INTERNATIONAL STANDARD

ISO 9283

Second edition
1998-04-01

Manipulating industrial robots — Performance criteria and related test methods

Robots manipulateurs industriels — Critères de performance et méthodes d'essai correspondantes

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Contents

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Annex

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. In accordance with ISO/IEC Directives they are approved if two-thirds of the votes cast by the P-members of the technical committee or sub-committee are in favour, and not more than one-quarter of the total number of votes cast are negative.

International Standard ISO 9283 was prepared by Technical Committee ISO/TC 184, *Industrial automation systems and integration*, Subcommittee SC 2, *Robots for manufacturing environment*.

This second edition cancels and replaces the first edition (ISO 9283:1990 and Amendment 1:1991), of which it constitutes a technical revision.

Annex A forms an integral part of this International Standard. Annexes B and C are for information only.

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Introduction

ISO 9283 is part of a series of International Standards dealing with manipulating industrial robots. Other International Standards cover such topics as safety, general characteristics, coordinate systems, terminology, and mechanical interfaces. It is noted that these International Standards are interrelated and also related to other International Standards.

ISO 9283 is intended to facilitate understanding between users and manufacturers of robots and robot systems. It defines the important performance characteristics, describes how they shall be specified and recommends how they should be tested. An example of how the test results should be reported is included in Annex C of this International Standard. The characteristics for which test methods are given in this International Standard are those considered to affect robot performance significantly.

It is intended that the user of this International Standard selects which performance characteristics are to be tested, in accordance with his own specific requirements.

The tests described in this International Standard may be applied in whole or in part, depending upon the robot type and requirements.

The core part of ISO 9283 deals with testing of individual characteristics. Specific parameters for comparison testing is dealt with in Annex A (normative) for pose-to-pose characteristics and path characteristics.

Annex B (informative) of this International Standard provides guidance for selection of tests for typical applications.

Annex C (informative) of this International Standard provides a recommended format of the test report including the minimum required information and the summary of the test results.

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Manipulating industrial robots — Performance criteria and related test methods

1 Scope

This International Standard describes methods of specifying and testing the following performance characteristics of manipulating industrial robots:

- pose accuracy and pose repeatability;
- multi-directional pose accuracy variation;
- distance accuracy and distance repeatability;
- position stabilization time;
- position overshoot;
- drift of pose characteristics;
- exchangeability;
- path accuracy and path repeatability;
- path accuracy on reorientation
- cornering deviations;
- path velocity characteristics;
- minimum posing time;
- static compliance;
- weaving deviations.

This International Standard does not specify which of the above performance characteristics are to be chosen for testing a particular robot. The tests described in this International Standard are primarily intended for developing and verifying individual robot specifications, but can also be used for such purposes as prototype testing, type testing or acceptance testing.

To compare performance characteristics between different robots, as defined in this International Standard, the following parameters have to be the same: test cube sizes, test loads, test velocities, test paths, test cycles, environmental conditions.

Annex A provides parameters specific for comparison testing of pose-to-pose characteristics and path characteristics.

This International Standard applies to all manipulating industrial robots as defined in ISO 8373. However, for the purpose of this International Standard the term "robot" means manipulating industrial robot.

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2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All International Standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 8373:1994, *Manipulating industrial robots — Vocabulary.*

ISO 9787:1990, *Manipulating industrial robots — Coordinate systems and motions.*

ISO 9946:1991, *Manipulating industrial robots — Presentation of characteristics.*

3 Definitions

For the purpose of this International Standard, the definitions given in ISO 8373 and the following definitions apply.

3.1 cluster: Set of measured points used to calculate the accuracy and the repeatability characteristics (example shown diagrammatically in figure 8).

3.2 barycentre: For a cluster of *n* points, defined by their coordinates (x_j — y_j — z_j), the barycentre of that cluster of points is the point whose coordinates are the mean values $\bar{x}$, $\bar{y}$, and $\bar{z}$ calculated by formulae given in 7.2.1.

3.3 measuring dwell: Delay at the measurement point prior to recording data (e.g. time between control signal "in position" and the "start measuring" of the measuring device).

3.4 measuring time: Time elapsed when measurements are recorded.

4 Units

Unless otherwise stated, all dimensions are as follows:

— length in millimetres .... (mm)
— angle in radians or degrees............................. (rad) or (°)
— time in seconds .... (s)
— mass in kilograms .... (kg)
— force in newtons .... (N)
— velocity in metres per second...................... (m/s),
degrees per second .... (°/s) or
radians per second .... (rad/s)

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5 Abbreviations and symbols

For the purposes of this International Standard, the following abbreviations and symbols apply.

5.1 Basic abbreviations

A	Accuracy
R	Repeatability
v	Variation
F	Fluctuation
d	Drift
P	Pose
D	Distance
T	Path (trajectory)
V	Velocity
W	Weaving
E	Exchangeability

5.2 Quantities

a, b, c	Orientation (angular components) about the *x, y, and z*-axis
x, y, z	Linear coordinates along the *x-, y-, z*-axis
n	Number of measurement cycles
m	Number of measurement points along the path
S	Standard deviation
D	Distance between two points
l	Distance between the attained pose and the barycentre of the attained poses
v	Path velocity
AP	Pose accuracy
RP	Pose repeatability
vAP	Multi-directional pose accuracy variation
AD	Distance accuracy
RD	Distance repeatability
t	Position stabilization time
OV	Position overshoot
dAP	Drift of pose accuracy
dRP	Drift of pose repeatability
AT	Path accuracy
RT	Path repeatability
CR	Cornering round-off error
CO	Cornering overshoot
AV	Path velocity accuracy
RV	Path velocity repeatability

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FV	Path velocity fluctuation
WS	Weaving stroke error
WF	Weaving frequency error

5.3 Indices

a, b, c	Indicates an orientation characteristic about the *x*-, *y*-, *z*-axis
x, y, z	Indicates a positioning characteristic along the *x*-, *y*-, *z*-axis
c	Command
i	Indicates the *i*-th abscissa
j	Indicates the *j*-th cycle
k	Indicates the *k*-th direction
h	Indicates the *h*-th direction
1,2	Indicates the pose number 1,2 ....
e	Corner point (edge)
g	Point where the robot performance falls within the specified path characteristics
p	Position

5.4 Other symbols

C_1 to C_8	Corners of the test cube
E_1 to E_4	Corners of the rectangular plane for the measurement of path characteristics
G	The barycentre of a cluster of attained poses
O_c	Origin of the measurement system coordinates

NOTE 1 — Further symbols are explained in the respective subclauses.

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6 Performance testing conditions

6.1 Robot mounting

The robot shall be mounted in accordance with the manufacturer's recommendations.

6.2 Conditions prior to testing

The robot shall be completely assembled and fully operational. All necessary levelling operations, alignment procedures and functional tests shall be satisfactorily completed.

The tests shall be preceded by an appropriate warm-up operation if specified by the manufacturer, except for the test of drift of pose characteristics which shall start from cold condition.

If the robot has facilities for adjustment by the user that can influence any of the tested characteristics, or if characteristics can be recorded only with specific functions (e.g. calibration facility where poses are given by off-line programming), the condition used during the test shall be specified in the test report and (where relevant for individual characteristics) shall be kept constant during each test.

6.3 Operating and environmental conditions

The performance characteristics as specified by the manufacturer and determined by the related test methods in this International Standard, are valid only under the environmental and normal operating conditions as stipulated by the manufacturer.

6.3.1 Operating conditions

The normal operating conditions used in the tests shall be as stated by the manufacturer.

Normal operating conditions include, but are not limited to, requirements for electrical, hydraulic and pneumatic power, power fluctuations and disturbances, maximum safe operating limits (see ISO 9946).

6.3.2 Environmental conditions

6.3.2.1 General

The environmental conditions used in the tests shall be as stated by the manufacturer, subject to the requirements of 6.3.2.2.

Environmental conditions include temperature, relative humidity, electromagnetic and electrostatic fields, radio frequency interference, atmospheric contaminants, and altitude limits.

6.3.2.2 Testing temperature

The ambient temperature (θ) of the testing environment should be 20° C. Other ambient temperatures shall be stated and explained in the test report. The testing temperature shall be maintained at

$(\theta \pm 2)°$ C

The robot and the measuring instruments should have been in the test environment long enough (preferably overnight) so that they are in a thermally stable condition before testing. They shall be protected from draughts and external thermal radiation (e.g. sunlight, heaters).

6.4 Displacement measurement principles

The measured position and orientation data (x_j, y_j, z_j, a_j, b_j, c_j) shall be expressed in a base coordinate system (see ISO 9787), or in a coordinate system defined by the measurement equipment.

If the robot command poses and paths are defined in another coordinate system (e.g. by off-line programming) than the measuring system, the data must be transferred to one common coordinate system. The relationship between the coordinate systems shall be established by measurement. In this case the measurement poses given in 7.2.1 shall not be used as reference positions for the transformation data. Reference and measurement points should be inside of the test cube and should be as far away from each other as possible (e.g. if P_1 to P_5 are measurement points, C_3, C_4, C_5, C_6 may be used).

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For directional components of the performance criteria, the relationship between the base coordinate system and the selected coordinate system shall be stated in the test results.

The measurement point shall lie at a distance from the mechanical interface as specified by the manufacturer. The position of this point in the mechanical interface coordinate system (see ISO 9787) shall be recorded (see figure 7).

The sequence of rotation used when calculating the orientation deviation should be in a way so that the orientation can be continuous in value. This is independent if the rotation is about moving axes (navigation angles or Euler angles), or rotation about stationary axes.

Unless otherwise specified, the measurements shall be taken after the attained pose is stabilized.

6.5 Instrumentation

For path characteristics, overshoot and pose stabilization measurements, the dynamic characteristics of the data acquisition equipment (e.g. sampling rate) shall be high enough to ensure that an adequate representation of the characteristics being measured is obtained.

The measuring instruments used for the tests shall be calibrated and the uncertainty of measurement shall be estimated and stated in the test report. The following parameters should be taken into account:

- instrumentation errors;
- systematic errors associated with the method used;
- calculation errors.

The total uncertainty of measurement shall not exceed 25 % of the magnitude of the characteristic under test.

6.6 Load to the mechanical interface

All tests shall be executed with a test load equal to 100 % of rated load conditions, i.e. mass, position of centre of gravity, moments of inertia, according to the manufacturer's specification. The rated load conditions shall be specified in the test report.

To characterize robots with load dependent performances, additional optional tests can be made with the mass of rated load reduced to 10 % as indicated in table 1 or some other value as specified by the manufacturer.

When a part of the measuring instrumentation is attached to the robot, its mass and position shall be considered as part of the test load.

Figure 1 shows an example of test end effector with CG (centre of gravity) and TCP (tool centre point) offsets. The TCP is the measurement point (MP) during the test. The measurement point position shall be specified in the test report.

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Table 1 - Test loads

Characteristics to be tested	**Load to be used**	
	100 % of rated load (X = mandatory)	**The mass of rated load reduced to 10 %** (O = optional)
Pose accuracy and pose repeatability	X	O
Multi-directional pose accuracy variation	X	O
Distance accuracy and distance repeatability	X	—
Position stabilization time	X	O
Position overshoot	X	O
Drift of pose characteristics	X	—
Exchangeability	X	O
Path accuracy and path repeatability	X	O
Path accuracy on reorientation	X	O
Cornering deviations	X	—
Path velocity characteristics	X	O
Minimum posing time	X	O
Static compliance	—	See clause 10
Weaving deviations	X	O

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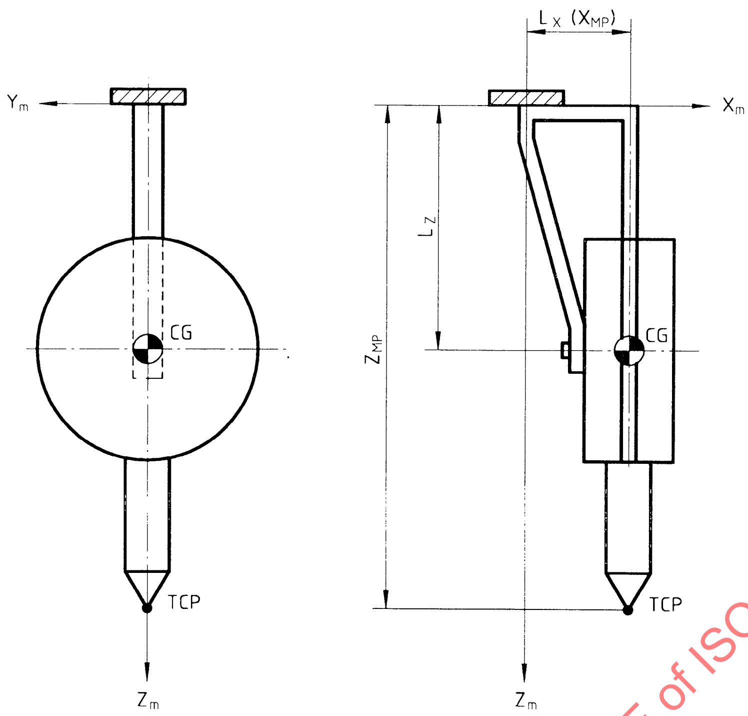

Figure 1 - An example of test end effector

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6.7 Test velocities

All pose characteristics shall be tested at the maximum velocity achievable between the specified poses, i.e. with the velocity override set to 100 %, in each case. Additional tests could be carried out at 50 % and/or 10 % of this velocity.

For path characteristics, the tests shall be conducted at 100 %, 50 %, and 10 % of rated path velocity as specified by the manufacturer for each of the characteristics tested (see table 3). Rated path velocity shall be specified in the test report. The velocity specified for each test depends on the shape and size of path. The robot shall be able to achieve this velocity over at least 50 % of the length of the test path. The related performance criteria shall be valid during this time.

It shall be reported if the velocity has been specified in pose-to-pose mode or continuous path mode, if selectable.

A summary of the test velocities is given in tables 2 and 3.

Table 2 - Test velocities for pose characteristics

Characteristics to be tested	Velocity	
	100 % of rated velocity (X = mandatory)	**50 % or 10 % of rated velocity** (O = optional)
Pose accuracy and pose repeatability	X	O
Multi-directional pose accuracy variation	X	O
Distance accuracy and repeatability	X	O
Position stabilization time	X	O
Position overshoot	X	O
Drift of pose characteristics	X	—
Exchangeability	X	O
Minimum posing time	See clause 9 and table 20	

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Table 3 - Test velocities for path characteristics

Characteristics to be tested	Velocity		
	100 % of rated path velocity (X = mandatory)	**50 % of rated path velocity** (X = mandatory)	**10 % of rated path velocity** (X = mandatory)
Path accuracy and path repeatability	X	X	X
Path accuracy on reorientation	X	X	X
Cornering deviations	X	X	X
Path velocity characteristics	X	X	X
Weaving deviations	X	X	X

6.8 Definitions of poses to be tested and paths to be followed

6.8.1 Objective

This subclause describes how five suitable positions are located in a plane placed inside a cube within the working space. It also describes test paths to be followed. When robots have a range of motion along one axis, small with respect to the other, replace the cube by a rectangular parallelepiped.

6.8.2 Location of the cube in the working space

A single cube, the corners of which are designated C_1 to C_8 (see figure 2), is located in the working space with the following requirements fulfilled:

- the cube shall be located in that portion of the working space with the greatest anticipated use;
- the cube shall have the maximum volume allowable with the edges parallel to the base coordinate system;

A figure showing the location of the cube used in the working space shall be included in the test report.

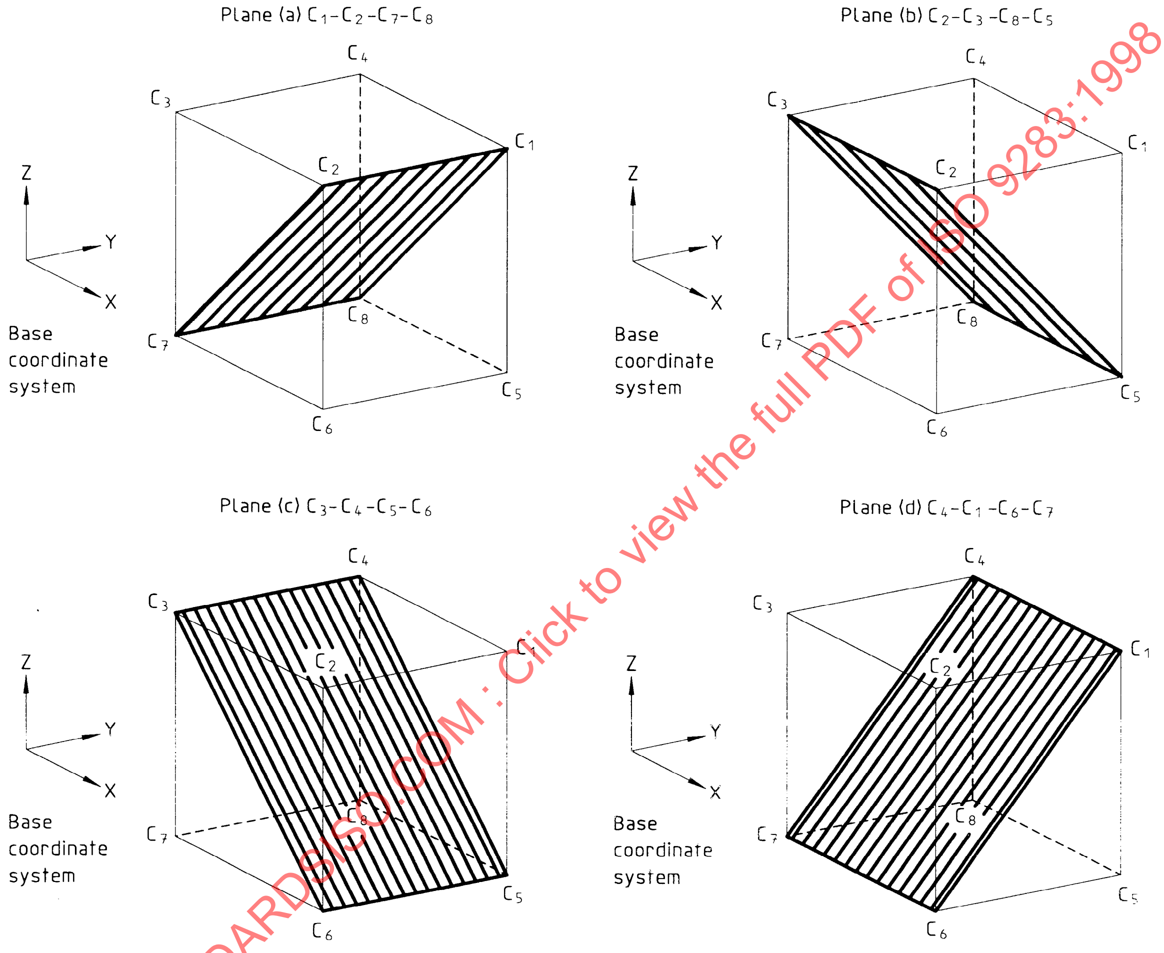

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Figure 2 - Cube within the working space

6.8.3 Location of the planes to be used within the cube

One of the following planes shall be used for pose testing, for which the manufacturer has declared the values in the data sheet to be valid:

a) C_1 - C_2 - C_7 - C_8

b) C_2 - C_3 - C_8 - C_5

c) C_3 - C_4 - C_5 - C_6

d) C_4 - C_1 - C_6 - C_7

The test report shall specify which of the four planes has been tested.

6.8.4 Poses to be tested

Five measurement points are located on the diagonals of measuring plane and correspond to (P_1 to P_5) in the selected plane transformed by the axial (X_{MP}) and radial (Z_{MP}) measurement point offset. The points P_1 to P_5 are the positions for the wrist reference point of the robot.

The measurement plane is parallel to the selected plane, see figures 3 and 7.

The test poses shall be specified in base coordinates (preferred) and/or joint coordinates, as specified by the manufacturer.

P_1 is the intersection of the diagonals and is the centre of the cube. The points P_2 to P_5 are located at a distance from the ends of the diagonals equal to (10 ± 2) % of the length of the diagonal (see figure 4). If this is not possible then the nearest point chosen on the diagonal shall be reported.

The poses to be used for pose characteristics are given in table 4.

Table 4 - Poses to be used for pose characteristics

Characteristics to be tested	Poses				
	P_1	P_2	P_3	P_4	P_5
Pose accuracy and pose repeatability	X	X	X	X	X
Multi-directional pose accuracy variation	X	X	—	X	—
Distance accuracy and distance repeatability	—	X	—	X	—
Position stabilization time	X	X	X	X	X
Position overshoot	X	X	X	X	X
Drift of pose characteristics	X	—	—	—	—
Exchangeability	X	X	X	X	X

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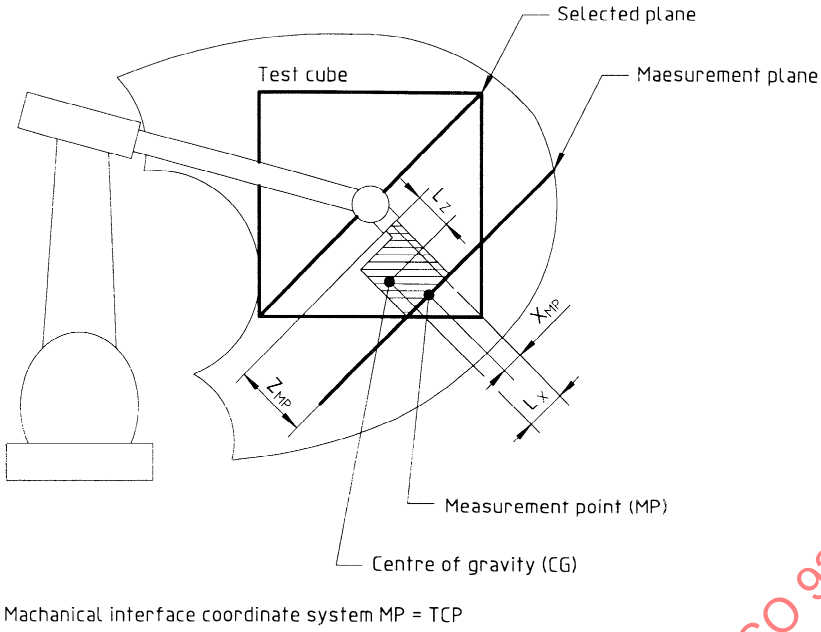

Figure 3 - Selected plane and measurement plane

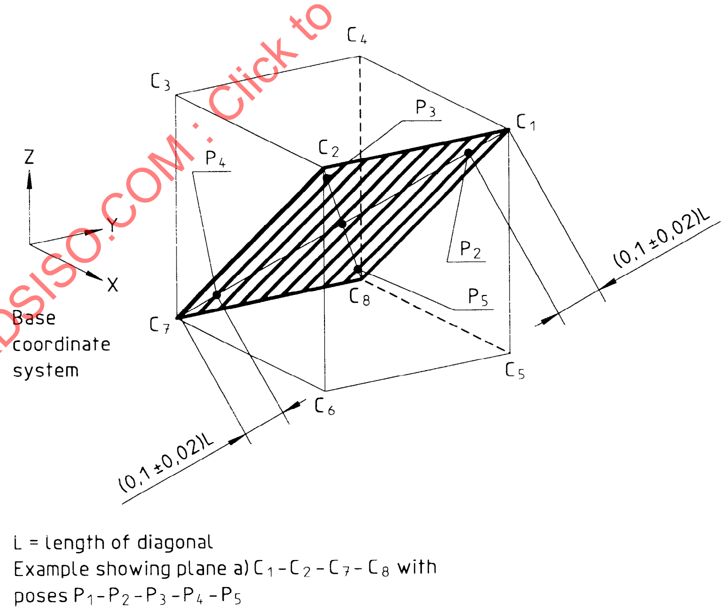

Figure 4 - Poses to be used

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6.8.5 Movement requirements

All joints shall be exercised during movement between all poses.

During the test care should be taken not to exceed the manufacturing operation specification.

6.8.6 Paths to be followed

6.8.6.1 Location of the test path

The cube described in 6.8.2 shall be used.

The test path shall be located on one of the four planes shown in figure 5. For six axis robots, plane 1 shall be used unless otherwise specified by the manufacturer. For robots with less than six axes the plane to be used shall be as specified by the manufacturer.

During the measurement of the path characteristics the centre of the mechanical interface should lie in the plane selected (see figure 3), and its orientation should be kept constant to that plane.

6.8.6.2 Shapes and sizes of the test paths

Figure 6 gives an example of the position of a linear path, a rectangular path and two circular paths in one of four available test planes.

The shape of the test path should be linear or circular except for cornering deviations (see 8.5 and figure 22). If paths of other shapes are used they shall be as specified by the manufacturer and added to the test report.

For a linear path in the diagonal of the cube, the length of the path shall be 80 % of the distance between opposite corners of the selected plane. An example is the distance P_2 to P_4 in figure 6.

Another linear path P_6 to P_9 can be used for a reorientation test, described in 8.4.

For the circular path test, two different circles should be tested. See figure 6.

The diameter of the large circle shall be 80 % of the length of the side of the cube. The centre of the circle shall be P_1 .

The small circle should have a diameter of 10 % of the large circle in the plane. The centre of the circle shall be P_1 . See figure 6.

A minimum number of command poses shall be used. The number and location of the command poses and the method of programming (teach programming or numerical data entry through manual data input or off-line programming) shall be specified in the test report.

For a rectangular path, the corners are denoted E_1, E_2, E_3 and E_4, each of which is at a distance from its respective corner of the plane equal to (10 ± 2) % of a diagonal of the plane. An example is shown in figure 6 in which P_2, P_3, P_4 and P_5 coincide with E_1, E_2, E_3 and E_4 respectively.

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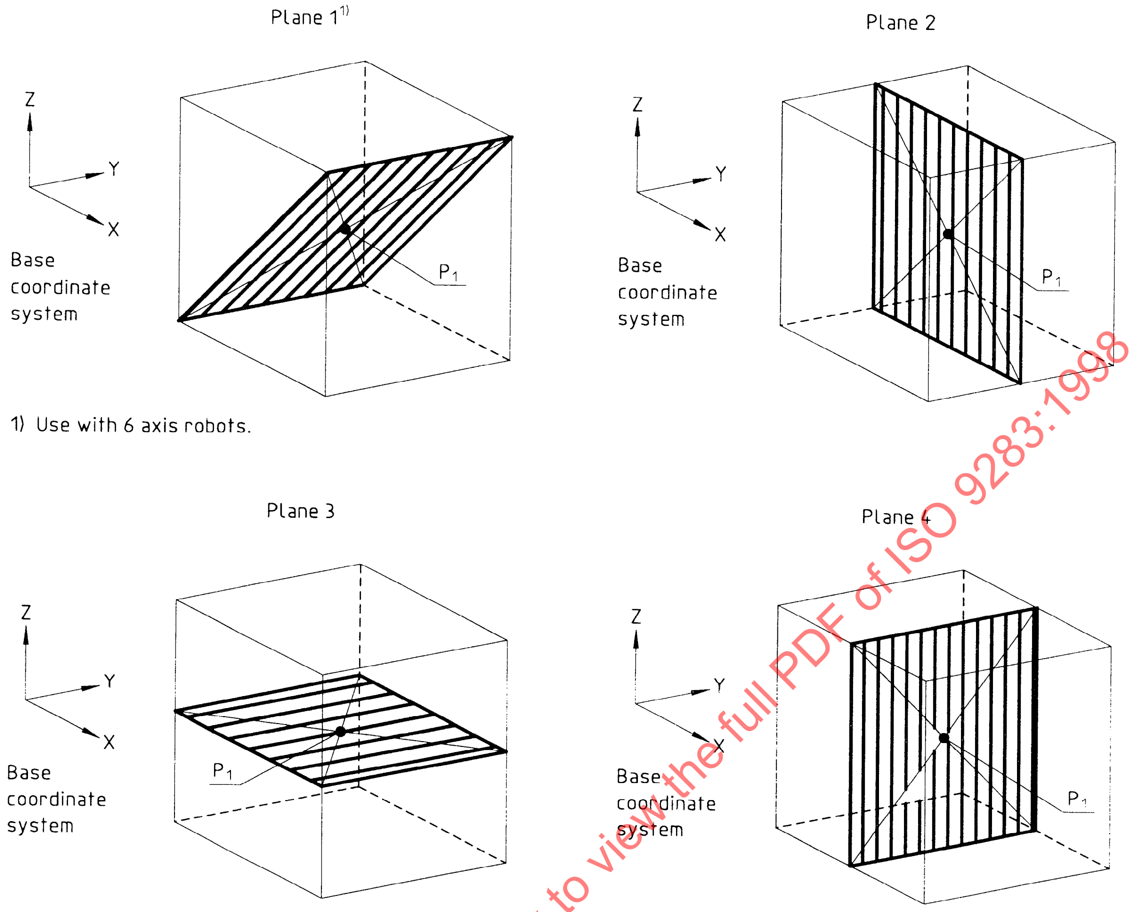
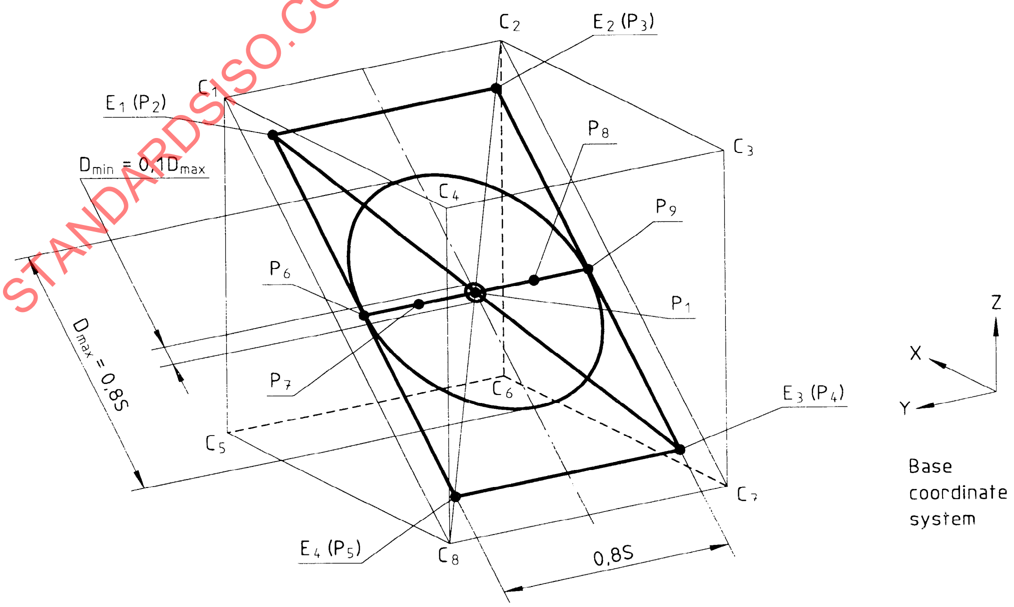


Figure 5 - Definitions of planes for location of test path



S = side length of cube.

Figure 6 - Examples of test paths

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6.9 Number of cycles

The number of cycles to be performed when testing each characteristic is given in table 5.

Table 5 - Number of cycles

Characteristic to be tested	Number of cycles
Pose accuracy and pose repeatability	30
Multi-directional pose accuracy variation	30
Distance accuracy and distance repeatability	30
Position stabilization time	3
Position overshoot	3
Drift of pose characteristics	Continuous cycling during 8 hours
Exchangeability	30
Path accuracy and path repeatability	10
Path accuracy on reorientation	10
Cornering deviations	3
Path velocity characteristics	10
Minimum posing time	3
Weaving deviations	3

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6.10 Test procedure

The sequence of testing has no influence on the results, but it is recommended to perform position stabilization time test prior to the pose repeatability test, for determination of the measuring dwell. Tests for overshoot, pose accuracy and repeatability may be performed concurrently. The test for drift of pose characteristics shall be performed independently.

Pose characteristics shall be tested under pose-to-pose or continuous path control. Path characteristics shall be tested under path control.

The determination of the path accuracy and repeatability can be done in parallel to that of the velocity, provided that the measuring device is suitably equipped.

It is recommended that the velocity tests are performed prior to the measurement of the path accuracy and to use the identical path parameters. This ensures the usage of the correct reference quantities during determination of the path criteria.

When programming the constant path velocity, care should be taken to ensure that the velocity override control is set at 100 % and that the velocity is not automatically reduced as a result of any limitations of the robot along the path to be followed.

Simultaneous testing could be

— path accuracy/repeatability and velocity characteristics;
— cornering overshoot and round-off error.

Except for drift of pose characteristics, data collection for one characteristic with one set of conditions shall be carried out over the shortest period of time.

Any programmed delays used for measurements, e.g. measuring dwell and measuring time, should be stated in the test report.

6.11 Characteristics to be tested - Applications

The tests described in this International Standard may be applied in whole or in part, depending upon the robot type and requirements (application).

Guidance for the selection of essential robot tests for some typical applications is provided in Annex B.

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7 Pose characteristics

7.1 General description

Command pose (see figure 7): Pose specified through teach programming, numerical data entry through manual data input or off-line programming.

The command poses for teach programmed robots are to be defined as the measurement point on the robot (see figure 7). This point is reached during programming by moving the robot as close as possible to the defined points in the cube (P_1 , P_2 ......). The coordinates registered on the measuring system are then used as "command pose" when calculating accuracy based on the consecutive attained poses.

Attained pose (see figure 7): Pose achieved by the robot under automatic mode in response to the command pose.

Pose accuracy and repeatability characteristics, as defined in this clause, quantify the differences which occur between a command and attained pose, and the fluctuations in the attained poses for a series of repeat visits to a command pose.

These errors may be caused by

- internal control definitions,
- coordinate transformation errors,
- differences between the dimensions of the articulated structure and those used in the robot control system model,
- mechanical faults such as clearances, hysteresis, friction, and external influences such as temperature.

The method of data entry for the command pose depends on the facilities of the robot control and has a significant influence on the accuracy characteristics. The method used shall be clearly stated in the data sheet or test report.

If the command pose is specified by numerical data entry, the relationship (i.e distance and orientation) between different command poses is known (or can be determined) and is required for the specification and measurement of distance characteristics (see 7.3).

For the measurement of pose accuracy using numerical data entry, the position of the measurement system needs to be known relative to the base coordinate system (see 6.8.4).

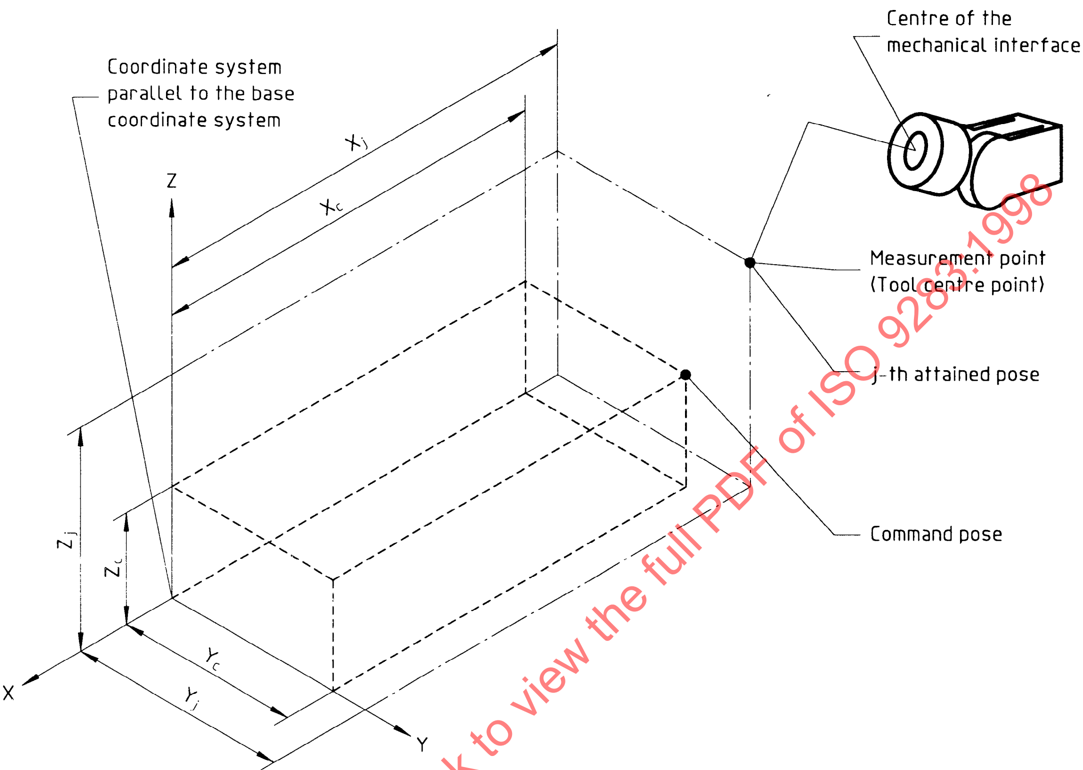

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Figure 7 - Relation between command and attained pose
(figures 8 and 9 also show this relationship)

7.2 Pose accuracy and pose repeatability

7.2.1 Pose accuracy (*AP*)

Pose accuracy expresses the deviation between a command pose and the mean of the attained poses when approaching the command pose from the same direction.

Pose accuracy is divided into

a) *positioning accuracy:* the difference between the position of a command pose and the barycentre of the attained positions, see figure 8;

b) *orientation accuracy:* the difference between the orientation of a command pose and the average of the attained orientations, see figure 9.

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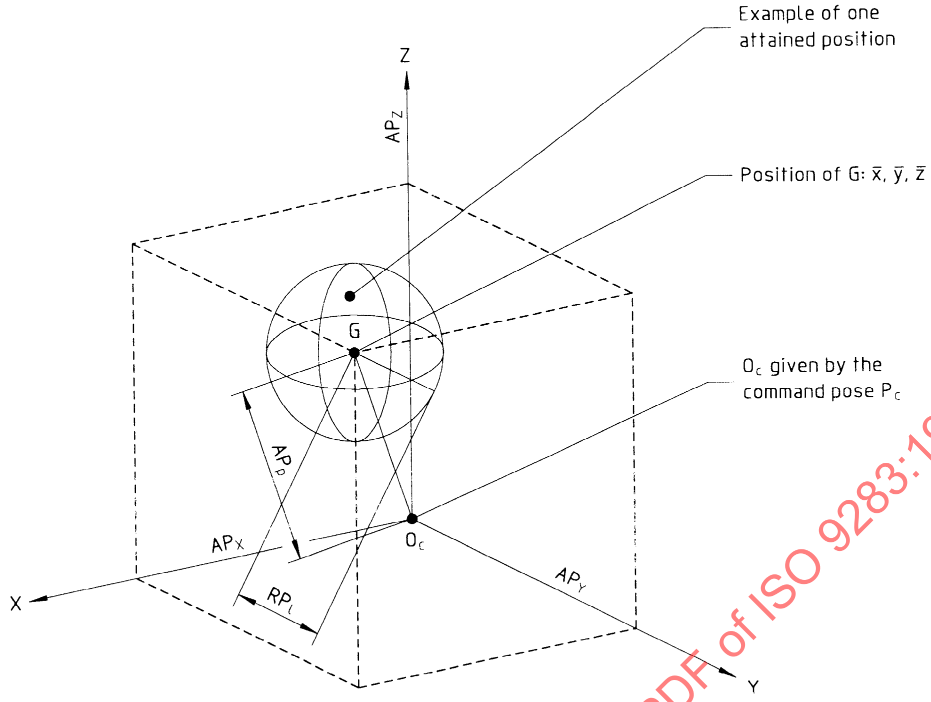
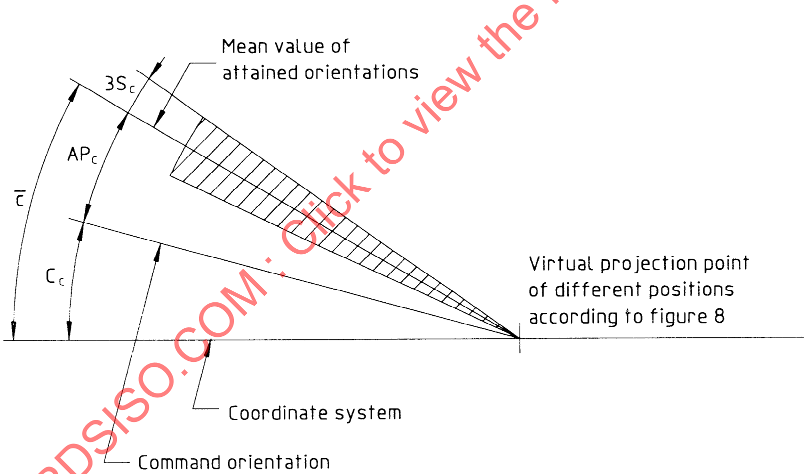


Figure 8 - Positioning accuracy and repeatability



NOTE - The same figure can be applied for $\bar{b}$ and $\bar{a}$.

Figure 9 - Orientation accuracy and repeatability

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The pose accuracy is calculated as follows:

Positioning accuracy

$$AP_P = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2 + (\bar{z} - z_c)^2}$$

$$AP_x = (\bar{x} - x_c)$$

$$AP_y = (\bar{y} - y_c)$$

$$AP_z = (\bar{z} - z_c)$$

with

$$\bar{x} = \frac{1}{n} \sum_{j=1}^{n} x_j$$

$$\bar{y} = \frac{1}{n} \sum_{j=1}^{n} y_j$$

$$\bar{z} = \frac{1}{n} \sum_{j=1}^{n} z_j$$

$\bar{x}$, $\bar{y}$, *and* $\bar{z}$ are the coordinates of the barycentre of the cluster of points obtained after repeating the same pose *n* times.

x_c, y_c and z_c are the coordinates of the command pose;

x_j, y_j and z_j are the coordinates of the *j*-th attained pose.

Orientation accuracy

$$AP_a = (\bar{a} - a_c)$$
$$AP_b = (\bar{b} - b_c)$$
$$AP_c = (\bar{c} - c_c)$$

with

$$\bar{a} = \frac{1}{n} \sum_{j=1}^{n} a_j$$

$$\bar{b} = \frac{1}{n} \sum_{j=1}^{n} b_j$$

$$\bar{c} = \frac{1}{n} \sum_{j=1}^{n} c_j$$

These values are the mean values of the angles obtained at the same pose repeated *n* times.

a_c, b_c and c_c are the angles of the command pose.

a_j, b_j and c_j are the angles of the *j*-th attained pose.

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Table 6 gives a summary of test conditions for pose accuracy.

Table 6 - Summary of test conditions for pose accuracy

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	$P_1 — P_2 — P_3 — P_4 — P_5$	30
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

- Starting from P_1, the robot successively moves its mechanical interface to the poses P_5, P_4, P_3, P_2, P_1. Each of the poses should be visited using a unidirectional approach as shown by either of the cycles illustrated in figure 10. Approaching directions used during the test shall be similar to those used when programming.
- For each pose, positioning accuracy (AP_p) and orientation accuracy (AP_a, AP_b, AP_c) are calculated.

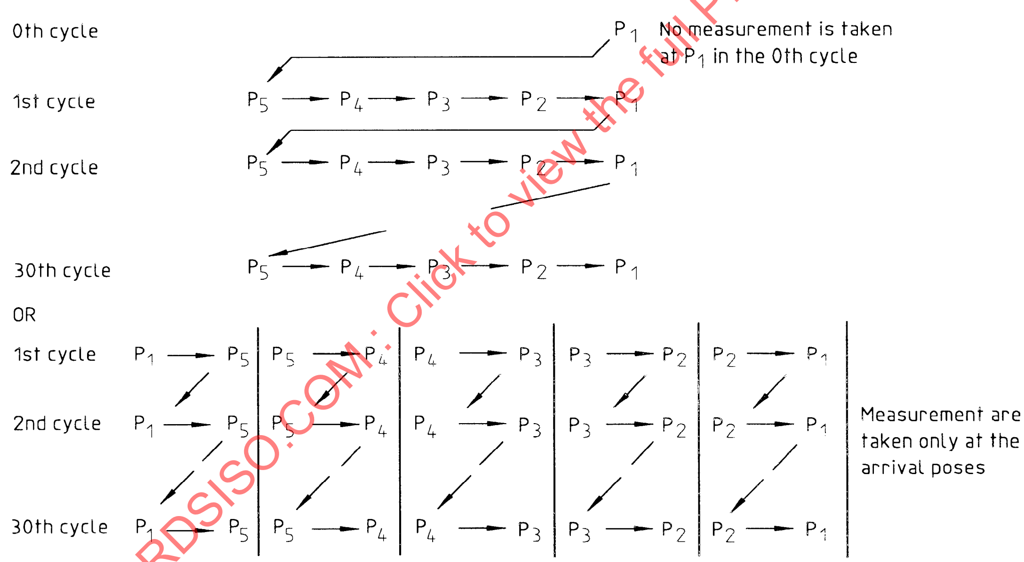

Figure 10 - Illustration of possible cycles

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7.2.2 Pose repeatability (RP)

Pose repeatability expresses the closeness of agreement between the attained poses after n repeat visits to the same command pose in the same direction.

For a given pose, the repeatability is expressed by

— the value of RP_l, which is the radius of the sphere whose centre is the barycentre and which is calculated as below (see figure 8);

— the spread of angles $\pm 3S_a$, $\pm 3S_b$, $\pm 3S_c$ about the mean values, $\bar{a}$, $\bar{b}$, and $\bar{c}$ where S_a, S_b and S_c are the standard deviations (see figure 9)

where

Positioning repeatability

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

with

$$\bar{l} = \frac{1}{n}\sum_{j=1}^{n} l_j \; ;$$

$$l_j = \sqrt{(x_j - \bar{x})^2 + (y_j - \bar{y})^2 + (z_j - \bar{z})^2}$$

with

$\bar{x}$, $\bar{y}$, $\bar{z}$ and x_j, y_j, z_j defined as in 7.2.1.

$$S_l = \sqrt{\frac{\sum_{j=1}^{n}(l_j - \bar{l})^2}{n-1}}$$

Orientation repeatability

$$RP_a = \pm 3S_a = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(a_j - \bar{a})^2}{n-1}}$$

$$RP_b = \pm 3S_b = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(b_j - \bar{b})^2}{n-1}}$$

$$RP_c = \pm 3S_c = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(c_j - \bar{c})^2}{n-1}}$$

NOTE 2 — This criterion can be calculated even if the distances are not normally distributed.

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Table 7 gives a summary of test conditions for pose repeatability.

Table 7 - Summary of test conditions for pose repeatability

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	P_1 — P_2 — P_3 — P_4 — P_5	30
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

– The procedure is the same as in 7.2.1.

– For each pose, *RP* and angular deviations RP_a, RP_b and RP_c are calculated. For special applications *RP* may also be expressed by its components RP_x, RP_y, RP_z.

7.2.3 Multi-directional pose accuracy variation (*vAP*)

Multi-directional pose accuracy variation expresses the deviation between the different mean attained poses achieved when visiting the same command pose *n* times from three orthogonal directions (see figure 11).

— vAP_p is the maximum distance between the barycentres of the cluster of points attained at the end of different paths.

— vAP_a, vAP_b, vAP_c is the maximum deviation between the mean value of the angles attained at the end of different paths.

Multi-directional pose accuracy variation is calculated as follows:

$$vAP_P = \max \sqrt{(\overline{x}_h - \overline{x}_k)^2 + (\overline{y}_h - \overline{y}_k)^2 + (\overline{z}_h - \overline{z}_k)^2} \qquad h, k = 1, 2, 3$$

Three is the number of approaching paths.

$$vAP_a = \max \left|(\overline{a}_h - \overline{a}_k)\right| \quad h, k = 1, 2, 3$$

$$vAP_b = \max \left|(\overline{b}_h - \overline{b}_k)\right| \quad h, k = 1, 2, 3$$

$$vAP_c = \max \left|(\overline{c}_h - \overline{c}_k)\right| \quad h, k = 1, 2, 3$$

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Table 8 gives a summary of test conditions for multi-directional pose accuracy variation.

Table 8 - Summary of test conditions for multi-directional pose accuracy variation

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	$P_1 — P_2 — P_4$	30
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

- The robot is programmed to move its mechanical interface to the poses according to three approach paths parallel to the axes of base coordinate system. For P_1 in the negative direction and for P_2 and P_4 approach from inside the main body of the cube (see figures 11 and 12). If this is not possible, the approach directions used shall be as specified by the manufacturer and shall be reported.

- For each pose vAP_P , vAP_a, vAP_b, vAP_c are calculated.

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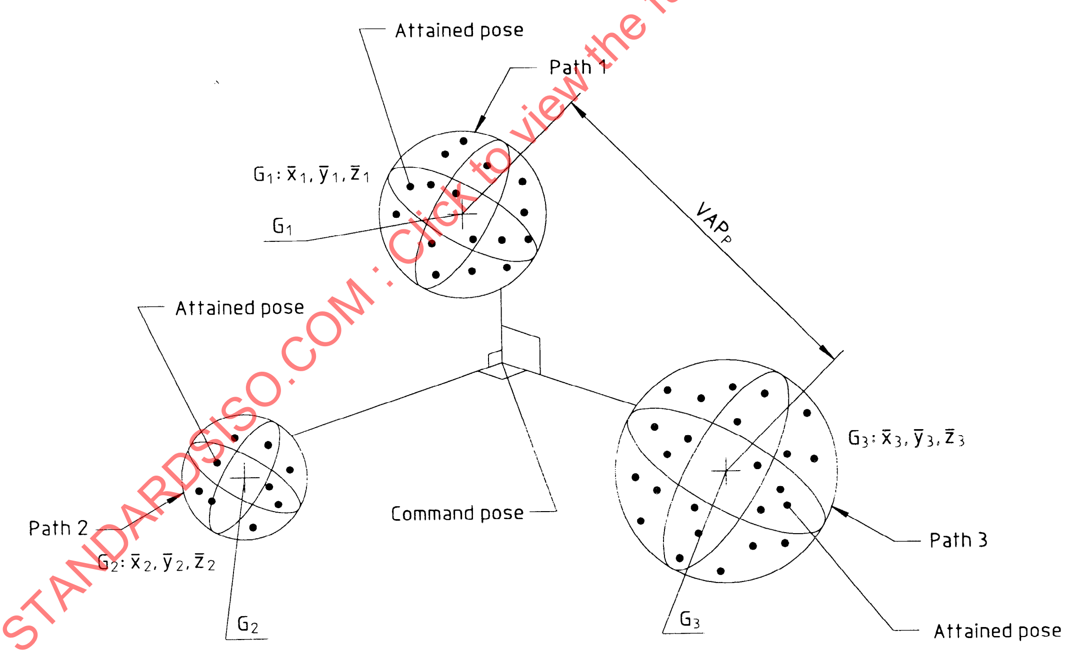

Figure 11 - Multi-directional pose accuracy variation

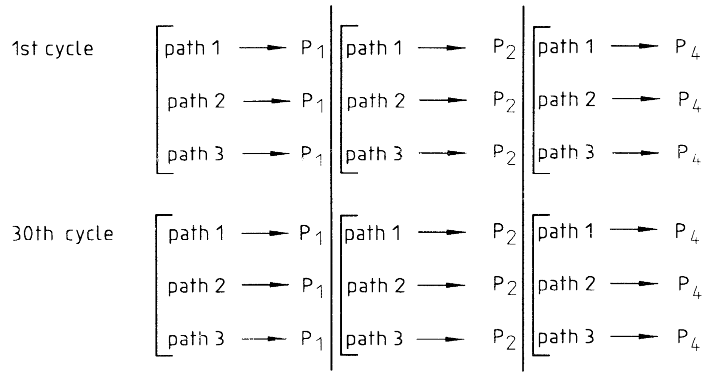

Figure 12 - Illustration of the cycle

7.3 Distance accuracy and repeatability

Characteristics applicable only to robots with the facility for off-line programming or manual data input.

7.3.1 General

Distance accuracy and repeatability characteristics as defined in this clause quantify the deviations which occur in the distance between two command poses and two sets of mean attained poses, and the fluctuations in distances for a series of repeat movements between the two poses.

The distance accuracy and repeatability can be measured by commanding the pose in one of two ways:

a) by commanding both poses using off-line programming

b) by commanding one pose by teach and programming a distance through manual data input.

The method used shall be reported.

7.3.2 Distance accuracy (*AD*)

Distance accuracy expresses the deviation in positioning and orientation between the command distance and the mean of the attained distances.

Given that the command poses are P_{c1}, P_{c2} and the attained poses are P_{1j}, P_{2j}, the positioning distance accuracy is the difference in distance between P_{c1}, P_{c2} and P_{1j}, P_{2j} (see figure 13) and the distance being repeated *n* times.

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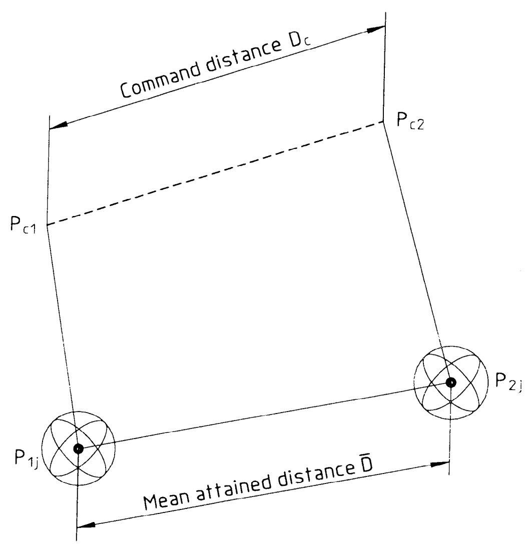

Figure 13 - Distance accuracy

Distance accuracy is determined by the two factors positioning distance accuracy and orientation distance accuracy.

The positioning distance accuracy AD_P is calculated as follows

$$AD_P = \overline{D} - D_c$$

where

$$\overline{D} = \frac{1}{n} \sum_{j=1}^{n} D_j$$

$$D_j = \left| P_{1j} - P_{2j} \right|$$

$$= \sqrt{(x_{1j} - x_{2j})^2 + (y_{1j} - y_{2j})^2 + (z_{1j} - z_{2j})^2}$$

$$D_c = \left| P_{c1} - P_{c2} \right|$$

$$= \sqrt{(x_{c1} - x_{c2})^2 + (y_{c1} - y_{c2})^2 + (z_{c1} - z_{c2})^2}$$

with

x_{c1}, y_{c1}, and z_{c1}	as the coordinates of P_{c1} available in the robot controller
x_{c2}, y_{c2}, and z_{c2}	as the coordinates of P_{c2} available in the robot controller
x_{1j}, y_{1j}, and z_{1j}	as the coordinates of P_{1j}
x_{2j}, y_{2j}, and z_{2j}	as the coordinates of P_{2j}
n	as the number of repetitions

Positioning distance accuracy can also be expressed for each base coordinate system axis. The calculation is as follows:

$$AD_x = \overline{D_x} - D_{cx}$$

$$AD_y = \overline{D_y} - D_{cy}$$

$$AD_z = \overline{D_z} - D_{cz}$$

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where

$$\overline{D_x} = \frac{1}{n}\sum_{j=1}^{n} D_{xj} = \frac{1}{n}\sum_{j=1}^{n} |x_{1j} - x_{2j}|$$

$$\overline{D_y} = \frac{1}{n}\sum_{j=1}^{n} D_{yj} = \frac{1}{n}\sum_{j=1}^{n} |y_{1j} - y_{2j}|$$

$$\overline{D_z} = \frac{1}{n}\sum_{j=1}^{n} D_{zj} = \frac{1}{n}\sum_{j=1}^{n} |z_{1j} - z_{2j}|$$

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$D_{cx} = |x_{c1} - x_{c2}|$

$D_{cy} = |y_{c1} - y_{c2}|$

$D_{cz} = |z_{c1} - z_{c2}|$

The orientation distance accuracy is calculated equally to single axis distance accuracy

$$AD_a = \overline{D_a} - D_{ca}$$
$$AD_b = \overline{D_b} - D_{cb}$$
$$AD_c = \overline{D_c} - D_{cc}$$

where

$$\overline{D_a} = \frac{1}{n}\sum_{j=1}^{n} D_{aj} = \frac{1}{n}\sum_{j=1}^{n} |a_{1j} - a_{2j}|$$

$$\overline{D_b} = \frac{1}{n}\sum_{j=1}^{n} D_{bj} = \frac{1}{n}\sum_{j=1}^{n} |b_{1j} - b_{2j}|$$

$$\overline{D_c} = \frac{1}{n}\sum_{j=1}^{n} D_{cj} = \frac{1}{n}\sum_{j=1}^{n} |c_{1j} - c_{2j}|$$

$D_{ca} = |a_{c1} - a_{c2}|$

$D_{cb} = |b_{c1} - b_{c2}|$

$D_{cc} = |c_{c1} - c_{c2}|$

with

a_{c1}, b_{c1}, and c_{c1}	as the orientations of P_{c1} available in the robot controller
a_{c2}, b_{c2}, and c_{c2}	as the orientations of P_{c2} available in the robot controller
a_{1j}, b_{1j}, and c_{1j}	as the orientations of P_{1j}
a_{2j}, b_{2j}, and c_{2j}	as the orientations of P_{2j}
n	as the number of repetitions.

Table 9 gives a summary of test conditions for distance accuracy.

Table 9 - Summary of test conditions for distance accuracy

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	P_2 — P_4	30

– The robot is programmed to move its mechanical interface successively to poses P_2 and P_4, starting from P_4. The measurements are taken unidirectionally (see figure 14).

– At least as a minimum, the value of AD_p shall be reported.

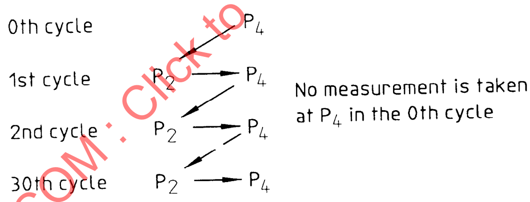

Figure 14 - Illustration of the cycle

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7.3.3 Distance repeatability (*RD*)

Distance repeatability is the closeness of agreement between several attained distances for the same command distance, repeated n times in the same direction.

Distance repeatability includes positioning and orientation repeatability.

Distance repeatability for a given command distance is calculated as follows:

$$RD = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_j - \overline{D})^2}{n-1}}$$

$$RD_x = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_{xj} - \overline{D_x})^2}{n-1}}$$

$$RD_y = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_{yj} - \overline{D_y})^2}{n-1}}$$

$$RD_z = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_{zj} - \overline{D_z})^2}{n-1}}$$

For orientation the following calculation apply

$$RD_a = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_{aj} - \overline{D_a})^2}{n-1}}$$

$$RD_b = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_{bj} - \overline{D_b})^2}{n-1}}$$

$$RD_c = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_{cj} - \overline{D_c})^2}{n-1}}$$

with the different variables as defined in 7.3.2.

Table 10 gives a summary of test conditions for distance repeatability.

Table 10 - Summary of test conditions for distance repeatability

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	P_2 — P_4	30

— Same procedure as in 7.3.2. At least as a minimum, the value of *RD* shall be reported.

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7.4 Position stabilization time

The position stabilization time is a robot performance which quantifies how quickly a robot can stop at the attained pose. Figure 15 illustrates in three dimensions an example of approach to the attained pose. It shall be understood that the position stabilization time is also related to the overshoot and other performance parameters of robots.

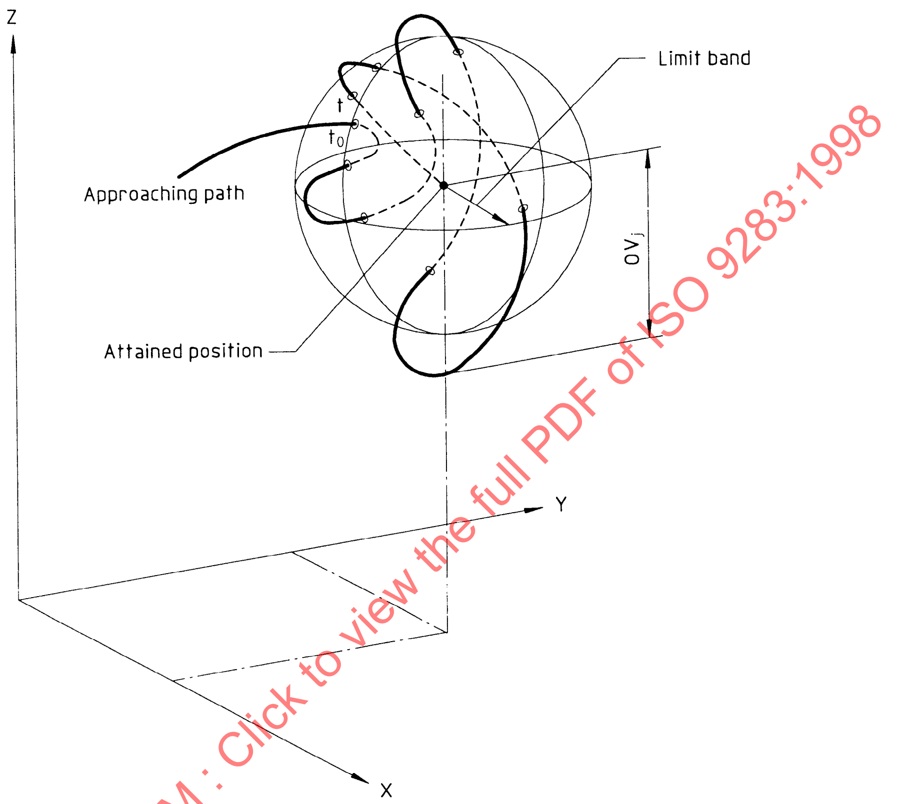

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Figure 15 - Stabilization time and position overshoot, three dimensional presentation

The position stabilization time shall be measured in the same manner as the overshoot in 7.5. The robot runs the same cycle as in 7.2.1 with the test load and the test velocities. After the robot approaches the command pose P_n, the position of the measurement point shall be continuously measured until stabilization is achieved.

The position stabilization time is measured as the elapsed time from the instance of the initial crossing into the limit band until the instance when the robot remains within the limit band. The limit band is defined as the repeatability as defined in 7.2.2 or a value stated by the manufacturer.

This procedure shall be repeated three times, for each pose the mean value *t* of the three cycles is calculated (see figure 16).

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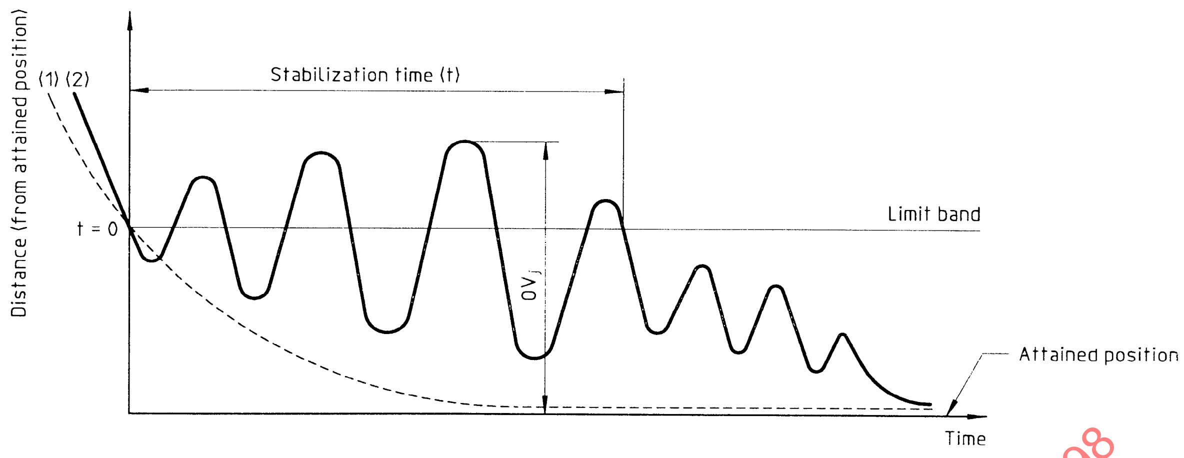

Curve (1): Example of an overdamped approach, see note 3
Curve (2): Example of an oscillating approach where OV_j exists

Figure 16 - Stabilization time and position overshoot

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Table 11 gives a summary of test conditions for position stabilization time.

Table 11 - Summary of test conditions for position stabilization time

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	P_1	3
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

7.5 Position overshoot

The purpose of measuring position overshoot is to quantify the robot capability to make smooth and accurate stops at attained poses. It shall be understood that the position overshoot is also related to the position stabilization time.

The overshoot is measured as the maximum distance from the attained position after the instance of the initial crossing into the limit band and when the robot goes outside the limit band again.

NOTE 3 — For robots which are overdamped (curve 1 in figure 16) the overshoot will be zero.

To measure the position overshoot, the robot runs the same cycle as in 7.2.1 with the test load and the test velocities. The position overshoot is equal to the over travel distance at the measurement point P_1 . The overshoot shall be measured three times, the maximum value of the three cycles shall be calculated (see figure 16).

$$OV = \max OV_j$$

$$OV_j = \max D_{ij} \text{ if } \max D_{ij} > \text{ limit band}$$
$$= 0 \qquad \text{if } \max D_{ij} \leq \text{ limit band}$$

$$\max D_{ij} = \max \sqrt{(x_{ij} - x_j)^2 + (y_{ij} - y_j)^2 + (z_{ij} - z_j)^2} \qquad i = 1, 2, \ldots\ldots m$$

where i represents the number of samples measured after the robot has reached the limit band.

For special applications OV may also be expressed by its components OV_x, OV_y, OV_z.

Table 12 gives a summary of test conditions for position overshoot.

Table 12 - Summary of test conditions for position overshoot

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	P_1	3
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

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7.6 Drift of pose characteristics

Drift of pose accuracy (dAP) is the variation of pose accuracy over a specified time (T). This can be calculated as follows:

$dAP_p = | AP_{t=1} - AP_{t=T} |$

$dAP_a = | AP_{at=1} - AP_{at=T} |$

$dAP_b = | AP_{bt=1} - AP_{bt=T} |$

$dAP_c = | AP_{ct=1} - AP_{ct=T} |$

where AP is defined in 7.2.1, with relation to the command pose taught under cold conditions.

The maximum values should be reported.

Drift of pose repeatability (dRP) is the variation of pose repeatability over a specified time (T). This can be calculated as follows:

$dRP_p = | RP_{t=1} - RP_{t=T} |$

$dRP_a = | RP_{at=1} - RP_{at=T} |$

$dRP_b = | RP_{bt=1} - RP_{bt=T} |$

$dRP_c = | RP_{ct=1} - RP_{ct=T} |$

where *RP* is defined in 7.2.2.

The maximum values should be reported.

Table 13 gives a summary of test conditions for drift of pose characteristics.

Table 13 - Summary of test conditions for drift of pose characteristics

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	P_1	8 h continuous cycling

– Drift measurements should begin from cold (immediately after actuation of the main power) and continued over several hours in the warmed up state. The following sequence should be followed:

1. Programming of test cycle with power on;
2. Power off the robot for 8 h;
3. Restart the robot and start programmed automatic cycle.

– Measurement cycle: The robot is programmed to move its mechanical interface to P_1 starting from P_2. All joints have to be moved when returning from P_1 to P_2 (10 times)

– Warm-up cycle: All joints have to be moved over 70 % of its full range with maximum possible velocity (see also table 13) when returning from P_1 to P_2 sequence (10 times). See also diagram in figure 17. The values may be selected different for special applications

– The measurements can be stopped before eight hours if the rate of change of the drift (*dAP*) for five continuous sets is less than 10 % of the largest rate of change during the first hour. The measurements are used to calculate pose accuracy and repeatability (see 7.2.1 and 7.2.2). The results are plotted on a graph as a function of time. The time between the measurement cycles shall be 10 minutes (warm-up program, see figures 17 and 18).

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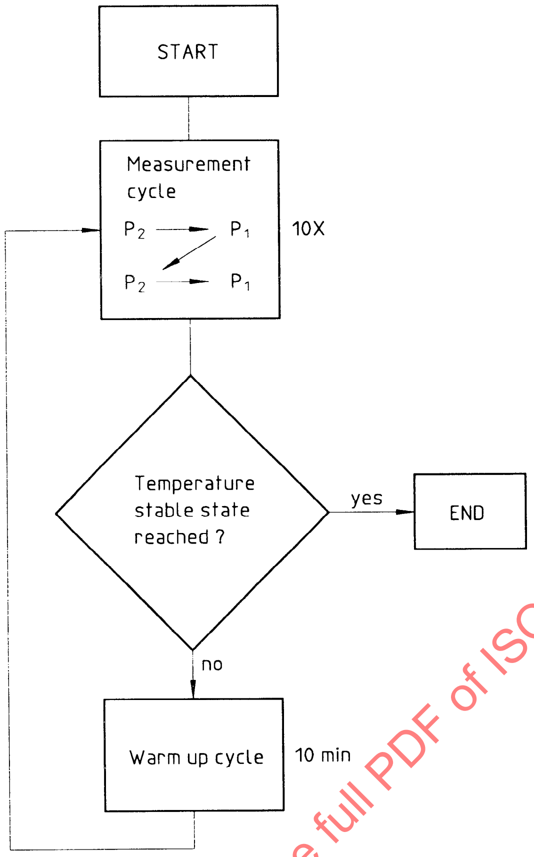

Figure 17 - Illustration of the drift measurement

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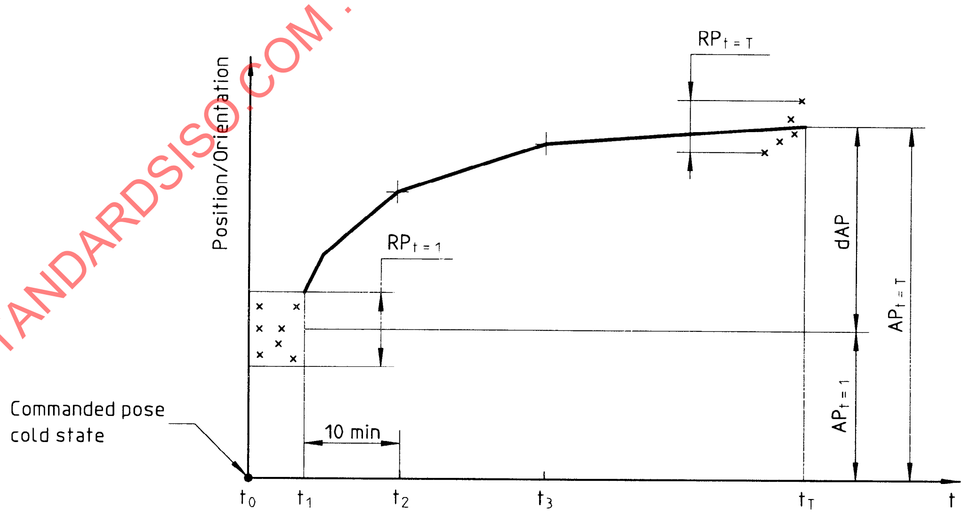

Figure 18 - Drift of pose characteristics

7.7 Exchangeability (*E*)

Exchangeability expresses the deviation of the barycentres when different robots of the same type are exchanged under the same environmental conditions, mechanical mounting and use of the same task programme.

The *E* value is the distance between barycentres from the tests of the two robots which have the maximum deviation in the tests (see figure 19).

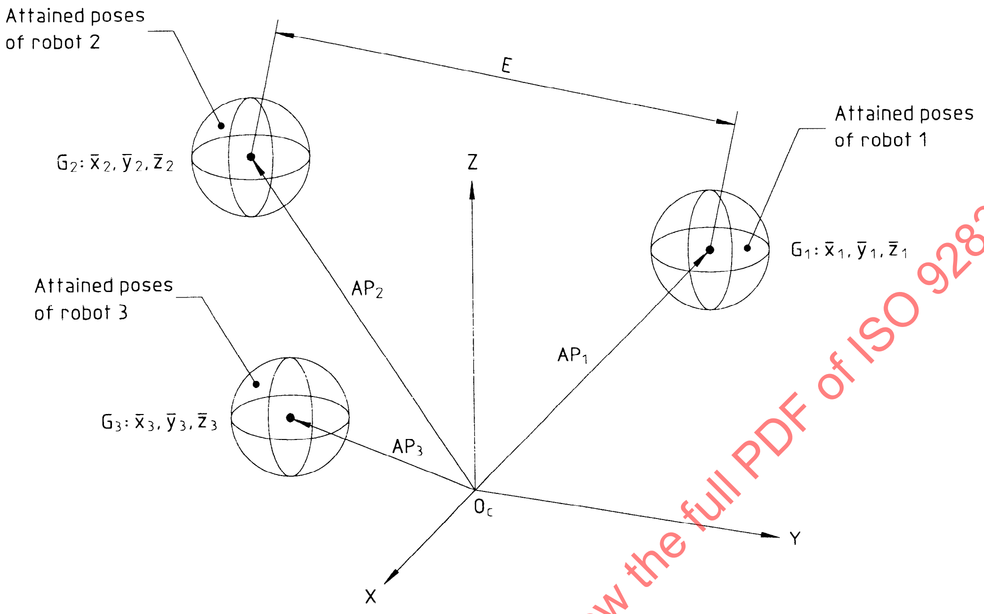

Figure 19 - Exchangeability

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The exchangeability is due to mechanical tolerances, errors of axis calibration and robot mounting errors.

The test poses for the exchangeability test shall be P_1 , P_2 , P_3 , P_4 and P_5 and shall be the same for all the robots tested.

The command poses for all five points shall be set using the first robot and shall remain the same for the other robots during the test.

The test shall be executed at 100% of rated load and 100% of rated velocity and shall be performed on five robots of the same type.

Table 14 gives a summary of test conditions for exchangeability.

Table 14 - Summary of test conditions for exchangeability

Load	Velocity	Poses	Number of cycles for each robot	Number of robots
100 % of rated load	100 % of rated velocity	P_1 — P_2 — P_3 — P_4 — P_5	30	5

The first robot shall be installed on a mounting place as specified by the manufacturer. For each point P_1 , P_2 , P_3, P_4 and P_5 the barycentres shall be calculated in the same reference coordinate system.

The position accuracy (AP_{pj}) for each of the other robots shall be calculated using the same mechanical base mounting reference while maintaining the measurement system fixed and using the same task programme.

The exchangeability is calculated as below

$$E = \max \sqrt{(x_h - x_k)^2 + (y_h - y_k)^2 + (z_h - z_k)^2} \qquad h, k = 1, 2, \ldots\ldots 5$$

NOTE 4 — The test can be executed with the same robot controller, using the calibration data specific for each manipulator (definition, see ISO 8373), in accordance with the manufacturer specifications.

8 Path characteristics

8.1 General

Path accuracy and repeatability definitions are independent of the shape of the command path. Figure 20 gives a general illustration of path accuracy and path repeatability.

The path characteristics described in the following subclauses are generally valid for all methods of programming.

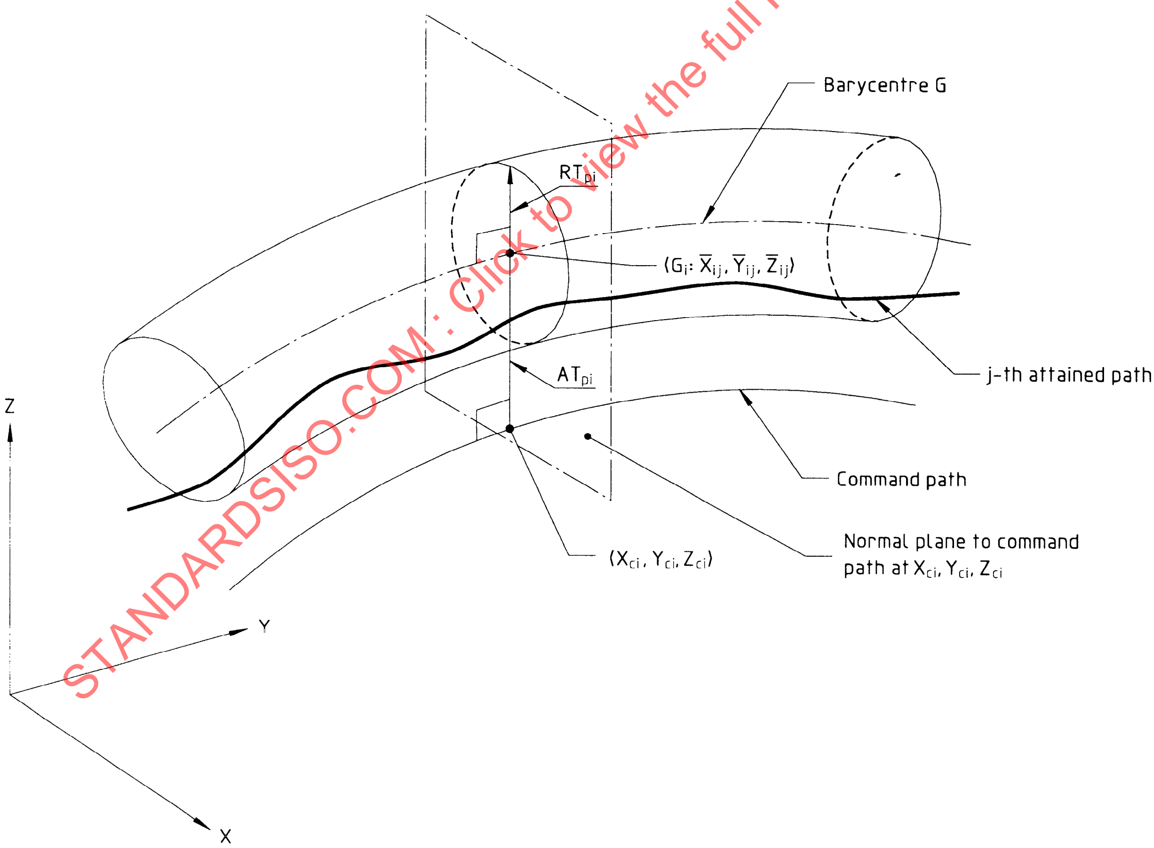

Figure 20 - Path accuracy and path repeatability for a command path

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8.2 Path accuracy (AT)

Path accuracy characterizes the ability of a robot to move its mechanical interface along the command path in the same direction n times.

Path accuracy is determined by the two factors

- the difference between the positions of the command path and the barycentre line of the cluster of the positions of the attained paths (i.e. positioning path accuracy, AT_p, in figure 20);
- the difference between command orientations and the average of the attained orientations (i.e. orientation path accuracy).

The path accuracy is the maximum path deviation along the path obtained in positioning and orientation.

Positioning path accuracy, AT_p, is defined as the maximum of the distances between the positions of the command path and the barycentres G_i, of the n measurement cycles, for each of a number of calculated points (m) along the path.

The positioning path accuracy is calculated as follows

$$AT_P = \max \sqrt{(\overline{x}_i - x_{ci})^2 + (\overline{y}_i - y_{ci})^2 + (\overline{z}_i - z_{ci})^2} \qquad i = 1 \ldots\ldots m$$

where

$$\overline{x}_i = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \qquad \overline{y}_i = \frac{1}{n}\sum_{j=1}^{n} y_{ij} \qquad \overline{z}_i = \frac{1}{n}\sum_{j=1}^{n} z_{ij}$$

When calculating AT_p the following should be taken into account

- depending on the shape of the command path and the test velocity, the number of points along the command path and corresponding normal planes are selected. The selected number of normal planes shall be stated in the test report.
- x_{ci} , y_{ci} and z_{ci} are the coordinates of the i-th point on the command path.
- x_{ij} ,y_{ij} and z_{ij} are the coordinates of the intersection of the j-th attained path and the i-th normal plane.

Orientation path accuracies AT_a , AT_b and AT_c are defined as the maximum deviation from commanded orientations along the path.

$$AT_a = \max \left|\overline{a}_i - a_{ci}\right| \qquad i = 1 \ldots\ldots m$$

$$AT_b = \max \left|\overline{b}_i - b_{ci}\right| \qquad i = 1 \ldots\ldots m$$

$$AT_c = \max \left|\overline{c}_i - c_{ci}\right| \qquad i = 1 \ldots\ldots m$$

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where

$$\overline{a}_i = \frac{1}{n}\sum_{j=1}^{n} a_{ij} \qquad \overline{b}_i = \frac{1}{n}\sum_{j=1}^{n} b_{ij} \qquad \overline{c}_i = \frac{1}{n}\sum_{j=1}^{n} c_{ij}$$

a_{ci}, b_{ci} and c_{ci} are the command orientations at the point (x_{ci}, y_{ci}, z_{ci}).

a_{ij}, b_{ij} and c_{ij} are the attained orientations at the point (x_{ij}, y_{ij}, z_{ij})

Table 15 gives a summary of test conditions for path accuracy.

Table 15 - Summary of test conditions for path accuracy

Load	Velocity	Shape of path	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	Linear path E_1 — E_3 Circular paths Large and small circles See 6.8.6.2 and figure 6	10
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

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Whilst the calculation of path accuracy is made in planes orthogonal to the command path, the measurements of the attained path may be carried out as a function of either distance or time.

The programmed start and end points of the cycle shall lie outside the chosen test path.

8.3 Path repeatability (*RT*)

Path repeatability expresses the closeness of the agreement between the attained paths for the same command path repeated *n* times.

For a given path followed *n* times in the same direction, path repeatability is expressed by

– RT_p is the maximum RT_{pi} which is equal to the radius of a circle in the normal plane and with its centre on the barycentre line (see figure 20).

– the maximum of the spread of angles about the mean value at the different calculated points.

The path repeatability is calculated as follows:

$$RT_P = \max RT_{pi} = \max [\overline{l}_i + 3S_{li}] \quad i = 1 \,....... \, m$$

where

$$\overline{l}_i = \frac{1}{n}\sum_{j=1}^{n} l_{ij}$$

$$S_{li} = \sqrt{\frac{\sum_{j=1}^{n}(l_{ij} - \overline{l}_i)^2}{n-1}}$$

$$l_{ij} = \sqrt{(x_{ij} - \overline{x}_i)^2 + (y_{ij} - \overline{y}_i)^2 + (z_{ij} - \overline{z}_i)^2}$$

with $\overline{x}_i, \overline{y}_i, \overline{z}_i, x_{ij}, y_{ij}$ and z_{ij} as defined in 8.2.

$$RT_a = \max 3\sqrt{\frac{\sum_{j=1}^{n}(a_{ij} - \overline{a}_i)^2}{n-1}} \qquad i = 1 \ldots\ldots m$$

$$RT_b = \max 3\sqrt{\frac{\sum_{j=1}^{n}(b_{ij} - \overline{b}_i)^2}{n-1}} \qquad i = 1 \ldots\ldots m$$

$$RT_c = \max 3\sqrt{\frac{\sum_{j=1}^{n}(c_{ij} - \overline{c}_i)^2}{n-1}} \qquad i = 1 \ldots\ldots m$$

with $\overline{a}_i, \overline{b}_i, \overline{c}_i, a_{ij}, b_{ij}$ and c_{ij} as defined in 8.2.

Path repeatability shall be measured using the same test procedure as that used for the measurement of path accuracy.

For special applications *RT* may also be expressed by its components RT_x, RT_y, RT_z.

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8.4 Path accuracy on reorientation

To record the influence of three-directional orientation alterations on a linear path in a simple way, i.e. with measuring only positioning path accuracy (AT_P) the following test, as illustrated in figure 21 shall be applied.

a)
Definition of the orientation alteration around Y_n

B_n-angle at P_6 (Start)	+ 30°
B_n-angle from P_6 to P_1	- 30°
B_n-angle from P_1 to P_9	+ 30°

b)
Definition of the orientation alteration around X_n and Z_n

A_n-angle at P_6 (Start)	+ 30°
A_n-angle from P_6 to P_7	0°
C_n-angle from P_7 to P_1	- 30°
C_n-angle from P_1 to P_8	0°
A_n-angle from P_8 to P_9	- 30°

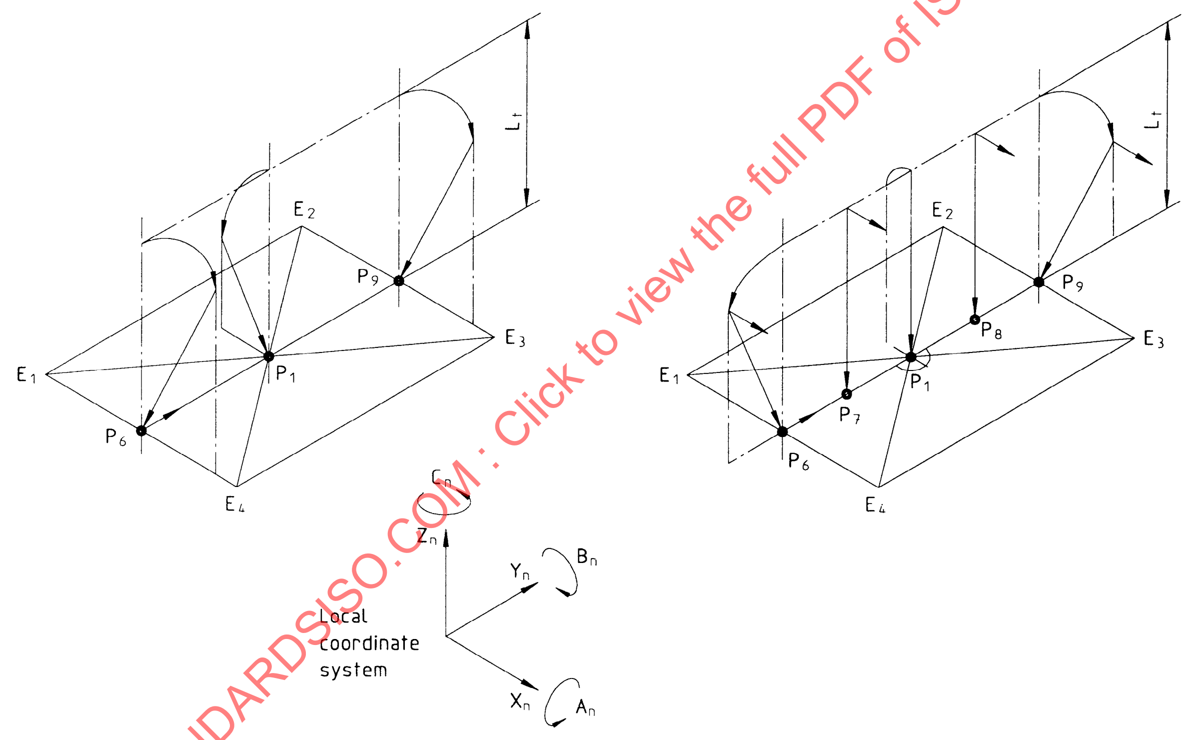

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Figure 21 - Definition of orientation alterations a) around y_n -axis, b) around x_n - and z_n -axes

In the test plane E_1....E_4, according to figure 4, additional points P_6...P_9 will be marked, as defined in figure 6, with equal distances from each other. A local coordinate system shall be arranged for definition of orientations with X_nY_n-plane parallel to the selected plane E_1...E_4 and the linear path P_6...P_9 parallel to the Y_n-axis.

The path shall be followed with constant velocity of the tool centre point, TCP, from start point P_6 to P_9 and back from P_9 to P_6. The orientation shall be done continuously in the areas described in figure 21, without stop at the points P_6...P_9. Velocity and load shall be in accordance with 8.2, see also table 16.

Path accuracy on reorientation shall be calculated similar to the path accuracy as defined in clause 8.2.

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Table 16 gives a summary of test conditions for path accuracy on reorientation.

Table 16 - Summary of test conditions for path accuracy on reorientation

Load	Velocity	Shape of path	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	Linear path $P_6 — P_9$ See 8.4, figures 6 and 21	10
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

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8.5 Cornering deviations

Cornering deviations can be categorized into two general types:

- sharp corners;
- rounded corners.

To achieve sharp corners changes of the velocity have to be allowed to maintain precised path control. This normally results in large velocity fluctuations. To maintain constant velocity, rounding of corners is required.

Sharp corners are realised when the robot moves from the first path without delay time and with programmed constant path velocity to the second path orthogonal to the first one.

Velocity variation around the corner depends of the type of control system and shall be recorded. (In certain cases the reduction can be nearly up to 100% of the applied test velocity).

Rounded corners are used in order to prevent considerable overshoot and to keep mechanical strain under certain limits. Depending of the control system discrete paths such as radii or spline functions (smoothing methods) are programmable or will be automatically used. In this case a reduction of the velocity is not desired and if not otherwise stated limited by maximum 5% of the applied test velocity.

If a smoothing method is used in programming, it shall be stated in the test report.

8.5.1 Cornering round-off error (*CR*)

Cornering round-off error is defined as the maximum value calculated from three consecutive measurement cycles. For each cycle the minimum distance between the corner point (x_e, y_e, z_e in figure 22) and the attained path is calculated as follows.

$$CR = \max CR_j \qquad j = 1, 2, 3$$

$$CR_j = \min \sqrt{(x_i - x_e)^2 + (y_i - y_e)^2 + (z_i - z_e)^2} \qquad i = 1 \ldots\ldots m$$

where

x_e, y_e, and z_e are the coordinates of the command corner point;
x_i, y_i, and z_i are the coordinates of the command corner point on the attained path corresponding to the measurement point i.

8.5.2 Cornering overshoot (*CO*)

Cornering overshoot is defined as the maximum value calculated from three consecutive measurement cycles. For each cycle the maximum deviation from the command path after the robot started on the second path without delay time and with programmed constant path velocity is measured.

If the second command path is defined as the Z-axis and the first command path is in negative Y-direction, the cornering overshoot is calculated as follows:

$$CO = \max CO_j \quad j = 1, 2, 3$$

$$CO_j = \max \sqrt{(x_i - x_{ci})^2 + (y_i - y_{ci})^2} \quad i = 1 \ldots\ldots m$$

where

x_{ci}, and y_{ci} are the coordinates of the point on the command path corresponding to measurement point z_{ci};
x_i, and y_i are the coordinates of the point on the attained path corresponding to measurement point z_i.

This equation is only true when $(y_i - y_{ci})$ has a positive value. If $(y_i - y_{ci})$ has a negative value, cornering overshoot does not exist.

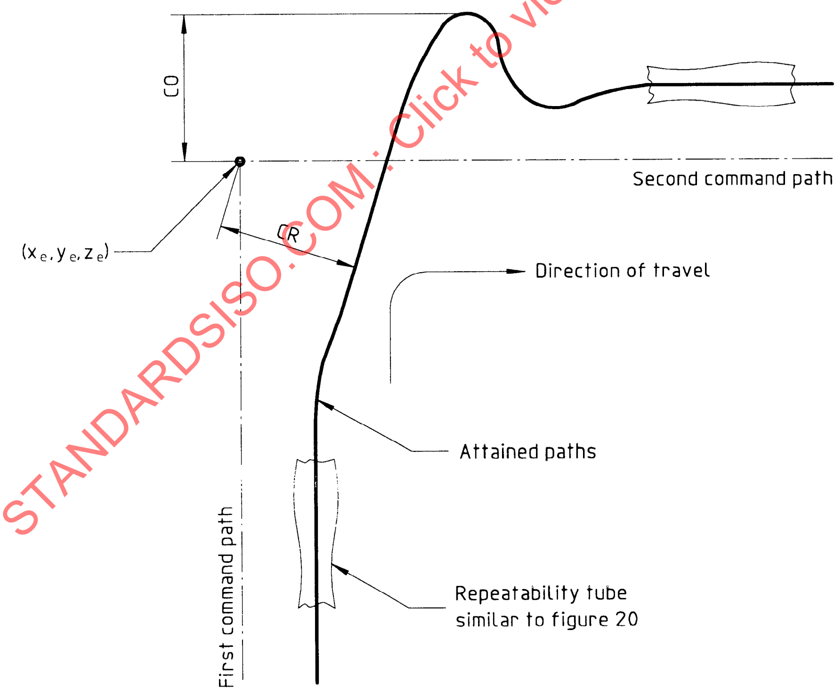

Figure 22 - Cornering overshoot and cornering round-off error at a sharp corner

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8.5.3 General test conditions

Table 17 gives a summary of test conditions for cornering deviations.

Table 17 - Summary of test conditions for cornering deviations

Load	Velocity	Corners	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	E_1 — E_2 — E_3 — E_4 (see figure 6 in 6.8.6.2)	3

The start position shall be halfway between E_1 and E_4. All four corners shall be measured. Continuous path programming shall be used to command the rectangular path. Any automatic reduction in velocity when executing the path shall be as specified by the manufacturer and shall be stated in the test report.

If not stated otherwise the orientation is orthogonal to the plane of the rectangular path.

Cornering overshoot can be calculated from measuring the deviation from the command path and each path measured. To establish command path values the position of the corner points can be either measured during teaching in the case of teach programming or known in the case of manual data input.

Both criteria *CR* and *CO* shall be measured at the same measuring sequence. Any programming alternative (e.g. sharp corner, smoothing) shall be reported.

8.6 Path velocity characteristics

8.6.1 General description

Performance characteristics of a robot with respect to path velocity are divided into three criteria. These are

– path velocity accuracy (*AV*);

– path velocity repeatability (*RV*);

– path velocity fluctuation (*FV*).

An idealized graph of these criteria is shown in figure 23.

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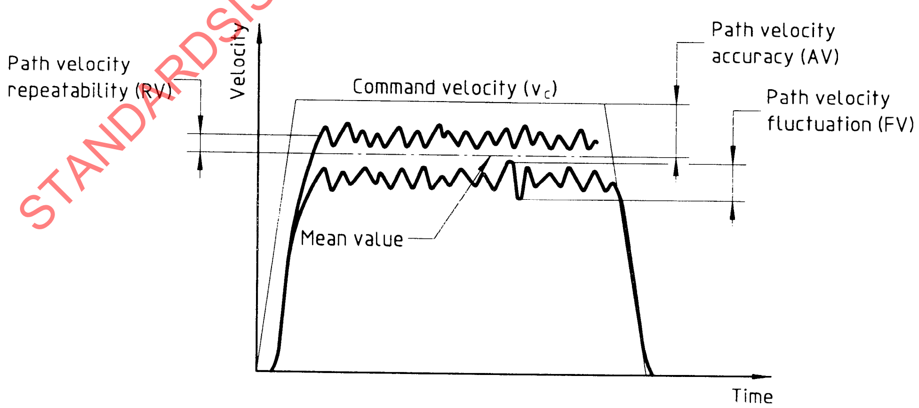

Figure 23 - Path velocity characteristics

Table 18 gives a summary of test conditions for path velocity characteristics.

Table 18 - Summary of test conditions for path velocity characteristics

Load	Velocity	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	10
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	10

In cases where significant velocity fluctuations along the path occur, repeated measurements taken as a function of time must be referred to the same points in space along the command path.

The measurement shall be taken during the stable velocity state on the centre portion of the test path length and on 50 % of the length.

Path velocity characteristics are tested on the same linear path as that used for path accuracy (see 8.2). *AV*, *RV* and *FV* are calculated with $n = 10$.

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8.6.2 Path velocity accuracy (*AV*)

Path velocity accuracy is defined as the error between the command velocity and the mean value of the attained velocities achieved during n repeat traverses along the path and is expressed as a percentage of the command velocity. Path velocity accuracy is calculated as follows:

$$AV = \frac{\overline{v} - v_c}{v_c} \times 100$$

where

$$\overline{v} = \frac{1}{n}\sum_{j=1}^{n} \overline{v_j}$$

$$\overline{v_j} = \frac{1}{m}\sum_{i=1}^{m} v_{ij}$$

where

v_c is the command velocity;
v_{ij} is the attained velocity for i-th measurement and j-th replication;
m is the number of measurements along the path.

8.6.3 Path velocity repeatability (*RV*)

Path velocity repeatability is a measure of the closeness of agreement of the velocities attained for the same command velocity.

Unless otherwise stated, path velocity repeatability shall be stated as a percentage of command velocity

$$RV = \pm\left(\frac{3S_v}{v_c} x\ 100\right)$$

where

$$S_v = \sqrt{\frac{\sum_{j=1}^{n}(\overline{v}_j - \overline{v})^2}{n-1}}$$

with v_c, $\overline{v}_j$, and $\overline{v}$ as defined in 8.6.2.

Path velocity repeatability shall be measured using the same test procedure as that used for the measurement of path velocity accuracy.

8.6.4 Path velocity fluctuation (*FV*)

Path velocity fluctuation is the maximum deviation in velocity during one replication with one command velocity.

The path velocity fluctuation is defined as the maximum of velocity fluctuation for each replication.

$$FV = \max\left[\max_{i=1}^{m}(v_{ij}) - \min_{i=1}^{m}(v_{ij})\right] \qquad j = 1 \ldots\ldots n$$

with v_{ij} as defined in 8.6.2.

Path velocity fluctuation shall be measured using the same test procedure as that used for the measurement of path velocity accuracy.

9 Minimum posing time

The posing time is the time between departure from and arrival at a stationary state when traversing a predetermined distance and/or sweeping through a predetermined angle under pose-to-pose control. The time taken for a robot to stabilize at the attained pose, as defined in 7.4, is included in the total posing time.

Unless otherwise stated the robot shall be able to achieve the specified pose accuracy and repeatability characteristics when making moves between the test poses in the specified minimum posing time.

Posing time is a non linear function of the distance travelled.

NOTE 5 – The posing time of a robot forms a contribution to, but is not the only factor involved in, the determination of cycle time. Therefore the results of the posing time measurements can be used to give an indication of cycle time but cannot be used to calculate cycle time directly.

Load to the mechanical interface and velocities during the test are the same as for pose characteristics indicated in 6.6.

The velocities to be used for the test are 100 % of the rated velocity and in addition the test shall be performed with optimized velocities for each part of the cycle if applicable to achieve a shorter posing time. The velocities used shall be stated in the test report.

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The number of cycles is three.

Tables 19 and 20 give a summary of test conditions for minimum posing time.

Table 19 - Poses and distances for minimum posing time

Poses	P_1	P_{1+1}	P_{1+2}	P_{1+3}	P_{1+4}	P_{1+5}	P_{1+6}	P_{1+7}
Distance from previous pose ($D_x = D_y = D_z$)	0	- 10	+ 20	- 50	+ 100	- 200	+ 500	- 1000

Table 20 - Summary of test conditions for minimum posing time

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity Optimized velocities	P_1 — P_{1+1} — P_{1+2} — P_{1+3} — P_{1+4} — P_{1+5} — P_{1+6} — P_{1+7} (see table 19)	3
The mass of rated load reduced to 10 % (optional)	100 % of rated velocity Optimized velocities		3

- In order to include short distances for posing time measurement, a number of poses are programmed or taught along the diagonal of the cube defined in 6.8.4 with centre point P_1. The component distances $D_x = D_y = D_z$ between consecutive poses follow an alternating progression as shown in table 19. See also figure 24.
- The number of poses and distances depends on the size of the selected cube.
- For each travel, the mean value of the three cycles is calculated and the results are given in a table, with the distance between poses indicated.

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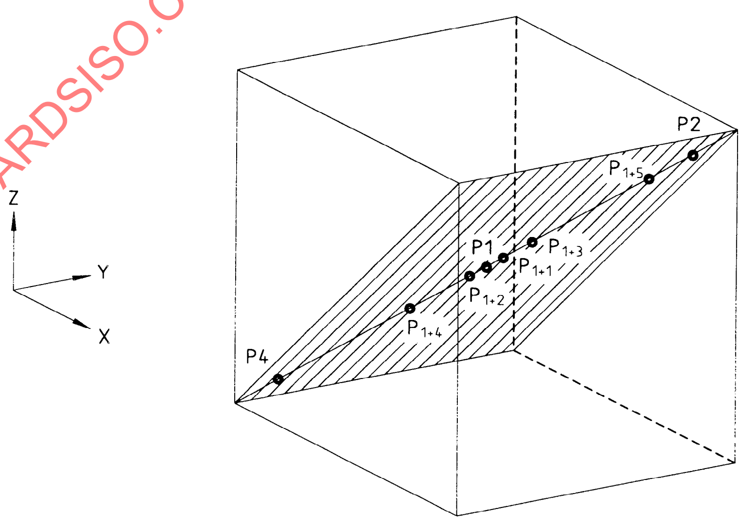

Figure 24 - Illustration of the cycle

10 Static compliance

Static compliance is the maximum amount of displacement per unit of applied load. The load should be applied to and the displacement measured at the mechanical interface.

The static compliance should be specified in millimetres per newton with reference to the base coordinate system.

The forces used in the tests shall be applied in three directions, both positive and negative, parallel to the axes of the base coordinate system.

The forces shall be increased in steps of 10 % of rated load up to 100 % of rated load, one direction at a time. For each force and direction the corresponding displacement is measured.

The measurement shall be made with the servos on and the brakes off.

The measurement procedure is repeated three times for each direction. This test is done with the centre of the mechanical interface placed at P_1 as defined in 6.8.4.

11 Application specific performance criteria

11.1 Weaving deviations

Performance characteristics of a robot with respect to weaving deviations are devided into two criteria. These are:

- weaving stroke error (*WS*)
- weaving frequency error (*WF*)

Weaving is a combination of one or more motions superimposed on a path, mainly used for arc welding.

11.1.1 Weaving test path

The path defined in figure 25 is a saw-toothed wave path with a command weaving stroke S_c and a weave distance WD_c generated by a command weaving frequency F_c , both stated by the manufacturer. At least 10 weave distances shall be located within the selected plane according to figures 5 and 6 with P_1 as symmetric point and the centre line parallel to P_2 - P_3.

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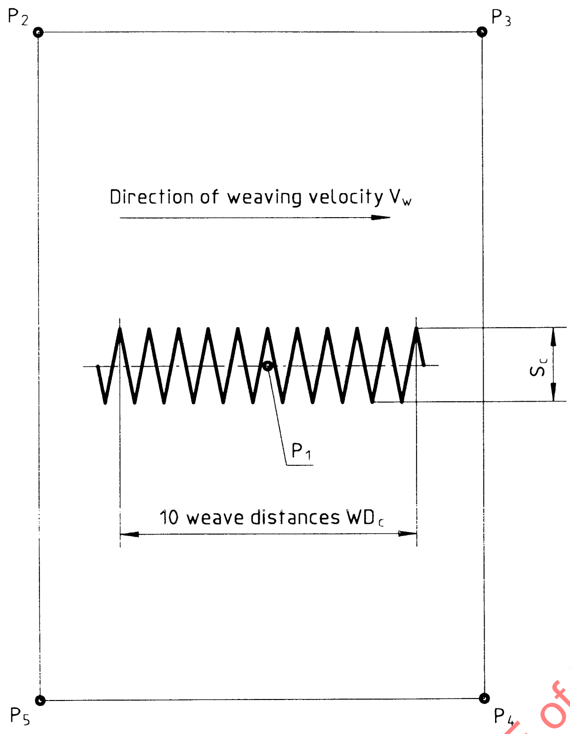

Figure 25 - Weaving test path in the selected plane

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11.1.2 Weaving stroke error (*WS*)

The weaving stroke error, in percentage, shall be calculated from the difference between the command weaving stroke S_c and the measured mean attained weaving stroke S_a , see figure 26, as follows:

$$WS = \frac{S_a - S_c}{S_c} \times 100\ (\%)$$

11.1.3 Weaving frequency error (*WF*)

The weaving frequency error, in percentage, shall be calculated from the difference between the command weaving frequency F_c and the attained weaving frequency F_a, as follows:

$$WF = \frac{F_a - F_c}{F_c} \times 100\ (\%)$$

where

$$F_a = 10 \times \frac{WV_a}{10\ WD_a} \text{ and } F_c = 10 \times \frac{WV_c}{10\ WD_c}$$

with

WV_c = command weaving velocity
WV_a = attained weaving velocity
WD_c = command weave distance
WD_a = mean attained weave distance

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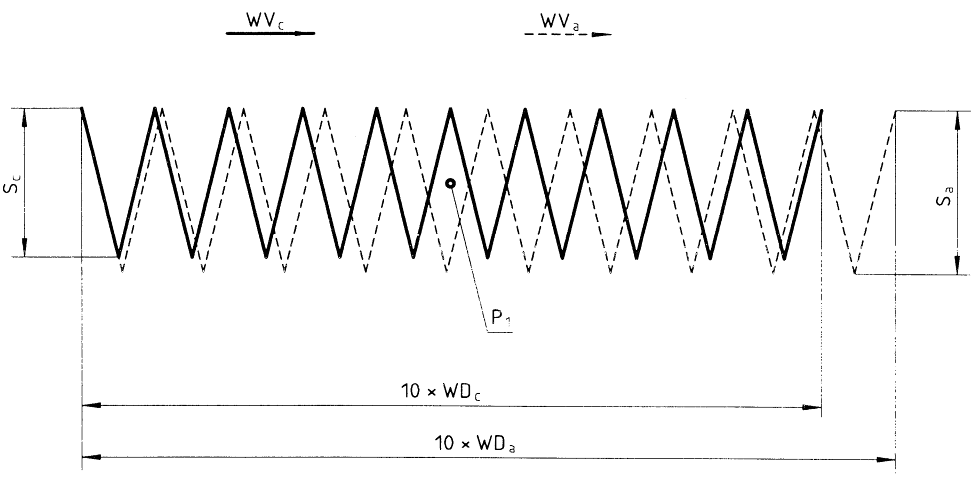

Figure 26 - Illustration of attained and command weaving path

12 Test report

The test report shall consist of a cover sheet(s) and one or more test result sheets. The cover sheet shall provide general information regarding the robot, measurement set-up and the test conditions (physical environment, set-up/warm-up, instrumentation, programming method etc.) and the tests conducted. The test result sheets shall provide a summary of the various tests performed with the uncertainty of measurement.

All reports shall include all robot programmes and software programme parameters used during each test.

Annex C gives an example of a test report and shows the minimum required information for the cover sheet and result sheets.

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