CHAPTER 27
Industrial Robotics Standards

NICHOLAS G. DAGALAKIS

National Institute of Standards and Technology
Intelligent Systems Division
Gaithersburg, Maryland, U.S.A.

27.1 INTRODUCTION

A standard is defined in [1] as:
"A prescribed set of rules, conditions, or requirements concerning definition of terms; classification of components; specification of materials, performance, or operations; delineation of procedures; or measurement of quantity and quality in describing materials, products, systems, services, or practices."

A good standard under the proper market conditions can help to increase competition, reduce the cost of products and services, break trade barriers, and expand markets. The phenomenal success of the Personal Computer (PC) market is the best example of good architecture and interface standards. An additional benefit is the countless lives which have been saved and accidents which have been prevented by health and safety standards.

Due to space limitation only a brief review of the subject of industrial robot standards can be provided here. The objective is to cover the following three subjects. Provide a brief general description of the U.S. standards setting process. Describe a few of the most important standards. Provide as many relevant references known to the author as possible.

In the U.S., the only organization that is active in writing Industrial Robotics Standards is the Robotic Industries Association (RIA) [2]. RIA is a member of the American National Standards Institute (ANSI) [3], which has generated a legal framework within which the various member associations can write standards. The RIA committees and subcommittees have to follow the rules set by ANSI for standards-writing so that the standards conform to its legal framework. As member of the International Standardization Organization (ISO) [4], ANSI has designated RIA as the U.S. representative to ISO on matters relating to international standards in the field of industrial robots. In order to fulfill its role as the ISO representative, RIA has set up Technical Advisory Groups (TAGs) of experts to advise the RIA standards manager on matters of international standards.

The authority to initiate a standards-writing effort has been given to the RIA Executive Committee for Standards Development, R15, and the RIA Board of Directors. Any interested party can apply to R15 and petition the creation of a standards subcommittee to write a standard on a certain subject. If the petition is accepted, a subcommittee is set up and is assigned the responsibility of preparing the standard. The subcommittee has to follow the ANSI rules of balance and voting [7] to achieve this goal. The procedure is intentionally long to achieve consensus, and it could last for many years. All proposed standards must be approved by the RIA Committee for Standards Approval before they become public.

The Appendix lists all the U.S. and international standards on industrial robots that are known to the author. Also listed in the Appendix are the committee drafts. Although the drafts are not standards, they have been written by field experts and contain useful information. The most important and controversial of the standards have been those related to safety and performance. These two standards will be discussed in the next section.

27.2 SIGNIFICANT STANDARDS ACTIVITIES

27.2.1 U.S. Robot Performance Standard

This standard consists of two volumes. R15.05-1 covers the point-to-point and static performance characteristics [see Appendix, Section U.S.A. Standards: #4], and R15.05-2 covers the path related and dynamics performance characteristics [see Appendix, Section U.S.A. Standards: #6].

The philosophy of the U.S. subcommittee on robot performance standards R15.05 is to write standards which are useful to buyers to help them select the best robot for their specific applications.

TEST LOAD CATEGORY	MASS (KG_f)	AXIAL CG OFFSET (mm)	RADIAL CG & TP OFFSET (mm)	AXIAL TP OFFSET (mm)
1	1.0	20	10	40
2	2.0	40	20	80
3	5.0	60	30	120
4	10.0	80	40	160
5	20.0	100	50	200
6	40.0	120	60	240
7	60.0	140	70	280
8	80.0	160	80	320
9	100.0	180	90	360
10	120.0	200	100	400
11	140.0	220	110	440
12	OPTIONAL			

CG - Center of Gravity
TP - Test Point

Table 27.2.1.1 Standard Test Load Categories
[see Appendix, Section U.S.A. Standards: #6].

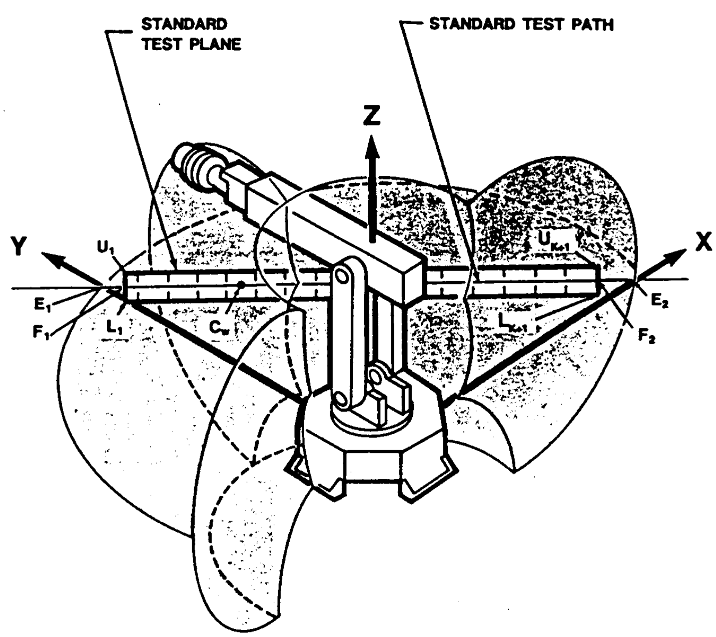

Figure 27.2.1.1 Standard Test Path Location in Working Space
[see Appendix, Section U.S.A. Standards: #4].

The main tools used to force comparability of test results are the use of a standard test path and standard test loads. The test loads are limited to the ones shown in Table 27.2.1.1.

Thus, if two different robots from two different vendors are being considered for an application, and one has a payload capacity of 45 kg and the other 50 kg, they will both be tested under a standard load of 40 kg. The center of gravity of the 40 kg load with its associated support brackets shall have an axial CG offset of 12 cm and a radial CG offset of 6 cm from the mechanical interface coordinate system (mechanical flange and end-effector interface). The standard test path is located on the standard test plane and lies along a reference center line as shown in Figure 27.2.1.1. The standard test path segments can only assume three lengths 200 mm, 500 mm, or 1000 mm. Detailed instructions to determine the position and orientation of the standard test plane and the reference center line are given in the standard. The rules to select the proper size segment for a particular size robot are also given in the standard. Thus, two comparably sized robots from two different vendors will probably have the same size test path.

The performance characteristics used by R15.05-1 are accuracy, repeatability, cycle time, overshoot, settling time, and compliance. This standard allows the vendor to tune operating parameters to optimize the values of desired performance characteristics. For example, they can maximize repeatability at the expense of cycle time. To identify the type of characteristic that is being optimized during a particular test, the standard establishes four performance classes. If class II testing is performed, the robot operates under optimum cycle time conditions. If class III testing is performed, the robot operates under optimum repeatability conditions. Due to the importance of the position repeatability Figure of Merit (FOM), it should be mentioned here that its mathematical definition in this standard is different from that of the ISO standard. These two definitions will be discussed and compared in the next section. Class I testing requires no specific parameter optimization. Class IV testing allows optimizing of robot performance characteristics not covered by classes II and III.

The R15.05-2 standard defines the fundamental path-related performance characteristics and dynamic performance characteristics. Again, to assure comparability of test results, the standard specifies the use of the standard loads shown in Table 27.2.1.1 and the physical point on the end-effector where the path is measured, called the test point (TP). The standard test path is comprised of a rectangle and a circle which are located on the standard test plane. Their dimensions are functions of the three standard lengths 200 mm, 500 mm, or 1000 mm which assures that robots of approximately the same size will probably be tested on the same size paths. The measurement of the path performance characteristics is done on the evaluation planes. The concept of the evaluation planes was established by the committee to eliminate serious sources of inaccuracies in path metrology. All modern metrology systems use a digitizer that records data at discrete instances of time. A path tracking test is repeated several times. The measurement data from each test with the same sequence number are grouped together to calculate the performance characteristics. Unfortunately, since it is impossible to perfectly synchronize the metrology system with the robot controller, the grouping of the measurement data points is in error. The metrology system data from each test are shifted with respect to the robot motion by the amount of time the metrology system and the robot controller are out of phase. This out of phase amount of time varies from test to test. The use of the evaluation planes eliminates the effect of time synchronization. Figure 27.2.1.2 shows the evaluation planes for the rectangular reference path. Evaluation planes are aligned normal to the standard test plane and the corresponding test path. The intersections between the attained paths and the evaluation planes define the points which will be used for the path related figures of merit calculations. Linear interpolation shall be used when an attained (measured) point does not lie on the evaluation plane.

Again, to identify the type of characteristic that is being optimized during a particular test, the standard establishes three performance classes. If class I testing is performed, the robot operates under optimum path following conditions. The performance characteristics used to evaluate path following are path accuracy and path repeatability. It is interesting to note that the committee has defined two types of accuracy, relative and absolute. The relative path accuracy uses a previously measured path as the reference, while the absolute path accuracy, which is at the present optional, uses a mathematically defined path as the reference. The origin and coordinate system of this path are defined through manual teach programming. The objective of the committee is to use this technique to evaluate the manual teach off-line programming ability of the robot. This is a common method of programming robots today. It involves teaching a few points of a part or fixture and then making off-line programmed vector moves from those taught locations.

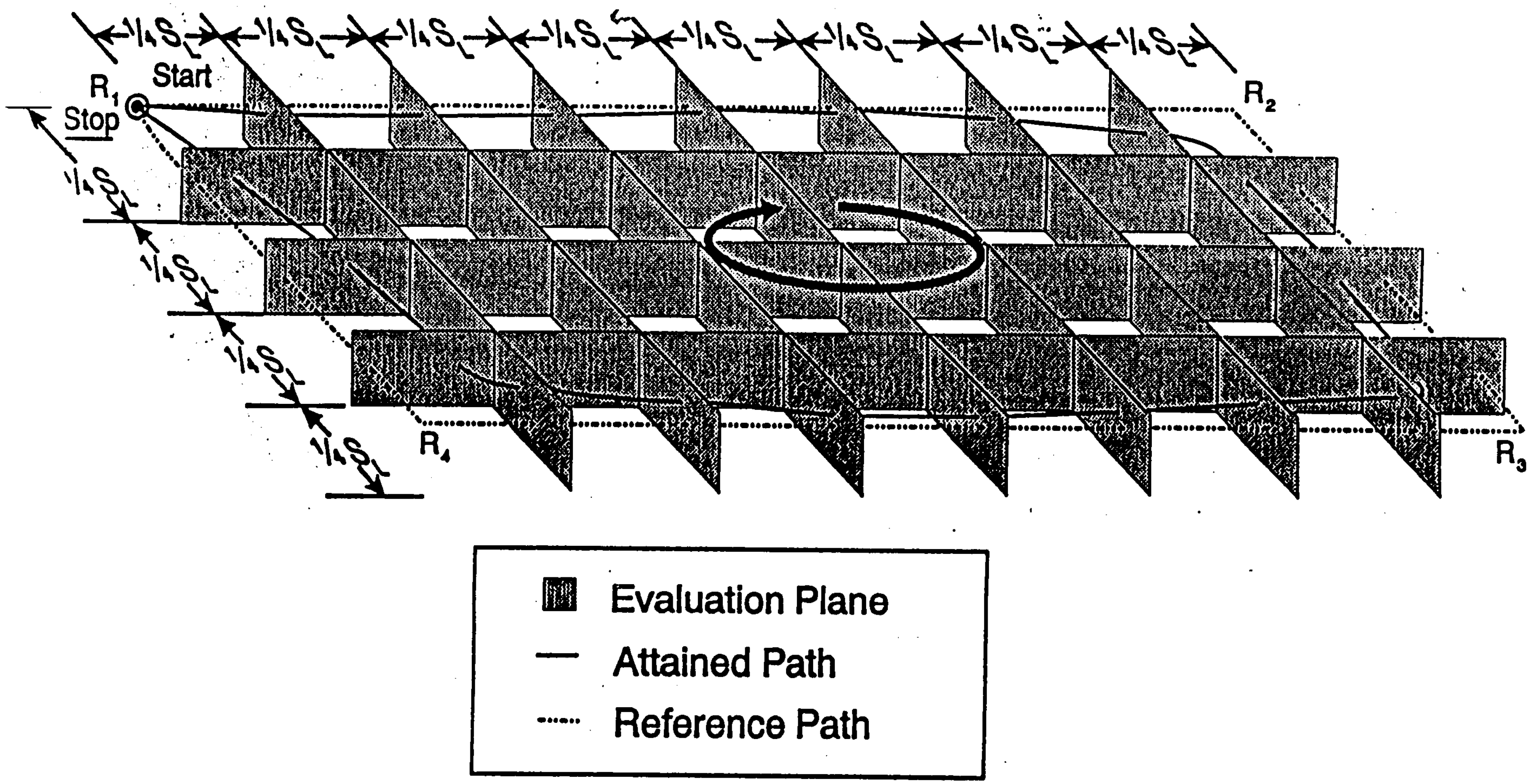

Figure 27.2.1.2 Rectangular reference and attained paths showing evaluation planes [see Appendix, Section U.S.A. Standards: #6].

27.2.2 ISO Robot Performance Standard

As the scope section of this standard states, the specified tests are primarily intended to develop and verify individual robot specifications, prototype testing, or acceptance testing. The philosophy of the ISO sub-committee that developed this standard was not to use it to compare the performance of similar capacity and size robots like that of the US R15.05-1 and R15.05-2. The first version of this standard, ISO 9283:1990, did not even specify standard test paths and test loads. The lengths of the paths and size of the test loads were specified as a percentage of the robot workspace and rated load. Since no two robots have the same workspace and rated load, it was not possible for them to be tested under the same conditions, thus making comparisons very difficult. The U.S. sub-committee complained to ISO about this, and ISO corrected the second version of this standard, which now contains an annex listing standard test path lengths, loads (same as R15.05-2) and velocities. The use of these standards is optional though.

The test planes and test paths of this standard are defined with respect to a cube located inside the workspace of the robot. Various diagonal planes of this cube are used to locate the test planes, paths, and points. This standard specifies tests for the measurement of fourteen performance characteristics. The most commonly used characteristics are those of accuracy and repeatability.

Figure 27.2.2.1 shows the results from a set of robot position performance test data. The robot was commanded to move to the origin of the coordinate frame (rectangle), but instead attained all the positions marked by the triangles. The centroid of these positions, called the barycenter by this standard, is marked by the cross. The cloud of attained positions usually forms an ellipsoid. The lengths and orientations of the principal axes of this ellipsoid provide significant information about the performance of the robot at this position of its workspace. To average the results of this test over a significant portion of the workspace, both the U.S. and ISO standards require that this test be performed at several locations on the test plane and that the data are mixed together. Since the orientation of the ellipsoid is different at each location, the mixing of the data gives a cloud that can be approximated by a sphere. The distance between the commanded position and the barycenter represents the systematic part of the error (bias) and its main contributor is kinematic model errors. The cloud represents the random part of the error caused by electronic noise and friction. The mathematical description of the results of this test is different whether one uses the mathematical formulas or the other standard. Table 27.2.2.2 lists the formulas used to calculate positioning accuracy and repeatability by the two standards. For the same position data, the R15.05-1 calculated accuracy d_{PA} is always greater than the ISO calculated accuracy AP_p. For the same position data, the R15.05-1 calculated repeatability r_{REP} is always smaller than the ISO calculated repeatability RP_l.

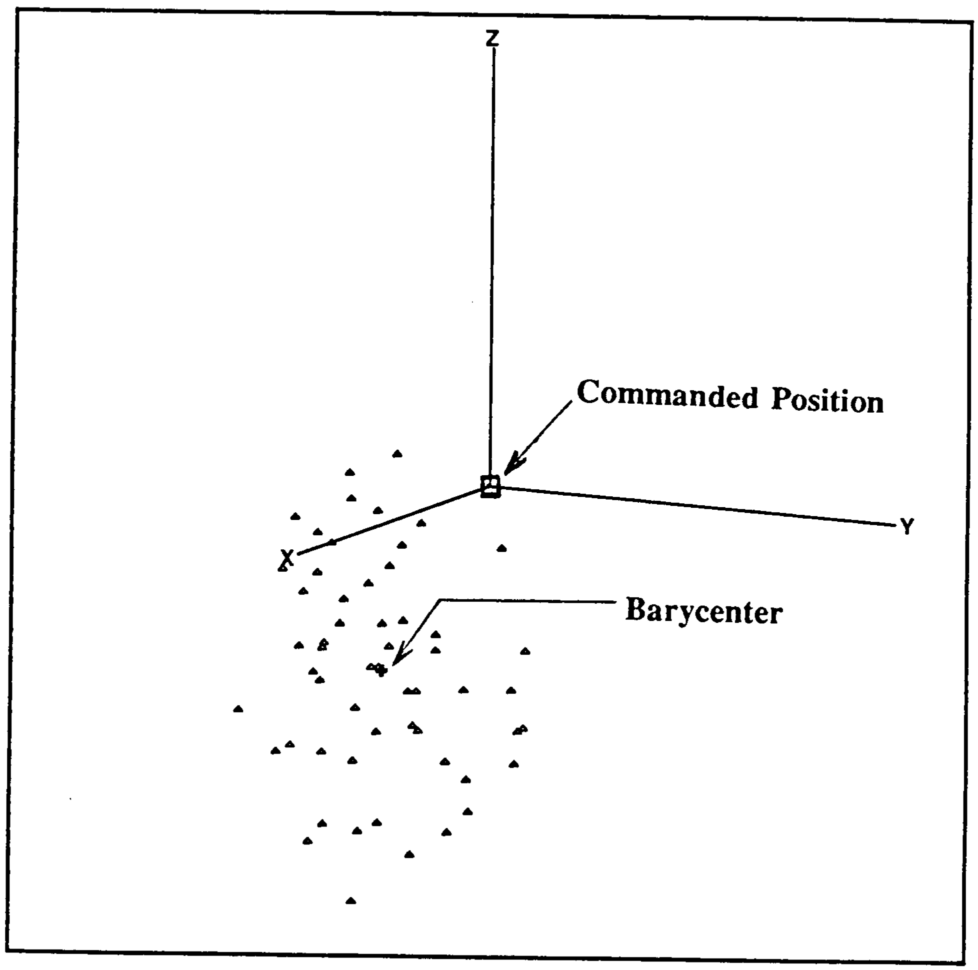

Figure 27.2.2.1 Robot position test data

The path accuracy and repeatability tests specified by this standard created problems from the beginning. The first version of this standard, ISO 9283:1990, did require that a path tracking test be repeated several times and the measurement data from each test with the same sequence number be grouped together for the calculation of the performance characteristics. The U.S. and Chinese robot performance sub-committees complained that grouping the measurement data this way can introduce errors, as is explained in section (27.2.1). The U.S. subcommittee offered the use of the evaluation planes as a solution to this metrological problem. This was partially accepted. The new version of the ISO standard does require the use of calculation planes that are perpendicular to the commanded path. Unfortunately, the new method leaves the number and location of the planes up to the discretion of those who perform the test. Thus, a creative vendor can locate the calculation planes at those locations where the path errors are small and make the robot appear to perform better than it actually does. Comparing path related performance of robots from different robot manufacturers is impossible based on the present test specifications.

Attained Position i: X_{ai}, Y_{ai}, Z_{ai} Commanded Position: X_C, Y_C, Z_C

Mean Attained Position

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} X_{ai},\ \bar{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_{ai},\ \bar{Z} = \frac{1}{N}\sum_{i=1}^{N} Z_{ai}$$

$$l_i = \sqrt{(X_{ai}-\bar{X})^2+(Y_{ai}-\bar{Y})^2+(Z_{ai}-\bar{Z})^2},\ \ \bar{l} = \frac{1}{N}\sum_{i=1}^{N} l_i,\ \ S_l = \sqrt{\frac{\sum_{i=1}^{N}(l_i-\bar{l})^2}{N-1}}$$

ISO 9283

Position Accuracy:

$$AP_p = \sqrt{(\bar{X}-X_c)^2+(\bar{Y}-Y_c)^2+(\bar{Z}-Z_c)^2}$$

Positioning Repeatability:

$$RP_l = \bar{l} + 3S_l$$

ANSI/RIA R15.05-1

Mean Position Accuracy:

$$\bar{d}_{PA} = \frac{1}{N}\sum_{i=1}^{N}\{\sqrt{(X_{ai}-X_c)^2+(Y_{ai}-Y_c)^2+(Z_{ai}-Z_c)^2}\}$$

Positional Repeatability:

$$\bar{r}_{REP} = \bar{l}$$

Table 27.2.2.2 Accuracy and Repeatability Definitions

In the early nineties, several proposals to develop application specific performance standards were submitted to ISO. The most notable were ones for arc welding, another for spot welding, and a third for sealing/adhesive. None of them moved beyond the draft status. At some point, the decision was made to not have separate application specific standards but to make them appendices to ISO 9283. That has not happened yet.

27.2.3 U.S. Robot Safety Standard

Because of safety concerns, this is probably the most popular industrial robots standard in the US [see Appendix, Section U.S.A. Standards: #7]. There are also European Union [6], Japanese and ISO standards [see Appendix, Section International Standards: #4]. The U.S. standard is currently under review. The new version will become available in 1998. The discussion here will concentrate on the new version of the standard.

One of the fastest growing markets of industrial robots is that of used robots. Large industrial users are modernizing their fleet of robots and selling the old used ones. An industry of robot re-manufacturers has developed to re-build and re-sell these robots. The RIA subcommittee that is responsible for the safety standard (R15.06) decided to strengthen the section on ". . . remanufacture and rebuild of robots," to address the safety concerns of users who want to buy these robots. This section contains a detailed list of requirements that must be met by any robot that changes ownership (this assures the healthy growth of this market).

A robot component that will see significant changes after this standard becomes effective is the teach pendant. Ordinary teach pendants are required to be equipped with an enabling device. This is usually a spring loaded switch that must be kept pressed in order to enable any machine motion to take place. Most people call this device a "dead man switch," because it will deactivate when the operator drops the teach pendant in an emergency. Recent research has revealed that some people in a panic state freeze and hold onto an emergency device instead of releasing it. This has prompted the safety committee to require that all teach pendants be equipped with an enabling device that, upon release or maximum compression, stops any robot motion and all associated equipment, which may present a hazard.

The practice of placing the robot controller console anywhere it is convenient on the plant floor will not be acceptable anymore. The location of the operator controls shall be constructed to provide clear visibility of the area where work is performed. The controller and all equipment requiring access during automatic operation shall be located outside the safeguarded space of the robot. This will reduce the likelihood of equipment and machinery being operated when another person is in a hazardous position. Restricted space is the volume of space to which a robot, including the end-effector, workpiece and attachments is restricted by limiting devices. The safeguarded space is defined by safeguards. Safeguards are positioned so as to prevent access to a hazardous location in the workspace.

For personnel safety, the new standard allows the implementation of firm safeguarding procedures or a comprehensive risk assessment study and then installation of the safeguards determined to be appropriate. This study shall be prepared by the user or supplier during the design of the robot workcell and revised and updated any time there is a change that can affect safety. Based on this study, the minimum required safeguard devices and their location shall be determined. Table 27.2.3.1 (given in the standard) clearly illustrates the steps to determine the types of safeguards needed. In this table, PSSD stands for Presence Sensing and Safeguarding Device. The standard provides two very informative tables on safeguarding devices and expected typical performance.

The manual teaching operation brings the teacher into close proximity with the moving robot and all its associated moving equipment thus increasing the possibility of an accident. The standard provides a long list of safety rules which must be followed during this type of operation. Only trained personnel are allowed to perform this operation. Before teaching commences, all safety devices must be tested. The teacher is allowed to enter the safeguarded space, but only under slow speed control mode. This is a required control mode for all controllers that provide for pendant control. The speed specified by the standard is 250 mm/sec (approximately 10 in/sec), and it is measured at the tool center point (TCP). The objective of this requirement is to allow the operator sufficient time to react in an emergency during manual teaching. If additional personnel are allowed into the safeguarded space, they must be furnished with enabling devices, which give them the ability to stop motion independently.

SEVERITY OF INJURY	EXPOSURE	AVOIDANCE	SAFEGUARD CATEGORY AND SELECTION (PERFORMANCE)	EXAMPLES
S2 SERIOUS INJURY Normally irreversible	**F2** Frequent access, long duration	**P2** Scarcely Possible	Category 4 Safeguards Category 3 requirements plus: Follow prescribed safeguarding procedures contained in 6.3 Protection inside safeguarded space Eliminate trapping/pinch hazards Category 4 stopping circuits	PSSD's at pinch points Limiting devices Dual channel control circuitry with full fault detection and output testing
		P1 Possible	Category 3 Safeguards Category 2 requirements plus: Minimize the restricted space Elimination of hazards Category 3 stopping circuits	Limiting devices Design out hazard Dual channel control circuitry with practical fault detection
	F1 Seldom access, short duration	**P2** Scarcely Possible		
		P1 Possible	Category 2 Safeguards Category 1 requirements plus: Perimeter guarding Point of operation guarding Passive safeguarding devices, as appropriate Category 2 stopping circuits	PSSD or fixed barrier Single channel circuitry with periodic testing
S1 SLIGHT INJURY Normally reversible	Robots rated at <2Kg and <250mm/sec		Category 1 Safeguards Awareness means Training Administrative procedures	Awareness: Barriers Signs Signals Single Channel Stopping circuit Well tried components Well tried safety principles

Table 27.2.3.1 Safeguard Selection Decision Matrix

[see Appendix, Section U.S.A. Standards: #7 Revised, Draft 14, 1997-09-30
The reader is advised to consult the standard for the final version of this matrix.
Paragraph 6.3 and Category 2, 3 and 4 stopping circuits, can be found in the standard].

A special mode of operation designed to confirm that a robot's programmed path and process performance are consistent with expectations is defined by the new standard. It is called the "Attended Program Verification" (APV) mode and allows personnel inside the safeguarded space. This is a testing mode when the robot is allowed to move at full programmed speed, which presumably exceeds the slow speed velocity limits. The reason this is allowed is because some operations, like welding, or laying adhesive, depend on speed and require close observation to identify trouble spots. When it is impractical to remotely observe the operation, APV is permitted. A long list of robot safety requirements and user safety rules shall be obeyed during APV.

The work of the operator and maintenance and repair personnel is safeguarded with rules similar to those specified for the teacher. The main difference is that in this case no human body parts are allowed inside the safeguarded space while a robot is in motion. To assist the release of trapped colleagues clear directions shall be provided for the emergency movement without drive power of the robot mechanisms.

CONCLUSIONS

Most of the industrial applications of robots today do not require high accuracy and repeatability. Furthermore, manual teach programming is used for most of these applications, which eliminates the effect of the kinematic mechanism model errors. For that reason, there has not been a great demand for standard performance tests results from the robot manufacturers. The situation is changing though more and more people realize the economic benefits of off-line programming and a hybrid manual-teach-off-line programming technique is growing in popularity. New robotic applications in arc welding, optoelectronic devices assembly, etc., have high performance requirements. These new developments might revive the interest in performance testing. Most users would like to have application specific performance test results. Right now this luxury is only available for a few big buyers.

The first generation of safety standards have been rather easy to comply with. With the passage of time, and after numerous industrial accidents involving robots, the situation is changing. The new version of the robot safety standard is far more stringent, requiring much more effort and expense to achieve compliance. An unexpected consequence of this will probably be the complete replacement of the present generation of robots, which could bring a technological renewal to the industry.

APPENDIX

U.S.A. Standards:

1. "Standard Guide for CLASSIFYING INDUSTRIAL ROBOTS," American Society for Testing and Materials (ASTM) [5], Designation: F 1034-86.
This standard defines methods that may be used to classify industrial robots.

2. "American National Standard for Industrial Robots and Robot Systems - Common Identification Methods for Signal- and Power- Carrying Conductors," American National Standards Institute (ANSI) [3], ANSI/RIA R15.01-1-1990.
This standard defines common identification methods for signal and power carrying conductors applicable to industrial robots and robot systems.

3. "American National Standard for Industrial Robots and Robot Systems - Hand-Held Robot Control Pendants - Human Engineering Design Criteria," American National Standards Institute (ANSI) [3], ANSI/RIA R15.02/1-1990.
This standard defines human factors characteristics for hand-held control devices that accompany industrial robots and industrial robot systems

4. "American National Standard for Industrial Robots and Robot Systems - Point-to-Point and Static Performance Characteristics -Evaluation," American National Standards Institute (ANSI) [3], ANSI/RIA R15.05-1-1990.
This standard defines methods for the static performance evaluation of Industrial Robots. Its main objective is to facilitate comparison based on performance.

5. "American National Standard for Industrial Robots and Robot Systems - Infant Mortality Life Test," Robotic Industries Association (RIA) [2], BSR/RIA R15.05-3-1991.
This standard defines the minimum testing requirements that will qualify a newly manufactured or rebuilt robot to be placed into use without additional testing.

6. "American National Standard for Industrial Robots and Robot Systems - Path-Related and Dynamic Performance Characteristics -Evaluation," American National Standards Institute (ANSI) [3], ANSI/RIA R15.05-2-1992.
This standard defines methods for the dynamic performance evaluation of Industrial Robots. Its main objective is to facilitate comparison based on performance.

7. "American National Standard for Industrial Robots and Robot Systems-Safety Requirements," American National Standards Institute (ANSI) [3], ANSI/RIA R15.06-1992.
This was the first version of the Industrial Robots safety standard. A revision of this standard was initiated a few years ago which resulted in significant changes of the original standard. The new version will probably become available to the public sometime in 1998.

International Standards:

1. "Manipulating industrial robots - Coordinate systems and motions," International Standardization Organization (ISO) [4], 9787, First edition 1990-12-01.
This standard defines and specifies three robot coordinate systems and also gives the axis nomenclature. A revision of this standard was initiated a few years ago. The new version will probably become available to the public sometime in 1997.

2. "Manipulating industrial robots - Performance criteria and related test methods," International Standardization Organization (ISO) [4], 9283, First edition 1990-12-15.
This standard describes methods of specifying and testing several performance characteristics of manipulating industrial robots. A revision of this standard was initiated a few years ago which has resulted in significant changes of the original standard. The new version will probably become available to the public sometime in 1998.

3. "Manipulating industrial robots - Presentation of characteristics," International Standardization Organization (ISO) [4], 9946, First edition 1991-02-15.
This standard specifies requirements for how characteristics of robots shall be presented by the manufacturer.

4. "Manipulating industrial robots - Safety," International Standardization Organization (ISO) [4], 10218, First edition 1992-01-15.

This standard provides guidance on the safety considerations for the design, construction, programming, operation, use, repair, and maintenance of manipulating industrial robots and robot systems.

Committee Drafts:

1. "Manipulating industrial robots - Vocabulary," Revision of ISO/TR 8373:1988, Draft International Standard ISO/DIS 8373, 1993.
Provides a list of terms most commonly used for industrial robots. The terms are briefly defined or explained.

2. "Manipulating industrial robots - Mechanical interfaces - Part 1: Circular (form A)," Revision of ISO 9409-1:1988, Committee Draft ISO/CD 9409-1, 1992-09-21.
This Committee Draft (CD) defines the main dimensions, designation and markings for the circular mechanical interface of the manipulator end-effector.

3. "Manipulating industrial robots - Mechanical interfaces - Part 2: Cylindrical shafts," Committee Draft ISO/CD 9409-2, 1992-09-21.
This Committee Draft (CD) defines the main dimensions, designation and markings for the shaft mechanical interface of the manipulator end-effector.

4. "Manipulating industrial robots - Automatic end-effector exchange systems - Vocabulary and presentation of characteristics," Committee Draft ISO/CD 11-593, 1992-06.
This Committee Draft (CD) defines the terms which are necessary to describe automatic end-effector exchange systems.

5. "Manipulating industrial robots - An overview of test equipment and metrology methods for robot performance evaluation in accordance with ISO 9283," Committee Draft Technical Report ISO/DTR 13309, 1994-03.
This Committee Draft Technical Report (DTR) provides information on the state of the art metrology instruments for the testing and calibration of industrial robots.

6. "Manipulating industrial robots - Vocabulary of object handling with end-effectors and of characteristics of grasp-type grippers," Committee Draft ISO/CD 14539, 1996.

This Committee Draft (CD) defines the terms which are necessary to describe object handling.

REFERENCES

1. "National Policy on Standards for the United States and a Recommended Implementation Plan," National Standards Policy Advisory Committee, Washington, D.C., Dec., 1978, p.6.

2. Robotic Industries Association, 900 Victors Way/P.O. Box 3724, Ann Arbor, MI 48106.

3. American National Standards Institute, 11 West 42ND St., New York, New York, 10036.

4. International Organization for Standardization, Case postale 56. CH-1211 Geneve 20. Switzerland.

5. American Society for Testing and Materials (ASTM), 1916 Race St., Philadelphia, Pa. 19103, U.S.A.

6. "Manipulating industrial robots - Safety," European Standard, EN 775:1992, October 1992.

7. ANSI Board Standards Review, "Procedures for the Development and Coordination of American National Standards".

Table 27.2.3.1 Safeguard Selection Decision Matrix

[see Appendix, Section U.S.A. Standards: #7 Revised, Draft 14, 1997-09-30
The reader is advised to consult the standard for the final version of this matrix.
Paragraph 6.3 and Category 2, 3 and 4 stopping circuits, can be found in the standard].

Table 27.2.1.1 Standard Test Load Categories

[see Appendix, Section U.S.A. Standards: #6].

Figure 27.2.1.1 Standard Test Path Location in Working Space

[see Appendix, Section U.S.A. Standards: #4].

Figure 27.2.1.2 Rectangular reference and attained paths showing evaluation planes

[see Appendix, Section U.S.A. Standards: #6].

Figure 27.2.2.1 Robot position test data

Commanded Position **Barycenter**

Attained Position i: X_{ai}, Y_{ai}, Z_{ai} Commanded Position: X_c, Y_c, Z_c

Mean Attained Position

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_{ai},\ \overline{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_{ai},\ \overline{Z} = \frac{1}{N}\sum_{i=1}^{N} Z_{ai}$$

$$l_i = \sqrt{(X_{ai}-\overline{X})^2+(Y_{ai}-\overline{Y})^2+(Z_{ai}-\overline{Z})^2},\ \ \bar{l} = \frac{1}{N}\sum_{i=1}^{N} l_i,\ \ S_l = \sqrt{\frac{\sum_{i=1}^{N}(l_i-\bar{l})^2}{N-1}}$$

ISO 9283	**ANSI/RIA R15.05-1**
Position Accuracy:	Mean Position Accuracy:
$AP_p = \sqrt{(\overline{X}-X_c)^2+(\overline{Y}-Y_c)^2+(\overline{Z}-Z_c)^2}$	$\overline{d}_{PA} = \frac{1}{N}\sum_{i=1}^{N}\{\sqrt{(X_{ai}-X_c)^2+(Y_{ai}-Y_c)^2+(Z_{ai}-Z_c)^2}\}$
Positioning Repeatability:	Positional Repeatability:
$RP_l = \bar{l} + 3S_l$	$\bar{r}_{REP} = \bar{l}$

Table 27.2.2.2 Accuracy and Repeatability Definitions

Abstract

A brief description of the industrial robots related standards activities at the national and international level is presented. The robot performance and safety standards are discussed in greater detail. A thorough list of national and international standards and committee drafts is provided with a brief description of each one of them.

Key Words

Industrial Robots, Standards, Performance, Safety