

# On the Development of a Portable Three-Degree-of-Freedom Force-Reflecting Manual Controller

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***Abstract** This paper addresses the development of a portable three-degree-of-freedom (3-DOF) force reflecting manual controller (FRMC) at Florida International University. In order to promote portability, which is the driving concept, a compact gimbal design is used. Furthermore, a parallel fault-tolerant architecture is incorporated in order to insure reliability. All degrees of freedom are directly actuated in order to reduce overall system backlash and consequently system parameters are decoupled allowing for improved performance. Modern control strategies are incorporated in the 3-DOF FRMC.*

## INTRODUCTION

As opposed to a master/slave system in which the operator has no sensory feedback, a Force Reflecting Manual Controller (FRMC) by definition, allows the operator to experience dynamic forces experienced by the remote system. By allowing the user to experience these forces, the tele-operation of the robotic system becomes more efficient. The primary objective of this project is to design and develop a portable three-DOF FRMC system, which provides the operator with tele-sensation feedback. In industry, the fore runners to this technology were large bulky devices impeded with gear backlash, friction and large inertial forces. The inertial forces are inherent and a direct consequence of large serial architecture prevalent in early six-DOF FRMCs.

In this paper, the design and development of a lightweight, portable three-DOF FRMC is addressed as a design problem. Two control strategies are compared; one based on classical PID feedback, and the other on fuzzy logic algorithm. Both control strategies are first developed and tested on a 1-DOF-prototype system. Evaluation and selection of the control strategies is based on the comparison of experimental and numerical simulations.

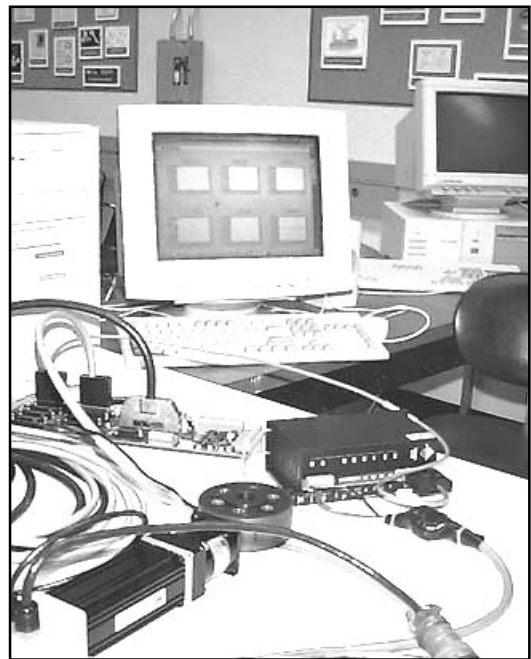


Figure 1. 1-DOF FRMC Prototype.

## 1-DOF FRMC

At the developmental stage, the overall dimensions of the FRMC system were not of primary concern. The intention here is to establish the necessary connection and to demonstrate the basic principles of the system before proceeding to the final 3-DOF system. The components comprised in the 1-DOF FRMC include force/torque sensor and processor. A PUMA 760 industrial robot is used to simulate a remote site via Floppy Talker, an interface software package.

Table 1 provides a summary of the hardware and software components used for the 1-DOF FRMC. This 1-

DOF FRMC is able to reflect forces up to 25 lb, which is generally much more than the force needed to provide an adequate level of force reflection.

### 3-DOF FRMC

At the developmental stage of the 3-DOF FRMC great consideration was given to ensure that the 3-DOF system would address the following concerns: compact architecture, low gear backlash, minimal friction, large work space, parallel fault tolerant structure, maintenance ease, and low cost. The basic controller concept starts with a simple 3-DOF gimbal configuration with each degree of freedom being directly driven by an ELCOM 41000 series actuator. The actuator's rotor assembly consists of samarium cobalt magnets secured to a soft iron core, which have a minimal torque ripple, and no cogging. The actuators are pulse-width modulation driven through an analog servo amplifier enabling a 2 N-m stall torque at the actuator shaft and 12 N continuous force for each actuator. With the gimbal spherical configuration, two actuators are used for the X and Y axes allowing for both greater torque per axis and a fault-tolerant arrangement.

Table 1. Listing of Hardware/Software Components for 1-DOF FRMC System.

Components	Model	Company
Brushless DC servomotor	BM200	Aerotech
Encoder	MS-E1000H	Aerotech
Controller	UNIDEX500	Aerotech
Amplifier	BA20	Aerotech
Interface Board	BB501	Aerotech
Force/Torque Sensor	100M40A-U760	JR3
ISA-Bus Receiver/Processor	p/n 1523	JR3
Control Software	C++ 4.0	Borland
Computer	IBM Pentium 166 MHz.	Dell
Remote System Industrial Robot	PUMA 760 6-DOF Robot	Unimation
Robot Interface Software	PUMA Floppy Talker	Antenen Research

The FRMC's displacements are sensed by Hewlett Packard incremental optical encoders coupled to each actuator shaft with a resolution of 0.044 degree (or 176 $\mu$ m at the handgrip). A six-axis 100M40A-U760 Force/Torque Sensor provides additional system sensing. The forces  $F_x$ ,  $F_y$ ,  $F_z$  at the manipulator handle are related

to the actuator torques  $\tau\alpha$ ,  $\tau\beta$ ,  $\tau\zeta$  by the following relation:

$$F_x = \left( \frac{\cos \beta \sqrt{1 - \sin^2 \alpha \sin^2 \beta}}{R_0 \cos \alpha} \right) \tau\beta \quad (0.1)$$

$$F_y = \left( \frac{\cos \alpha \sqrt{1 - \sin^2 \alpha \sin^2 \beta}}{R_0 \cos \beta} \right) \tau\alpha \quad (0.2)$$

$$F_z = \left( \frac{\cos \zeta \sqrt{1 - \sin^2 \alpha \sin^2 \beta}}{R_0 \cos \zeta} \right) \tau\zeta \quad (0.3)$$

where  $R_0$  is the handle length from the handgrip to the origin of the (x, y, z) system of coordinates, and  $\alpha$ ,  $\beta$ , and  $\zeta$  are the handle orientation angles versus the rotation of axes (x, y, and z). Thus the actuator torque is decoupled in the x y z plane, each contributing either to  $F_x$ ,  $F_y$ , or  $F_z$ .

### 3-DOF Controller Architecture

The proposed manual controller uses a gimbal assembly, as shown in Figures 2 and 3, where each of the joints is independently controlled. The additional actuator per degree of freedom complements the assembly by providing a greater amount of torque and a higher degree of fault tolerance to the overall system. Since each axis can be controlled independently, the simulations, presented below, were developed for three independent actuator systems with varying system parameters.

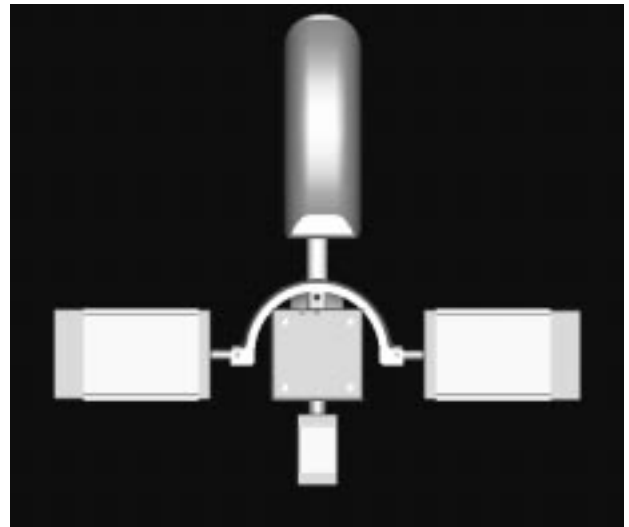


Figure 2. Proposed Gimbal Design.

## DYNAMIC MODEL

Before we proceed with the controller design, we first define the dynamic model of the system. The importance of an efficient dynamic model is well documented, although previous manipulators did not utilize them due to their computational intensiveness, and therefore sluggish response. Current computer systems can outperform previous systems 1000 fold or more giving rise to new technological opportunities. The dynamic model of an n-DOF robotic system is usually given as:

$$\tau = M(q)\ddot{q} + C(q, \dot{q}) + G(q) + F(q, \dot{q}) \quad (1)$$

where  $\tau$  is the n input actuator torque,  $M(q)$  is the n x n generalized inertia matrix,  $q$  represents the n-dimensional joint displacement vector,  $C(q, \dot{q})$  represents the velocity-induced inertial acceleration loads (centrifugal and Coriolis terms),  $G(q)$  represents the gravitational load terms, and  $F(q, \dot{q})$  represents the frictional load terms.



Figure 3. 3-DOF Gimbal Structure.

## CONTROL STRATEGIES

### PID CONTROLLER

The PID feedback was originally used for the U500 controller. It uses a dual control loop having an inner velocity loop and an outer position loop.

The system performance can be obtained in two distinct aspects. First, the attempt to obtain the smallest amount of position error that is allowable by pre-defined tolerances and have smooth motion. Second, the attempt

to obtain the smallest amount of position error that is allowable by pre-defined tolerances and have minimal settling time with no concern of smoothness of motion. The optimal performance, therefore, would be to compromise both aspects. Within the safe and stable region of the system response, different gains have been tested to obtain the best possible system response.

Table 2 lists some of the gain values used in laboratory experiments, whereas Figures 4 through 6 show system response. Figure 7 compares resulting error in position.

Table 2. System Gains Used in PID Experiments.

	$K_P$	$K_I$	$K_D$
<b>PID1</b>	14	28,000	40,000
<b>PID2</b>	2	20,000	40,000
<b>PID3</b>	4	20,000	40,000
<b>PID4</b>	2	10,000	10,000
<b>PID5</b>	12	10,000	10,000
<b>PID6</b>	8	30,000	10,000

The main objective of the PID controller is to determine the values of the three gains so that the performance of the system meets the design requirements. Among the three system responses shown in these figures, PID3 gain set tracks the command signal fairly closely; however, it shows this performance for slower commands. PID6, on the other hand, has a faster settling time, but a non-zero steady-state error disappears in a much longer time period. So, the system response to PID1 gain set is judged to be the best response among these three simulations.

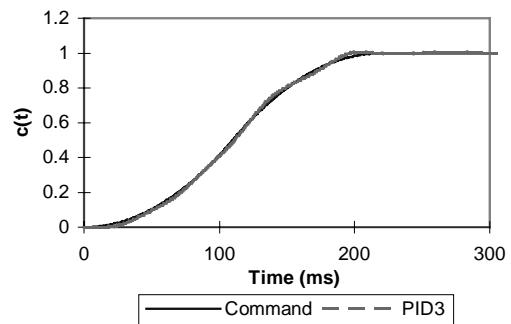


Figure 4. Command Response to PID 3 Gains.

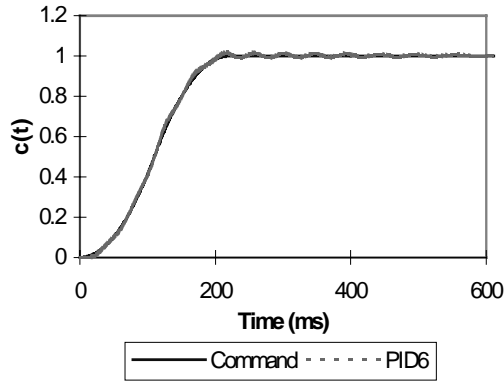


Figure 5. Command Response to PID 6 Gains.

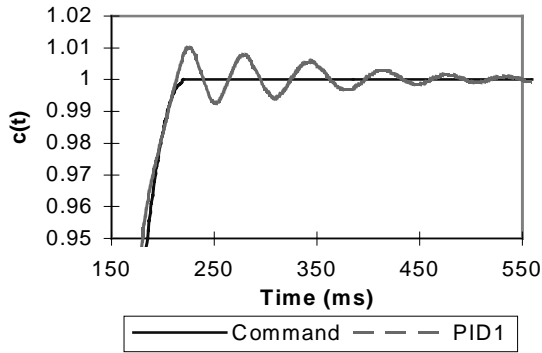


Figure 6. Position Response to PID1 Gains.

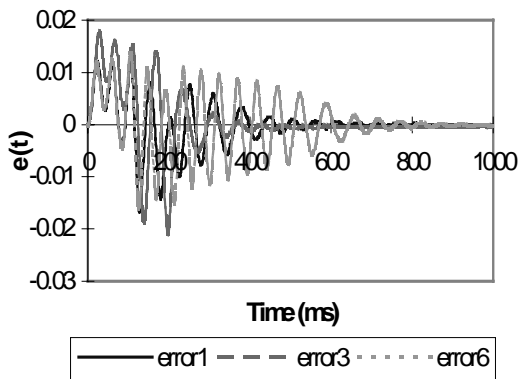


Figure 7. Comparison of the Response Errors.

## FUZZY LOGIC CONTROL

Fuzzy logic control stems from a new branch of controls, which does not adhere to traditional control theory. FLC attempts to mimic human decision-making behavior.

- FLC schemes originated in control engineering
- FLC models are rule-based systems

The IF-THEN rule base is formulated explicitly by the FLC designer and is used to derive the output in FLC systems. The rule mechanism is generally of the form

$R^{(1)}$ : IF  $x_1$  is  $F_1^1$  and  $x_2$  is  $F_2^1$  and ... and  $x_n$  is  $F_n^1$ , THEN  $y^1 = c^1$

•  
•  
•

$R^{(k)}$ : IF  $x_1$  is  $F_1^k$  and  $x_2$  is  $F_2^k$  and ... and  $x_n$  is  $F_n^k$ , THEN  $y^k = c^k$

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$R^{(m)}$ : IF  $x_1$  is  $F_1^m$  and  $x_2$  is  $F_2^m$  and ... and  $x_n$  is  $F_n^m$ , THEN  $y^m = c^m$

where  $R^{(k)}$  means the  $k^{th}$  rule,  $x_i$  is a real-valued input variable,  $F_i^k$  is a fuzzy set specified by membership functions  $\mu_{F_i^k}(x_i)$  (often defined as triangular functions),  $n$  specifies the number of input variables,  $c^k$  is a real valued constant, and  $y^k$  is the system output for this rule. Since  $m$  rules are defined in the rule base, the system output is

$$y = \Lambda \frac{\sum_{k=1}^m w^k \cdot c^k}{\sum_{k=1}^m w^k}$$

where  $w^k$  represents a variable weight assigned to the corresponding constant  $c$  and  $\Lambda$  is a positive diagonal gain matrix for scaling and tuning purposes. The individual weights are computed as

$$w^k = \prod_{i=1}^n \mu_{F_i^k}(x_i)$$

The output of the controller is simply taken from equation as applied to robotic manipulators; the IF-THEN rules of the form

IF  $e_1$  is  $E_j$  and  $ce_1$  is  $CE_i$ , THEN  $y = C_{ij}$

where  $e_1$  defines the error of the first input variable (position),  $ce_1$  defines the change in error of the first input variable (or velocity error),  $E_j$  and  $CE_i$  are the linguistic measures of the fuzzy sets of error and velocity error, respectively, and  $C_{ij}$  is a constant representing the torque to be applied found on a look-up table. The membership functions provide the continuity of control inputs rather than the on/off Boolean logic strategy. The weights of equation 2 are now computed as

$$\underline{w}_{ij} = \underline{\mu}_{E_j}(e) \cdot \underline{\mu}_{CE_i}(\dot{e}) \cdot C_{ij}$$

since  $n = 2$ . Substituting these weights into the above equation,

$$\underline{u} = \frac{\sum_{i=1}^q \sum_{j=1}^v \underline{\mu}_{E_j}(e) \cdot \underline{\mu}_{CE_i}(\dot{e}) \cdot C_{ij}}{\sum_{i=1}^q \sum_{j=1}^v \underline{\mu}_{E_j}(e) \cdot \underline{\mu}_{CE_i}(\dot{e})}$$

where  $q$  and  $v$  define the size of the look-up table.

For the fuzzy logic simulations presented in this section, triangular membership functions are used as shown in Figure 8. Crossover of the non-zero membership functions is limited to one crossover for any point along the error and velocity error axes. The centers of the fuzzy sets are shown in Figure 8. The membership functions vary from 0 to 1 and can be calculated with the knowledge of the error and velocity errors. The control input can then be determined utilizing the membership functions and the look-up table of constant input values in Table 3. A fuzzy set center should be located at  $e = 0$  so that the errors may converge to zero.

### FLC Simulation Parameters

The FLC look-up table is essentially a set of gains for the system. In order to simplify the tuning process, the look-up table is set up as a function of a single base value. The base value is then multiplied by a constant corresponding to the position in the table. The further away the actual position is from the desired position the greater the penalty. The table is symmetrical with respect

to both planes in that similar offset from the axes will yield similar penalties. Applying the fuzzy logic controller to the one degree-of-freedom system is relatively simple but requires some initiative work. The control gains must be selected in order to optimize response time and minimize error. The fuzzy scheme attempts to mimic the human response and therefore the control gains should also follow along these lines. A look-up table with the selected control gains was generated. The look-up table is essentially being the set of tuning gains for the system. In order to simplify the tuning process, the look-up table was set up as a function of a single base value. The base value is multiplied by a constant corresponding to the position in the table. The names of the constants are shown in Table 3 for each individual position, and their values are also given.

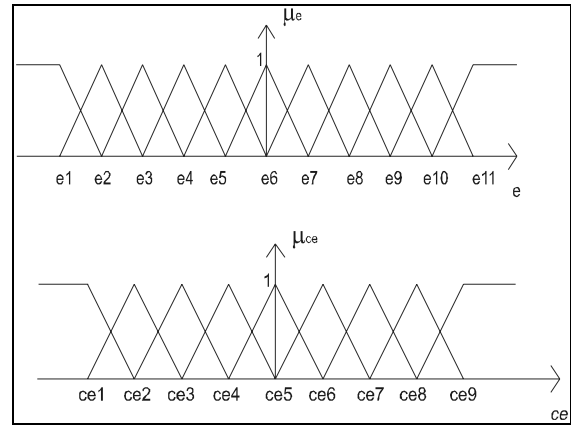


Figure 8. Triangular Membership Functions.

Table 3. Coefficients to the Base Value for Each of the Values of the Look-Up Table.

Name	Value
n4c	-40*base
n3c	-10*base
n2c	-3*base
n1c	-1*base
zxc	0.0
p1c	1*base
p2c	3*base
p3c	10*base
p4c	40*base

The set of gain values within the look-up table represents the human response to the system. The look-up table coefficients are chosen with the aim of sending the position and velocity errors to their respective zero. The location where both the velocity and position have a large negative error receives a large negative torque and respectively for the positive end. For the case where there is large positive position error and large negative velocity error, the corresponding table location receives a small input torque due to the relative correctness of the situation being somewhere in between the two error values. Similarly for the case where a large positive velocity error and a large negative position error exist, the corresponding table location receives a small input torque. All other values, which lie between these cases, are likewise selected so as to produce a continuous table flow towards zero.

### Fuzzy Logic Control Simulations

The system response under fuzzy logic control is displayed in Figures 9 through 13. The first figures demonstrate the system reaction to varying the gains for the individual joints.

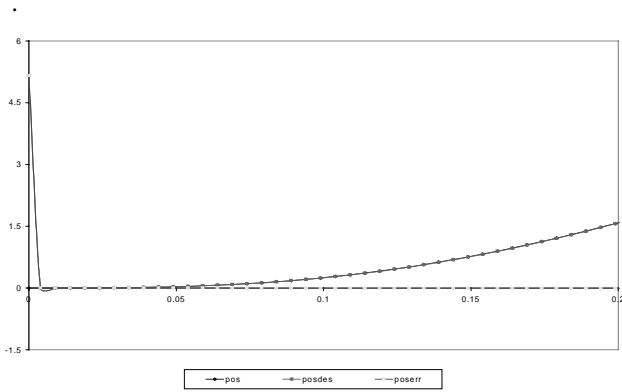


Figure 9. Position desired and actual vs. time base factor of .05 with initial error.

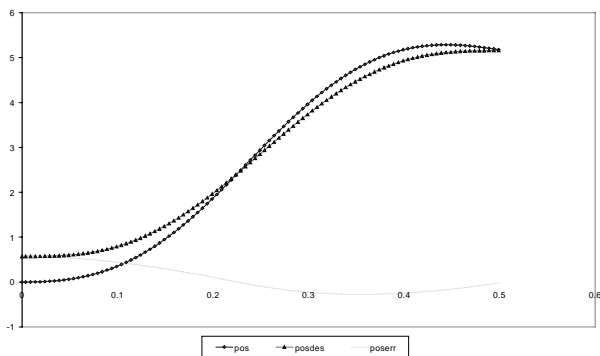


Figure 10. Position desired and actual vs. time base factor of .50 with initial error.

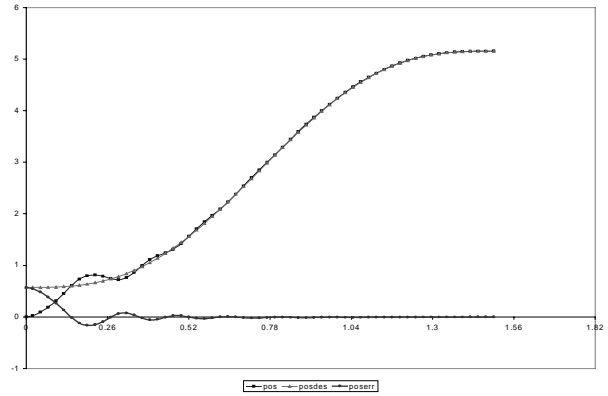


Figure 11. Position desired and actual vs. time base factor of 10 with initial error.

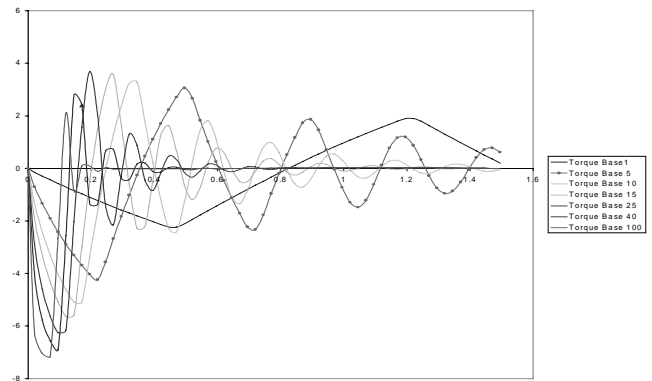


Figure 12. Torque response of the manipulator under fuzzy logic control with the gain values ranging from 1-100.

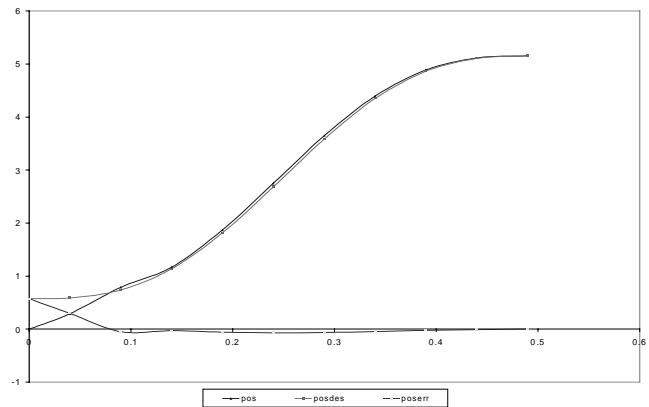


Figure 13. Position desired and actual vs. time base factor of 4.50 with initial error.

This variation was global since the gain matrix in its entirety was multiplied by a single base factor. Although the creation of a gain matrix might initially seem cumbersome, overall improvements in the total system response outweigh the drawbacks. A further drawback involves the selection of the base factor, which was used to tweak the system response. With a low base factor one could expect a sluggish response and low torque requirements. Using rather large base factors conversely requires large actuator torque and fast system response. The system is then optimized according to either the torque requirements or response time. To facilitate and expedite the base factor selection process the system response is plotted over a given range.

Figures 9–13 illustrate the effect of varying the gains for the individual joints. This is more cumbersome due to the larger amount of gains to be chosen but can be favorable if it improves the system response. The joint torque is found to be very good in the case of Figure 10 where the gain base factor was 5, later this was refined for this system with a base factor 4.5.

## CONCLUSIONS

Recent progress made in the development of a three-degree-of-freedom force-reflecting manual controller has been presented. Evaluation of the gimbal design and controllers continued. Specifically, PID feedback and fuzzy logic controllers have been studied to implement on the new controller.

## REFERENCES

[1] Erbatur, K., Kaynak, O., and Rudas, I., "A Study of Fuzzy Schemes for Control of Robotic Manipulators," *Proceedings - 1995 IEEE International Conference on Industrial Electronics, Control, and Instrumentation*, Part 1, Orlando, FL, pp. 63-68, 1995.

[2] Harrigan, R. W., "Automating the Operation of Robots in Hazardous Environments," *Proceedings of the 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Yokohama, Japan, pp. 1211-1219, July 26-30, 1993.

[3] Isermann, R., "On Fuzzy Logic Applications for Automatic Control, Supervision, and Fault Diagnosis," *Third European Congress on Fuzzy and Intelligent Technologies (EUFIT '95)*, Aachen, Germany, August 28-31, 1995.

[4] Monteverde, V. and Tosunoglu, S., "Development and Application of a Fault Tolerance Measure for Serial and Parallel Robotic Structures,"

*International Journal of Modelling and Simulation*, submitted for publication, 1997a.

- [5] Monteverde, V. and Tosunoglu, S., "Control of Fault-Tolerant Manipulators Experiencing Actuator Failure," *1997 Florida Conference on Recent Advances in Robotics*, Miami, FL, pp. 191-197, April 10-11, 1997b.
- [6] Monteverde, V., and Tosunoglu, S., "Fault Tolerance in Robotics and Mechanical Systems: An Introductory Survey," *The Third ASME Biennial Joint Conference on Engineering Systems Design & Analysis, ASME ESDA'96*, Montpellier, France, Vol. 2, pp. 259-264, July 1-4, 1996.
- [7] Sreevijayan, D., Tosunoglu, S., and Tesar, D., "Architectures for Fault-Tolerant Mechanical Systems," *Mediterranean Electrotechnical Conference - MELECON*, Vol. 3, pp. 1029-1033, Antalya, Turkey, 1994.
- [8] Thomas, M. and Tesar, D., "Dynamic Modeling of Serial Manipulator Arms," *Journal of Dynamic Systems, Measurement, and Control*, Vol. 104, pp. 218-228, September 1982.
- [9] Ting, Y., Tosunoglu, S., and Fernandez, B., "Control Algorithms for Fault-Tolerant Robots," *IEEE International Conference on Robotics and Automation*, Part 2, pp. 910-915, 1994.
- [10] Ting, Y., Tosunoglu, S., and Tesar, D., "A Control Structure for Fault-Tolerant Operation of Robotic Manipulators," *IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 684-690, 1993.
- [11] Visinsky, M. L., Cavallaro, J. R., and Walker, I. D., "A Dynamic Fault Tolerance Framework for Remote Robots," *IEEE Transactions on Robotics and Automation*, Vol. 11, No. 4, pp. 477-489, August 1995.
- [12] Wu, E. C., Hwang, J. C., and Chladek, J. T., "Fault-Tolerant Joint Development for the Space Shuttle Remote Manipulator System: Analysis and Experiment," *IEEE Transactions on Automatic Control*, Vol. 35, No. 12, pp. 1345-1350, December 1990.
- [13] Zimmerman, H. J., "Fuzzy Set Theory - and Its Applications," Kluwer-Nijhoff Publishing, Boston, MA, 1985.

- [14] J.V. Draper, "Teleoperators for Advanced Manufacturing: Applications and Human Factors Challenges," *The International Journal of Human Factors in Manufacturing*, Vol. 5, No. 1, pp. 53-85, 1995.
- [15] Batsomboom, P., Tosunoglu S., Repperger D., "Design and Construction of a Prototype Force-Reflecting Manual Controller," *Florida Conference on Recent Advances in Robotics*, Florida International University, Miami, Florida, April 10-11, 1997.
- [16] Bejczy, A. K., "Sensors, Controls, and Man-Machine Interface for Advanced Teleoperation," *Science*, Vol. 208, No. 4450, pp. 1327-1335, 1980.
- [17] Jacobson, S. C., Iversen, E. K., Davis, C. C., Potter, D. M., and McLain, T. W., "Design of a Multiple Degree-of-Freedom, Force-Reflective Hand Master/Slave with a High Mobility Wrist," *Proceedings of ANS/IEEE/SMC 3 rd Topical Meeting on Robotics and Remote Systems*, March 13-16, 1989.
- [18] Kim, W., "A Study on the Design and Operation of Force Feedback Controllers," Ph.D. Dissertation, University of Texas at Austin, January 1991.
- [19] Lindemann, R., Tosunoglu S., and Tesar, D., "Construction and Demonstration of a 9-String 6-DOF Force Reflecting Joystick for Telemanipulation," *Final Report to the U.S. DOE*, Department of Mechanical Engineering, University of Texas at Austin, October 1987.
- [20] Repperger, D. W., Phillips, C. A., and Chelette, T. L., "Study on Spatially Induced 'Virtual Force' with an Information Theoretic Investigation of Human Performance," *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 25, No. 10, pp. 1392-1404, 1995.