N88-17271

# DEVELOPMENT OF A FACILITY USING ROBOTICS FOR TESTING AUTOMATION OF INERTIAL INSTRUMENTS

Joy Y. Greig
Central Inertial Guidance Test Facility
6585th Test Group, Holloman AFB, NM 88330

Gary B. Lamont, Daniel J. Biezad,
Zdsislaw H. Lewantowicz
Department of Electrical and Computer Engineering
Air Force Institute of Technology
Wright-Patterson AFB
Dayton, Ohio 45433

ABSTRACT

The development of a facility for inertial instrument testing using a robot arm involves a variety of studies. Foremost is a feasibility study of the application which involves accuracy analysis of the static and dynamic configurations. As part of this aspect, simulation of a robot arm in performing the tests is desired along with modeling evaluations. Also, economic analysis of various arm configurations should focus on appropriate commercial systems that have a high probability of providing an applicable testing environment.

In this study, the Integrated Robotics System Simulation (ROBSIM) was used to evaluate the performance of the PUMA 560 arm as applied to testing of inertial sensors. Results of this effort were used in the design and development of a feasibility test environment using a PUMA 560 arm. The implemented facility demonstrated the ability to perform conventional static inertial instrument tests (rotation and tumble). The facility included an efficient data acquisition capability along with a precision test servomechanism function resulting in various data presentations which are included in the paper. Analysis of inertial instrument testing accuracy, repeatability and noise characteristics are provided for the PUMA 560 as well as for other possible commercial arm configurations. Another integral aspect of the effort was an in-depth economic analysis and comparison of robot arm testing versus use of contemporary precision test equipment.

## INTRODUCTION

Specialized test facilities, such as the Central Inertial Guidance Test Facility (CIGTF) at Holloman Air Force Base, New Mexico, are responsible for the testing of high quality inertial rate sensors and accelerometers. Due to the large investment in resources, it is important that all sensors be free from major defects when scheduled for precision testing. Initial sensor checkout tests, for example, should not tie up unique and specialized test equipment which may cost millions of dollars (2,4).

Although these expensive devices for testing inertial sensors have been very effective, due to their unique design they often lack the flexibility required to implement new test procedures. Moreover, there is little evidence of rapid innovation in designing and building new test fixtures with enhanced capabilities. These problems of cost, inflexibility, and lack of new capabilities impose significant constraints on component testing programs.

A potential approach to addressing these problems comes from the rapidly developing engineering science of robotics, where cost is decreasing due to the exponential rise in the number of units being produced (increasing from 20,000 units in 1976 to 250,000 in 1984), and where the digital capabilities being designed into robots have the potential to provide flexibility in systems tests and data acquisition (16). Finally, robotics is a highly innovative area fueled by vast research funding. It is probable that if the key difficulty of precision can be solved, the use of programmable robots for inertial testing should become a reality.

This paper discusses the feasibility of robotics applications to inertial component testing by addressing three major areas: technical feasibility, economic feasibility, and limitations. Facilities at the Air Force Institute of Technology (AFIT) provided the testing environment. Technical advice and the accelerometer for the study were provided by CIGTF.

In the following sections we discuss feasibility objectives and robot specifications, approach and design of the experiment, results of the experiment, economic analysis of a robotics test facility, and conclusions and recommendations resulting from the study.

## OBJECTIVES/SPECIFICATIONS

The robot in itself is not a precision test device relative to inertial sensor accuracies. Both inertial sensor and robot accuracies were investigated in this study to determine the feasibility of using a robot as a testbed. Three tests on a PUMA 560 robot arm were accomplished to illustrate this and to examine robot performance criteria for sensor/system laboratory testing.

Once technical feasibility is established, the next important question is, "Is the proposal economically feasible?" To determine cost-effectiveness, a life cycle costing analysis was performed for both the robotic and non-robotic testing units.

Limitations of robotic testbeds are a final consideration. Practical engineering limits, computer modeling limits, and measurement and instrumentation limits are addressed and related to the component test facility application.

APPROACH/DESIGN OF EXPERIMENT

The overall approach of the experiment was to design tests which would determine the feasibility of using a robot arm as a testbed for inertial sensors and thus the feasibility of developing a robotic inertial guidance test facility.

Simulation and Emulation

An effective approach to the development of robotics applications is to proceed first with simulation and then follow with emulation. Simulation is performed using a comprehensive robot simulation program (3,11,17). At AFIT a powerful computer program called ROBSIM produced by Martin Marietta Aerospace for NASA Langley was employed. A good simulator such as ROBSIM includes arm and environment synthesis (or definition), joint motion or joint torques and forces simulation, and analysis of the simulation.

Emulation of a test facility followed, using a PUMA 560 Robot Arm, data acquisition equipment, and a precision accelerometer and gyroscope.

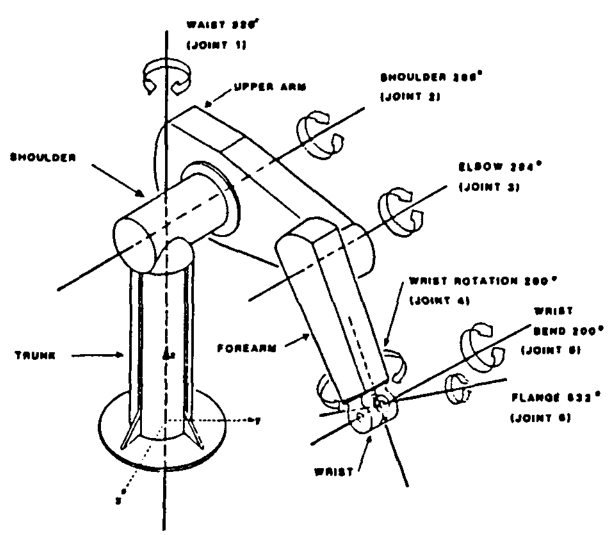


Figure 1. PUMA 560 Robot Arm (Reference 19)

Robot Flexure

In the inertial sensor testing application, ROBSIM was used to characterize arm flexure before performing the sensor tests. The flexure experiment was performed by securing a high-accuracy Systron-Donner 4841F accelerometer to an aluminum mount which was screwed on to the robot tool flange (Figure 1). The flange was rotated 90 degrees from the READY position (Figure 2) to position the input axis of the accelerometer vertical up. From this position the flange was first rotated counterclockwise in ten-degree increments to 90 degrees from vertical and then back to vertical in ten-degree increments. The accelerometer output was stabilized and recorded at each position. The experiment was then repeated in the same configuration but with the flange fixed and the shoulder rotated in ten-degree increments about the base y-axis starting from a vertical position. Shoulder and flange rotation alignment errors were calculated and compared. Larger shoulder rotation alignment errors would indicate flexibility of the robot arm. Performing this experiment on both ROBSIM and the PUMA provided a basis for comparison; the rigid-link model on which ROBSIM was predicated (7,8) aided in identifying actual robot positioning errors (7,8).

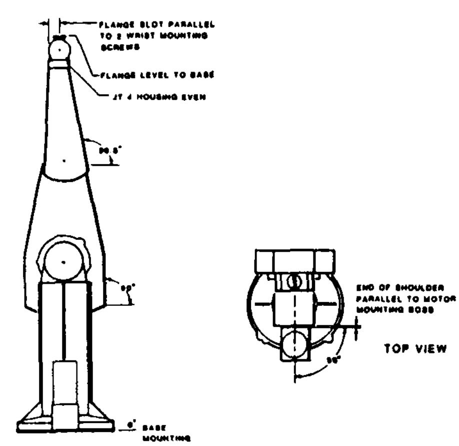


Figure 2. READY Position of PUMA 560 (Reference 20)

## Robot Alignment

As with any other test stand, a robot must be calibrated and aligned. To demonstrate the alignment of the robot arm with local vertical, a vertical-seeking test was designed, using the output of the Systron-Donner accelerometer and the PUMA 560's operating system to accomplish the calibration. In an actual testing situation a high-precision accelerometer, a triad of accelerometers, a laser, or some other means could be used either to verify the robot's position or to position it (if its own positioning system were limited). In this demonstration, however, a single accelerometer was used to locate local vertical.

The direction of vertical could be determined by simply maximizing a single accelerometer reading and using a numerical algorithm to zero in on vertical. However, most practical applications are faced with limited numerical accuracy in reading an accelerometer. Because of the non-linear nature of accelerometer reading accuracies, it is more accurate to find two orthogonal horizontal vectors and compute their cross-product to locate vertical. The natural precision geometry of the PUMA 560 manipulator supplies the proper configuration to determine vertical, using wrist bend (Joint 5) in conjunction with a 90-degree rotation in the waist (Joint 1); see Figure 1. For an expanded discussion of the theory behind finding horizontal and the calculations involved in this test, see Reference 10.

## Robot Precision

The degree of testing precision achievable with the PUMA 560 Robot Arm was investigated by performing an accelerometer four-point test using the arm as a testbed and the Systron-Donner 4841F as the test item.

The Systron-Donner 4841F accelerometer is a conventional single-axis, pendulous, fluid floated, torque rebalance accelerometer, with an analog output in volts direct current (VDC) proportional to the applied acceleration. For the series of four-point tests, the accelerometer on its aluminum mount was secured to the flange and aligned parallel to local gravity. The pendulous axis (PA) of the accelerometer was aligned parallel to the Y-axis of the tool flange and its input axis (IA) perpendicular to the Y-axis of the tool flange. The robot wrist joint was rotated 90 degrees, followed by a 90 degrees rotation of Joint 5, in order to position the accelerometer IA up and parallel to local vertical (just as in the flexure test). The four-point test was then performed.

The software was designed to rotate the accelerometer to the four positions (by rotating the flange) and allow sufficient time to read the accelerometer output voltage at those positions. This was accomplished by the VAL II operating system DRIVE command.

The accelerometer output was analyzed by calculating and determining the stability of the accelerometer scale factor, 1-g bias, null bias, and misalignment angle, using standard four-point test analysis (see Reference 10). This data was placed in a table and compared to tests of the same type of accelerometer on precision non-robotic test units (21:27).

## Robot Adaptability

Robot adaptability was demonstrated by performing a gyroscope (gyro) step-tumble test. This test demonstrated the maneuverability of a robot arm and the ease of reconfiguring the robot for different tests. For the step-tumble test the robot must be positioned to align the gyro's output axis parallel to the earth's rotational axis pointing north and then pointing south. The output of the gyro in these orientations is used to calculate the gyro drift characteristics. (For a thorough discussion of the gyro error model and drift coefficient determinations, see References 10 and 22).

The gyro used for the experiment was a Humphrey Model RG51-0106-1, a conventional single-degree-of-freedom (SDOF) torque-rebalance rate gyroscope. The PUMA 560 Robot Arm was again used as a test platform. The gyro was mounted to a metal support base which was in turn attached to the robot flange. The step-tumble test required the following gyro orientations to separate the drift coefficients for the gyro:

(1) Gyro OA parallel to the earth's spin axis (EA) pointing north, IA pointing west at the start of the rotations (OA//+EA)

(2) OA parallel to EA pointing south, IA pointing west at the start of the rotations (OA//-EA).

To align the gyro with the EA it was first necessary to determine the relationship between the PUMA World Coordinate System (WCS) and the EA. To find the WCS relative to EA it was necessary to know the latitude of the robot and the direction of True North with respect to the robot. This information was readily available for the test site and was used to determine the proper robot joint angles to align the gyro OA with the EA.

Once the OA and IA were properly aligned, the gyro was stepped through 360 degrees of rotation by rotating the flange 360 degrees clockwise (cw) followed by 360 degrees counterclockwise (ccw), pausing at each 45-degree increment to record the gyro output. One cw and ccw rotation of the flange for each orientation constituted one set of data for each step-tumble test. Eight sets of data were collected with OA south and eight with OA north (a total of 128 points in each direction).

The software was written for the robot's VAL II operating system which was accessed through a Zenith 100 (Z-100) running communication software to act as a smart terminal. The programs, written in the VAL II language, positioned the robot arm for each of the required gyro orientations and rotations.

The statistical package BMDP was used to perform the least squares fit of the output voltage to the gyro model. The drift coefficients calculated from the fit were then summarized in tabular form.

## RESULTS OF EXPERIMENT

Results of the experiment demonstrated both the advantages and the current limitations of robotic testbeds and simulations.

### Robot Control and Alignment

The results of the flexure test showed larger shoulder rotation alignment errors than flange alignment errors when the position was 30 degrees to 90 degrees from vertical. The accelerometer outputs demonstrated the inaccuracies of robot positioning and indicated that the flexibility of the robot arm should be a consideration when precise positioning and orientation is needed. A plot of the actuator torque versus time for the shoulder rotation as generated by ROBSIM showed that the torque is a function of the robot orientation and that the orientation errors are due in part to mechanical flexure.

Robot control is also limited by control method and unmodelled forces, and by the restrictions of robotic programming languages. The most widely used control method today applies a separate axial control loop for each joint designed with linear-control laws (12:80), often with fixed gain (12:72). The required gain is highly dependent on the moment of inertia at each joint of the robot arm which in turn varies with the arm position and robot payload. A variety of schemes, including adaptive control, have been proposed and implemented (12:51-81), but research is still being done to represent previously unmodelled forces (13) and implement adaptive control.

Robot programming languages, too, can be a control limitation in that they often do not include the facilities to implement complex mathematical formulas. One must bypass the robot operating system to implement experimental techniques and gain greater precision.

The theory and analysis involved in performing the alignment (vertical-seeking) test presumed no robot joint positioning errors. There are, however, small accumulated errors via quantization of robot movement and calculations by the robot arm controller (19). No attempt was made to include these errors in the vertical-seeking algorithm. The algorithm did, however, locate vertical more precisely than could be done by simply placing the arm in the READY position, or by using a single accelerometer output determination.

### Robot Precision and Adaptability

The results of the four-point tests in the following table (Table I) show that positioning precision can be achieved. Although the performance characteristic values are larger than those derived from four-point tests of similar instruments (see Table 2.3 from 21:27-28), the standard deviations and peak-to-peak spread are comparable. The laboratory environment for this research was much less controlled than that of a test facility such as CIGTF; noise sources from the laboratory and perhaps from the robot arm itself, and lack of temperature control contributed to the magnitude of the coefficients. However, the stability of the outputs is an indication of the positioning repeatability of the robot arm.

Table II summarizes the drift coefficients (and their standard error) of the performance model gyro equation. Since the duration of the tests was approximately three hours and the gyro's output axis was aligned with the earth's rotational axis, error sources did not include earth rate. All drift coefficients except D(O) were significant. From previous rate-table tests D(F) was determined to be 1.5 volts. Except for D(F), there was no test data with which to compare the drift coefficients. However, the coefficients are reasonable and, as with the accelerometer four-point test, indicated the feasibility of using the robot arm for testing inertial sensors.

The main purpose of the gyro test was to demonstrate the robot arm's ease of reconfigurability and its maneuverability and therefore its usefulness as a multi-purpose testbed. This was clearly demonstrated by the gyro step-tumble test.

Establishing testing feasibility using the PUMA 560 then led to determining a general set of robot criteria for the inertial sensor application, including economic considerations.

## ECONOMIC ANALYSIS OF APPROACH

All the criteria for selecting a robot for industrial applications are fully described in the robotics literature (6:214-301; 12:263-272; 15). In this study we were addressing only the criteria pertinent to inertial sensor/system testing. A summary of the criteria is as follows:

(1) Load requirement - 5 to 25 pounds
(2) Drive method - Electric motor driven
(3) Number of axes - 6
(4) Axis rotation - Wrist pitch, roll, or yaw of at least 360 degrees; at least 180 degrees of rotation in other joints
(5) Off-line programming capability
(6) Repeatability of 0.010 inches or less
(7) Variable acceleration/deceleration desirable
(8) Floor mount.

An expanded discussion of these selection criteria is found in Reference 10.

Table I
Accelerometer Performance Characteristics from Four-point Tests

| | Scale Factor (volts/g) | 1-g Bias (μg) | Null Bias (μg) | Misalign (arcsec) |
|---|---|---|---|---|
| ON ROBOT ARM: | | | | |
| Mean | 1.018805 | 1207 | 1720 | 8154 |
| Standard Deviation (ppm) | 29 | 60 | 66 | 9 |
| Peak-to-peak Variation | 115 | 241 | 255 | 30 |
| ON VERTICAL TABLE (21:27): | | | | |
| Mean | 0.02493 | 184.5 | 148.4 | -30.6 |
| Standard Deviation (ppm) | 40 | 45.8 | 36.4 | 7.5 |
| Peak-to-peak Variation (ppm) * | 471 | 471 | 244 | 58 |

* Over 39 days. No data available for a single day's testing.

Table II
Performance Model Equation Coefficients

| Drift Coefficient | Calculated Value | Standard Error |
|---|---|---|
| $D_P$ | 1.49999 | 0.00188 |
| $D_I$ | 0.00249 | 0.00031 |
| $D_s$ | 0.07619 | 0.00031 |
| $D_O$ | 0.00188 | 0.00295 |
| $D_{IS}$ | 0.00117 | 0.00035 |
| $D_{II}$ | 0.00107 | 0.00035 |
| $D_{SS}$ | 0.00107 | 0.00035 |
| $D_{OI}$ | 0.00389 | 0.00036 |
| $D_{OS}$ | 0.00120 | 0.00036 |

A comprehensive listing of prospective robots containing their physical characteristics and estimated base prices was obtained (18) using a commercial computer package called "Robot Search Program" (Robot Analysis Associates, Inc.). This list was reduced to four robots by entering the data into a spreadsheet (Lotus 1-2-3) and using the spreadsheet's capabilities to highlight the manipulators with the maximum performance capabilities (5:435-448). The results are summarized in Table III, along with non-robotic test tables.

The non-robotic tables have the advantage of continuous rotation and accuracies in the arcseconds range. However, the load capabilities are comparable, including the 100-pound load. For example, in addition to the robots listed, the Cincinnati Milacron T3-776 meets the rotational and accuracy requirements while carrying a load of 150 pounds. The robotic testbeds, however, are more versatile and less expensive and have other potentials discussed in the conclusions section.

Life cycle costing (LCC) over a 5-year period was the tool used to determine economic feasibility (9:66-67; 1:20; 2). Research and development costs, investment costs, and operational costs were included for the analysis. Table IV summarizes the results for both the selected robots and the non-robotic tables.

From the economic analysis it is feasible that a prototype robotic test station, the T3-646 for instance, could replace one table, perhaps the vertical table, with a resultant decrease in LCC of $17,364. Of course the savings increase

Another important advantage and source of savings is the versatility of a robot arm. Over the long term both standard and experimental inertial instrument tests can be performed by simply re-programming the robot, rather than rebuilding or developing a new test table. In the short term, as was the case for the gyro tests, the robot can be quickly reconfigured at any point in the test with no manual readjustments involved.

CONCLUSIONS AND RECOMMENDATIONS

In an attempt to control robots more precisely and to interface with computers (and computer simulations) other than the robot's particular controller, research is in progress to control robots from computers such as the VAX 11-780 (AFIT, NASA Langley) or interface with such computers for control and data acquisition (for example, Cincinnati Milacron's Robot Offline Programming System, or ROPS).

From the facility development study presented here, one can conclude that robots large and small could begin to be used as checkout testbeds for inertial sensors, possible in such applications as immediate flightline checkout of sensors or inertial measurement units (IMU's) suspected of being inoperable rather than sending them away to a depot for checkout.

Robots can be multi-purpose testbeds for performing standard tests on inertial sensors, and the potential for devising unique inertial sensor/system tests exists. Robots with variable acceleration/deceleration and a large rotational range suggest dynamic test possibilities that have not yet been explored. Perhaps subjecting the sensor/system to a helical motion, or to a rapid swinging motion of the robot followed by a sudden deceleration would excite sensor/system error

Table III
Performance Characteristics and Base Prices of Robotic and Non-Robotic Testing Units

| Name | Mount | Max Rot (Wrist) | Other Rot | Joint | Max Load (lbs) | Accuracy (ins) | At (ips) | Variable Accel/Decel | Base Price |
|---|---|---|---|---|---|---|---|---|---|
| A'matix AID-900 | Floor | 440 | p315 | Wrist | 66 | 0.008 | 30 | Y | 50000 |
| Yaskawa | F/O/W | 360 | YR330 | Wrist | 26 | 0.008 | 80 | Y | 69600 |
| Cinn Mil T3-646 | Floor | 900 | PY238 | Wrist | 50 | 0.010 | 25 | N/A | 70000 |
| PUMA 560 | Floor | 532 | P200 | Wrist | 5.5 | 0.004 | 20 | N | 80000 |
| **Name** | **Mount** | **Max Rot (Wrist)** | **Other Rot** | **Joint** | **Max Load (lbs)** | **Accuracy (arcsec per axis)** | **At (ips)** | **Variable Accel/Decel** | **Base Price** |
| Vertical Table | Floor | Contin. | | | 50 | < 1 | | N | 150000 |
| 2-axis Contraves | Floor | Contin. | | | 75 | 1 | | N | 500000 |
| 3-axis Contraves | Floor | Contin. | | | 100 | # 3 | | N | ## 3000000 |

# Difference in accuracy due to different type of bearings, not number of axes
## Estimated cost of new 3-axis table

Table IV
Total Life Cycle Costs

| Device | LCC |
|---|---|
| Automatix AID-900 | $ 146,279 |
| Cincinnati Milacron T3-646 | 186,618 |
| Yaskawa V-12 | 185,811 |
| PUMA 560 | 206,787 |
| Vertical Table | 203,982 |
| 2-axis Contraves | 522,239 |
| 3-axis Contraves | 2,818,062 |

terms and thus enhance or replace centrifuge or other testing. Variations of system trajectories could be tracked with lasers and the system errors analyzed by comparison with the laser position data. With extensive computer simulation capabilities such as those of ROBSIM, engineering theory could devise new tests which would be efficiently and safely produced on the simulator, saving both time and money. The simulator-robot combination would encourage engineering creativity, an important commodity in the realm of research and development, where new tests and testing units are needed to keep pace with hardware developments (2).

This study raises further questions. Are robots feasible for system tests? Can the limitations be overcome? What should be done to extend the work presented here?

The solution for robot accuracy constraints may lie not in improving the robot's precision, but rather in providing precision reference measurements for use in sensor output analysis. Laser technology and other instrumentation advances have the potential to accomplish this. For example, providing precision through reference measurement is already in use in noisy, imprecise environments such as the test track at Holloman Air Force Base; and laser technology is currently being used for robot positioning accuracy (14). A cost analysis for laser or other precision measurement technology should be accomplished to extend the economic feasibility study.

The potential for testing precision sensors/systems should be further determined by noise characterization of the robot arm. In addition, the sensors used in this study, or similar sensors, should be tested under more controlled laboratory conditions and compared to test results from non-robotic units.

It is also recommended that test engineers and analysts take a new look at the possibilities for dynamic tests using robotic capabilities and begin devising those tests. The groundwork for a prototype effort has been presented in this study and is recommended for future implementation.

REFERENCES


1. Abundis, M., "Making Robots Count," ROBOTICS ENGINEERING, December 1986, pp. 17-20.

2. Alexander, R., Telephone interview, Central Inertial Guidance Test Facility (CIGTF), Holloman AFB, New Mexico, April 1987.

3. Black, A. J., A PROGRAMMER'S ASSISTANT FOR A SPECIAL-PURPOSE DATAFLOW LANGUAGE, MS Thesis, AFIT/GCS/ENG/85D-2, School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB OH, December 1985.

4. Bustle, A., Telephone interview, Central Inertial Guidance Test Facility (CIGTF), Holloman AFB, NM, January, 1987.

5. Cobb, D., DOUGLAS COBB'S 1-2-3 HANDBOOK, Bantam Books, New York, 1986.

6. Critchlow, A. J., INTRODUCTION TO ROBOTICS, Macmillan Publishing Company, New York, 1985.

7. "Evaluation of Automated Decisionmaking Methodologies and Development of an Integrated Robotic System Simulation," NASA CONTRACTOR REPORT 172401, Martin Marietta Aerospace, Denver CO, September 1984.

8. "Evaluation of Automated Decisionmaking Methodologies and Development of an Integrated Robotic System Simulation," NASA CONTRACTOR REPORT 178050, Martin Marietta Aerospace, Denver, CO, March 1986.

9. Fisher, G. H., COST CONSIDERATIONS IN SYSTEMS ANALYSIS, American Elsevier Publishing Co., Inc., New York, 1971.

10. Greig, J. Y., ROBOTICS APPLICATIONS FOR THE TESTING OF INERTIAL SENSORS, MS Thesis, AFIT/GE/ENG/87J-4, School of Engineering, Air Force Institute of Technology, Wright-Patterson AFB OH, June 1987.

11. Greig, J. Y., D. A. Karnick, D. J. Biezad, and G. B. Lamont, "Implementing and Testing a Robot Simulator," PROCEEDINGS OF THE NORTH CENTRAL AND INDIANA-ILLINOIS SECTIONS OF THE ASEE, Purdue University, West Lafayette, IN, 1986, pp. 404-411.

12. Koren, Y., ROBOTICS FOR ENGINEERS, McGraw-Hill Book Company, New York, 1984.

13. Leahy, M. B. Jr. and G. N. Saridis, "Compensation of Unmodeled PUMA Manipulator Dynamics," PROCEEDINGS OF THE IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION, Raleigh, NC, March 30-April 3, 1987, pp. 151-156.

14. Montalbano, G. and R. Schlais, "Laser Guided Precision Positioning With A Gantry Robot," ROBOTICS ENGINEERING, Vol. 8, February 1986, pp. 23-25.

15. Nof, S. Y. editor, HANDBOOK OF INDUSTRIAL ROBOTICS, John Wiley & Sons, New York, 1985.

16. O'Toole, T. and M. Cetron, "The Coming Trend of Robots," Press interview, 1984.

17. Pai, A. L. and J. W. Pan, "A Computer Graphics Simulation System for Robot Manipulator Kinematics," PROCEEDINGS OF THE PHOENIX CONFERENCE ON COMPUTERS AND COMMUNICATIONS, March 1985, pp. 237-241.

18. Simmons, W., Rohr Industries, Inc., Riverside, CA, February 1987, personal correspondence.

19. Unimation, Inc., UNIMATE INDUSTRIAL ROBOT USER'S GUIDE TO VAL II, PART 1, VERSION 1.4B, Danbury, CT, 1983.

20. Unimation, Inc., UNIMATE INDUSTRIAL ROBOTS AND CARTESIAN COORDINATES, Danbury, CT, 1983.

21. Laboratory Tests of Systron-Donner 4841F Accelerometer Conducted by the Central Inertial Guidance Test Facility (CIGTF), REPORT NO. AD-TR-81-13, Holloman AFB, NM, CIGTF, 6585th Test Group, January 1981.

22. Wrigley, W., W. Hollister, and W. Denhard, GYROSCOPIC THEORY, DESIGN AND INSTRUMENTATION, The M.I.T. Press, Cambridge, MA, 1969.