimental evaluation of a whole breadth of simple force control strategies
on both, a compliant as well as a rigid environment. Development of a PID control strategy for the effective post-contact force regulation of the robotic manipulator against an environment. The PID strategy used does not require the force derivative to provide effective damping.

2) Understanding of the impact phenomenon. Experimental demonstration of the bandwidth limitations of the robotic manipulator to effectively respond to the impact. It is also shown that previous results based on a force sensor sampling at a frequency lower than the Nyquist rate are incapable of detecting the loss of contact at the initial stages of impact.

3) The proposition of a Knowledge-based controller based on the PID structure for successful control of the robotic contact task. This controller does not require a \textit{apriori} knowledge of the environment, but is able to estimate it and vary the controller gains accordingly so as to give the best suitable response. The set-up of an experimental basis for formal modelling of the unified controller.

4) Identifies some limitations in impact and post-contact robot/environment modelling methods proposed in the literature.

5) Presents experimental results at significantly low sampling times as compared to those in the literature.
CHAPTER 2

BACKGROUND AND OVERVIEW

2.1 Introduction

This chapter presents a brief literature review, and discusses the issues associated with the robotic contact task problem. As mentioned in the previous chapter, the robotic contact task may be split up into three distinct stages, viz. Free-space motion, Post-contact force control and the Impact stage. A brief literature review in the context of these three stages is presented. In the following, post-contact is used to refer to a case where the manipulator is in contact with the environment right from the start of the experiment, whereas post-impact to refer to a case where the manipulator starts from free-space, and then, after impacting with the environment, is in contact with the environment.
2.2 Literature Survey

While there has been a prolific number of publications in recent times on free-space motion, and to some extent on post-contact force control, there is not much in the literature about the impact stage.

2.2.1 Free-space motion

Khosla [32, 33], An and Hollerbach [7], and Tarn [35, 36] have reported experimental results on the use of model-based control strategies for the trajectory control of robotic manipulators. Model-based control utilizes the dynamic model of the robotic manipulator in either the feedback (computed torque control) or the feedforward path (feedforward dynamics compensation control).

An and Hollerbach [7] implemented both the feedforward as well as the computed torque model-based schemes, and compared the performance of the two with respect to a simple PD controller. Both the feedforward as well as the computed torque model-based schemes performed similarly, but gave a result better than the simple PD controller. An increase in the sampling rate resulted in a much better performance of all the three controllers. The effect of sampling rate in the context of increasing the feedback gains and thereby improving the performance was also discussed.

Khosla [32] implemented the same model-based schemes as above, along with a reduced form of the feedforward scheme at a sampling rate of about 500Hz, and found the three to perform similarly.
Figure 2.1: Parametric uncertainty vs. average tracking error tradeoff

Asada[6] presents a mathematical analysis of model-based as well as robust non-model based controllers for robot trajectory tracking, and came up with the curve shown in figure 2.1 for parametric uncertainty vs. average tracking error tradeoff for the computed torque scheme and a robust scheme utilizing a simplified "decoupled" model. His conclusion was that the crossing point $\alpha$ tends to zero as the allowable bandwidth of the robotic system increases. Viewed in another way, the above indicates that given a fast sampling time and a good bandwidth system, the need for accurately modelling a system is obviated, as simple robust schemes will perform equally well.

From the above literature, it is obvious that sampling time and bandwidth of the robotic system play a role in the trajectory tracking control of the robotic manipulator. The fastest sampling rate at which results have been presented in the literature is 500Hz., and no comparison of the model based schemes has been made with a local PID controller.
2.2.2 Post-contact force control

Some of the works of researchers in the area of post-contact force control are summarized below. It may be mentioned that though some of the papers reviewed here propose schemes that are for impact as well as post-impact force control, they are reviewed here, as they have been evaluated only for the case of a robot in contact with an environment.

Recent work in the area of contact force control has addressed the general problem of contact between manipulators and the environment. A number of reasons have been propounded to explain the contact instability problem.

Whitney[2], was the first to provide a stability analysis of a force controlled manipulator, and showed that a tradeoff exists between the force feedback gain and the combined stiffness of the force sensor and the environment. He modelled a manipulator as a velocity input integrator, i.e the motion device of the manipulator (actuator) was modelled as an integrator, the input to which was a motion command (velocity), and assumed that proportional position, velocity, and force feedback were implemented in discrete time. He modelled the environment as a spring and derived the following stability result:

\[ 0 < T_s G k_{se} < 1 \]

where \( T_s \) is the sampling rate, \( G \) is the force feedback gain, and \( k_{se} \) is the combined stiffness of the sensor and the environment. For fixed \( T_s \), this indicates that a tradeoff exists between \( G \) and \( k_{se} \). In other words, high bandwidth force control requires a compliant sensor or environment.
Whitney[1] briefly sketches the developments in robot force control research and the principal problems that remain to be solved. Different implicit force feedback architectures such as stiffness control, damping control, impedance control and explicit force control are described, and it is demonstrated that for stiffness and damping control, when interacting with stiff environments, stability can only be obtained with low gains, implying sluggish behavior.

An and Hollerbach[7] analyse the dynamic stability problems associated with force control (here, dynamic instability refers to instabilities caused by the interaction of the dynamics of the robot with the dynamics of the environment), and attribute the instability problem to unmodelled higher order dynamics, and conclude that for stability of the robot, there must be some initial compliance either in the robot or in the environment. The combination of the force sensor and stiff environment is approximated as a very stiff spring and from stability point of view, force feedback is shown to be very high gain position feedback, which affects stability. Experimentally, stiffness and impedance control are implemented, and it is shown that a force controller is stable for soft surface, but not for hard surface.

Eppinger and Seering [12, 9] develop lumped parameter (such as mechanical mass, spring and damper) modelling and analysis techniques to investigate the stability of closed-loop force control systems. Using a series of lumped parameter models, it is shown that a simple force control algorithm (i.e one using a proportional force control law) is stable when the higher order dynamics of the arm can be neglected, and that it can be unstable if those effects are significant. Starting from a simple rigid body model of the robot and environment, a fourth order arm/sensor/environment model is developed which is used to predict the behaviour of a simple proportional
controller against stiff and compliant environments. However, these models were not experimentally derived, and further they did not take into consideration the effect of digital implementation.

Eppinger and Seering[12] is an extension of the work in Eppinger and Seering[9], and provides an analytical overview of the dynamics involved in force control. Models are developed which demonstrate, for the one axis explicit force control case, the effects on system closed loop bandwidth of robot system dynamics, drive train and task nonlinearities, and actuator and controller dynamics. If the actuator has limited bandwidth, i.e. if the actuator cannot respond well to components of the input signal above some cutoff frequency, then this can also drive a system to instability. Plant nonlinearities such as dynamic coupling between axes, joint friction etc. also limit the closed loop bandwidth. The most significant of such nonlinearities is the workpiece contact discontinuity. This results in the system exhibiting limit cycles, and the system is stable for values of gain much lower than the critical gain predicted by linear analysis. A filtered force control law, PI, PD and lead compensator force control law are simulated, and it is observed that low pass filtering and PI control add destabilising poles, which introduce phase lag and limit closed loop bandwidth (the larger the phase lag, the lesser would be the gain margin, and hence lesser the bandwidth). On the other hand, PD control and lead compensator add zeros, which provide phase lead at low frequency. This has the effect of raising the closed loop bandwidth, thereby improving active force control performance.

Colgate and Hogan[5] explain the interactive behaviour of a manipulator in terms of the properties of it's impedance. Mechanical impedance (Z) is the dynamic relationship between velocity input and force output at some physical location. Using
passive physical equivalents, it is argued that an integrating controller is unstable when coupled to a stiff environment, though it does reduce steady state error. In the case of dynamic compensation, stable control of the force exerted on a rigid surface may be possible, however it will not exhibit high bandwidth or robustness to interaction with all passive environments.

Wen and Murphy[13] present a stability analysis for robot manipulators under the influence of external forces. The environment is modelled as a mass, spring, and damper, and it is shown that for rigid environments the feedback gain has to be small to ensure stability. However, in contrast to past explanations which suggest the culprit to be the unmodelled dynamics, the results offer two alternate explanations: time delay in force measurement in the direct force feedback case, and excessive gain in the integral force feedback case. Even when there are no unmodelled dynamics, the control gain should be selected based on environmental stiffness. For a stiff environment, integral force feedback is suggested. However, the integral force feedback gain has to be chosen sufficiently small. When the environment is rigid, direct unfiltered force feedback tends to be non robust with respect to the time delay in force measurement. They have observed that direct intergral force control is more robust than direct proportional force control with respect to the time delay in the control loop. In addition, direct intergral force control has better steady state error characteristics. This is in contrast to the findings of Eppinger and Seering[12, 9]

More recently, the focus of force control literature has been on using explicit methods of force control. Goldenberg [37], using linear models, argues that many different methods for force control are analytically equivalent, and that improvements suggested by their use could only be specific to the particular manipulator system used.
Volpe and Khosla [38], implemented simple explicit control strategies (proportional, proportional-derivative and integral force control) and have demonstrated the superiority of integral control for force trajectory tracking. They have also argued the fact that impedance control is just high gain proportional explicit force control. Their findings are in contrast to those of Eppinger and Seering [12, 9] and Colgate and Hogan [5].

Most of the recent publications in the literature have focussed on a non-model based approach to the force control problem. This may be attributed to the fact that it is difficult to model the situation of a robot in contact with an environment. Further, the stiffness of the environment may vary largely from stiff to compliant environments, and any dexterous force control strategy must be able to effectively deal with both stiff and compliant environments. Extending the idea of using simple strategies such as Integral control or a PD control Xu et. al.[50] proposed a nonlinear damping function in a PD controller for improved force tracking response. Wilfinger et. al.[58] proposed a method of increasing the disturbance rejection of an integral controller.

### 2.2.3 Impact Control

Though there has been a lot of work done on force control, surprisingly, there is not much literature dealing with the transition from free-space motion to the force control stage. This transition inherently involves impact, as the manipulator is moving at some velocity, and suddenly is stopped. Depending on the stiffness of the environment, as well as the approach velocity to it, this impact results in a force spike, which also
has to be compensated for or accommodated. A high force spike may not be desirable in the case of some environments (for example, if the robot is manipulating brittle objects such as glass). Typically, it is the force controller that has to deal with this transient phenomenon, since the large force does not occur until after the contact has occurred. However, the natural elasticity of an impact, or the response of the force controller to the force spike, can cause the manipulator to rebound from the environment. Thus, the manipulator is once again unconstrained. This phenomenon can establish oscillatory behaviour or worse. Obviously, it is the goal of any controller to pass through this transient period successfully, and have the manipulator stably exerting forces on the environment in the end.

Most of the previous work in the literature has treated this impact phase as a transient that has to be dealt with by the same controller used to follow commanded force. No change has been employed in the controller structure, and gains have been chosen for the post contact force control phase. Typically, modification of the control strategy has been attempted through active damping and/or passive compliance and damping.

Mills and Lockhorst [22] implemented a discontinuous controller that sought to reduce the problems of contact instability and also managed events of contact loss and trajectory tracking. However, this resulted in control chattering, due to the discontinuous behaviour of the control law about the system equilibrium.

Toumi and Gutz[4] present an analytical model for impact, and show that an integral force compensation with velocity feedback improves force tracking and impact response. It is also revealed that impact response can be tuned by selecting a favourable dimensionless ratio of force to approach velocity. The performance varies
with change of controller gains and approach velocity.

Khatib and Burdick[55] propose a method for dissipating impact oscillations that involves increasing the derivative gains of a proportional-derivative force controller for a limited time following impact. By disabling the high velocity feedback gain after the impact oscillations decayed, response times to subsequent force commands were decreased.

Qian and De Schutter[40] present an active nonlinear damping approach. This method examines the force derivative and effectively adds a columb friction term to the output force command when this derivative exceeds a threshold.

Hyde and Cutkosky[42] suggested an input command preshaping to improve the impact performance of a force control scheme. Viewed in another way, this method involves a time duration during which a fraction of the desired force to be exerted on the environment is specified immediately after impact, thus allowing the impact dynamics to die down before specifying the full desired force (a sample “shaped” step input is shown in figure 2.2). They also experimentally evaluated the methods of Impedance control of Hogan[3], and introducing active impact damping of Khatib and Burdick[55], as well as active nonlinear damping of Qian and De Schutter[40], using a compliant finger tip, and found that the performance of the damping methods was sensitive to the noise in the measured force signal.

Volpe and Khosla [39] present an experimental evaluation of a strategy for impact control based upon proportional and integral control. Proportional control was employed during the impact phase, and, after the dynamics of impact died down, integral control was resorted to for the post-contact phase.
Roberts[18] reported the effect of mechanical stiffness of the force sensor on impact control, and found that mechanically compliant force sensors permitted faster approach velocities. Whitney[1] also suggested the use of soft sensors. However, one drawback of a soft sensor is poor dynamic performance of the force sensor.

Paul[20] identifies research issues in position and force control, and addresses the stability problem for the case of a manipulator making contact with a rigid environment. A reason suggested for contact instability is that the time constant of integration of the force sensor is much shorter than that of the regulator. On contact, the force sensor sees a rapidly increasing force, and the sensor output goes immediately off scale. The time scale of this interaction is of the order of a few microseconds. This signal is processed by a regulator which has a well defined minimum time response of the order of milliseconds. Contact is long since over before the regulator can respond and any damage to occur has already occurred.
2.3 Discussion

From the above literature survey, it is clear that many ambiguous results have been presented in the literature. Further, many propositions have been qualified by simulation, which are in direct contradiction with experimental findings of other researchers. Recently, Goldenberg[37] and Volpe and Khosla[39] have argued that many schemes proposed in the literature are equivalent, and that the improvement in the response may have been achieved due to the merits of the hardware used.

In this thesis, simple force control strategies are evaluated due to contradictions in the literature.

The contact task problem may be studied under the three distinct stages mentioned above. The important criteria for controllers for the three stages may be outlined thus. During free-space motion, the robotic manipulator should have a good trajectory tracking response, and low absolute and steady state position errors. In the post-contact stage, the robot should have a fast force trajectory tracking response, along with a minimal overshoot and steady state error. During impact, it is desired that the robot maintain contact with the environment, and also that the impacting forces should not be very high.
CHAPTER 3

HARDWARE SET UP

This chapter discusses the hardware set up used to perform the experiments.

3.1 Hardware Set up

The block diagram of the system set-up is shown in Figure 3.1. The computational system used was a PC 386 as the host and the spectrum 320C30 DSP board as the servocontroller. The user writes the control code on the DOS development system in C, compiles and links the program and downloads it to the DSP for execution. During runtime, the DSP executes without interference from the host. The DSP has dual-ported memory, which means that the PC can access this memory for reading or writing without interrupting the DSP, and vice-versa. The trajectory planning of the manipulator was done on the host computer, which calculated the reference set points for the controller to follow. These references were then passed on to the DSP.
controller. One limitation of the above method was that only the position references could be passed on to the DSP, and the reference velocity signal had to be constructed from the position reference. The implication of this limitation is discussed in successive chapters. Two NSK Megatorque direct drive motors were used as actuators for the two links. The motors are capable of delivering extremely high torque (up to 254 N*m for the link 1 motor, and up to 39.2 N*m for link 2 motor), have low friction, and come equipped with extremely accurate (153600 counts per revolution) direct drive angular position measurement devices (Megatorque motor system, user's manual [61]).

A six axis (ATI 15/50) force/torque sensor was used for measuring the forces. This six axis sensor can read forces up to 15 pounds and torques up to 50 inch-pounds, and has a maximum sampling frequency of 2500 Hz. analog output. The stiffness of the force sensor was $50 \times 10^3$ pounds/inch. The force sensor was mounted rigidly onto the second link of the manipulator. A circular aluminum plate of 150mm diameter was attached to the top of the force sensor. This plate acted as the manipulator’s end effector.
3.2 A note on digital implementation

Although in the following chapters the control strategies have been discussed in continuous time, they were implemented in discrete time. It is assumed that the discretization has no effect on the controller performance.

The derivative of variables was obtained using the backward differencing. Thus, the derivative of $x_d(k)$ was obtained as

$$\dot{x}_d(k) \approx \frac{x_d(k) - x_d(k - 1)}{T_s} \quad (3.1)$$

and the second derivative of $x_d(k)$:

$$\ddot{x}_d(k) \approx \frac{\dot{x}_d(k) - \dot{x}_d(k - 1)}{T_s} \quad (3.2)$$

where $T_s$ is the sampling period. The discrete integral of variables was obtained using the summation as

$$\int_0^t x_d(t)dt \approx \sum_{i=0}^{k} x_d(i) \times T_s \quad (3.3)$$
CHAPTER 4

FREE SPACE MOTION

4.1 Introduction

Free space motion forms the first stage of the contact task. During this stage, the robot is approaching the environment at a specified velocity and acceleration, and along a pre-determined trajectory. The criteria for the robot during this stage is to have a low absolute trajectory tracking error. Further, the understanding of free-space controllers is essential for the implementation of implicit (impedance based) methods of force control, which rely on position errors between the actual and desired position in order to exert a force on the environment (Mandal and Payandeh [44]).

This chapter presents experimental results of the different schemes that may be used to control the robotic manipulator for free space motion. A comparison is made of the model based schemes, as well as non-model based ones, and the importance of bandwidth and sampling time on the controller performance are discussed. Amongst
the model based schemes, both, the computed-torque and feedforward dynamics compensation schemes were implemented. The aim is to evaluate a robust controller that is insensitive to modelling errors, external disturbances, and is able to track the desired trajectory accurately. Unique to the presentation here are results for sampling times as low as 1ms, which results in a simple PID controller to perform as effectively as a model-based controller.

The manipulator trajectory control problem revolves around computing the joint torques to be applied to track the desired joint position, velocity, and acceleration trajectories.

Compared to the extensive simulation results found in the literature on model-based schemes, real time performance data is scant. This is attributed to lack of suitable manipulators for implementing these controllers. Commercial robots are characterized by high gear ratios, substantial joint friction and slow movement. Further, joint torque control is infeasible in these robots. Besides, there is also a tremendous real-time computational requirement of model-based control strategies.

Similar work on model-based schemes has been done by Khosla [32], [33], An [7], and Tarn [35], [36]. However, they did not compare the performance of their model-based controllers with a PID controller. Further, our work clearly demonstrates the effect of a high sampling rate on the performance of such control strategies.

These control techniques were implemented on the 2DOF DD arm of the Experimental Robotics Laboratory (ERL) described before. DD arms do not have the limitations of commercial robots, such as high gear ratios, substantial friction and
backlash effects, and therefore are apt for joint torque control. When gearing is eliminated, however, the full nonlinear dynamic interactions between moving links are manifested.

4.2 Modelling And Control

In the model based control scheme, the dynamic model of the manipulator is used in some path of the control scheme. This results in two types of model based schemes: the computed torque scheme, in which the dynamics are used in the feedback path, and the feedforward dynamics compensation scheme, in which the manipulator dynamics are used in the feedforward path. Both these schemes depend on the manipulator dynamic model for calculation of the gross input torque of the joints, and use an inner or decentralized controller to compensate for small deviations in trajectory tracking. Commonly the inner loop is a PD one. Another implementation which has not been considered much in the literature is that of using an inner loop comprised of a PID controller instead of the simpler PD one. Based on the general servomechanism theory (Davison [27]), the integral term has the potential of driving the system errors to the resolution of the resolver, thereby compensating for model uncertainties as well as external disturbances that may be acting on the manipulator.

The dynamics of a manipulator are described by a set of highly nonlinear and coupled differential equations. The equations of motion of the manipulator were derived using the Lagrange-Euler approach (Craig[29], DD manipulator, users guide[60]). The complete dynamic model of a 2DOF manipulator is described by:
\begin{equation}
\tau = M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) \tag{4.1}
\end{equation}

where \(\tau\) is the 2-vector of the actuating torques; \(M(\theta)\) is the \(2 \times 2\) position dependent manipulator inertia matrix; \(V(\theta, \dot{\theta})\) is the 2-vector of Coriolis and centrifugal torques; \(G(\theta)\) is the 2-vector of gravitational torques; and \(\ddot{\theta}, \dot{\theta}\) and \(\theta\) are 2-vectors of the joint accelerations, velocities and positions respectively. As in our manipulator, the two links are horizontal, the term \(G(\theta)\) is ignored.

Both the computed torque and the feedforward schemes use the full dynamics model of the manipulator in different parts of the control loop. In the following, \(K_p\) and \(K_v\) are the constant and diagonal position and velocity feedback gain matrices respectively, and \(\theta\) and \(\theta_d\) are the measured and reference joint position vectors respectively, and \((\cdot)\) denotes there derivative with respect to time.
4.2.1 The computed torque scheme (CT)

The computed torque scheme, as depicted in Figure 4.1, utilizes non-linear feedback to decouple the manipulator. The control torque $\tau$ is computed by the inverse dynamics equation in (4.1), using the commanded acceleration $u$ instead of the measured acceleration $\ddot{\theta}$

$$\tau = \dot{M}(\theta)u + \dot{V}(\theta, \dot{\theta})$$

where (.) indicates that the estimated values of the dynamic parameters have been used in the computation. If the dynamic model of the manipulator were exact, and there were no exogenous disturbances acting on the system, then $u = \ddot{\theta}_d$ would suffice in achieving the desired trajectory control. However, in practice it is difficult to get an exact model of a manipulator (especially friction). Thus, an inner loop or decentralized PI controller is added to compensate for modelling errors. The input $u$ now gets modified to

$$u = K_p(\theta_d - \theta) + K_v(\ddot{\theta}_d - \dot{\theta}) + \ddot{\theta}_d$$

This results in a control torque of:

$$\tau = \dot{M}(\theta)[K_p(\theta_d - \theta) + K_v(\ddot{\theta}_d - \dot{\theta}) + \ddot{\theta}_d] + \dot{V}(\theta, \dot{\theta})$$
4.2.2 The feedforward scheme (FFS)

Sampling time is an important consideration in implementing a controller of the form as given in 4.4, and, plays an important role in the implementation of any controller and is crucial for high gain control and stiffness of the system. One way to achieve a faster sampling time is to use the model based control “outside” the inner servo loop. This way, the feedforward terms may be pre-computed offline, and then fed online to the controller. This results in the system as depicted in Figure 4.2. Essentially, this method “feedforwards” the torques computed from (4.1) by using the reference trajectory instead of the actual positions and velocities. An inner PD loop provides corrections for small deviations in trajectory tracking.

The control torque \( \tau \) in this case becomes:

\[
\tau = \dot{M}(\theta_d)\ddot{\theta}_d + \dot{V}(\theta_d, \dot{\theta}_d) + K_p(\theta_d - \theta) + K_v(\theta_d - \dot{\theta}) \tag{4.5}
\]
Unfortunately, the scheme of Figure (4.2) does not provide exact decoupling. Writing the error equation of this system (the error equation of the system is obtained by equating the commanded (feedback) torque to the torque specified in (4.1))\(^1\) gives:

\[ \ddot{E} + M^{-1}(\theta)K_v \dot{E} + M^{-1}(\theta)K_p E = 0 \]  

(4.6)

Where \( E = (\theta_d - \theta) \) is a 2-vector of joint errors. The \( M \) matrix in most cases is non-diagonal, and therefore there is a coupling effect. Thus, any disturbances on one link has an effect on the other links as well.

### 4.2.3 The reduced feedforward scheme (RFED)

In the reduced feedforward scheme, the effect of approximating the position dependent inertia matrix by a constant diagonal matrix is demonstrated. Thus, instead of using \( \hat{M}(\theta_d) \) in 4.5, the constant diagonal matrix \( \hat{M} \) is used, which results in a control torque of

\[ \tau = \hat{M} \ddot{\theta}_d + K_p (\theta_d - \theta) + K_v (\dot{\theta}_d - \dot{\theta}) + \hat{V}(\theta_d, \dot{\theta}_d) \]  

(4.7)

\(^{1}\)the following simplifying assumptions have been made, \( \hat{M}(\theta_d) = \hat{M}(\theta), \hat{V}(\theta_d, \dot{\theta}_d) = \hat{V}(\theta, \dot{\theta}) \)
4.2.4 Computed torque with inner PID loop

Another implementation of the model-based schemes that has not been considered much in the literature is that of using an inner loop comprised of a PID controller instead of the simpler PD one. Based on the general theory of the servomechanism problem (Davison[27]), the integral term acts as a servocompensator, compensating for model uncertainties as well as external disturbances that may be acting on the manipulator.

For the sake of brevity, implementation of the inner PID loop is considered for the computed torque case only; however, this suffices to illustrate the efficacy of integral compensation. The control law for the CT case now gets modified to

\[ u = K_p(\theta_d - \theta) + K_v(\dot{\theta}_d - \dot{\theta}) + \ddot{\theta}_d + K_i \int (\theta_d - \theta) dt \]  \hspace{1cm} (4.8)

4.2.5 A simple PID controller

The performance of the model-based schemes is also compared with a simple PID controller. The purpose of comparison was to see the performance of the model-based schemes relative to a simple PID, given a fast sampling time and good bandwidth.

The control law for the PID controller may be given as:

\[ u = K_p(\theta_d - \theta) + K_v(\dot{\theta}_d - \dot{\theta}) + K_i \int (\theta_d - \theta) dt \] \hspace{1cm} (4.9)
4.3 Experiments and Results

4.3.1 Gain matrices

Given an exact model of the system, and using the control laws (with inner PD loop) as detailed above, a linear system is obtained with the following closed loop characteristics.

\[ E(s^2 + k_{uj} s + k_{pj}) = 0 \]  

where \( k_{pj}, k_{uj} \) are the position and velocity gains of the \( j \)th joint.

Thus, for a critically damped response, the gains should be \( k_{uj} = 2\sqrt{k_{pj}} \). Also, to have high stiffness or disturbance rejection ratio, the gain \( k_{pj} \) should be as high as possible, which in turn results in a large \( k_{uj} \). In practice, however, the velocity gain is limited by the noise present in the velocity measurement from a tachometer. Due to the high resolution resolvers present in the system, it was found that better performance could be achieved using derived joint velocities.

An integral action has a drawback of overshoot. This is compounded by the fact that DD systems have almost zero damping (Asada and Toumi[28]) (mechanical damping being produced only at the bearings supporting the joint shafts. The back emf at the drive motor yields a damping effect, because the voltage applied to the motor is substantially reduced by the back emf, which is proportional to the motor speed). Thus, for the inner PID loop, a \( k_{uj} \) slightly higher than \( 2\sqrt{k_{pj}} \) was selected; the gains being experimentally tuned to give the best tracking response.
4.3.2 Friction

Typical errors caused by friction are: steady state errors and tracking lags. In some cases, the presence of friction may also generate an oscillatory behaviour (Wit and Seront[24]). A comprehensive model of friction would involve terms dependent on the position and velocity of the joints (Dupont[31]). A model for friction and stiction has not been incorporated in the control schemes above; however, they are compensated for by augmenting the voltage command to the controllers by friction/stiction parameter values that were determined experimentally (Tarn et.al.[35]). For each joint, the voltage to the motor drivers was increased incrementally, till the joint just started to move. About 70 percent of this value of voltage was used to compensate for friction (Wit and Seront[24], Dupont[31]).

4.3.3 Joint-Space Moves

The architecture for the DD robot is as shown in Figure 3.1. Here, the reference trajectory is generated on the host computer, and reference set points passed on to the DSP servo processor every sampling instant. The trajectory generator used for the experiments gave a linear interpolation with parabolic blends (Craig[29]). The absolute value of the maximum velocity and acceleration to be attained by the joints was 2 rad/s and 4.0 rad/s² respectively.

The implication of such an architecture was that the reference velocity signal could not be passed on to the DSP. Thus, the reference velocity signal was obtained by differentiating the reference position signal. A third order Butterworth filter was used to smoothen the signal; the filter coefficients were obtained using Matlab[62]
Table 4.1: Absolute tracking errors.

<table>
<thead>
<tr>
<th>Joint no.</th>
<th>CT pos. error (rad.)</th>
<th>FFD pos. error (rad.)</th>
<th>RFFD pos. error (rad.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.012</td>
<td>0.011</td>
<td>0.015</td>
</tr>
<tr>
<td>2</td>
<td>0.025</td>
<td>0.009</td>
<td>0.009</td>
</tr>
</tbody>
</table>

The function BUTTER for the design of Butterworth filters. For the model based schemes, this signal was again differentiated and filtered to obtain the commanded acceleration signal.

The controller sampling period chosen for the experiment was 1ms or 1000 Hz. Results are presented here for a simple trajectory used to evaluate the above control schemes. In this trajectory, joint 1 is commanded to start from its zero position and to reach the final position of 1.1 rad. Similarly, joint 2 moves from zero to the position -1.1 rad. in the same time. The joints are then commanded to stay at this position for one second. The performance data is collected up to this point only.

The absolute tracking error (i.e the absolute value of the maximum tracking error) is used as a measure of performance for the controllers. The plots depict the reference position, actual position and the joint errors for both the joints for the above schemes. The absolute tracking errors for the control schemes is shown in table 4.1. In the plots, data was collected at every hundredth of a second. The position (in radians) is shown on the vertical axis. The velocities have also been superimposed on the position curves.

Figures 4.3 and 4.6 show the performance of the computed torque scheme, figures 4.4 and 4.7 the performance of the feedforward scheme.
Table 4.2: Absolute tracking errors for no friction compensation.

<table>
<thead>
<tr>
<th>Joint no.</th>
<th>$CT$ (with inner PD) pos. error (rad.)</th>
<th>$CT$ (with inner PID) pos. error (rad.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.019</td>
<td>0.014</td>
</tr>
<tr>
<td>2</td>
<td>0.055</td>
<td>0.041</td>
</tr>
</tbody>
</table>

As can be seen from these plots and table 4.1, there is not much difference between the maximum tracking errors of the computed torque and the feedforward schemes. This is to be expected as the same model is being used in both the schemes, and, in the absence of large perturbations the differences in the feedback controller are not significant for trajectory following accuracy.

The reduced feedforward controller (figures 4.5 and 4.8) also gives a similar performance as the previous two controllers. This can be attributed to the low sampling time which was used in implementing the three controllers (Khosla[33]). Further, with high PD gains, the inner loop PD controller is able to compensate for tracking errors effectively. This result shows that where it is possible to achieve low sampling times, and correspondingly high PD gains, modelling errors are not of significant consequence in trajectory tracking, provided the actuators have a sufficiently high bandwidth response (Asada and Slotine[6]). With currently available hardware, low sampling times are possible, and therefore efforts to obtain accurate system models are obviated.

Next, the effect of removing the friction compensation term in the model is demonstrated. This is shown in Figure 4.9. For the sake of brevity, results are presented for only the computed torque for the rest of the experiments. From figure 4.12 it may be seen that there is an increase in the position error of the controller. Figure 4.10
shows the performance using the inner PID control law (equation 4.9). The absolute tracking errors for the two cases are given in table 4.2. The inner PID loop based controller results in a better performance in terms of both, the steady state error as well as the absolute tracking error.

To further study the robustness of the inner loop PID over the PD loop, an uncertainty in the accuracy of the manipulator model was introduced by reducing the mass value of link 2 by 25%. Table 4.3 gives a comparison of the absolute tracking errors for the inner PID and PD loop based controllers for this case, and the plots are shown in Figures 4.11, 4.14 and Figure 4.15, 4.17. The improvement in the steady state error for the inner PID loop is even more prominent.

The next experiment demonstrates the efficacy of using just a simple, non-model based, PID controller. As can be seen from figure 4.16 and 4.18, the PID controller also achieves comparable trajectory tracking.

### 4.4 Discussion

Our aim has been to study the implementation of model-based control strategies on a 2DOF robot manipulator with no gravity influence, with the intention of evolving the best strategy that has low absolute tracking error, and is robust to parameter
Figure 4.3: The CT scheme.

Figure 4.4: The FFD scheme.

Figure 4.5: The RFFD scheme.

Figure 4.6: Position errors, CT scheme.

Figure 4.7: Position errors, FFD scheme.

Figure 4.8: Position errors, RFFD scheme.
Figure 4.9: The CT scheme with no friction compensation.

Figure 4.10: CT with inner PID loop and no friction compensation.

Figure 4.11: CT scheme with model uncertainty.

Figure 4.12: Position errors, CT scheme with no friction compensation.

Figure 4.13: Position errors CT with inner PID and no friction compensation.

Figure 4.14: Position errors, CT with model uncertainty.
variations. We draw two important conclusions; the effect of sampling time, and the use of an inner PID loop in place of the simpler PD one. Sampling time plays an important role in the implementation of any control scheme. A low sampling time allows higher gains, thereby increasing the stiffness of the system. This not only reduces the tracking errors, but also makes the system more robust. In our earlier hardware configuration, we were using an Intel 8096 as the servocontroller. This permitted us a sampling time of about 9ms for implementing the model based schemes. The corresponding gains achievable were an order of magnitude less than the ones used in the current experiment. The absolute magnitude of the errors as a result of using the faster DSP servocontroller (which permitted a sampling time of 1ms.) was about half for both the joints, in comparison to the 8096 controller. On the other hand, however, if low sampling times are not achievable, and there are external disturbances acting on the system, or there are variations in the load mass, then an inner PID loop gives the best result. The inner PID loop is able to compensate for modelling errors as well as reduce the steady state error. Thus, there is a tradeoff between increasingly complex control schemes, and the sampling time required to implement them.

The choice of an appropriate control scheme must take into consideration the manipulators system’s hardware, the nature of task to be performed and the accuracies desired. For the case where there is a reasonably high bandwidth, and high sampling times are achievable, and the manipulator is performing free-space movements, without any significant variation of its load, simple schemes perform as well as more complex ones. The feedforward torque scheme provides a method of incorporating knowledge of the manipulator dynamic model on the controller, without too much computational overhead, as the feedforward torques may be computed off-line, and
Figure 4.15: The CT scheme with model uncertainty and integral action.

Figure 4.16: Simple PID controller.

Figure 4.17: Position errors for CTS with model uncertainty and integral action.

Figure 4.18: Position errors, simple PID controller.
added on-line to the controller. On the other hand, if there are external disturbances acting on the system, or there are large variations in the load mass, then the pre-computed torques are no longer accurate, and the computed torque scheme with an inner PID loop gives the best performance.
CHAPTER 5

POST CONTACT FORCE CONTROL

5.1 Introduction

This chapter describes force control of the robotic manipulator once it is in contact with the environment. The environment may be soft or stiff. In this stage of operation, the robot is no longer position controlled, but rather it is required to exert a specified force on the environment. Such tasks intrinsically require the robot to be force controlled.

Force control is the control of forces which are exerted by a robot on the environment. These forces are applied via the end-effector of the robot, and are ultimately controlled by controlling the motor torques of the robot joints. Force control algorithms can be roughly divided into two categories:
• direct methods (or explicit force control)

• indirect (impedance-based) methods

Direct methods control forces exerted by the robot on the environment by controlling the joint torques. The forces measured at the end-effector are used to directly calculate joint torques by using the transpose of the Jacobian of the robot arm (Asada and Slotine [6]). The control law often involves a proportional or integral term, as well as a feedforward term.

Indirect methods control forces by controlling end-effector positions. Force errors are converted to position errors, allowing a position-based control loop to drive the robot joints. Conversion of the force error into a position error is often done using a mass-spring-damper relationship; the resulting system causes the end-effector to respond to forces in a manner similar to a mass-spring-damper system. One indirect method, impedance control, is explained in detail in chapter seven.

In this chapter, only explicit force control methods are considered (Mandal and Payandeh[45]).

5.2 Explicit force control

An explicit force controller describes a force controller that compares the reference force with the measured force signal, processes it and provides an actuation signal directly to the plant. The reference force may also be fedforward and added to the signal going to the plant. The general controller is shown in Figure 5.1 , where $G$ is
Figure 5.1: Block diagram of a generic force-based explicit force controller

the plant, $H$ is the controller and $R$ is the feedforward transfer function, and $L$ is a force feedback filter.

The controller $H$ is usually some subset of a PID (i.e. P, I, PD etc.) controller. The specific forms of these controllers, as well as the experimental results are presented in the following sections.

5.3 Experimental results - compliant environment

Explicit force control is simply the direct feedback of the endpoint force into some compensation algorithm. All the controllers discussed below were tested on a wooden environment; the wooden surface having some cantilever effect, as shown in Figure 5.2, due to there being no support at the top of the wooden surface. This surface is referred to as a compliant environment. The same controllers were also tested against a rigid aluminum environment (section 5.4).

A force step response is used to evaluate the efficacy of each controller. This
provides a qualitative test for the stability of each controller. Both the joints of the manipulator were kept under force control. For the experiments, a step response in the \(x\) direction was used for evaluation. All the gains were experimentally tuned to give the best response.

### 5.3.1 Proportional (P) Control

The control law for a simple proportional force controller is given as:

\[
\tau = J^T[k_p f (F_{ref} - F_e)]
\]

For proportional control, \(H = k_p f\) and \(L = 1\) in figure 5.1. Figures 5.3 and 5.4 show the response of this controller to a step input. The horizontal axis shows number of controller cycles (as the sampling time used is only 0.6 ms., the plot is really for a short interval of time; however, data has been collected every controller cycle, as this gives a clearer look at rise time, settling time and overshoot). The step reference input was -3 pound force for all the experiments. The initial positive value on the plots is due to the force sensor bias.
As can be seen from the figure, the controlled system has a finite steady state error for a step input. To reduce this error, the gain $k_{pf}$ may be increased, but at the cost of increasing the overshoot. This highlights the underdamped nature of the controller. Thus a reduction in the steady state error comes at the expense of increased overshoot and settling time. However, increasing the gain too much leads to instability, and does not reduce the steady-state error altogether.

Another possible improvement to steady state error is to use a feedforward signal. This, however, does not eliminate the oscillations that are present. The response for the feedforward term is shown in figure 5.5.

### 5.3.2 PD control

As the system above is found to be quite underdamped, the next logical step would be to introduce damping to reduce the overshoot, and consequently to increase the proportional force gain in order to reduce the steady state error.

The control law for the PD controller is given as

$$
\tau = J^T[k_{pf}(F_{ref} - F_c) + k_{df}(\dot{F}_{ref} - \dot{F}_c)]
$$

Simple differencing of the force signal however is not successful due to the presence of noise in the force signal. Figure 5.6 shows the force signal from the force sensor in
Figure 5.3: Proportional controller $k_{pf} = 7.0$

Figure 5.4: Proportional controller $k_{pf} = 9.0$

Figure 5.5: Feedforward proportional controller $k_{pf} = 9.0, R = 1.0$

Figure 5.6: Signal from the force sensor

Figure 5.7: PD controller $k_p = 7.0, k_{df} = 0.03$

Figure 5.8: PD controller $k_p = 7.0, k_{df} = 0.1$
Figure 5.9: PD controller with filtering
\( k_p = 7.0, k_{df} = 0.35 \)

Figure 5.10: PD controller (estimated force derivative) \( k_p = 7.0, k_{df} = 0.35 \)

Figure 5.11: PD controller with velocity damping \( k_p = 7.0, k_d = 350 \)

Figure 5.12: PD controller with velocity damping \( k_p = 9.5, k_d = 350 \)

Figure 5.13: Integral control \( k_{fi} = 6.0 \)

Figure 5.14: Integral control \( k_{fi} = 9.0 \)
the absence of any forces acting on the sensor (the slight positive reading is due to the force sensor bias). This constrains the derivative force gain that may be applied, and the end result is not very different from that of a simple proportional force controller.

Figures 5.7 and 5.8 show the response of this controller. Though some measure of damping has been provided, yet the end result is not very satisfactory, and increasing the derivative gain causes the noise to dominate, and the system goes into oscillations.

Three alternative methods to obtain damping were implemented and their performance compared.

*Filtering:*

A third order Butterworth filter was designed and implemented to filter the force signal. The filter coefficients were obtained using Matlab[62] (the function `BUTTER` for the design of Butterworth filters). The filter had a cutoff frequency of 100Hz.

Figure 5.9 shows the plot for using the derivative of the filtered force signal. As can be seen, the filtered force signal provides good damping. However, there is still a steady state error in the response. The proportional gain may be increased to reduce the steady state error, but this results in an increased overshoot. Increasing the damping gain results in an unstable behaviour, as now the noise dominates the response. To achieve better performance, a higher order filter is required, but this also increases the time delay between the actual and the filtered force signal.

*Estimator:*

A full order observer was also designed to estimate the value of the force derivative.
The open loop dynamic equation of the system in figure 5.2 can easily be written in standard state space notation:

\[ \dot{x}(t) = Ax(t) + bu(t), \quad x(0-) = x_0 \]
\[ y(t) = cx(t) \quad t > 0^- \]

with state variables \( x_1 = F_c, x_2 = \dot{F}_c \), control input \( u = F_a \), (where \( F_a \) is related to the joint torques by \( \tau = J^T F_a \)) and system output \( y = F_c \). This system is observable, and an observer can be designed to observe \( \dot{F}_c \). A full order estimator was used. More details of the estimator may be found in appendix A.

Figure 5.10 shows the plots for the estimate of the force provided by the estimator. The estimator provides a good estimate of the force derivative, and the damping provided gives a good response. However, there is still a steady-state error. In the case of the estimator also, increasing the proportional gain results in an increased overshoot, as again, the damping gain cannot be increased sufficiently.

**Damping from the velocity term:**

Alternately, another method to damp the system is to use the velocity information by differentiating the position measurement. This results in a much simpler controller. The control law, using derived position for damping is

\[ \tau = J^T[k_p f(F_{ref} - F_c) - k_d \dot{x}_m] \quad (5.3) \]

where \( \dot{x}_m \) indicates the velocity obtained by differentiating the position measurement, and \( k_d \), the damping gain.
Figures 5.11 and 5.12 show the response of this controller. A comparison of the figures 5.9, 5.10 and 5.11 show that the three methods perform similarly. The use of the velocity damping in this case is attractive, as it is fast, resulting in the derivative being in phase with the actual signal, and, besides, it results in a much simpler controller.

5.3.3 Integral (I) control

Integral control is another candidate for force control; it is simple with a low pass nature, and is capable of reducing the steady state error to zero. The control law for pure integral force control becomes:

$$\tau = J^T[k_fi \int (F_{ref} - F_c)dt]$$  \hspace{1cm} (5.4)

Figures 5.13 and 5.14 show the response of this controller. As can be seen, there is negligible overshoot and the steady state error approaches zero. However, there is a longer rise time, due to some time required for the integral error to build up. Increasing the Integral gain $k_fi$, though reduces the rise time, causes an increased overshoot.

5.3.4 PI control

The control law for the PI controller takes the form
\[ \tau = J^T[k_p f(F_{ref} - F_c) + k_i \int (F_{ref} - F_c) dt] \] \hspace{1cm} (5.5)

Figures 5.15 and 5.16 show the performance of this controller. We see that though there is no steady state error, yet there is an overshoot and a high settling time. This may be attributed to the underdamped nature of the PI controller.

### 5.3.5 PID control

Lastly, the PID controller is considered. As the above three methods to provide damping gave similar results, the velocity damping method is used here. The PID control law has the form

\[ \tau = J^T[k_p f(F_{ref} - F_c) + k_i \int (F_{ref} - F_c) dt - k_d \dot{x}_m] \] \hspace{1cm} (5.6)

Figures 5.17 and 5.18 shows the response of this controller. A comparison with the previous methods shows that the PID gives the best response; though marginally better than the Integral controller in terms of overshoot, it has a better rise time, and due to the damping introduced, there is no overshoot.
Figure 5.15: PI control $k_{pf} = 7.0, k_{fi} = 7.0$

Figure 5.16: PI control $k_{pf} = 7.0, k_{fi} = 11.0$

Figure 5.17: PID control $k_{pf} = 7.0, k_{fi} = 35.0, k_d = 200$

Figure 5.18: PID control $k_{pf} = 7.0, k_{fi} = 45.0, k_d = 200$

Figure 5.19: P control for stiff environment $k_{pf} = 2.5$

Figure 5.20: P control for stiff environment $k_{pf} = 3.0$
Figure 5.21: PD control $k_{pf} = 3.5, k_d = 300.0$

Figure 5.22: PD control $k_{pf} = 3.5, k_d = 400.0$

Figure 5.23: PD control with filtering $k_{pf} = 3.0, k_{df} = 0.1$

Figure 5.24: PD control (estimated force derivative) $k_{pf} = 3.7, k_{df} = 0.2$

Figure 5.25: Integral control $k_{fi} = 45.0$

Figure 5.26: Integral control $k_{fi} = 55.0$
5.4 Experimental results - rigid environment

The same controllers were also tested against a rigid aluminum surface. A 0.5 inch thick aluminum plate, rigidly clamped was used for the purpose. Unlike the compliant wooden environment, the aluminum plate was supported with welded bars from top (figure 5.27). The force sensor surface was manually brought in contact with the aluminum surface before start of each experiment.

The figures 5.19 and 5.20 show the performance of the proportional controller alone. Velocity damping seemed promising for the softer wooden environment; however it does not sufficiently damp the response for the rigid environment case, as shown in figures 5.21 and 5.22; increasing the damping gain any further resulting in the system breaking into oscillations. This may be attributed to fact that for stiff environments, the transient response is fast in comparison with a compliant environment, in which case the calculated velocity may lag it’s ideal value, resulting in the damping being applied out of phase with the true velocity.

The other two methods of obtaining damping through filtration and estimation
were also implemented on a stiff surface. Figures 5.23 and 5.24 show the response for the PD controller with the filtered force signal and the estimated force signal. Both the methods do not perform any better. It may be noted though, that the estimator method results in a far better response than the filtering methods.

Figures 5.25 and 5.26 show the performance of the integral force controller. Though there is no steady state error or overshoot, the pure Integral controller has a slightly higher rise time. Increasing the Integral gain, results in a higher overshoot (figure 5.26).

The PI controller, as shown in figure 5.28 does not achieve any better response, as increasing either the P or the I gains results in a higher overshoot and settling time, if not in the controller exhibiting an oscillatory behaviour. We attribute this to the highly underdamped nature of the controller as well as the system (Asada and Toumi[28]).

The PID controller (figures 5.29 and 5.30) again gives the best response. There is a smaller rise time and settling time and negligible overshoot. It may be noted, however, that in comparison to the performance of the Integral force controller, the

Figure 5.28: PI control $k_{pf} = 2.5$, $k_{fi} = 55.0$
PID force controller’s response is marginally better, with an improvement in rise time.

5.5 Discussion

The table 5.1 shows the range of stable gains for proportional and integral control for the stiff and compliant environments.

From this it can be seen that the range of stable gains varies considerably for the two surfaces, and demonstrates that the kind of surface a robot contacts does affect the performance of a robot. It may also be pointed out that the mass spring damper models have been used in the literature for predicting the behaviour of the above controllers; however, the improvement in the stability of integral control for a stiff environment has not been demonstrated by any such model yet. This highlights the need for a better modelling technique.

The results presented in our previous sections indicate the usefulness of Integral and PID control for post-contact force control of both stiff and soft environments. While Integral control tends to be sluggish for soft environments, PID control achieves the same fast response in both cases. For the case of a noisy force sensor, obtaining a good measure of the force derivative is a real problem. In our experiments, we have highlighted three methods that may be employed for this purpose. The appropriate
choice of course will depend on the system being used, and the task at hand. If good position sensors are available, then simple differencing of the position information is sufficient. If computational power is not a limitation, then the estimator method can be used, as it gives a better performance over filtering. The disadvantage of the estimator is clear. For higher degrees of freedom in a robot, the complexity of the estimator increases rapidly. Further, the accuracy of the method is dependent on the ability to obtain a good model, and is thus specific to the type of environment the manipulator is interacting with.

In this chapter, we have presented results for the response of a manipulator in contact with a compliant environment as well as a stiff aluminum environment. In both the cases the relative performance of each controller has been the same. The study is unique in that it examines a whole breadth of simple controllers against a stiff as well as compliant environment, and also issues in any practical implementation of such controllers. The superiority of integral control and PID control has been amply demonstrated in these experiments. The effect of damping in the response of these controllers has also been shown. Though useful for force control, with currently
available force sensors, it is difficult to generate sufficient damping.

The choice of an appropriate control scheme also depends on stability issues. It is unlikely that in a real world case, the robot will be in contact with its environment before it is required to exert a force upon it; rather it would make an impact with its environment and then be required to exert a force. This makes the issue of stability all the more important. This is explored in the next chapter in the context of impact.
CHAPTER 6

THE IMPACT STAGE

This chapter presents experimental results for impact control of the robotic manipulator against a stiff and compliant environment. The manipulator is commanded to approach the environment at a specified velocity, and, once in contact with it, to exert a specified force on it (Mandal and Payandeh[46]).

6.1 Introduction

The impact stage involves the transition of the robot from free space to constrained force control. However, switching from free space motion to constrained force control has the significant phase of impact forces. For stiff environments, these forces can be very large, and of short duration, and can cause the manipulator to lose contact with the environment. The manipulator again approaches the environment, and this results in an oscillatory behaviour. Obviously, any successful implementation of a control
strategy for impact control would attempt to maintain contact with the environment, during the impact phase, and also exert the desired force on the environment.

Compared to the extensive work done on post contact force control, there is not much in the literature about impact control. This is mainly attributed to the fact that previous work has focussed on impact as a transient that is dealt with by the same controller used to follow the commanded force. Thus, there has been no attempt to change the controller structure or varying its gains for the impact phase. Typical attempts at improvement in response have focussed on introducing active and/or passive damping. As reviewed in the literature survey previously, only recently have control strategies been proposed for the impact transition phase.

6.2 Experimental results

At first, (section 6.2.1) experimental results are presented for the impact phase for a rigid environment and the need for compliance demonstrated. Section 6.2.2 presents results for the impact phase after the introduction of compliance in the manipulator system. In the following experiments, both joints of the manipulator were kept under position control in the pre-contact stage, and switched to force control once force was detected. The x-direction component of the force was used for force regulation; a constant force (-3lb. force) being specified for the manipulator to exert on the environment once contact was detected. In all the following experiments, the manipulator was commanded to impinge the environment at a certain approach velocity, $u_a$, and then exert a force of -3lb.force. All the gains were experimentally tuned to give the best response.
6.2.1 Very rigid environment

Consider the case of a rigid manipulator contacting a rigid surface. The manipulator approaches the environment at some velocity, and then it is stopped. As the time duration of this phenomenon is very small, a large amount of energy has to be dissipated in a short duration of time. This problem is compounded by the fact that the manipulator system and the environment both have very little damping to absorb this energy. A suitable approach to this problem would be to reverse the torque on the motors the moment contact is detected. Applying high reverse torques would cause fast deceleration, and thereby reduce the momentum of impact, which in turn results in a low impulsive force on the manipulator. As impulsive forces are high, a high gain PD force controller is an ideal candidate for such an approach. As the force error between the desired reference force and the impact force increases, the high gain PD controller would cause high torques to be applied in the reverse direction.

In our first experiment, we use a 0.5 inch thick aluminium plate, rigidly clamped.

Figure 6.1: Top view of setup.
The aluminium plate was supported with welded bars from top as well, and did not have any cantilever effect (figure 6.1). The arm approaches the environment at a velocity $v_a \approx 30cm/sec$. For the first experiment, the force sensor is sampled at 0.4ms, and the controller sampling time is also 0.4ms. Figure 6.4 shows the plot for this case. At the moment of impact, the controller switches from PID position control to PD force control. The control laws are given as

\[ \tau = k_p(\theta_d - \theta) + k_v(\dot{\theta}_d - \dot{\theta}) + k_i\int(\theta_d - \theta)dt \]  

(6.1)

in free space motion, and

\[ \tau = J^T(k_{pf}(F_{ref} - F_c) - k_d\dot{x}_m) \]  

(6.2)

from the moment of contact. From figure 6.4, we see that the arm impinges upon the environment, loses contact, and then impinges again (the positive values of force beyond the bias indicate loss of contact). Table 6.1 shows the data from the force sensor, the output torque, and the resolver counts for the moment of contact. A decrease in the value of the resolver output indicates that the manipulator is moving towards the stiff environment. The controller switches from position control to PD force control the moment the reading from the force sensor falls below zero.

The NSK motor used in our experiment has a maximum output torque of 249 Nm. If we look at table 6.1, we find that at the moment of contact, the torque being applied to the motor is maximum in the reverse direction. A look at the resolver output (which corresponds to position) indicates that even so, the applied maximum reverse torque is insufficient to make the manipulator respond to the fast impact.
Table 6.1: Force, torque and position data for Figure 6.4

<table>
<thead>
<tr>
<th>Force(lb.)</th>
<th>Torque(N*m)</th>
<th>Position resolver</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>18.6</td>
<td>13232</td>
</tr>
<tr>
<td>0.5</td>
<td>19.1</td>
<td>13228</td>
</tr>
<tr>
<td>0.4</td>
<td>18.9</td>
<td>13223</td>
</tr>
<tr>
<td>-3.1</td>
<td>17.9</td>
<td>13219</td>
</tr>
<tr>
<td>-5.8</td>
<td>-207</td>
<td>13214</td>
</tr>
<tr>
<td>-0.7</td>
<td>-249</td>
<td>13210</td>
</tr>
<tr>
<td>7.3</td>
<td>-249</td>
<td>13207</td>
</tr>
<tr>
<td>8.9</td>
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<td>-249</td>
<td>13200</td>
</tr>
<tr>
<td>-0.2</td>
<td>-249</td>
<td>13196</td>
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phenomenon. Viewed in another way, this means that at this approach velocity, the momentum of the manipulator system dominates the response, and no matter what scheme be used for this transition phase, successful impact control cannot be achieved. This indicates that the impact phenomenon is well beyond the response time of the manipulator. Thus, even though the PD controller applies peak reverse torque, it is not sufficient to reduce the momentum during impact, and the manipulator still bounces back.

Figure 6.5 shows a plot for a slower approach velocity( \( v_a \approx 20 \) cms/sec.) In this case, a stable impact was possible. Thus, stable impact may be obtained only at low approach velocities, or if the robot system has an unreasonably high bandwidth.

It may be pointed out at this stage that results have been presented in the literature using a force sensor sampling at 1000Hz or less. To demonstrate that such a result is
inconclusive unless a relatively less stiff environment was used, we again carried out
the same experiment with the force sensor being sampled at 1ms ($T_f$). The figure 6.6
shows the plot for this case. All gains and the approach velocity have been kept same
as in figure 6.4. We can see that now the force sensor does not show the manipulator
losing contact during the initial phase of impact.

6.2.2 Introduction of compliance

The above experiments clearly demonstrate the need for compliance in the system for
higher approach velocities. If the manipulator is to respond effectively to the impact
forces, the duration of impact should be at least the order of the response time of
the system. Compliance, either in the workpiece or in the robotic system helps in
two ways. First, the material used naturally provides passive damping, which helps
absorb some of the energy of impact. Second, the compliance results in an increase
in the time duration of the impact phenomenon, which now enables the manipulator
to respond effectively to the impact forces.

Another novel motivation for introduction of compliance in the system may also
be presented in the context of stiffness scaling. To demonstrate this, consider a single
DOF case.

Figure 6.2 shows a model of a robot in contact with an environment. The robot
is modelled as a rigid mass, and the environment as a spring and a damper.

The force acting on the robot may be given as $F = k_e x$ where $k_e$ is the stiffness
of the environment. In general, the type of materials a robot may interact with can
have stiffness ranging from $10^3$ to $10^7$ N/m. Clearly, as shown in the previous chapter
Figure 6.2: Rigid body robot model and environment.

This can have a strong effect on the stability of the controller.

If now, a compliant covering (of stiffness $k_c$) is introduced between the robot and the environment, as shown in figure 6.3, then the force $F$ may be given as:

$$F = \frac{k_c k_e}{k_c + k_e} x$$

The effect of the compliance is obvious. If $k_c \ll k_e$, then the effective stiffness of the system may be approximated as $k_c$. If on the other hand, $k_c \approx k_e$, then the effective stiffness may be approximated as $k_c/2$. In either case, the effect of the compliance has been to scale the stiffness of the environment as perceived by the robot.

Our next experiments determine the efficacy of introducing passive compliance in the system. For this purpose, a 0.4 cm thick visco-elastic covering was attached to the end of the force sensor. Our criteria here is the increase in approach velocity that may be obtained for the same rigid environment; we are again interested only in the transition stage from pre-contact to post-contact. Figures 6.7 and 6.8 show plots for the manipulator with a compliant covering on the force sensor impacting the same rigid environment. The approach velocity in figure 6.7 is $v_a \approx 30 cm/sec.$, whereas
6.3 Post impact force regulation

Once the impact phase is over, we are interested in force regulation. The PD controller itself is not sufficient for force regulation in the post impact stage, and, as shown in figures 6.9 and 6.10 for the two cases of no compliance \( v_a = \sim 15 \text{cm/sec} \) and compliance \( v_a = \sim 35 \text{cm/sec} \) respectively, results in a considerable steady state error.

In the previous chapter, we demonstrated the efficacy of integral and PID force control in dealing with both compliant as well as rigid and stiff environments. In our last set of experiments we evaluate both Integral and PID control to determine the best strategy for force regulation in the post impact stage. These controllers are evaluated for the case of no compliance (at \( v_a = \sim 20 \text{cm/sec} \)) as well as for the case of there being compliance in the system (at \( v_a = \sim 40 \text{cm/sec} \)).
Figure 6.4: Stiff environment, $k_{pf} = 2.0, k_d = 430, v_a \approx 30 \text{cm/sec}$

Figure 6.6: Stiff environment, $k_{pf} = 2.0, k_d = 430, v_a \approx 30 \text{cm/sec}, T_f = 1 \text{ms}$

Figure 6.5: Stiff environment ($v_a \approx 20 \text{cm/sec}$) $k_{pf} = 2.0, k_d = 300$

Figure 6.7: Introduction of compliant covering, $k_{pf} = 5.0, k_d = 225, v_a \approx 30 \text{cm/sec}$
Figure 6.8: Introduction of compliant covering, $k_{pf} = 6.0, k_d = 245v_a = \sim 55\text{cm/sec}$

Figure 6.9: PD controller (without compliance) $k_{pf} = 4.0, k_d = 250, v_a = \sim 20\text{cm/sec}$

Figure 6.10: PD controller (with compliance) $k_{pf} = 7.0, k_d = 170v_a = \sim 40\text{cm/sec}$

Figure 6.11: Post-impact Integral control (no compliance) $k_{fi} = 35v_a = \sim 20\text{cm/sec}$
Figure 6.12: Post-impact Integral control (no compliance) $k_f = 45v_a = \sim 20\text{cm/sec}$

Figure 6.14: Post-impact PID control (no compliance) $k_p = 2.0$, $k_d = 250$, $k_f = 45v_a = \sim 20\text{cm/sec}$

Figure 6.13: Post-impact PID control (no compliance) $k_p = 3.0$, $k_d = 250$, $k_f = 35v_a = \sim 20\text{cm/sec}$

Figure 6.15: Post-impact Integral control (with compliance) $k_f = 10v_a = \sim 40\text{cm/sec}$
6.3.1 Post impact force regulation - no compliance

In the first case, the manipulator after detecting a force switches to PD force control, and after the impact phase is over, switches to Integral control. Figure 6.11 shows the response for the control being switched to Integral force control after 500 control cycles from the time of impact. As it may be seen, the manipulator loses contact with the environment during the switching stage. This is because of the fact that it takes a while for the integral action to build up. Further increase in the gain of the integrator may lead to severe oscillations as shown in figure 6.12.

Figures 6.13 and 6.14 show the performance of the PID controller after 500 cycles from the time of impact. The PID controller achieves a far better result than Integral control alone.

6.3.2 Post impact force regulation - with compliance

We achieved similar results for the case of a compliant covering on the force sensor. Figure 6.15 shows the performance for the integral control alone. Again it may be seen that the Integral action takes a while to build up, because of which the response is not very even. Increasing the Integral gain $k_I$ results in a higher overshoot(figure 6.16). As shown in figures 6.17 and 6.18, the PID again achieves a far better performance.

For a compliant system, the dynamics of the impact phenomenon are slow, and a PID controller may be used during the impact stage as well. However, the Integral gain value is kept low during impact, and the switched to a higher value for fast force regulation in the post impact stage. Figure 6.19 shows a plot for a PID force controller
from the moment of contact.

6.4 Discussion

Our results indicate two fundamental requirements for a robot impacting a rigid environment; first, the sampling time of the force sensor, and second, the bandwidth of the manipulator system.

As shown in figure 6.6, a loss of contact with the environment may not be detected by a force sensor sampling at 1000hz.

The magnitude and duration of the impact force will depend on the velocity of approach of the manipulator to the environment as well as the stiffness of the contacting materials. The impulse force can be modelled as a pulse of magnitude \( j \) and duration \( h \) given by

\[
jh = \int_0^{\delta_i} (F \, dt) = (e + 1) \frac{m_r m_e}{(m_r + m_e)} (V_a - V_e) \tag{6.3}
\]

where \( m_r \) is the mass of the robot, \( m_e \), the mass of the environment, \( V_a \) the velocity of approach and \( V_e \) the velocity of the environment (zero for our case) and \( e \) the coefficient of restitution. \( h \), the modelled value of duration should be chosen less than \( \delta_i \).

At the onset of impact, the controller switches to a PD force controller regardless of subsequent events, and regulates a desired force. If the manipulator loses contact with the environment, it again approaches it, and again there is impact. Using the above
equation, this can again be modelled as a pulse. However, this time the approach velocity is reduced due to the damping property $k_d \dot{x}_m$ of the controller, as well as the energy lost during the previous impact. The net result is a series of oscillations which die out with time, and the frequency of the response signal reduces to zero at steady state.

Considering the fact that both the environment and the manipulator are of very high stiffness, and that there is no compliance in the system, the impact duration is of the order of a millisecond or so. This corresponds to an initial impact frequency of the order of 1000Hz, and the corresponding Nyquist rate required to recover the continuous time impact force signal is 2000Hz. For the case of a sensor sampling at less than this rate, we have the aliasing effect, in which the high frequency component of the continuous signal takes on the identity of the lower frequency component, and the continuous signal can no longer be properly recovered (Oppenhiem and Schafer[49]).

Thus, during the initial stages of contact, the sampling rate has to be the Nyquist rate or more in order avoid aliasing and be able to recover the continuous time signal from its samples.

With the introduction of compliance, the duration of the impact pulse increases, with the result that the corresponding initial frequency of the response signal is much lower (depending of course on the amount of compliance introduced). In this case, a sampling rate of 1000Hz is sufficient to give a true reproduction of the continuous force response signal, and it may correctly be concluded that no loss of contact has taken place.
6.4.1 System bandwidth

By system bandwidth, here we mean the closed-loop bandwidth of the system. Of course, the controller sampling rate has to be at least the same as that of the force sensor if it is to respond to the impact phenomenon. For the sake of our discussion, we assume here that the controller sampling time and the force sensor sampling time are the same.

With the force sensor sampling frequency at 2500Hz., the impact impulse input (for a rigid manipulator-environment, at high approach velocity) to the manipulator system is also 2500Hz. If the bandwidth of the manipulator system is less than 2500Hz., the manipulator cannot respond to this input.

The explicit PD force control law as given in equation 1 assumes the manipulator system to respond perfectly. In [12], Eppinger and Seering suggest limited actuator bandwidth to be another reason that may contribute to instability, the actuator unable to respond to components of the input signal above a certain cut-off frequency. However, with the force sensor sampling at a 1000Hz., or less, such an input is not measurable, and there is no way for the closed loop system to compensate for it. Any such system, even though exhibiting a stable behaviour may actually have lost contact with the environment. With the force sensor sampling at the Nyquist rate, the frequency of the applied signal may be above that of the bandwidth of the manipulator system, and though the impact and the consequent loss of contact are detected, the actuator is unable to respond effectively to the input. In our case, as shown in table 6.1, it is the limited actuator bandwidth that causes the manipulator not to respond (at high approach velocity) effectively to the force transient. With compliance, the
frequency of the impact impulse (for the same approach velocity) is well within the bandwidth of the manipulator, and thus the system is capable of the proper response.

6.5 Defining a stable impact

In this chapter so far, we have gone along with our definition of a stable impact as one in which the manipulator does not lose contact with the environment. This, however, as we have seen, requires a very high bandwidth system in order to achieve such a contact for an environment of high stiffness, such as Aluminum. At this stage, we would also like to ask ourselves the question as to the reasonability of our definition. Surely, bouncing at some scale could be permissible in some cases, and, even then "stable impact" achieved.

However, if we were to relax our definition of stability, other issues need to be addressed. For instance, once having lost contact, the manipulator is again in free-space, i.e. not constrained by the environment. The manipulator may now again be commanded either in position or in force. If it is to continue operating in force, then the manipulator must not have an integrating element during the impact phase. Stable contact may now be achieved only if the velocity of the second impact is less than the first, and so on for successive impacts. For this purpose, the gains on the manipulator cannot be very high, and further, there has to be a damping element in the controller. If the manipulator were to be again position controlled, and it is commanded to again impact the environment at the same approach velocity, then again there will be the same impact, and the same result, and the manipulator may not achieve a stable contact again. In the limit, if this is a fast phenomenon, as is the
case for stiff environments, this switching itself may lead to an unstable behaviour.

6.6 Conclusion

In this chapter we have presented results for the case of a manipulator approaching a stiff environment for the purpose of exerting a constant force on the environment. We show that for stiff environments, the impact phenomenon is of a very short duration, and no matter what the compensation scheme used, successful impact control can be achieved only at very low approach velocities due to the limited bandwidth of the manipulator system to respond effectively to the impact forces. Experiments were also carried out for the force sensor sampling at 1ms, and it is shown that the sensor is incapable of detecting the loss of contact during the initial moments of impact, and that previous results that have been shown using a force sensor sampling at a rate of 1ms or below are not conclusive. For stiff environments, force regulation in the post-contact stage is also a challenging proposition. Though integral control gives a good response for the post-contact stage, using it for the impact stage is fraught with peril (Volpe and Khosla[39]). This underscores the need for damping to be introduced in the system/controller. The PID controller has the best trade-off for impact control.

Results have also been shown for the case of a compliant covering on top of the force sensor. In addition, compliance has been motivated for increased controller robustness due to stiffness scaling, and hence, less dependence on the environment. Proper impact control as well as force regulation in the post-contact stage was achieved for this case. We found that a PID force control was the best strategy for force regulation in the post-contact stage. However, gains that are appropriate for the impact suppression
Figure 6.16: Post-impact Integral control (with compliance) $k_f = 25$

Figure 6.18: Post-impact PID control (with compliance) $k_p = 4.0, k_d = 250, k_f = 30, v_a = \sim 40 cm/sec$

Figure 6.17: Post-impact PID control (with compliance) $k_p = 4.0, k_d = 200, k_f = 10, v_a = \sim 40 cm/sec$

Figure 6.19: PID control (with compliance) from the moment of contact $k_p = 4.0, k_d = 200, k_f = 35, v_a = \sim 40 cm/sec$
phase are not good for the force tracking phase, and the best result may be achieved by switching the gains appropriately once the impact phase is over.

There is a trade off between the approach velocity, stiffness of the environment and the bandwidth of the manipulator system; for stiff systems with low bandwidth, only low approach velocities are possible. There is also a trade off between the approach velocity to an environment and the force to be exerted on the environment. Compliance has been proposed as the only solution consistent with low cost, fast response and low contact forces for a long time.
CHAPTER 7

A UNIFIED CONTROL STRATEGY FOR CONTACT TASKS.

7.1 Introduction

In this chapter, we propose a unified control strategy for robotic contact tasks. The control structure is of PID type (the results of the previous chapters the efficacy of using such an approach for contact tasks), which switches from position control to force control upon impact with the environment, and, we describe a method for knowledge based tuning of the gains of the controller for the three distinct stages of the robotic contact task, viz. free-space motion, impact and post-impact force regulation. A knowledge base is created for PID gains to be used in different stages of the contact
task, and for different approach velocities as well as different environmental stiffnesses. A method for estimating environmental stiffness is also described. The experimental performance of such a controller is also compared to impedance control (Mandal and Payandeh[47]).

7.2 The unified control strategy

In the previous chapters, we have seen the efficacy of a PID type controller in dealing with the three stages of the contact task. However, upon impact with an environment, the controller switches from position to force control. Besides, the P, I, and D gains also have to be switched during transition from the impact stage to the post contact stage. Further, the values of these gains depends strongly on the stiffness of the environment that the robot has to deal with, and also to some extent on the approach velocity of the manipulator to the environment.

In this chapter, we attempt to tune the gains of the PID controller based on the knowledge of the environment, and the velocity at which the manipulator approaches the environment. First, a look up table is created in which suitable values of gain parameters are stored for free space motion, the impact stage, and the post-impact force regulation stage. The criteria for gain selection in the free space motion is the minimum absolute trajectory tracking error. During impact, it is desired that the robot maintain contact with the environment, and also that the impacting forces should not be very high. In the post contact stage, the gain selection criterion is that once the impact stage is over, the robot asymptotically regulate the desired force quickly.
Using the above criterion, gain values are stored in a look-up table for very stiff, stiff and compliant environments at different approach velocities. The force sensor has a compliant covering on top of it. A loosely clamped wooden block, with a slight cantilever effect was used as a compliant environment, and a rigid steel plate for a very stiff environment. Then, depending on the approach velocity, and the environment specified (by the user), the robot uses the best gains from the look-up table for the task.

In order to make the Knowledge based PID controller independent of the user's specification of the environment, estimation of the environmental stiffness using the impact force response is also described. Finally, the performance of using such a PID control scheme is also compared with impedance control - another method which has been proposed in the literature for successful contact task control.
7.3 Structure of the Knowledge-Based tuner

Figure 7.1 shows the block diagram of the Knowledge-Based tuner. Here \( x_r \) is the reference input to the PID controller, and of the form

\[
x_r = \begin{cases} 
F_{\text{ref}} & \text{if } F_c > 0 \\
P_{\text{ref}} & \text{if } F_c < 0 
\end{cases}
\]

where \( P_{\text{ref}} \) is the reference position command, \( F_{\text{ref}} \) the reference force command, and \( F_c \) the measured contact force acting on the manipulator. The controller switches from position reference to force reference once the force sensor senses a force acting upon it.

The Knowledge-Based tuner makes use of the switching action, reference input, the error and the actual position (force) information to tune the gains of the PID controller. In the following section, we demonstrate the efficacy of the Knowledge-Base tuned PID controller against three types of environments.

7.3.1 Creating a Knowledge-Base

During free-space motion, the PID control law is given as

\[
\tau = K_p(\theta_d - \theta) + K_v(\dot{\theta}_d - \dot{\theta}) + K_i \int (\theta_d - \theta) dt 
\]  

(7.1)

Once a force is detected, the jacobian transpose of the manipulator is used to convert the cartesian-space force to its components in joint-space. This results in the
Figure 7.2: The Knowledge-Based tuning process.
PID force control law:

$$\tau = J^T[k_{pf}(F_{ref} - F_c) + k_{fi}\int (F_{ref} - F_c)dt - k_i{\dot{x}_m}]$$  \hspace{1cm} (7.2)

where $J^T$ is the transpose of the Jacobian of the manipulator. When force is detected, 7.2 switches to a PID controller in force.

The knowledge base consists of different P, I and D gains that are to be used at different approach velocities and for different environments. The gain values for the different environments, and velocities are selected for the three different stages using the following criteria:

For the case of free space motion, a PID controller with high gains gives a good trajectory tracking, with low position errors. The specification of the gains for free space motion are independent of the environmental stiffness, and so remain the same for all approach velocities and environments.

With the presence of compliance, the robot may impact a rigid environment at a faster approach velocity, and yet not lose contact with it. In such a case, it was found that a PID controller is able to give a good response. The choice of the PID gains, however, depend on the stiffness of the environment, as well as the approach velocity to the environment.

In the post impact stage it is desirable to achieve a good force reference trajectory tracking. As shown previously, gains that are suitable for the impact stage result in poor force trajectory tracking in the post contact stage. Importantly, a high value of Integral gain is required in the post impact stage. The gain selection also depends on the environmental stiffness.
With these criteria, a look up table was constructed, in which best gain parameters were stored for the different environments and at the different approach velocities.

Further, the impact switching duration (duration after which the gains switch from their impact values to their post impact values) $\Delta_i$ is a function of the velocity of approach, $v_a$, to the environment as well as the environmental stiffness (the stiffness of the manipulator system remaining the same for all the cases). Impact switching duration here refers not just to the impulse force response, but also the settling time. The impact switching duration is an important criteria in dealing with stiff environments; as the impulse response does not die out quickly, a greater duration of time has to be allowed before the onset of the post contact stage. The converse is true for compliant environments; as the impact transient dies out fast, the impact phase lasts a shorter duration, i.e the controller may switch to the high post impact gains quickly. The knowledge-base also contains a look up table of the impact switching duration $\Delta_i$ for different environments, and these values are used to determine the onset of the post impact phase.

### 7.4 Experimental results

Experiments were conducted for “very stiff”, “stiff” and “compliant” environments at velocities classified as “high”, “medium” and “low”. It may be noted that the terms “high”, “medium” and “low”, refer to a range of velocities rather than a certain fixed value. This is due to the fact that the Knowledge-Base has a limited resolution, beyond which it is unable to make any distinction between the different approach velocities. The same is also true for the compliance of environments.
In the following experiments, the environment is user specified. Both the joints of the manipulator were kept under position control in the pre-contact stage, and switched to force control once force was detected. The x-direction component of the force was used for force regulation; a constant force ( -3lb. force) being specified for the manipulator to exert on the environment once contact was detected. Figure 7.3 shows the response for the very stiff environment for high approach velocity ( the slight positive reading is due to the force sensor bias), and figure 7.6 shows the variation of the gains during the different stages of figure 7.3. Figure 7.4 shows the response for the very stiff environment at low approach velocity; the corresponding gain variation is shown in figure 7.7. Figures 7.5 and 7.9 show the response for the stiff environment at medium and low velocities. Figures 7.10 and 7.11 show the response for the compliant environment at medium and low approach velocity, and figures 7.13 and 7.14, the variation of gains for the response of figures 7.10 and 7.11.

We note from figures 7.7, 7.12, and 7.14 the difference in the impact switching duration for the three different environments at the same approach velocity, and also the difference in the rise time of the force. This difference in the force response of the three different environments may be made use of for the purpose of estimating the environmental stiffness, which is explained in the next section.

7.5 Estimation of environment compliance

In this section a method is described to make the gain selection of the PID controller independent of the user's specification of the environment. Of course, one trade off in such an approach is the time lost in estimating the compliance of the environment,
which may slightly limit the approach velocity, or the ability of the controller to respond effectively in the initial moments of impact. However, this capability is a desirable feature, as it lends to the exploratory capability of the robot, and contributes to the intelligence of the manipulator system. In recent literature, the trend seems to be to use compliant materials for robotic fingertips, and exploit this compliance factor for exploring a robot’s environment (Sinha et. al. [63]).

Various methods such as Least squares estimation, and the adaptive observer technique have been proposed in the literature which can be used to estimate the stiffness of the environment. The stringent requirement of any estimation technique for impact control is the time duration in which the stiffness has to be estimated. The method used in this thesis was to integrate the force value for a short duration, and come up with the area under the force vs time curve. This is referred to as the force-area method. Knowing the velocity of approach, and, the area under the force time curve during the first few sampling instances provides a reasonable measure for environmental stiffness, and, therefore, the corresponding gains to be used. However, the problem is complicated by fact that the force sensor information is noisy. Indeed, obtaining a good estimate in the presence of noise is no trivial problem; at best only a coarse stiffness resolution can be obtained. From the moment impact was detected, the force-area was calculated for a time duration of about 12ms.

The force rise time is a function of the approach velocity $v_a$, as well as the environmental stiffness $k_e$. The tuning rule base may be expressed as

$$\text{IF}( v_{rmin} < v_a < v_{rmax} \text{ AND } f_{rmin} < f_{ar} < f_{rmax})$$
THEN (classify environment as very stiff, stiff or soft and select $k_p$, $k_f$, $k_d$, $\Delta_i$

corresponding to this classification from gain table)

where $v_{r_{\min}}$ and $v_{r_{\max}}$ correspond to the range that contains the velocity $v_a$ and

$f_{r_{\min}}$ and $f_{r_{\max}}$ correspond to the range of values in the knowledge-base that contains
the estimated force-area $f_{ar}$.

A look up table is created in which the force gradient values are stored for the
different environments and at different approach velocities. The duration of impact
is also stored in the Knowledge-Base. Using the information of approach velocity, the
force gradient is compared with those in the Knowledge-Base, and the environment
classified as either very stiff, stiff or compliant. The gains corresponding to the envi-
ronment’s classification are then chosen. Further, the Knowledge-Base also predicts
the impact duration based on the force step response, and the approach velocity.

From the moment contact is detected to the moment the Knowledge-Base is able
to estimate the stiffness and provide the appropriate gain selection, the value of gain
chosen is based on the criteria that even if the environment is very stiff, the manipu-
lator should not lose contact with it.

For the sake of brevity, here we present experimental results for the stiff and
compliant environments at a high medium velocity.
Figure 7.3: Very stiff environment, high approach velocity

Figure 7.4: Very stiff environment, low approach velocity

Figure 7.5: Stiff environment, medium approach velocity

Figure 7.6: PID gain variation for figure 7.3

Figure 7.7: PID gain variation for figure 7.4

Figure 7.8: PID gain variation for figure 7.5
Figure 7.9: Stiff environment, low approach velocity

Figure 7.10: Compliant environment, medium approach velocity

Figure 7.11: Compliant environment, low approach velocity

Figure 7.12: PID gain variation for figure 7.9

Figure 7.13: PID gain variation for figure 7.10

Figure 7.14: PID gain variation for figure 7.11
Figure 7.15: Very stiff environment, medium approach velocity

Figure 7.16: Very stiff environment, low approach velocity

Figure 7.17: Compliant environment, medium approach velocity

Figure 7.18: PID gain variation for figure 7.15

Figure 7.19: PID gain variation for figure 7.16

Figure 7.20: PID gain variation for figure 7.17
Figure 7.21: Block diagram for impedance control

Figure 7.15 shows the force response for the manipulator contacting a very stiff environment at "medium" speed. Figure 7.18 shows the gain variation. Figure 7.16 shows the force response for the same environment at "low" speed, and figure 7.19 the gain variation. A comparison of figures 7.15 and 7.5 shows equally good performance using an estimate of the environmental stiffness; the knowledge-Base correctly predicting the impact switching duration, as well as the values of gains to be used. The short duration of the estimation time may also be noted in figure 7.18. Figure 7.17 shows the response for the compliant environment at medium velocity.
7.6 Impedance control

This section presents a brief theory and experimental results of implementing impedance control. The implementation follows from Kazerooni, Waibel and Kim's [11].

Figure 7.21 shows the block diagram of the impedance controller (Kazerooni, Waibel and Kim [11]). The control law for free-space motion may be given as:

\[
\tau = K_p(\theta_d - \theta) + K_v(\dot{\theta}_d - \dot{\theta}) + \ddot{M}(\theta)\ddot{\theta}_d + \dot{V}(\theta, \dot{\theta})
\]  

(7.3)

and upon contact with the environment,

\[
\tau = K_p(\theta_d - \theta) + K_v(\dot{\theta}_d - \dot{\theta}) + \ddot{M}(\theta)\ddot{\theta}_d + \dot{V}(\theta, \dot{\theta}) + J^T F_c
\]  

(7.4)

The outer loop in the block diagram of figure 7.21 serves as a compliance compensator. Once force is detected, the outer loop closes, and the effect of the loop is to create an incremental position value, which alters the reference set-points in such a way as to vary the stiffness of the manipulator. In our experiment, \( H \) was chosen to be of the form

\[
H = \begin{pmatrix}
\frac{H_o}{T_{x+1}} & 0 \\
0 & 0
\end{pmatrix}
\]

In free-space motion, the input command vector is used as an input trajectory command, and upon contact with the environment, as a command to control force. Thus, in impedance control, no force set point is commanded.

Figure 7.22 shows the force response for using impedance control on the very stiff environment at a high velocity. The value selected for \( H_o \) was 0.0003. Clearly, the
manipulator loses contact with the environment, and as compared to figure 7.3, the Knowledge-base tuned PID achieves a better performance.

One of the greatest problems with impedance control is its requirement of an exact model of the environment and the robot, in order for the designer to be able to specify an exact force that the robot will be able to exert on the environment. This is particularly so in the case of a stiff environment, where a small position error can result in high forces acting on the environment. However, in reality it is very difficult to obtain an exact model of the manipulator system, and the environment. Thus, it becomes extremely difficult to exert a specified force on the environment. Moreover, force regulation is achieved in a static manner; any change in the position of the
manipulator or environment and its subsequent effect on the force being exerted on the environment cannot be accommodated for. In the case of the figure 7.22, it was not possible to command an exact force of -3lb. force on the environment.

The loss of contact by the manipulator in figure is made clear once we look at the way the compliance has been introduced in the robot. The outer most loop comes into effect once a force is detected, and its effect is to alter the set points to the controller in such a way as to make the system compliant. However, at the instant of contact, due to the high impact forces, the outer loop causes the set point to be altered in such a way as to be in front of the environment again (as opposed to behind the environment, which is needed to exert force). This in effect means that the robot should now lose contact with the environment. Table 1 shows the force, actual set points and the modified set points during the instant of contact. An increasing value of z indicates that the robot is approaching the environment. We see that till the force goes below, the modified set points are the same as the actual set points. This is so, as the outer loop comes into effect only when a force is acting on the manipulator system. Once the force sensor value goes below, the set points are modified as shown. From the figure it is evident that if the manipulator is following the set points effectively, it will lose contact with the environment; if the value of $H_o$ is high, this could result in the manipulator hopping around the environment.

7.7 Discussion

In this chapter, experimental results for Knowledge-Based tuning of a PID controller suitable for contact tasks have been presented. A knowledge base was created with
information of P, I and D gains to be used for the different stages of the contact tasks, for environments with varied stiffnesses and at different approach velocities. The knowledge based controller was also able to estimate environmental stiffness and impact switching duration and apply suitable gain values.

The superiority of using such a Knowledge-Based controller has also been demonstrated against impedance control, another control strategy proposed in the literature for robotic contact tasks.

The Knowledge-Base, though gives a suitable response, is of coarse resolution. This is primarily due to the fact that it is difficult to obtain a good estimate of environmental stiffness due to the noise in the force sensor. As the technology of force sensors improves, this method is bound to give better performances.
CHAPTER 8

CONCLUSION AND FUTURE WORK

In this chapter, we present our conclusion and future work.

In this thesis, we explored the issues relating to achieving a stable contact, and the subsequent post-contact force control, and the control strategies that may be used for the purpose.

1) A comparison was made of the model-based control schemes for trajectory control of the robot along with a simple PID controller, and it was found that for the case of a 2DOF DD manipulator with no gravity effect, the simple PID controller performs comparably.

2) A whole breadth of simple force control strategies were evaluated against a stiff and compliant environment, and it was found that a PID controller gives the best
response for both types of environments. The usefulness of damping was highlighted, and three methods of obtaining damping identified, along with their merits.

3) A simple understanding of the impact phenomenon was presented, along with experimental demonstration of the bandwidth limitations of the robotic manipulator to effectively respond to impact for stiff environments. It was also shown that previous results based on a force sensor sampling at a frequency lower than the Nyquist rate are incapable of detecting the loss of contact at the initial stages of impact.

4) A Knowledge-based PID controller was developed for successful control of the robotic contact task for environments of different stiffnesses, and it’s superiority demonstrated against impedance control.

8.1 Future work

Although in this thesis we have developed a method to ensure a stable contact for environments of different stiffnesses, there is still some more work to be done.

1) In our knowledge base, we have used only three-different values of gains for the three stages of the contact tasks. In the future, we would like to replace this with a non-linear function, which may be able to give a better response.

2) The unified control strategy has been demonstrated to be effective for environments of varying stiffnesses as well as at different velocities. As part of future work, the robustness of this method with respect to disturbances also needs to be studied. In particular, the effect of integrator windup if the robot were to lose contact with the environment. Some remedies, such as clipping the integrator value, as error scaling
that have been proposed in the literature (Wilfinger et al. [58]) need to be evaluated in this regard.

4) A tradeoff exists between bandwidth, approach velocity, and compliance in the environment. As part of future work, a proper mathematical model relating the three needs to be developed.
An estimator or observer estimates the state variables of a system based on the measurements of the output and control variables.

Consider a system given by

\[ \dot{x}(t) = Ax(t) + bu(t), \quad x(0-) = x_0 \]  \hspace{1cm} (A.1)

\[ y(t) = cx(t) \quad t > 0- \]  \hspace{1cm} (A.2)

Assume that the state \( x \) is to be approximated by the state \( \hat{x} \) of the dynamic model

\[ \dot{\hat{x}}(t) = A\hat{x}(t) + bu(t) + l[y(t) - c\hat{x}(t)], \quad \hat{x}(0) = \hat{x}_0 \]  \hspace{1cm} (A.3)

where \( \hat{x}_0 \) = an estimated initial state vector

and \( l \) = a feedback gain vector, \textit{suitably chosen}

The above represents the state observer. The state observer has \( y \) and \( u \) as inputs.
Figure A.1: Observer for the force derivative

and $\hat{x}$ as output. The last term on the right side of this model equation is a correction term that involves the difference between the measured output $y$ and the estimated output $cx$. Matrix $l$ serves as a weighting matrix. The correction term monitors the state $\hat{x}$. In the presence of discrepancies between $A$ and $b$ matrices used in the model and those of the actual system, the addition of the correction term will help reduce the effects due to the difference between the dynamic model and the actual system. Figure A.1 shows the block diagram of the system and the full order state observer.

To obtain the observer error equation, let us subtract equation A.3 from equation A.1

$$\dot{x}(t) - \dot{\hat{x}}(t) = Ax(t) - A\dot{\hat{x}}(t) - l(cx - c\hat{x}) = (A - lc)(x - \hat{x}) \quad (A.4)$$

define the difference between $x$ and $\hat{x}$ as the error vector $e$, or
\[ e = x - \dot{x} \]  
(A.5)

Then, equation A.4 becomes

\[ \dot{e} = (A - lc)e \]  
(A.6)

From equation A.6 we see that the dynamic behaviour of the error vector is determined by the eigenvalues of the matrix \( A - lc \). If matrix \( A - lc \) is a stable matrix, the error vector will converge to zero for any initial error vector \( e(0) \). That is, \( x(t) \) will converge to \( x(t) \) regardless of the values of \( x(0) \) and \( \dot{x}(0) \). If the eigenvalues of the matrix \( A - lc \) are chosen in such a way that the the dynamic behaviour of the error vector is asymptotically stable and is adequately fast, then any error vector will tend to zero (origin) with adequate speed.

If the system is completely observable, then it is possible to choose matrix \( l \) such that \( A - lc \) has arbitrarily desired eigenvalues. That is the observer gain matrix \( l \) can be determined to yield the desired matrix \( A - lc \).

The necessary and sufficient condition for the existence of the full order state observer is that the system as given by equations A.1 be completely observable, that is the rank of the observability matrix

\[ Q_o = [e \ cA \ cA^2 \ ... \ cA^{n-1}]^T \]  
(A.7)

be equal to \( n \), the order of the system.

For a low order system \( (n = 1, 2, or 3) \), the direct substitution approach may be
used to obtain the state observer gain matrix $l$.

Rewriting the equation A.3 for the state observer dynamics as

$$\dot{x}(t) = (A - lc)\dot{x}(t) + Bu + lc x(t)$$

(A.8)

the characteristic polynomial is given as

$$|sI - (A - lc)|$$

(A.9)

Now, for example, if $x$ is a 2-vector, then, writing the observer gain matrix $l$ as

$$l = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}$$

(A.10)

we may substitute this $l$ matrix into the desired characteristic polynomial

$$|sI - (A - lc)| = (s - \mu_1)(s - \mu_2)$$

(A.11)

Here $\mu_1$ and $\mu_2$ are the eigenvalues of the observer matrix. Thus, depending on the choice of the eigenvalues of the observer matrix, the equation A.11 may be used to determine the observer gain matrix.

The desired eigenvalues or characteristic equation should be chosen so that the state observer responds at least two to five times faster than the closed loop system considered.

For the configuration of the manipulator as shown in figure A.2, a simplifying assumption is made, i.e. the force acting on the tip of the manipulator also acts at
Figure A.2: manipulator in contact with the environment

the end of joint 1 (i.e. joint 2 is perpendicular to joint 1. If joint 2 is not perpendicular to joint 1, then the component \( F_c \cos(\theta_2) \) is used). The environment here has been modelled as a spring of stiffness \( k_e \). Writing the equation for the above figure,

\[
m_r(\ddot{\theta}) = F_a - F_c
\]  

(A.12)

Further, the force \( F_c \) may also be expressed as \( F_c = K_e x \), where \( K_e \) is the stiffness of the environment, and \( x \) the incremental displacement from the initial position \( x_o \). Expressing \( x \) in terms of the angular joint displacement (assuming \( \sin(\theta_1 \approx \theta_1) \theta_1 \), we get

\[
x = r \theta_1
\]

where \( r \) is the length of link 1. Thus, \( \dot{x} = r \dot{\theta}_1 \) and \( \ddot{x} = r \ddot{\theta}_1 \). Equation A.12 may now be expressed as
\[ m_r \left( \frac{\ddot{x}}{r} \right) = F_a - F_c \]  

Now, we also have \( \ddot{x} = \frac{\ddot{F}_c}{K_c} \), and so we get

\[ m_r \left( \frac{\ddot{F}_c}{K_c} \right) = F_a - F_c \]  

whence

\[ \ddot{F}_c = \frac{K_c r}{m_r} F_a - \frac{K_c r}{m_r} F_c \]  

Putting the above equation in state space form, we get

\[
\begin{bmatrix}
\dot{\ddot{F}}_c \\
\dddot{F}_c 
\end{bmatrix}
= 
\begin{bmatrix}
0 & 1 \\
-\frac{K_c}{m_r} & 0
\end{bmatrix}
\begin{bmatrix}
\dot{\ddot{F}}_c \\
\dddot{F}_c
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
-\frac{K_c}{m_r}
\end{bmatrix}
\dddot{F}_c
\]  

\[ y = [1 \ 0] \begin{bmatrix}
\dot{F}_c \\
\dddot{F}_c
\end{bmatrix} \]  

In the design of the state observer, several observer gain matrices \( l \) were determined based on several different desired characteristic equations, and the best \( l \) matrix was selected. The selection of the best \( l \) matrix boiled down to a compromise between speedy response and sensitivity to noise.
REFERENCES


[47] N. MANDAL, and S. PAYANDEH. Knowledge-Based Tuning of a PID Controller for Robotic Contact Tasks, Accepted for publication in the Dynamic Systems and Control Division of the 1993 ASME Winter Annual Meeting.


