ROBOT FORCE CONTROL: A COMPARATIVE STUDY OF CONVENTIONAL AND FUZZY CONTROL TECHNIQUES

Bryan Alexander Bilbrey

University Undergraduate Fellow, 1993-1994

Texas A&M University

Department of Computer Science

(Fellows Advisor)

(Honors Director)

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ABSTRACT

Robot Force Control: A Comparative Study of

Conventional and Fuzzy Control Techniques. (May 1994)

Bryan Alexander Bilbrey, B.S., Texas A&M University

Fellows Advisor: Dr. Jeffrey C. Trinkle

In order to provide the CS Robotics Lab with a functional tool in the form of an instrumented compliant wrist two main goals were identified for completion during the 1993-1994 school year. The first goal, the acquisition of an accurate representation of the wrist's force-to-deflection relationship in the form of a stiffness matrix, was performed via calibration. The second goal was the implementation of a conventional hybrid position/force controller using the compliant wrist. Calibration of the wrist and the implementation of a conventional force controller using the wrist are significant in that they allow for study of hybrid position/force control using compliance by the CS Robotics Lab; both areas of active research within the robotics community. Given the calibration and implementation of the wrist, a secondary goal of implementing a fuzzy hybrid position/force controller and performing a comparative study between conventional and fuzzy control techniques was identified.

To date, due mainly to hardware problems, the calibration of the compliant wrist has not been successfully completed and implementation of a conventional hybrid position/force controller utilizing the theoretically calculated stiffness matrix of the wrist is only partially complete. Although work has begun on a fuzzy logic based hybrid position/force controller

and this subject still holds much fascination for me, I have not been able to devote sufficient time to it's implementation to result in a working fuzzy position/force controller [1].

In this document an explanation of the compliant wrist, a method for calibrating the wrist and methods for implementing conventional and fuzzy hybrid position/force controllers using the wrist are presented. Along with the overall results of this year's work, a comparison of both controllers is presented, followed by a section detailing where future work in the areas of compliance and fuzzy hybrid position/force control might lie.

[1] See the Future Research section of this document.

To Susie-Q

Perhaps the greatest contributions to engineering

have come from those with the

ability to build bridges between specialties.

ACKNOWLEDGMENTS

I would like to acknowledge the help of everyone in the CS Robotics Lab who made my year spent here both enjoyable and educational. I would like to acknowledge Sean Graves for his explanations on the workings of the lab and for the hours he gave to repair the Merlin Robot everytime it blew up. I would also like to thank Ayman Farahat for his patience in answering my mathematical questions.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

I.A Hybrid Position/Force Control

The vast majority of industrial robots in use today are solely position controlled. In order for a robot to successfully interact with its environment via position control, the robot must know the exact location of every object in its environment. Provided a robot can successfully make contact with objects in its environment without errors in its position control mechanisms, it is still limited in the types of tasks which it can perform. Position control alone precludes robots from performing tasks such as complex assembly, (e.g., the fitting of parts together) inspection of objects in an environment, (e.g., the surface of space station) or the exploration of an environment, (e.g., the surface underneath a robotic foot or limb).

Given these limitations, it is desirable to have a method of control which allows a robot to safely contact its environment in circumstances where uncertainty exists. Force control, or more specifically the hybrid mixture of force and position control proposed by Craig [4] provides just such an opportunity.

Conventional hybrid position/force control is achieved by dividing the directions of control into position- and force-controlled subsets (figure 1). The compliant wrist provides for such a division to take place by allowing for the measurement of deflections experienced by the wrist from its initial position while under the force of contact. From this known deflection and the known force-deflection relationship of the wrist, one can measure the

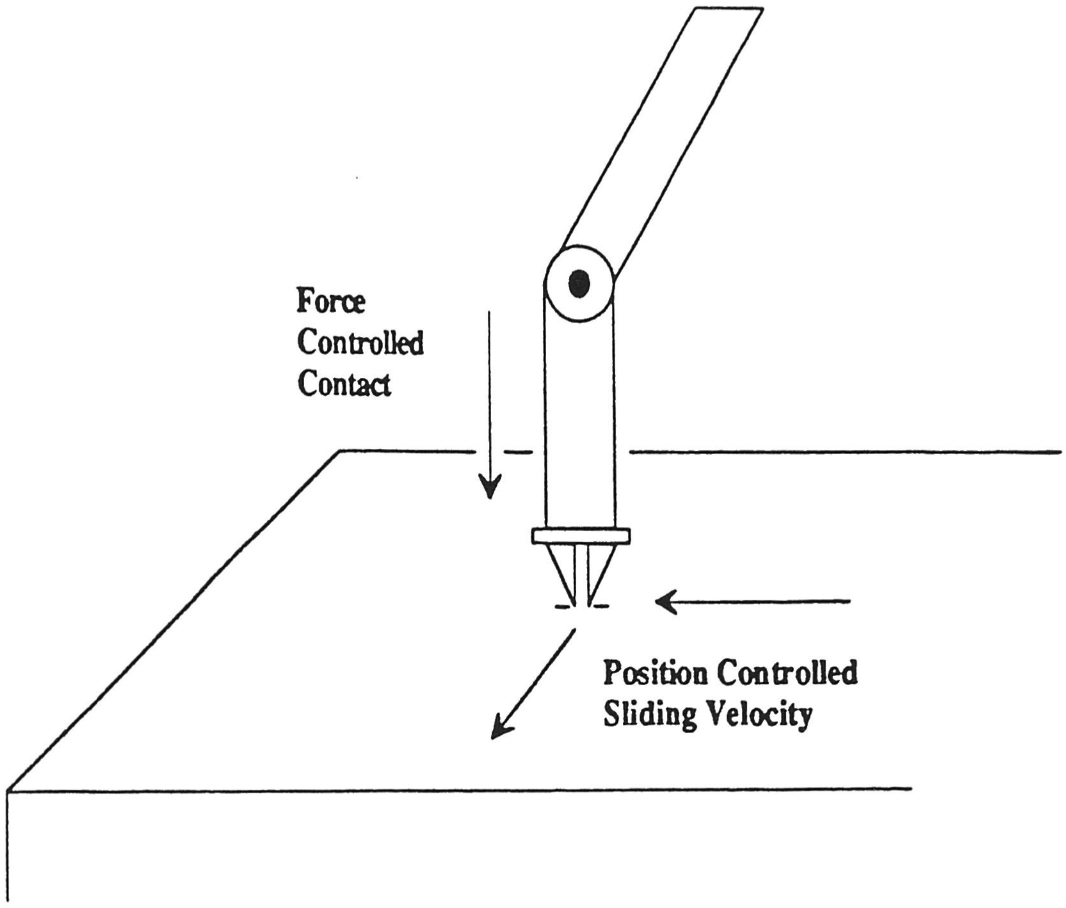

Fig. 1. Robot Maintaining Contact with a Planar Surface

position of the end effector and simultaneously calculate the forces which the end effector is experiencing.

With the limitations of using position control alone to control a robotic manipulator apparent, the overriding goal of the research presented herein is to implement the conventional hybrid position/force control algorithm presented in Craig [4]. In order to accomplish the implementation of a hybrid position controller the force-deflection relationship of the wrist must be known. This relationship is assumed to be given by $\mathcal{F} = K\delta X$, where $\mathcal{F}$ is a 6×1 vector representing the forces and moments at the base plate of the wrist, δX is 6×1 vector representing the 3 translational and 3 rotational deflections of the wrist from the undeflected position, and K is the the 6×6 stiffness matrix of the compliant wrist which characterizes the force-deflection relationship of the wrist. Thus the second major goal of the proposed research was the calibration of the wrist, which required the identification of the wrist mechanism's, deflection measurement sensors and the 36 elements of the stiffness matrix, K.

The calculation of the force-deflection relationship of the wrist, given by the stiffness matrix, K in $\mathcal{F} = KX$, was the second major goal of the proposed research.

I.B Fuzzy Force Controller

Due to the complex nature of force controlling robotic manipulators a secondary goal of constructing a fuzzy logic based force controller was identified. Fuzzy logic provides for an efficient way to model complex control systems by establishing a set of If-Then rules operating on linguistic variables, which are represented mathematically by membership functions. The membership functions which define fuzzy variables give fuzzy logic the ability to operate on variables which are partial members of one or more sets. With both a conventional and fuzzy hybrid position/force controller in place a comparison of both control techniques was proposed so that the advantages and disadvantages of each type of controller could be identified.

I.C Document Outline

Chapter two of this document describes the construction, function and calibration procedure of the instrumented compliant wrist. Chapter three details the implementation of a conventional hybrid position/force controller, while Chapter four details how fuzzy logic can be useful in an application such as force control of robotic manipulators. A comparison of both forms of force control is continued in Chapter five and conclusions from the the semesters research are presented. Chapter six concludes with thoughts on future research relative to the work of this year.

CHAPTER II

THE COMPLIANT WRIST

II.A Importance of Wrist

The Compliant Wrist used in the CS Robotics Lab was designed and built by Tom Lindsay [5] of the GRASP Lab, University of Pennsylvania. The wrist is an important tool because it allows for compliance when a robot end effector comes into contact with and exerts forces on objects in its environment. The sensing mechanism of the wrist, a six degree-of-freedom serial linkage with potentiometers at each joint, allows for a measurement of the deflection experienced by the wrist during compliance. If the force-deflection relationship of the wrist is known, then from the measured deflection of the wrist, the forces which the robot manipulator is exerting on environment (or that the environment is exerting on the end effector) can be calculated.

The compliance of the wrist aids in smoothing transitions between differing contact situations during robotic tasks by lessening the effect of high impact forces. The compliance of the wrist also alleviates jamming, high contact forces and other problems caused by positioning errors. The ability to compensate for positioning errors via compliance allows for a relaxation of part tolerances.

II.B Mechanical and Electrical Overview of Wrist

While a brief explanation and overview of the mechanical and electrical components of the compliant wrist is presented, for a more in depth explanation of techniques developed for overcoming problems encountered in working with the compliant wrist, the interested reader should see [2] and [3].

II.B.1 Mechanical Overview of Wrist

The wrist used in the Lab consists of a compliant structure to allow for compliance and a serial linkage with potentiometers at each of six joints to allow for the calculation of deflection (figure 2). The range of deflection in the wrist is approximately a quarter of an inch, with rotation on the order of 10 degrees, allowing the end effector to experience relatively large deflections during contact. While forces of contact can be measured with force sensors which do not experience a large degree of compliance (e.g., those using strain gauges) these forces might be so great and the sensors that monitor them so uncompliant that damage might be caused to objects in the environment. The wrist, while acting as a force sensor, also allows for compliance when interacting with an environment.

II.B.2 Electrical Overview of Wrist

To measure the change in rotation about each joint in the wrist linkage, the change in voltage across each joint potentiometer must be measured, and the change-in-voltage to change-in-rotation relationship for each type of potentiometer must be known. The voltage signals from each potentiometer are then sent through a signal conditioning board to strengthen them and reduce the effect of electrical noise. These signals are then read by computer via an A/D card and the change in rotation about each of the joints in the wrist linkage is calculated. Once the change in rotation about each of the 6 linkage joints is known, the change in deflection of the wrist, from environmental interaction, can be calculated. A figure of the electrical connections of the wrist to both power and the A/D

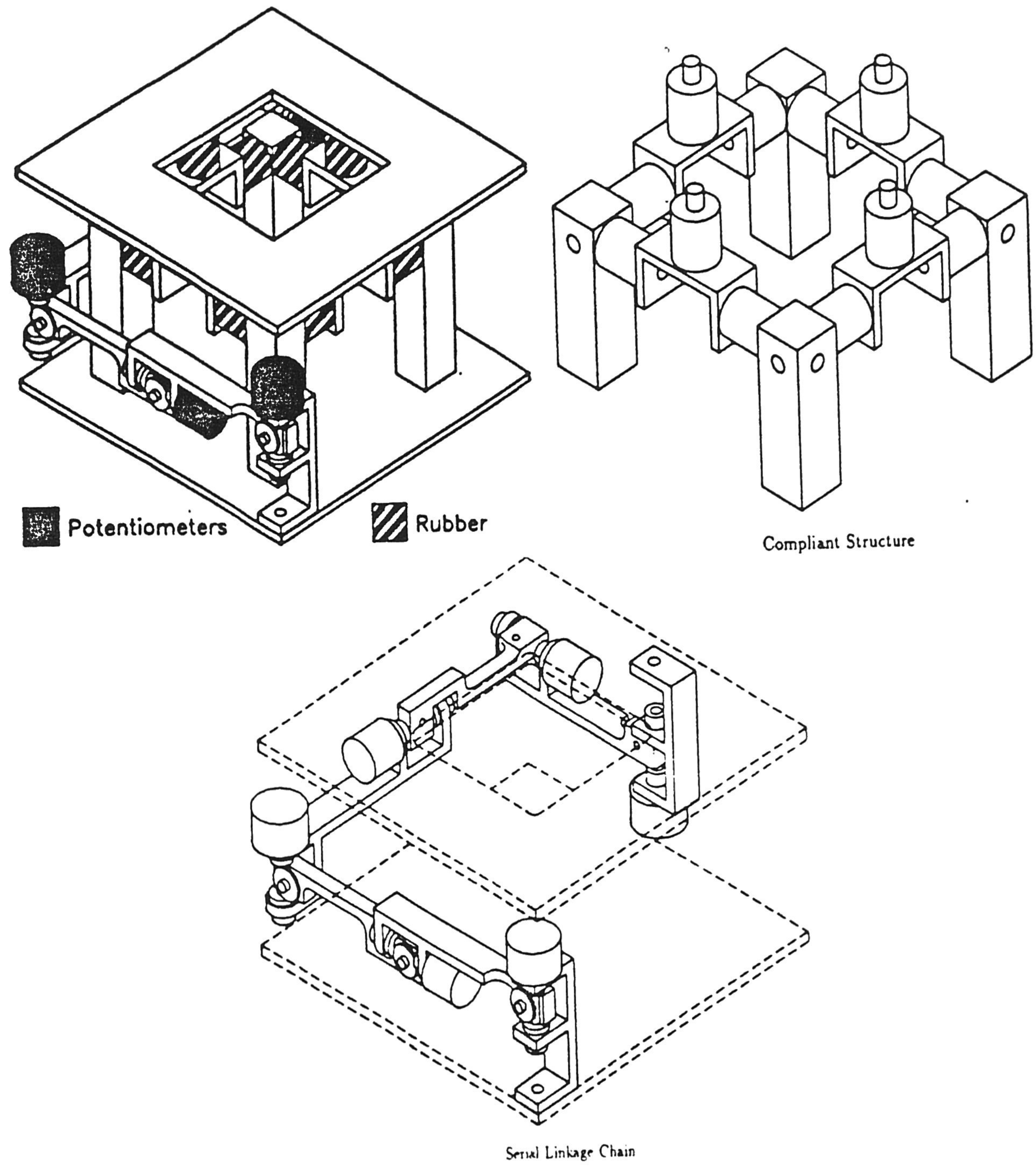

Fig. 2. a) the compliant wrist b) the compliant structure c) the serial linkage chain

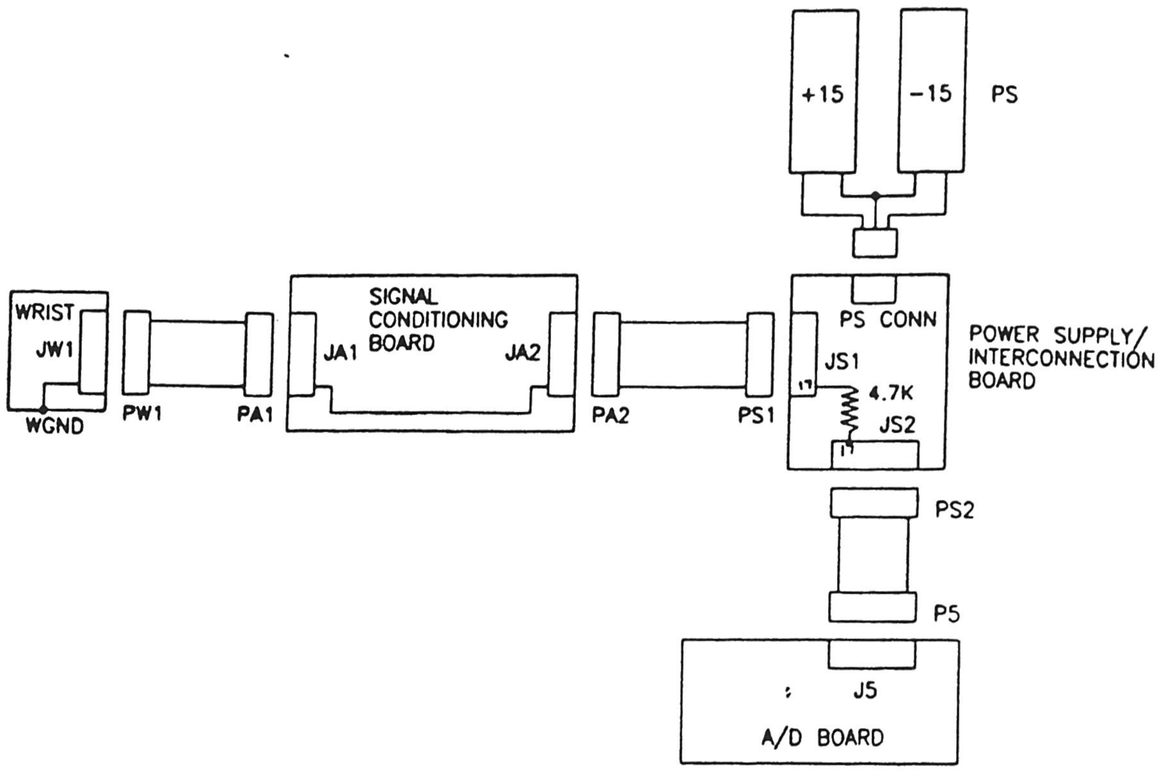

Fig. 3. Wrist power and connections

card can be seen in figure 3.

II.C Calibration of the Compliant Wrist

Due to the effects of age and wear on the compliant rubber elements of the wrist, the decision was made to develop a method of calibrating the wrist. The wrist can be characterized mathematically using the manufacturers axial and shear stiffness rating for each of the rubber elements in the wrist [5], however unmodeled effects exist which lead to significant off diagonal cross coupling terms in the stiffness matrix which characterizes the wrist. Therefore a pure mathematical characterization was judged to be inaccurate.

The force-deflection relationship of the wrist is given by the stiffness matrix K_{w_base} in the equation,

$$^{w\_base}\mathcal{F}_{w\_base} = K_{w\_base}\delta X_{w\_base}$$

The 6×6 matrix K_{w_base} is the goal of the calibration procedure. $^{w\_base}\mathcal{F}_{w\_base}$ is a 6×1 vector representing the forces and moments at the base plate of the wrist, and δX_{w_base} is a 6×1 vector representing the 3 translational and 3 rotational deflections of the wrist from the undeflected position. From this equation it is seen that the wrist has the characteristics of a six-dimensional spring.

II.C.1 Wrist Calibration Procedure

By subjecting the wrist to a known force, $^{w\_base}\mathcal{F}_{w\_base}$, and measuring the resultant displacement of the wrist, δX_{w_base}, the stiffness matrix of the wrist, K_{w_base} can be calculated. $\mathcal{F}_{w\_base}$ is obtained via a JR3 digital force torque sensor mounted between the end of a robot and the base plate of the wrist (figure 4). The JR3 is configured to measure and return the forces at the base plate of the wrist. δX_{w_base} is obtained by measuring the change in angle at each joint of the wrist and calculating the wrist transform using the Denavit-Hartenberg parameters of the wrist [5] [4].

Once N readings of $^{w\_base}\mathcal{F}_{w\_base}$ and δX_{w_base} have been taken, for each reading, i, recorded during calibration the equation

$$F = D\mathcal{K}$$

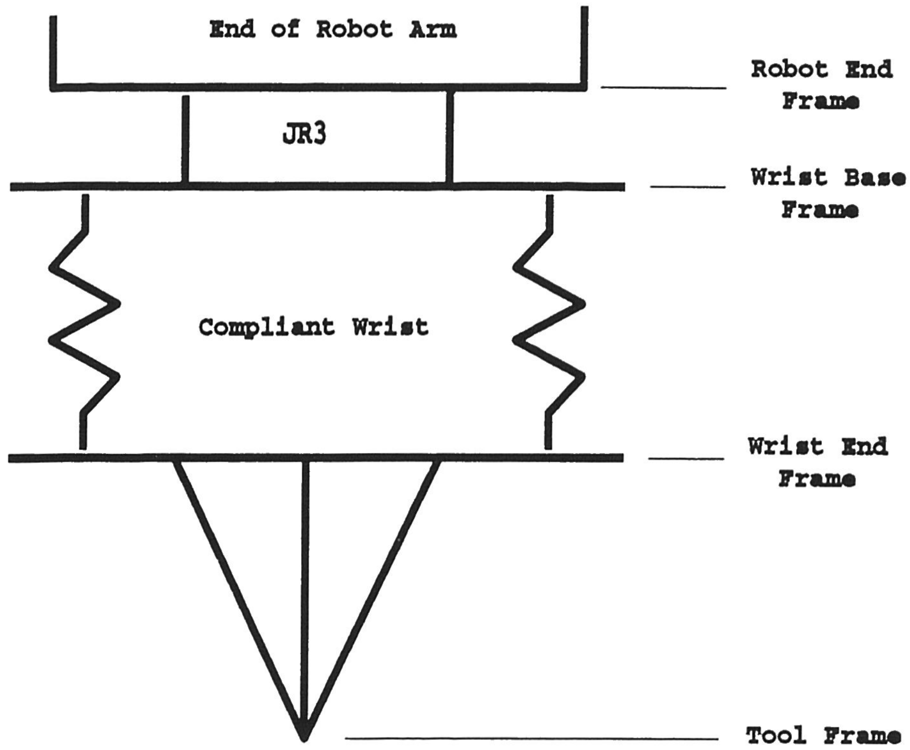

Fig. 4. Diagram representing the placement of the JR3 force/torque sensor between the end of robot arm and compliant wrist

is formed, where

$$F_{[6N\times 1]} = \begin{bmatrix} \mathcal{F}_{1x} \\ \mathcal{F}_{1y} \\ \mathcal{F}_{1z} \\ \mathcal{F}_{1\gamma} \\ \vdots \\ \mathcal{F}_{Nz} \\ \mathcal{F}_{N\gamma} \\ \mathcal{F}_{N\beta} \\ \mathcal{F}_{N\alpha} \end{bmatrix}$$

and

$$D_{[6N\times 36]} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_{N-1} \\ D_N \end{bmatrix}$$

where for each reading i,

$$D_{i_{[6\times36]}} = \begin{bmatrix} \delta_{ix}\delta_{iy}\delta_{iz}\delta_{i\gamma}\delta_{i\beta}\delta_{i\alpha} & 0_{[6\times1]} & \cdots & \cdots & 0_{[6\times1]} \\ 0_{[6\times1]} & \delta_{ix}\delta_{iy}\delta_{iz}\delta_{i\gamma}\delta_{i\beta}\delta_{i\alpha} & 0_{[6\times1]} & \cdots & 0_{[6\times1]} \\ \vdots & & \ddots & & \vdots \\ 0_{[6\times1]} & \cdots & \cdots & 0_{[6\times1]} & \delta_{ix}\delta_{iy}\delta_{iz}\delta_{i\gamma}\delta_{i\beta}\delta_{i\alpha} \end{bmatrix}$$

The stiffness matrix of the wrist is calculated by minimizing $\mathcal{K}$, such that $D\mathcal{K} - F \cong 0$, or

$$\underset{\mathcal{K}}{Min}\ (D\mathcal{K} - F)^T(D\mathcal{K} - F)$$

where,

$$\mathcal{K}_{[36\times1]} = \begin{bmatrix} K_{11} \\ K_{12} \\ K_{13} \\ K_{14} \\ K_{15} \\ K_{16} \\ \vdots \\ K_{61} \\ K_{62} \\ K_{63} \\ K_{64} \\ K_{65} \\ K_{66} \end{bmatrix}$$

The $\mathcal{K}$ with the minimum squared error is obtained numerically using the appropriate minimization routine from the IMSL software package for scientific computing.

II.C.2 Results of Wrist Calibration

Early in the Fall semester the wrist calibration was attempted by subjecting the wrist to known forces via weights while rotating the robot through a series of positions and orientations, taking force and position data. The robot was moved in such a manner that the only force applied to the end effector was in the negative Z direction of the robots world frame (i.e., straight down), and no undo moments were introduced. At that time, however, the wrist was not functioning correctly (see Chapter 6 Future Research, An Improved Compliant Wrist), and data analyzed using the minimum squared error was erroneous.

The procedure outlined above has not been implemented do to the unavailability of a JR3 force/torque sensor. At the time of the writing of this document a new digital JR3 has arrived in the Lab and is currently being configured for operation. The calibration procedure to obtain the stiffness matrix, K_{w_base}, should be completed without incident.

CHAPTER III

CONVENTIONAL HYBRID POSITION/FORCE CONTROL

III.A Implementation of a Hybrid Position/Force Controller

It was stated in the introduction that a conventional hybrid position/force controller is achieved by dividing the directions of control into position- and force-controlled subsets. These position- and force-controlled subsets are determined by the differing contact situations a robot encounters during a task utilizing force control. Natural position constraints arise for directions in and orientations about which a robot cannot move due to contact with it's environment, and natural force constraints arise for directions in and orientations about which a robot is unable to exert a force due to the absence of environmental contact. Complementary to the natural constraints placed on a robot by its environment during an operation are the artificial constraints, or the position and force controlled directions and orientations specified to complete a robotic force controlled task.

For a complex task involving several different contact situations, (e.g., assemblies such as a peg-in-hole insertion or removal) subtasks can be identified where specified (artificial) and natural constraints for each subtask remain constant. By observing the changes in the natural constraints during a subtask the transition points between different contact situations can be determined. The realization of robotic planers with the ability to automatically choose, determine and transition through the necessary artificial and natural constraints to complete an entire robotic task involving several contact situations is an area of current robotics research.

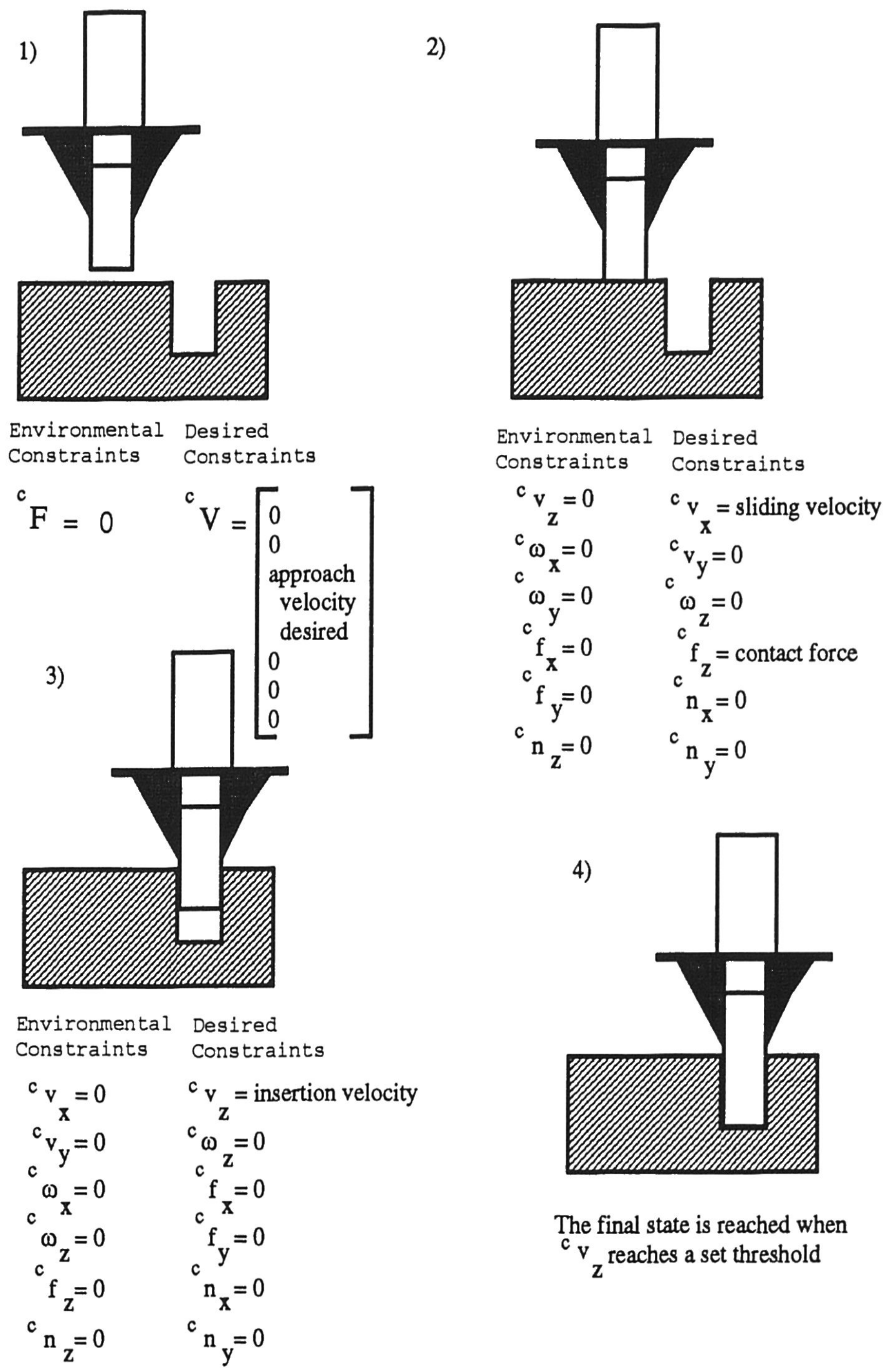

Fig. 5. The four contact situations for a peg-in-hole insertion

In figure 5 the four contact situations which arise during a peg-in-hole insertion operation are shown along with the resultant natural constraints and the complementary artificial constraints, which must be specified. Position constraints are specified by setting the velocity in a given direction. ω is the rotation about a given axis. f is the force in a given direction and n is the torque about a given axis. All constraints are specified with respect to the robot end effector frame.

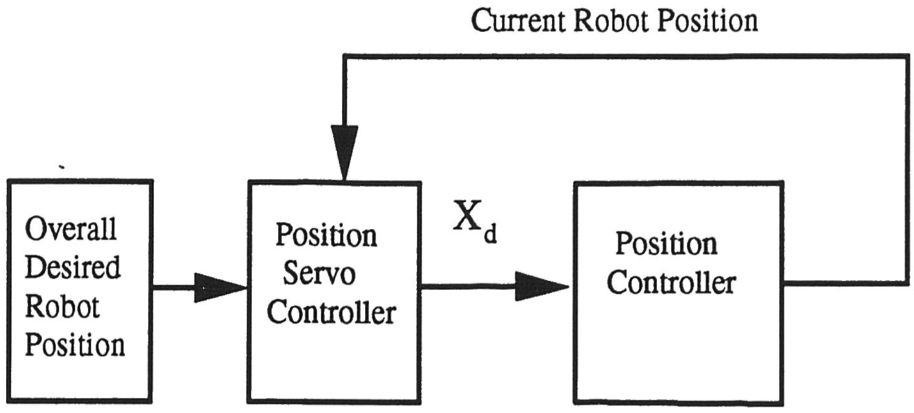

Fig. 6. Block diagram of servo controller for force control operation

The conventional hybrid position/force controller developed for use with the compliant wrist is an adaptation of the one used in the CS Robotics Lab to operate with the JR3 force/torque sensor. These force controllers are designed to work as part of an incremental servo controller which enables overall positions and orientations within the robot's work space to be specified and obtained. The servo controller (figure 6) operates by parsing desired robot positions into small incremental movements suitable for processing by the robots individual joint servo controllers. As the incremental positions are fed to the servo controllers in the form of joint encoder counts the robot moves with a constant velocity until the desired position and orientation are obtained. The servo controller has been implemented in a way which allows for control of the robot, with or without force control, telerobotically from remote locations via the Internet.

III.A.1 Position Controller Implementation

A control diagram of the robotic position controller implementation used with the servo controller mentioned above can be seen in figure 7. While this is not the only type of position control law available [4] the diagram does represent the algorithm used for position control in the hybrid position/force controller operating with the wrist. The reader should

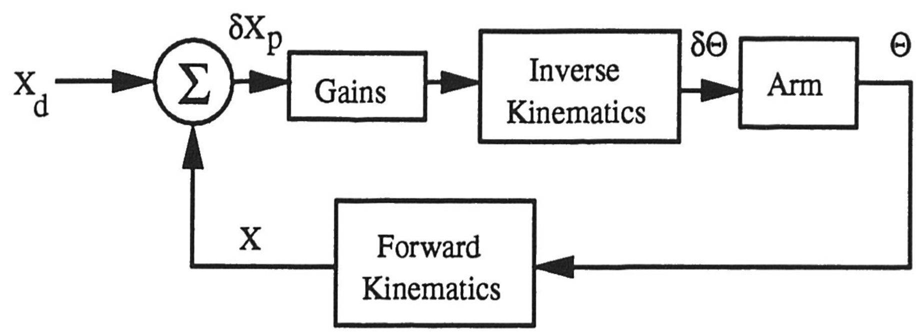

Fig. 7. Block diagram of position controller

note that due to the constant velocity motion of the robot under the aforementioned servo controller, acceleration effects are not taken into account. Since the robot is controlled by feeding small constant incremental movements to the individual joint servo controllers, the gains within the position control diagram are effectively all at unity and the effects of inertia, centrifugal forces, coriolis forces and gravity are compensated for directly by the individual robot joint controllers.

In the position controller diagrammed (figure 7), X_d is the desired position specified by the servo controller responsible for overall robot motions. δX_p is the cartesian representation of the arm displacement from the current position needed to achieve the position specified by X_d. $\delta\theta$ is the joint space representation of δX_p calculated via the inverse kinematics of the Merlin Robot and sent to the individual robot joint servo controllers. θ is the current position of each robot joint reported by the robot's joint servo controllers. X is the Cartesian representation of θ calculated via the forward kinematics of the Merlin Robot.

III.A.2 Force Controller Implementation

The force controller developed around the compliant wrist is diagrammed in figure 8. The desired forces, $\mathcal{F}_d$, are specified and utilizing the force to deflection relationship given by the stiffness matrix of the wrist, K, the displacement needed to achieve $\mathcal{F}_d$ can be calculated

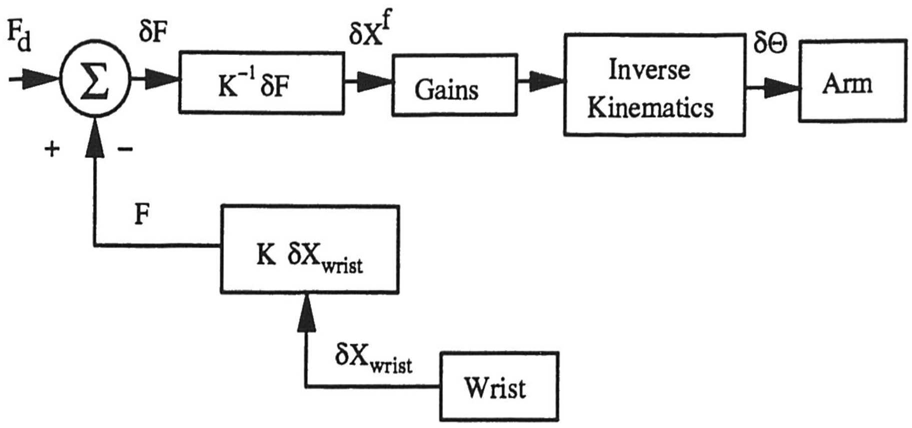

Fig. 8. Block diagram of force controller

using,

$$\delta X = K^{-1}(\mathcal{F}_d - \mathcal{F})$$

The force control function implemented is designed to work with the servo controller introduced previously, (figure 6), and provide fluid and even motion in a telerobotic environment. As a consequence the magnitude of δX_f for any iteration of the servo controller is dictated by the maximum allowable δX_p set for any interaction in the servo controller. The gains shown in the force controller must be empirically determined in order to critically damp the force control system.

In the force control diagram shown (figure 8), $\mathcal{F}_d$ represents the forces desired at the base plate of the wrist. F represents the forces currently at the base plate of the wrist. $\delta\mathcal{F}$ is the cartesian representation of the arm displacement needed to achieve the forces specified by $\mathcal{F}_d$. δX_{wrist} represents the current deflection of the wrist from its nondeflected state.

III.A.3 Position and Force Controller Combination

In order to resolve which axes in the tool frame of the robot are position controlled and which are force controlled the position and force controllers shown (figures 7 and 8, respectively), are combined into the hybrid controller shown in figure 8 with the use of

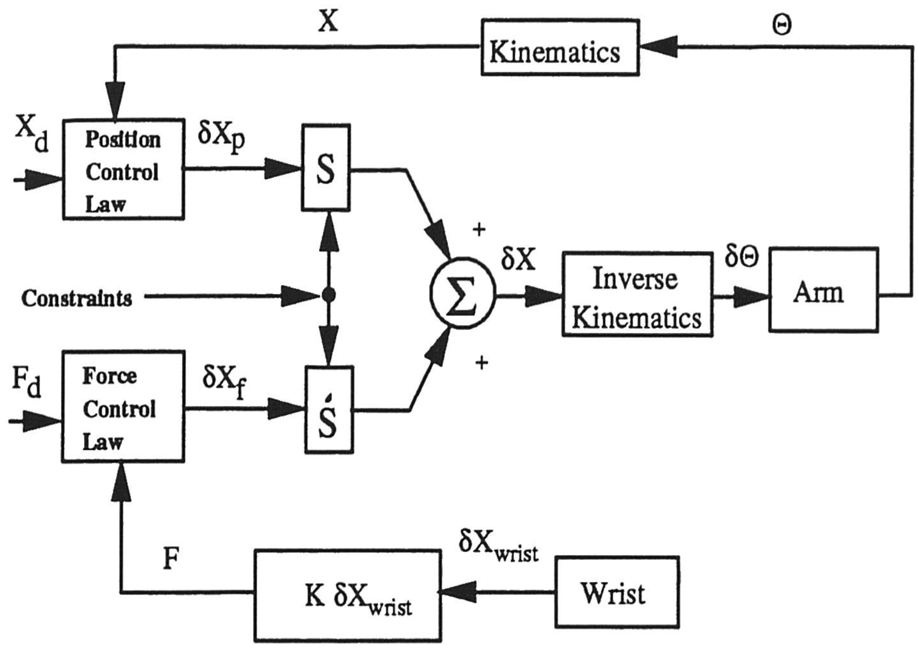

Fig. 9. Block diagram of hybrid position/force controller

the matrices S and $\acute{S}$. S and $\acute{S}$ are diagonal matrices, where $\acute{S} = I - S$, and I is the identity matrix. A one in the diagonal of S and a corresponding zero in the diagonal of $\acute{S}$ signal a position-controlled degree of freedom, and a one in the diagonal of $\acute{S}$ and a corresponding zero in the diagonal of S signal a force-controlled degree of freedom, thus $S\delta X_p + \acute{S}\delta X_f = \delta X$. The use of S and $\acute{S}$ in a hybrid position/force controller allow for an arbitrary mixing of position- and force-controlled degrees of freedom in any frame on the robot. This in turn allows for an efficient method of specifying desired velocities and forces for the given contact situations encountered during a robotic assembly, inspection, or other complex robotic task.

III.B Results of Hybrid Position/Force Controller Implementation

Although as of this writing the stiffness matrix of the compliant wrist has not been empirically determined, the hybrid position/force controller presented has been implemented using the stiffness matrix obtained from the axial and shear stiffness ratings of the rubber elements which make up the compliant wrist [6]. The ability to fully test the wrist and force controller, however, has been limited by both the absence of a servo position controller for the Merlin Robot and the absence of a Lynx device driver to interface an A/D card with the electronics of the wrist.

Currently the servo controller mentioned in the previous section on position control and the non-compliant hybrid position/force controller mentioned in the section on force control exist only for use with the Puma 560 robot and the JR3 force/torque sensor of the Lab. Before the force controller implementation outlined above can be fully tested on the Merlin 6500, device drivers to control the Merlin and the electronics which monitor the change in rotation about each joint of the wrist's serial linkage must be written for Lynx, the real-time operating system under which the servo controller works. (Lynx enables the performance telerobotics tasks via the Internet.)

The hybrid position/force controller has been tested using a crude MS-DOS servo controller by applying forces to the robot end effector attached to the wrist and verifying that the robot reacts correctly by changing its position. Until the Merlin Robot can be controlled via the Lynx servo controller, the correct gains for the force control law determined, and a more accurate stiffness matrix of the wrist calculated, the hybrid position/force control law implementation will be limited.

CHAPTER IV

FUZZY HYBRID POSITION/FORCE CONTROL

IV.A Fuzzy Logic/Control

Utilizing the idea that truth or membership in a set is a matter of degree, fuzzy logic lends itself to the construction of control systems with rules that follow human reasoning. The If-Then rules of a fuzzy control system operate on linguistic variables represented mathematically by membership functions. For example, the rule *If the air is* `HOT` *and the air temperature is changing* `VERY LITTLE` *Then turn the fan on* `COLD`, could be used to control the air conditioner unit for a room. The graphical representation of the membership function `HOT` can be seen in figure 10. The membership functions `VERY LITTLE` and `COLD` would have similar representations.

Any fuzzy system is made up of four distinct parts (figure 11). First, before crisp input sensor values to a fuzzy system can be used they must be fuzzified. Fuzzification is the act

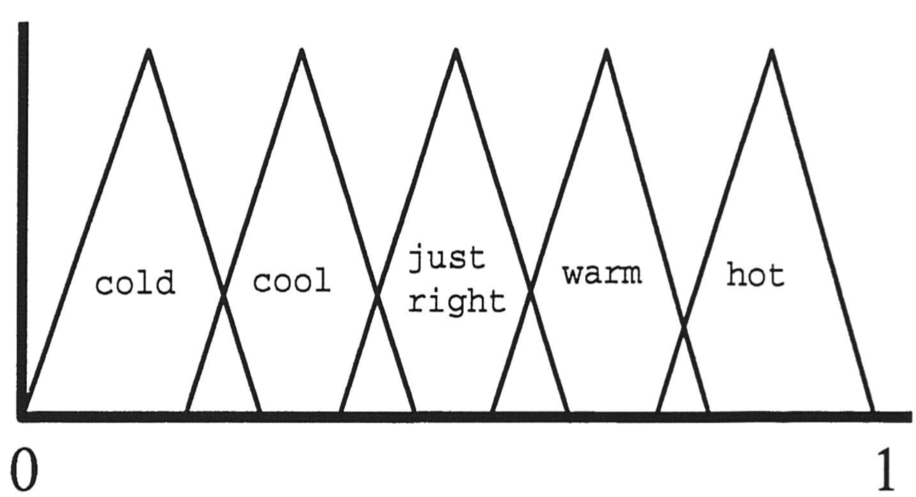

Fig. 10. Graphical representation of membership functions describing the current temperature of control area

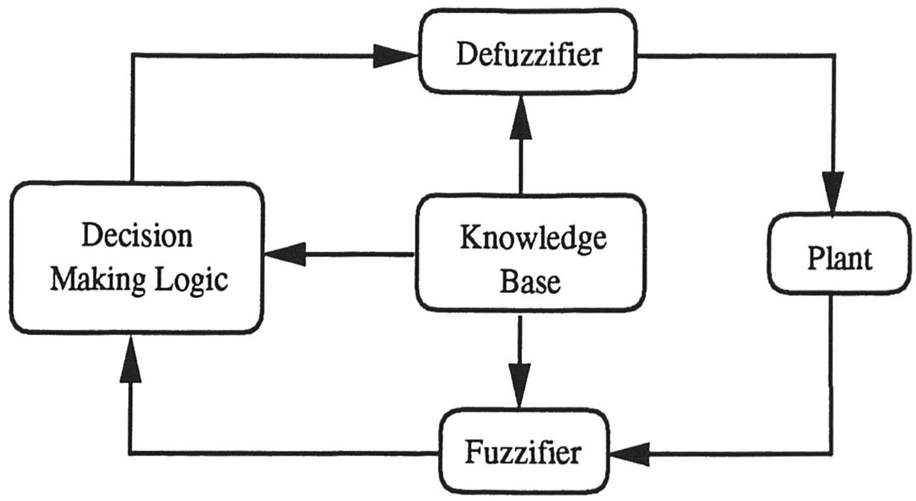

Fig. 11. Simple diagram of a fuzzy logic controller

of turning crisp sensor values into fuzzy values that can be used with the If-Then rules of the fuzzy system. The rules of a fuzzy control system and the membership functions upon which those rules operate, make up the knowledge base of a fuzzy system. The decision making logic unit of a fuzzy logic controller provides for conflict resolution in the event that more than one rule fires for a given set of inputs. Finally, the fuzzy output values produced by the fuzzy rules must be defuzzified, or turned into crisp control values which can be understood by the control system.

Although the rules of a fuzzy logic knowledge base can be obtained by modeling a human operator, process, or using computer learning methods, the most popular method of assigning the rules in a fuzzy control system is the use of an expert's experience or knowledge. In this way fuzzy logic lends itself to the control of ill-defined and complex systems, which might normally require a human operator. The assembly and mating of parts is one such complex task which the robotics research community is striving to solve and it is for this reason that the combination of force control and fuzzy logic was proposed.

TABLE I

Fuzzy Input Variables

Deflection Small	DS
Deflection Medium	DM
Deflection Big	DB
Deflection Very Big	DVB

TABLE II

Fuzzy Output Variables

Velocity Nil	VN
Velocity Small	VS
Velocity Medium	VM
Velocity Big	VB
Velocity Very Big	VVB
Velocity Very Very Big	VVVB

IV.B The Fuzzy Hybrid Position/Force Controller

The fuzzy controller outlined in this chapter is taken largely from the paper *Fuzzy Control of Robot and Compliant Wrist System* by Xu and Paul [7]. In the paper by Xu and Paul the implementation of a peg-in-hole insertion operation using compliance and a fuzzy logic force controller is discussed. The rules presented in Xu and Paul were assigned via human knowledge and judgment and the membership functions governing those rules were empirically determined. The knowledge base of the Xu and Paul fuzzy insertion controller consists of the fuzzy input and output variables shown in Table I and Table II and the fuzzy rules of Table III.

The peg-in-hole insertion test case in Xu and Paul assigns axes similar to those in figure 5. As the peg is driven towards the hole for insertion, small deflections in the wrist are ignored as compliant disturbance while moving in free space (rules 1 through 5). If

TABLE III

Fuzzy Insertion Controller Rule Base

Rule No.	Antecedent	Consequent
R1	Z_DS and X_DS	X_VN
R2	Z_DS and Y_DS	Y_VN
R3	Z_DS and θx_DS	θx_VN
R4	Z_DS and θy_DS	θy_VN
R5	Z_DS and θz_DS	θz_VN
R6	Z_DS and X_DM	X_VS
R7	Z_DS and Y_DM	Y_VS
R8	Z_DS and θx_DM	θx_VS
R9	Z_DS and θy_DM	θy_VS
R10	Z_DS and θz_DM	θz_VM
R11	Z_DM and X_DS	X_VS
R12	Z_DM and Y_DS	Y_VS
R13	Z_DM and θx_DS	θx_VS
R14	Z_DM and θy_DS	θy_VS
R15	Z_DM and θz_DS	θz_VS
R16	Z_DM and X_DM	X_VS
R17	Z_DM and Y_DM	Y_VS
R18	Z_DM and θx_DM	θx_VS
R19	Z_DM and θy_DM	θy_VS
R20	Z_DM and θz_DM	θz_VM
R21	Z_DB	X_VM
R22	Z_DB	Y_VM
R23	Z_DB	θx_VM
R24	Z_DB	θy_VM
R25	Z_DB	θz_VB
R26	Z_DVB	X_VB
R27	Z_DVB	Y_VB
R28	Z_DVB	θx_VB
R29	Z_DVB	θy_VB
R30	Z_DVB	θz_VVB

deflections in Z are still small, but the deflections in and around X and Y are significant, the robot is assumed to have made contact with objects in its environment and the corresponding corrective motions are taken (rules 6 through 10). As the deflection in the Z axis becomes larger the robot is assumed to have made contact with the hole and correction in and around the X and Y axes, and around the Z axis becomes increasingly important (rules 11 through 20). As the peg is inserted farther into the hole and jamming becomes more likely rules 21 through 30 play and increasingly larger role. When the peg is judged to have reached the bottom of the hole the insertion process is ended. Xu and Paul claim to have developed rules to account for the rate of change in deflection and the extraction of the peg from a hole, but these were not presented in their paper.

IV.C Significance of Fuzzy Hybrid Position/Force Controller

While a fuzzy force controller using the compliant wrist has yet to be implemented, the paper by Xu and Paul was chosen for presentation here for two reasons. First, it is one of the few papers in the literature which deals with the fuzzy force control of robotic manipulators for assembly or parts mating tasks. And second, it hints at significant aspects which fuzzy logic might be able to contribute to robotics force control. Despite being complicated, and tasks specific (i.e., the controller can only be used for insertion in the Z direction), Xu and Paul report that their fuzzy force controller takes fewer steps to full insertion than those of conventional controllers and that their fuzzy controller resulted in smoother performance and effective jamming avoidance. The significance which these aspects might play on force control development are developed in the two concluding chapters.

CHAPTER V

COMPARISON OF CONVENTIONAL AND FUZZY SYSTEMS

In his introduction of the concept of a hybrid position/force controller Craig [4] outlines three problems which a hybrid position/force controller must solve. A hybrid position/force controller must provide:

1. Position control of a manipulator along directions in which natural force constraints exist.

2. Force control of a manipulator along directions in which natural position constraints exist.

3. and, A scheme to implement the arbitrary mixing of these modes along orthogonal degrees of freedom on an arbitrary frame.

While the fuzzy force controller presented in Xu and Paul [7], solves the first two criteria above for the an insertion task, it does little to address the third. The algorithm put forth by Craig solves the third criteria by using the matrices S and $\acute{S}$ to combine the results of a position and a force control law, and by the appropriate assignment of the frame in which the positions and forces are to be specified, sensed and controlled.

Conventional position/force controllers, however, are not ideal for transitioning smoothly between contact tasks, nor are they ideal at effectively avoiding jamming. The development of devices like the compliant wrist and the desire to interject measured compliance, in some cases even controlled (active) compliance into force controllers, is an effort to address these problems in conventional controllers. The ability of fuzzy controllers to transition between the contact states of the peg-in-hole insertion, and avoid jamming while smoothly inserting a peg into a hole suggests that the inherent ability of fuzzy controllers to efficiently control non-linear systems may hold some promise in robotics force control.

CHAPTER VI

FUTURE RESEARCH

VI.A An Improved Compliant Wrist

Although the design of the compliant wrist was an attempt to construct a simple, economical, and reliable method of combining the benefits of compliance in part mating and assembly with sensed deflection, in it's present state the wrist has been found to be far from reliable. While both simple and economical to build (the wrist and accompanying electronics cost around $1500), the wrist suffers from mechanical problems which make it's use, possible but tedious. An improved wrist design, eliminating these problems and culminating in a robust, simple-to-use tool, would benefit the research community at large and has definite commercial and industrial applications.

The small deflections which are generated in the serial linkage of the wrist are measured at the six joints of the wrist via potentiometers. Despite the sensitivity of the wrist potentiometers, and the signal conditioning of the analog potentiometer signals, the wrist potentiometers are subject to a large amount of noise relative to their deflection range. The ideal way to solve the noise problem is digital encoding and transmission of the deflection data. Commercially available rotary encoders, however seem ill-suited for working within the compact space required of the compliant wrist. Inductive, capacitive and position sensitive diode displacement sensing devices have been suggested as an improve method of measuring the small displacements within the serial linkage of the wrist.

In addition to being subject to electronic noise and positioning errors, the shafts of the wrist potentiometers are subject to stress during deflection of the wrist linkage. If the stress on the potentiometer shafts is too great the shafts may bend, and as a result refuse to turn properly within the linkage. The unturnable pot shafts resulted in erroneous wrist displacement measurements. Until this source of error in the wrist measurements was identified and understood progress was hindered by several months.

VI.B The Application of Fuzzy Logic to Force Controllers for General Tasks

The paper by Xu and Paul hinted at two areas where fuzzy logic might be able to play an important role in future robotic force controllers. First, fuzzy control systems, with their ability to model and control nonlinear systems seem well equipped for resolving and smoothing the transition between the contact situations which arise in a complex robotic task requiring force control. And second, rules 6 through 10 of Xu and Paul hint at how one might implement a hybrid position/force controller and completely use concepts of fuzzy logic, satisfying Crag's third criteria for a hybrid position/force controller.

The hybrid position/force controller presented in Craig [4] can conceivably handle any contact situation depending on the specification of the tool frame, the axes in the tool frame to be force controlled and the axes in the tool frame which are to be position controlled. In the literature search conducted no such ability exists for a fuzzy hybrid position/force controller operating with or without compliance. The implementation of such an all-purpose fuzzy controller would represent a significant contribution to both the fields of robotics force control and fuzzy logic.

The implementation of a totally reconfigurable fuzzy position/force controller would require that a user be allowed to assign the desired positions to be obtained and the desired forces to be maintained for any set of artificial or natural constraints resulting from a contact situation. Such a hybrid position/force controller based entirely on fuzzy control would require a large fuzzy knowledge base. Engineering methodologies provide a standard approach for the design of a conventional controller, but for one based on fuzzy logic the rules and the membership functions of the fuzzy knowledge base would have to be assigned and tuned heuristically. It is possible to assign rules and/or tune the membership functions of a fuzzy systems using neural nets, genetic algorithms and other methods[1], but for a completely fuzzy position/force controller, which would require several tens of rules, and an indeterminant amount of training/learning time, such an approach might be unrealistic. Aside from learning and heuristics, the definition of a robust means by which engineers would be able to build better controllers for non-linear complex systems, might be a benefit gained from contrasting conventional and fuzzy force control techniques.

[1]This is an area of current research in fuzzy systems.

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