Robot Characterization Testing

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I. ROBOT CHARACTERIZATION

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Abstract

This document describes the field of robot characterization which is broken into the areas of performance, parameter identification, and environmental interaction. Each area is explored by considering the tests, equipment, and manpower required to characterize the capabilities and performance of robots.

I.1 INTRODUCTION

Despite the tremendous growth in the use of robots during the last five years no standard robot acceptance and characterization tests have been developed yet. Currently several committees formed by the International Organization for Standardization (ISO) are working on the development of such standards on the international level [ISO, 1987]. In the US several technical committees of the Robotic Industries Association (RIA) in collaboration with the American National Standards Institute are working for the establishment of similar standards [RIA, 1988].

The issues relating to the characterization of robot arms will be discussed here from the point of view of a robot user rather than that of a robot manufacturer. This usually means that one has limited information about the inner working of a robot arm controller and incomplete information about tests performed on that robot, the testing conditions used and their results. The user has then to decide whether a certain robot can perform a particular task, its sensitivity to the environment where it is going to perform this task, and whether enough information exists to program this robot off-line. Depending on the requirements of the task the answer often is that there is incomplete amount of information about this type of robot in order to give a definitive answer to the above mentioned questions. A decision then has to be made whether to drop this robot from consideration, request more information from the manufacturer, or have additional tests performed by the user , the manufacturer, or a consultant.

The robot performance, the environmental effects, and sensitivity testing measurements might be grouped together in one general suitability tests category. Depending on the robot tasks, different

levels of performance and environmental sensitivity should be demanded. Robot calibration is a general term which usually refers to the identification by the robot controller of the kinematic and sometimes the dynamic model which describes the robot. Knowledge of the kinematic model is necessary for the operation of any robot, knowledge of the dynamic model is needed only when rapid motions are involved and advance performance robot controllers are used. Two of the main contributors of robot inaccuracies are the initial joints positions bias errors, introduced by the uncertainty of the robot controller as to the exact location of its links when arm power is turned on, and changes in the temperatures of the links. Additional sources of inaccuracies are fabrication and assembly errors, wear, deformation, etc. All these make necessary the periodic robot calibration to identify the above mentioned models. Good knowledge of the robot arm kinematic model is necessary if off-line programming of the robot controller will be used.

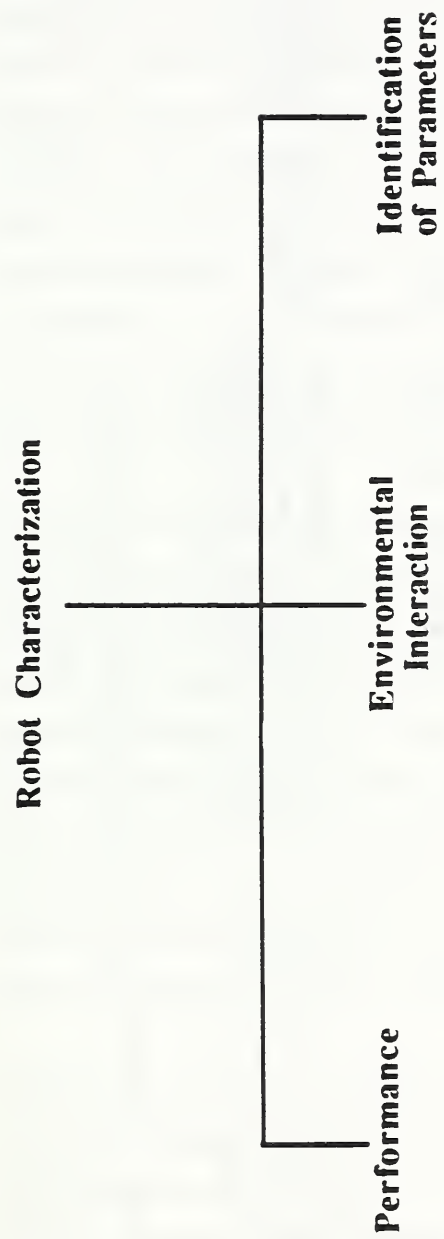## I.2 TYPES OF ROBOT CHARACTERIZATION

Three different types of robot characterization might be considered (see Figure I.1): 1. Performance   2. Identification of parameters   3. Environmental Interaction
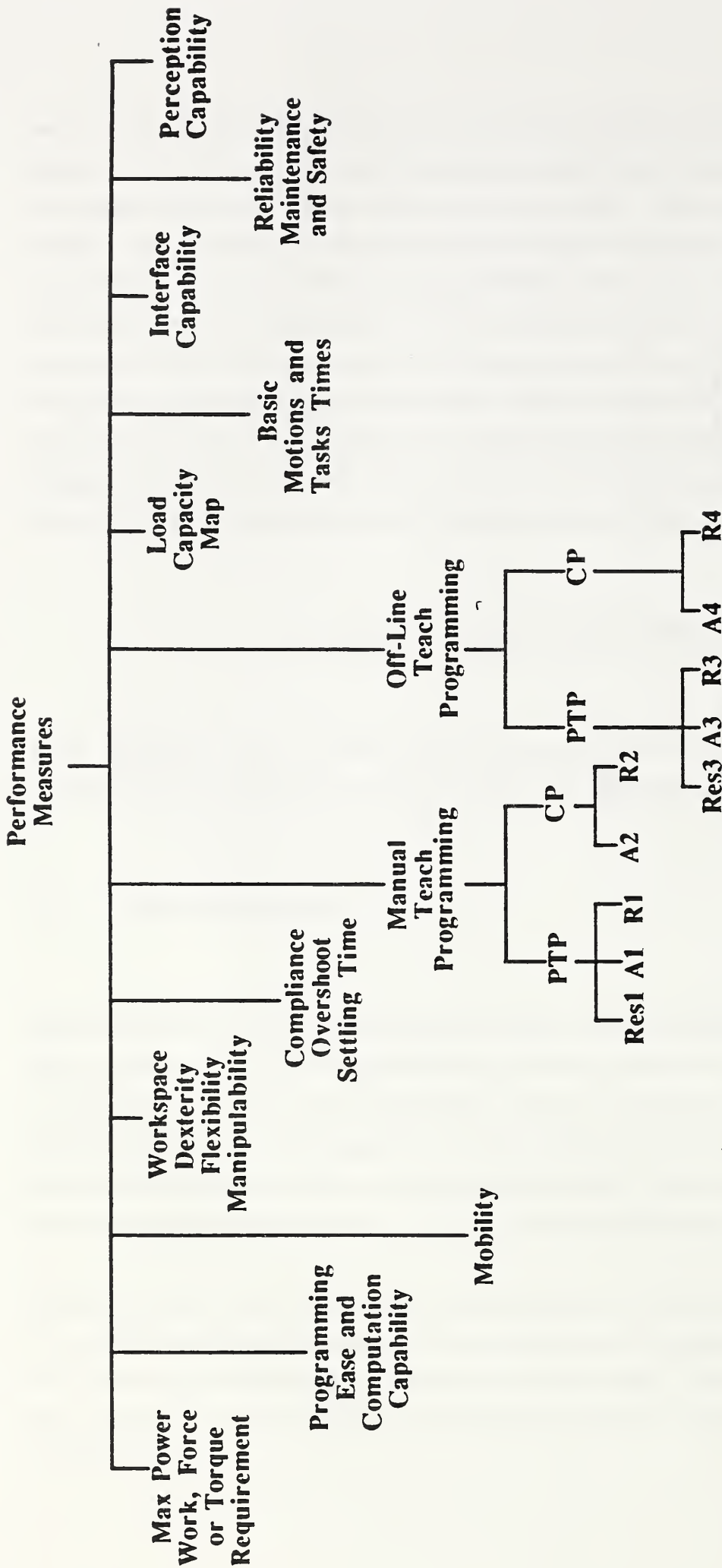
I.2.A   Robot Performance

Robot performance is a very general subject which includes everything that relates to the quality of robot operation. The performance measures chart of Figure I.2 lists most of the measures of performance which have been proposed by various investigators. Each robot application has different requirements and constraints, thus only a few of these measures of performance or others not listed in that figure might be considered important for a specific application. Here only those performance terms whose meaning is not obvious will be discussed.

Maximum power, work, force and/or torque requirements can be applied to the whole robot arm or the individual joints. These can be important because the joints actuators, or the robot arm base have force and/or torque limits, or power and/or work limits. The measured maximum values of these quantities depend not only on the manipulator itself but on the selected test trajectory and test conditions too.

Robot Characterization

Performance

Environmental
Interaction

Identification
of Parameters

Fig. 1.1

Fig. I.2

Performance Measures

Max Power Work, Force or Torque Requirement

Programming Ease and Computation Capability

Workspace Dexterity Flexibility Manipulability

Compliance Overshoot Settling Time

Mobility

Load Capacity Map

Basic Motions and Tasks Times

Interface Capability

Reliability Maintenance and Safety

Perception Capability

Manual Teach Programming

PTP

Res1 A1 R1

CP

A2 R2

Off-Line Teach Programming

PTP

Res3 A3 R3 A4

CP

R4

A1: PTP Relative Accuracy
A2: CP Relative Accuracy
A3: PTP Absolute Accuracy
A4: CP Absolute Accuracy

R1: PTP Relative Repeatability
R2: CP Relative Repeatability
R3: PTP Absolute Repeatability
R4: CP Absolute Repeatability

Res1: PTP Relative Resolution
Res3: PTP Absolute Resolution

PTP: Point To Point Control   CP: Continous Path Control

Dexterity, flexibility and manipulability are terms used to describe the capability of robot arms to move their end-effector within their workspace. The operating region or workspace of a robot arm is the volume of space which consists of all the points which can be reached by its end-effector gripping point, and may be divided into at least the dexterous (or primary) workspace and the secondary workspace [Roth, B., 1976, Kumar, A., et al. 1981, Gupta, K.C., et al. 1982, Beni, G., et al. 1985, Vijaykumar, R., et al. 1986, Gupta, K.C., 1986, Kohli, D., et al. 1987]. In the dexterous workspace, all the end-effector orientations around the end-effector gripping point are possible. The remainder of the workspace is called the secondary workspace and is that portion where only limited orientations are possible. A useful indicator of workspace quality is its dexterous fraction. In general it is desirable that this fraction and the workspace volume be as large as possible. A convenient way to illustrate the dexterity and approach properties of a point in the workspace of a robot is a ray graph [Hansen, J.A., 1983]. The ray graph shows the limits of the linear axial travel and orientations of the end-effector gripping point for any desired point.

Robot arm manipulation flexibility refers to the number of possible arm poses to reach a certain point of the workspace. This number corresponds to the acceptable number of inverse solutions of the robot arm kinematic equations. In general as the number of arm joints increases the number of solutions and associated manipulation flexibility increase, but the more complex arm kinematics raise the computation time and make the arm control more difficult. In practice several of these poses are not attainable due to joint limits or other physical constraints. The Jacobian volume index has been introduced [Hsu, M-S., et al., 1987] as a measure of the manipulation flexibility of a robot arm. It is equal to the sum of the volumes of the workspace where one, two, etc., poses are possible, multiplied by the corresponding number of possible poses. For two robot arms with the same workspace the one with the larger index should be more flexible.

Robot arm manipulability may be described as the easiness of changing the position and orientation of the end-effector, at a particular point in the workspace, as a function of the maximum allowable joint velocities [Yoshikawa, T., 1983, 1984, Uchiyama, M., et al., 1983, 1984, Togai, M., 1985]. For small displacements of the joints, at the limits of their velocities, the corresponding velocity vectors of the end-effector gripping point define a volume which may be called the manipulability volume. The larger this volume is the greater the capability of the robot arm is to move and maneuver around that point. The shape of the manipulability volume is a measure of directional uniformity. For example a spherical volume indicates that the end-effector can move with the same easiness in all directions. An ellipsoid volume indicates that there is a favorable direction in which the easiness of movement is at a maximum. It can be shown mathematically that

the manipulability volume is a function of the robot arm Jacobian and becomes proportional to the determinant of the Jacobian for non-redundant robot arms. As a result of this the manipulability volume goes to a minimum when the arm reaches a singularity, which indicates that it looses its ability to move in certain directions. Thus planning robot arm moves through locations of maximum manipulability volumes would make maneuvering of the end-effector easier and keep it away from degenerate poses. This idea of manipulability volume can be extended to force control too [Yoshikawa, T., 1984]. In this case the volume is defined by the force or torque vectors which correspond to the maximum allowable joints actuators forces or torques. An extension of the manipulability is the dynamic manipulability [Yoshikawa, T., 1985, 1986] which is a measure of the manipulability including the effect of robot arm dynamics. In this case the volume is defined by the end-effector acceleration vectors which correspond to the maximum allowable joints actuators forces or torques.

Compliance is a measure of the softness of a robot arm when it interacts with its environment. Its source could be flexibility of the joints transmission systems, the links, the servo drives, or even the base foundation [Good, M.C., et al., 1985]. For the majority of the currently used robot arms the principle source is the joints transmission [Rivin, E.I., 1984, 1985]. A large compliance corresponds to large deflections due to external forces or moments applied to the arm. This results in lower resonant frequencies for the overall arm dynamic response. This could mean significant oscillations during drilling, deburring, force control, etc., applications which require interaction of the end-effector with the environment, or significant accuracy and repeatability errors, especially path tracking errors.

Overshoot and settling time are common classical controls measures of performance [Dorf, R.C., 1967]. In the case of a robot arm they will affect such measures of performance as accuracy and repeatability. If it is desired they can be measured separately using classical controls testing techniques such as step or ramp response.

Most manipulators are designed to be programmed either manually by a human operator or off-line by a computer. In the case of manual teach programming all the manipulator motions are planned relative to taught points. In the case of off-line teach programming all the motions are planned with respect to a real or imaginary reference frame. Manual teach programming is the predominant programming technique used today. This is mainly due to the uncertainties associated with manipulator kinematic and dynamic models making the prediction of manipulator moves in three dimensional space rather difficult.

During operation most manipulators will either move under Point-To-Point (PTP) control mode, stopping everytime they reach a goal point, or under Continuous-Path (CP) control mode, flying by the goal points describing their desired path and stopping only at the last goal point describing the end of the path. Each of these operations generally involves different control algorithms and results in different magnitude of errors. These errors can be described by an accuracy and a precision or repeatability term. These are similar to the target shooting accuracy and precision errors [Todd, D.J., 1986] but now they have to be defined for a three dimensional space six degrees of freedom case (position and orientation).

Since there are two by two different operating conditions at least four different measures of accuracy and repeatability errors may be considered. For example PTP relative accuracy corresponds to Manual Teach Programming Point To Point control operation, CP relative accuracy corresponds to Manual Teach Programming Continuous Path control operation, etc. The Point-To-Point control operation might require the knowledge of the manipulator resolution, which is the minimum displacement in three dimensional space (position and orientation) by which can a manipulator move its end-effector. Since the accuracy and repeatability errors depend on the velocity of the robot arm movement, which does not remain constant during the move, the cycle time will have to be measured and reported each time an accuracy and repeatability test is performed, assuming that a standard test path is used.

Associated with the Point To Point accuracy and repeatability errors are the corresponding distance accuracy and repeatability errors, which represent the errors in moving on a straight line from one point to another. Associated with the Continuous Path accuracy and repeatability errors are the velocity accuracy and repeatability errors, which represent the velocity variation errors in moving on a straight line from one point to another. Since the temperature of the robot arm links and mechanical wear can influence the measured values of these errors a distinction should be made whether these errors were measured before or after a warm-up period and the number of operating hours of the robot should be given.

For each robot arm pose there is a maximum static load (force and moment) which can be carried by a manipulator end-effector without exceeding the limits of the capability of any of its actuators. Since each end-effector gripping point location in its workspace corresponds to several arm poses there must exist a maximum and a minimum static load which can be supported at each point of the workspace. The maximum load may be called the optimum load while the minimum load, at the same point, may be called the critical load [Yap, K.T., 1985, Chong, Y.W., et al., 1985]. If the actual robot arm load is lower than the critical load, at a particular location in the robot workspace,

it should have no problem to be supported by all the joint actuators. If the actual robot arm load though is between the optimum and critical limits load values some of the joint actuators may exceed their capacity limit and will not be able to support the load. A map of these two loads in three dimensional space, called "Load Capacity Map", gives a clear picture of the load carrying capability of a manipulator.

Measuring the time it takes for a manipulator to perform simple basic motions and benchmark test-piece tests provides a convenient method of comparing manipulators [Nof, S.Y., et al., 1980, Collins, K., et al., 1985]. Furthermore it provides a way to estimate the time it will take to perform complex tasks and the possibility to optimize the sequence of operations to minimize the execution time. This of course requires that the benchmark is designed carefully to require a variety of basic robot arm operations and it must be capable to be performed by the majority of the commercially available robots which it is supposed to test. Having established a set of basic motions and benchmark test-piece tests can facilitate the evaluation of various robot languages their programming ease and computation capability.

I.2.B   Identification of Parameters

Knowledge of the robot kinematic mechanism model and in many instances its dynamic model is very significant for proper robot operation. Usually these models are described in parametric form and the values of these parameters may be determined by a combination of experimental testing and system identification analysis (see Figure I.3).

Kinematic parameters are those which specify the characteristics of the kinematic mechanism governing the motion of the robot manipulator. They are usually divided into geometric and non-geometric [Whitney, D.E., et al., 1984]. Geometric parameters are usually considered to be the initial position of the links, when the arm power is turned on, the links lengths, the position and orientation of the joints axes in three dimensional space, the angular or linear displacements of the various joints, etc. Non-geometric parameters are usually considered to be the base foundation deformation, the links and joints deformations, the gears backlash and transmission errors, the deformation of the joints transmission systems, etc. Due to manufacturing and assembly errors and operating conditions heating and wear the values of these parameters change with time and cannot be predicted from blueprints with great accuracy. In the case of manual teach control
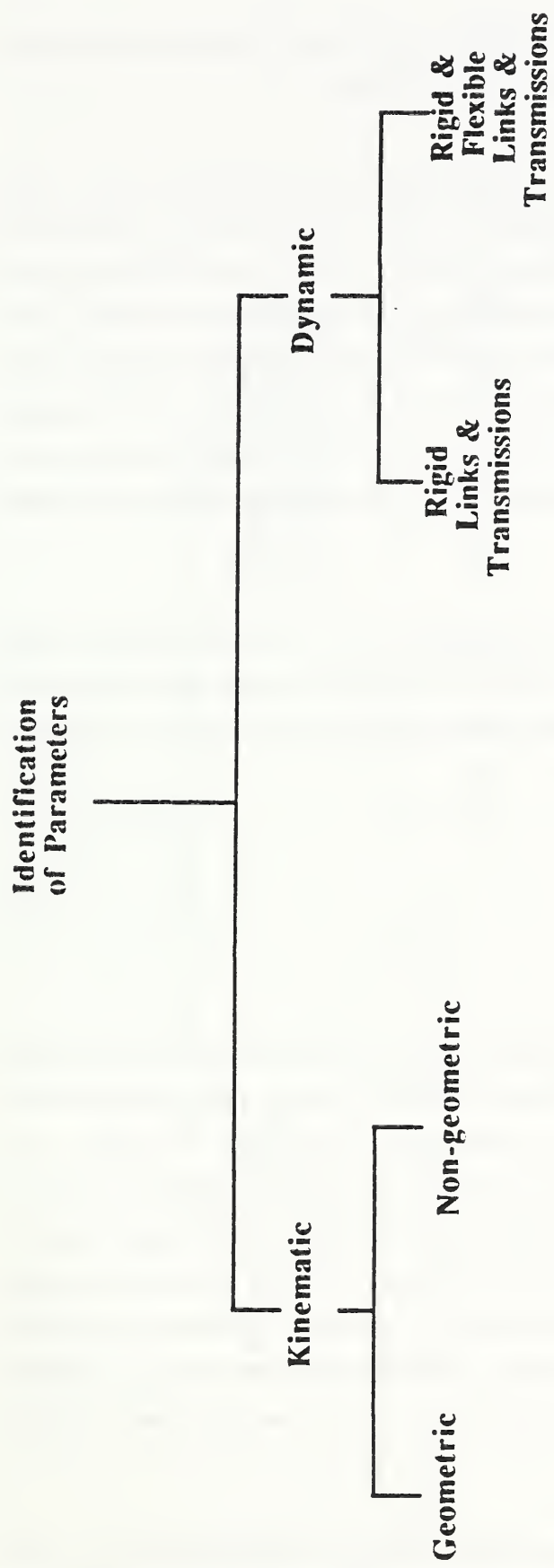
Fig. 1.3

operation only the initial links positions and deformation due to heating and wear has to be known. If off-line control is used all the kinematic parameters have to be known.

Dynamic parameters are those which specify the characteristics of the dynamic system which represents the moving robot arm. Usually the assumption is made that the joints transmission systems and the links are rigid. In that case dynamic parameters are usually considered to be the links masses and centers of gravity, the links mass moment of inertia tensors, the joints static, Coulomb and viscous friction coefficients, etc. The majority of the robot arms use large joint transmission ratios. In that case the dynamics of the robot are dominated by the actuator and the transmission itself. For heavy loads or rapid motions the compliance of the transmissions and/or links has to be included. This can complicate the problem of the dynamic modelling of the robot arm significantly.

Better knowledge of the kinematic and dynamic parameters of a robot arm means a better knowledge of its kinematic and dynamic equations. This could result in better motion control and accuracy, which could make faster operation, off-line programming, incipient failure prediction, defect detection, etc., possible.

I.2.C   Environmental Interaction

The chart of Figure I.4 lists some of the possible effects of a robot operation on the environment and of the environment to the robots. Personal experience has shown that the arm temperature has a significant effect on robot manipulator accuracy due to the thermal expansion of its links. The operation of the robot controller and electrical actuators can induce significant electronic noise to any robot sensor or device sharing the same ground. Electric power supply overvoltage or brown-outs can have a significant effect on robot operation. The first can cause the robot links to jump out of control, while the second removes the power from the link actuators, which are then left to move under the influence of the external loads. Most robot controllers have overvoltage protection circuits which turn off the power and activate the link brakes as soon as they detect such an occurrence.

Hydraulic robots are sensitive to dust which might enter their oil supply and block the flow of oil to parts of their system. If, for instance, a servovalve port is blocked the corresponding joint can

Environmental Interaction

Effects of Robot on Environment

Temp EM Vibration Dust Safety

Sensitivity of Robot to Environmental and Operating Conditions

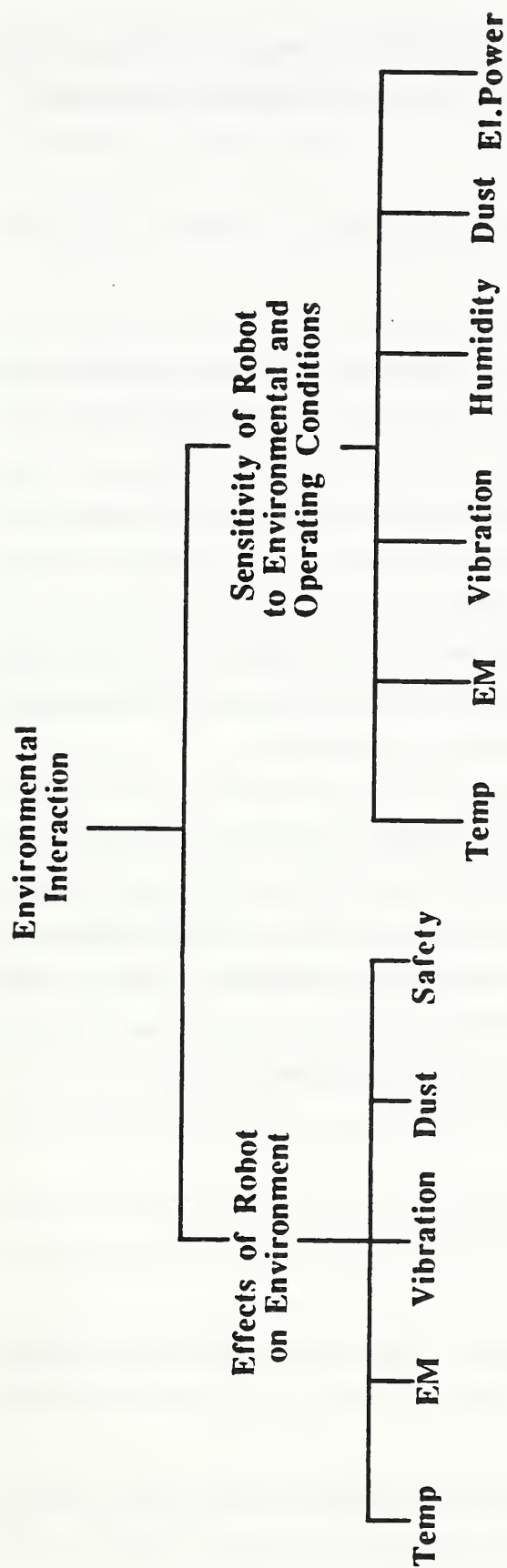Temp EM Vibration Humidity Dust El.Power

Fig. 1.4

move in only one direction. If the servovalve design is such that the other port is blocked open then the joint will continue to move until the energy stored in the hydraulic system is dissipated.

I.3 SUMMARY AND CONCLUSIONS

The characterization of robot arms was discussed. Three types of characterization were considered: 1. Performance 2. Identification of parameters 3. Environmental Interaction. Several robot performance measures were listed and some of them were briefly discussed. These performance measures relate to the load and power requirements and capabilities of a robot arm, controller computer characteristics, movement and dynamic properties, accuracy and repeatability, reliability and safety. Parameters to be identified were distinguished into those of the robot arm kinematic and dynamic mathematical model and were classified according to their nature and whether rigid or flexible links and joints are considered. A list of environmental interaction factors was compiled and some personal experiences on this subject were discussed.

As can be seen from this discussion there are a lot of performance factors which have to be considered before the decision to buy a certain type of robot. Which of these factors are important depends on the requirements of the specific application. The identification of robot parameters is important for robot calibration. A properly calibrated robot controller will always perform better than an uncalibrated one. The influence of environmental factors is important because they can affect safety and the proper operation on tools and sensors attached to the robot body.

I.4 REFERENCES

Beni, G., Hackwood, S., "Recent Advances in Robotics", Section 3, John Wiley & Sons Publishers, 1985.

Chong, Y.W., Kok, L.S., "A New Approach to Evaluating Robot Performance", Proc. Robots 9 Conf., Detroit, Michigan, June 1985, pp. 15.89-15.109.

Collins, K., Palmer, A.J., Rathmill, K., "Development of a European Benchmark for the Comparison of Assembly Robot Programming Systems", Int. Trends in Manufacturing Technology "Robotic Assembly", IFS Ltd. Publ., UK, 1985.

Dorf, R.C., "Modern Control Systems", Addison-Wesley Publ. Co., 1967.

Good, M.C., Sweet, L.M., Strobel, K.L., "Dynamic Models for Control System Design of Integrated Robot and Drive Systems", Jour. of Dynamic Systems, Measurement, and Control, Vol. 107, March 1985, pp. 53-59.

Gupta, K.C., "On the Nature of Robot Workspace", Int. Jour. of Robotics Research, Vol. 5, No. 2, 1986, pp. 112-121.

Gupta, K.C., Roth, B., "Design Considerations for Manipulator Workspace", ASME Jour. of Mechanical Design, Vol. 104, Oct. 1982, pp. 704-711.

Hansen, J.A., "Generation and Evaluation of the Workspace of a Manipulator", M.S. Thesis, Univ. of Illinois at Chicago, 1983.

Hsu, M-S., Kohli, D., "Boundary Surfaces and Accessibility Regions for Regional Structures of Manipulators", Mechanism and Machine Theory, Vol. 22, No.3, 1987, pp. 277-289.

ISO/TC 184/ SC 2, "Manipulating Industrial Robots-Performance Criteria and Related Testing Methods", 2nd Draft Proposal ISO/DP 9283, 1987.

Kohli, D., Hsu, M-S., "The Jacobian Analysis of Workspaces of Mechanical Manipulators", Mechanism and Machine Theory, Vol. 22, No.3, 1987, pp. 265-275.

Kumar, A., Waldron, K.J., "The Workspaces of a Mechanical Manipulator", ASME Jour. of Mechanical Design, Vol.103, No.3, 1981, pp. 665-672.

Nof, S.Y., Paul, R.L., "A Method for Advanced Planning of Assembly by Robots", Proc. of the Soc. of Manuf. Engineers Autofact-West Conf., Anaheim, California, Nov. 1980, pp. 425-435.

RIA, R15.05 Performance Subcommittee, "Proposed American National Standard for Industrial Robots-Evaluation of Static Performance Characteristics for the Comparison of Robots and Robotic Systems", Revision 10-Working Version, 1988.

Rivin, E.I., "Analysis of Structural Compliance for Robot Manipulators", Proc. Int. Conf. on Robotics and Factories of the Future, Charlotte, N. Carolina, Dec. 1984, pp. 262-269.

Rivin, E.I., "Effective Rigidity of Robot Structures: Analysis and Enhancement", Proc. Amer. Contr. Conf., Boston, Massachusetts, June 1985, pp. 381-382.

Roth, B., "Performance Evaluation of Manipulators from a Kinematic Viewpoint", Nat. Bureau of Standards Special Publication 459 "Performance Evaluation of Programmable Robots and Manipulators", Oct. 1976, pp. 39-61.

Todd, D.J., "Fundamentals of Robot Technology", John Wiley & Sons Publ., 1986.

Togai, M., "Manipulability and Sensitivity for Design and Evaluation of Industrial Robots: Kinematic Consideration", Proc. 15th Int. Symp. on Industrial Robots, Tokyo, Japan, Sept. 1985, pp. 865-872.

Uchiyama, M., Hakomori, K., Shimizu, K., "Performance Evaluation of Robotic Arm Mechanisms Using the Jacobian", Proc. 26th Joint Conf. of Automatic Control, Tokyo, Japan, Nov. 1983, pp. 231-232.

Uchiyama, M., Shimizu, K., Hakomori, K., "Performance Evaluation of Manipulators Using the Jacobian and its Application to Trajectory Planning", Proc. 2nd Int. Symp. on Robotics Research, Kyoto, Japan, Aug. 1984, pp. 447-454.

Vijaykumar, R., Waldron, K.J., Tsai, M.J., "Geometric Optimization of Serial Chain Manipulator Structures for Working Volume and Dexterity", Int. Jour. of Robotics Research, Vol. 5, No. 2, 1986, pp.91-103.

Whitney, D.E., Lozinski, C.A., Rourke, J.M., "Industrial Robot Calibration Method and Results", Proc. Int. Comp. in Engineering Conf., Las Vegas, Nevada, Aug. 1984, pp. 92-100.

Yap, K.T., "Robot Evaluation Using Contours of Performance", Proc. Robots 9 Conf., Detroit, Michigan, June 1985, pp. 15.43-15.54.

Yoshikawa, T., "Analysis and Control of Robot Manipulators with Redundancy", Proc. 1st Int. Symp.of Robotics Research, New Hampshire, 1983, pp. 735-746.

Yoshikawa, T., "Manipulability of robotic Mechanisms", Proc. 2nd Int. Symp. on Robotics Research, Kyoto, Japan, Aug. 1984, pp. 439-446.

Yoshikawa, T., "Dynamic Manipulability of Robot Manipulators", Proc. IEEE Int. Conf. on Robotics and Automation, St. Louis, Missouri, Mar. 1985, pp. 1033-1038.

Yoshikawa, T., "Dynamic Manipulability of Articulated Robot Arms", Proc. 15th Int. Symp. on Industrial Robots, Tokyo, Japan, Sept. 1985, pp. 879-886.

Yoshikawa, T., "Analysis and Design of Articulated Robot Arms from the Viewpoint of Dynamic Manipulability", Proc. 3rd Int. Symp. on Robotics Research, Gouvieux, France, 1985, pp. 273-279.

4. TITLE AND SUBTITLE

Robot Characterization Testing

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This document describes the field of robot characterization which is broken into the areas of performance, environmental interaction, and parameter identification. Each area is explored by considering the tests, equipment, and manpower required to characterize the capabilities and performance of robots.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

classification; environmental interaction; parameter identification; performance; robotic characterization; testing.