184

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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

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 voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 9283 was prepared by Technical Committee ISO/TC 184, *Industrial automation systems and integration*.

Annex A of this International Standard is for information only.

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 are 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 A of this International Standard. The characteristics for which test methods are given in this International Standard are those considered to affect robot performance significantly.

The selection of tests given in this International Standard is not addressed by the standard; 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.

Future International Standards will deal with application oriented and comparison testing.

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

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:

- unidirectional pose accuracy and pose repeatability;
- multi-directional pose accuracy variation;
- distance accuracy and distance repeatability;
- pose stabilization time;
- pose overshoot;
- drift of pose characteristics;
- path accuracy and path repeatability;
- cornering deviations;
- path velocity characteristics;
- minimum positioning time;
- static compliance.

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.

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

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 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/TR 8373:1988, *Manipulating industrial robots — Vocabulary.*

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

ISO 9946:—[1], *Manipulating industrial robots — Presentation of characteristics.*

3 Definitions

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

3.1 cluster: Set of attained poses, corresponding to the same command pose, used to calculate the accuracy and the repeatability characteristics (shown diagrammatically in figure 6).

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.

1) To be published.

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, degrees per second or radians per second (m/s), (°/s) or (rad/s)

5 Abbreviations and symbols

For the purpose 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
V	Velocity

5.2 Quantities

a, b, c	Orientation (angular components) about the x-, y-, 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	Unidirectional pose accuracy
RP	Unidirectional pose repeatability
vAP	Multi-directional pose accuracy variation
AD	Distance accuracy
RD	Distance repeatability
t	Pose stabilization time
dAP	Drift of pose accuracy
dRP	Drift of pose repeatability
AT	Path accuracy
RT	Path repeatability
CR	Cornering round-off error
CO	Cornering overshoot
SPL	Stabilization path length
AV	Path velocity accuracy
RV	Path velocity repeatability
FV	Path velocity fluctuation

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
g	Point where the robot performance falls within the specified path characteristics

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.

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.

Prior to testing, the robot motions shall be restricted to those necessary for setting up the measuring instruments.

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, the condition used during the test shall be specified in the test report and shall be kept constant during each test.

6.3 Environmental and operating 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

Where the ambient temperature of the testing environment can be controlled, it shall be maintained at

a) (20 ± 2) °C; or

b) (θ ± 2) °C;

where

1) θ °C is between 5 °C and 40 °C;

2) θ °C is as stated by the manufacturer.

Where the ambient temperature of the testing environment is not 20 °C, it shall be stated in the test report.

The robot and the measuring instruments shall 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 (coordinates x_j, y_j, z_j, a_j, b_j, c_j) shall be expressed in a coordinate system, the axes of which are parallel to those of the base coordinate system (see ISO 9787).

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 5).

The sequence of rotation used when calculating the orientation deviation shall either be rotation about moving axes Z, Y', X'' or rotation about stationary axes X, Y, Z.

Wherever possible, a non-contact measurement method shall be used.

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.

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

For path characteristics measurements, the data acquisition equipment sampling rate shall be high enough to ensure that an adequate representation of the characteristics being measured is obtained.

6.5 Instrumentation

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 including repeatability and freedom from bias; 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 at 100 % of rated load conditions (mass, position of centre of gravity, moments of inertia) according to the manufacturer's specification.

To characterize robots with load dependent performances, additional optional tests can be made with the mass of rated load reduced to 50 %, as indicated in table 1, or some other value as specified by the manufacturer.

The position of the centre of gravity of the test loads used shall be the same for all tests.

6.7 Test velocities

All pose characteristics shall be tested at the maximum velocity achievable between the specified poses, i.e. with the speed 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). The velocity specification shall be such that the robot is able to achieve this velocity over at least 50 % of the length of the test path (cornering overshoot and round-off test excepted) and that the related performance criteria shall be valid during this time.

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

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 50 %** (O = optional)
Unidirectional pose accuracy and pose repeatability	X	O
Multi-directional pose accuracy variation	X	O
Distance accuracy and distance repeatability	X	—
Pose stabilization time	X	O
Pose overshoot	X	O
Drift of pose characteristics	X	—
Path accuracy and path repeatability	X	O
Cornering deviations	X	—
Path velocity characteristics	X	O
Minimum positioning time	X	O
Static compliance	—	See clause 10

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)
Unidirectional pose accuracy and pose repeatability	X	O
Multi-directional pose accuracy variation	X	O
Distance accuracy and distance repeatability	X	O
Pose stabilization time	X	O
Pose overshoot	X	O
Drift of pose characteristics	X	—
Minimum positioning time	X	O

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
Cornering deviations	X	X	X
Path velocity characteristics	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 measurement 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 1), 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.

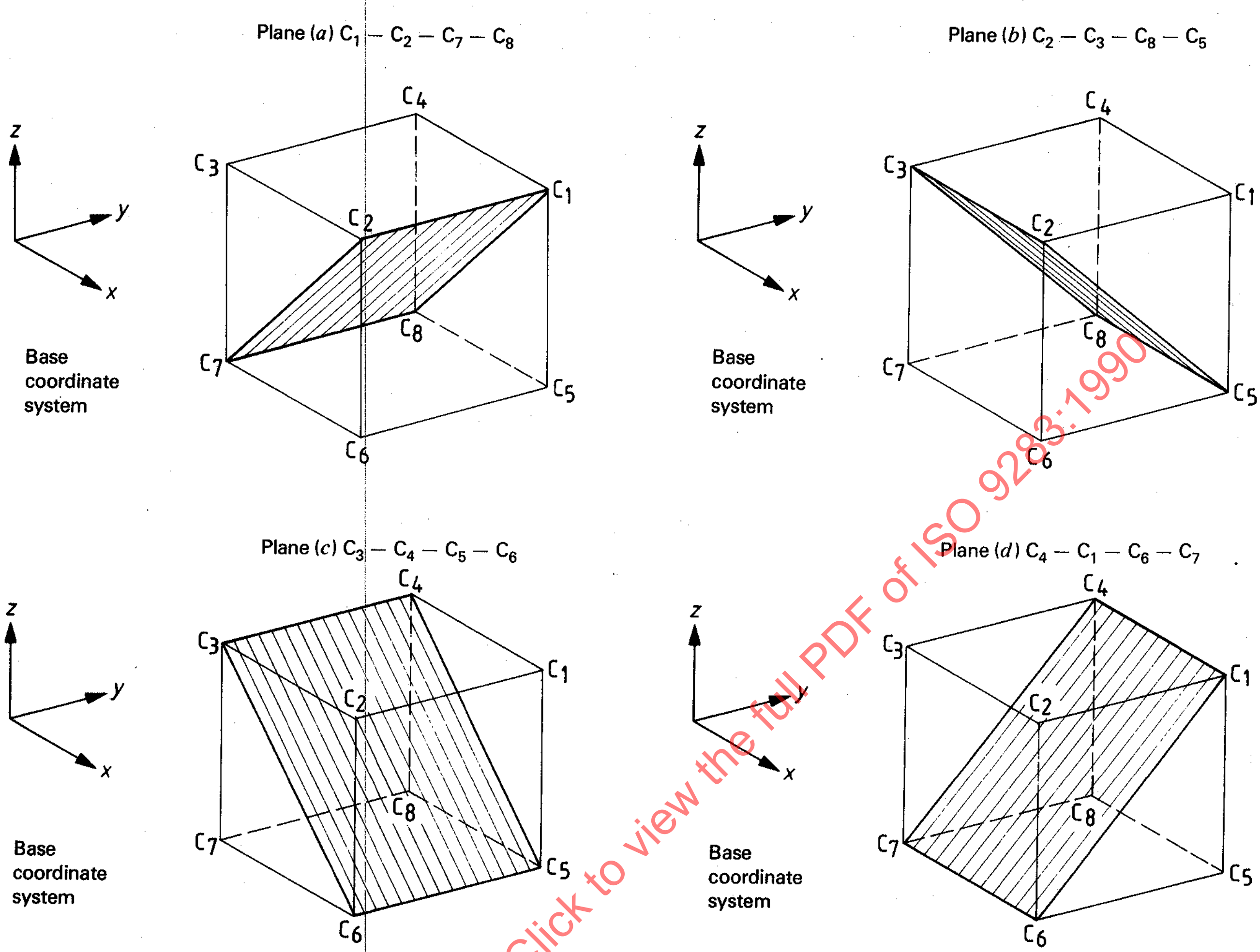


Figure 1 — Cube within the working space

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 points (P_1 to P_5) are located on the diagonals of the selected plane. These points, together with the orientations specified by the manufacturer, constitute the test poses at which the centre of the mechanical interface is placed for the test. The test poses shall be specified in base coordinates and/or joint coordinates, as specified by the manufacturer.

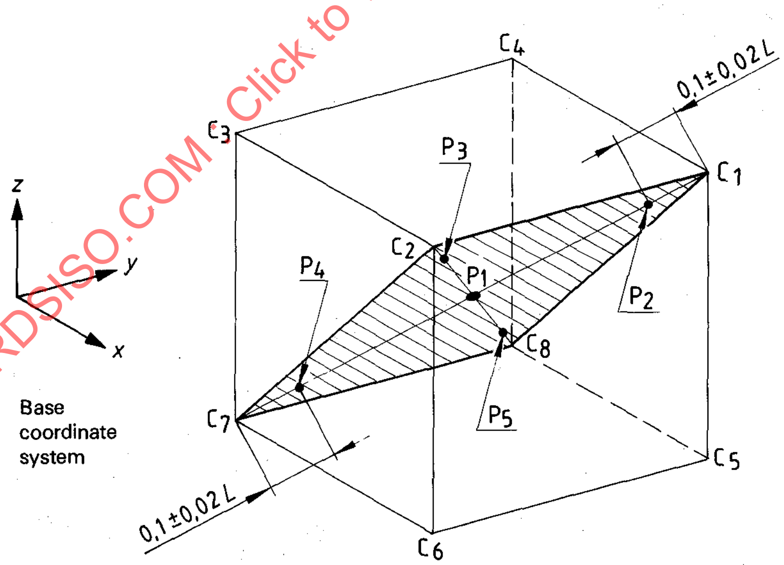
NOTE 2 The use of base coordinates is preferred.

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 2). 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
Unidirectional 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	—
Pose stabilization time	X	X	X	X	X
Pose overshoot	X	X	X	X	X
Drift of pose characteristics	X	—	—	—	—



L = length of diagonal

Example showing plane *a)* $C_1 - C_2 - C_7 - C_8$ with poses $P_1 - P_2 - P_3 - P_4 - P_5$

Figure 2 — Poses to be used

6.8.5 Movement requirements

All joints shall be exercised during movement between all poses.

Care should be taken during the test 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 3. 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, and its orientation should be kept constant to that plane.

6.8.6.2 Shape and size of the test path

Figure 16 in 8.2 gives an example of a command linear path and figure 17 in 8.2 gives an example of a command circular path.

The shape of the test path should be linear or circular except for cornering deviations (see 8.4 and figure 18). If paths of other shapes are used they shall be as specified by the manufacturer and added to the test report.

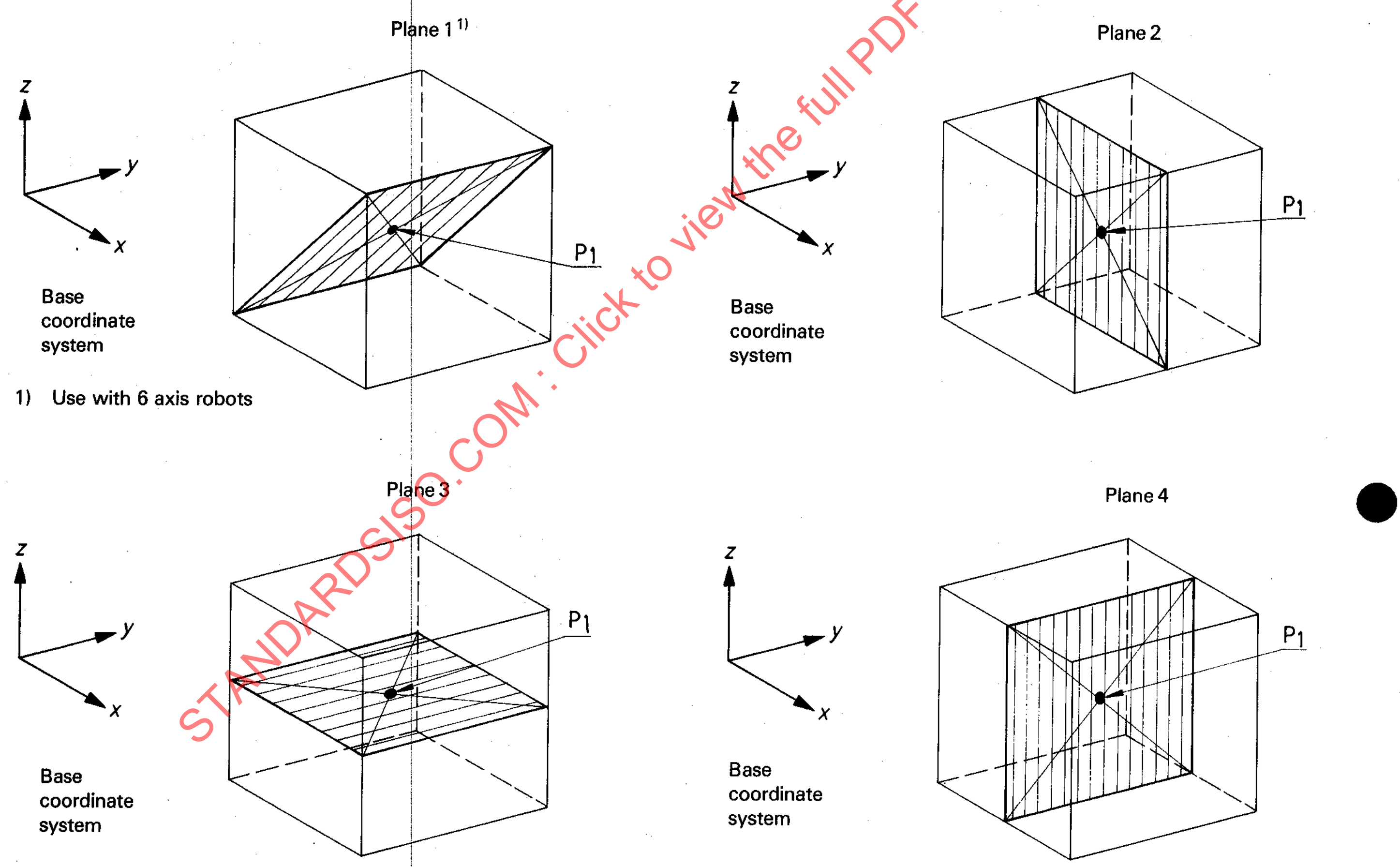


Figure 3 — Definition of planes for location of test path

For a linear path, the length of the path shall at least be equal to 80 % of the distance between opposite corners of the selected plane. An example is the distance P_2 to P_4 in figure 4.

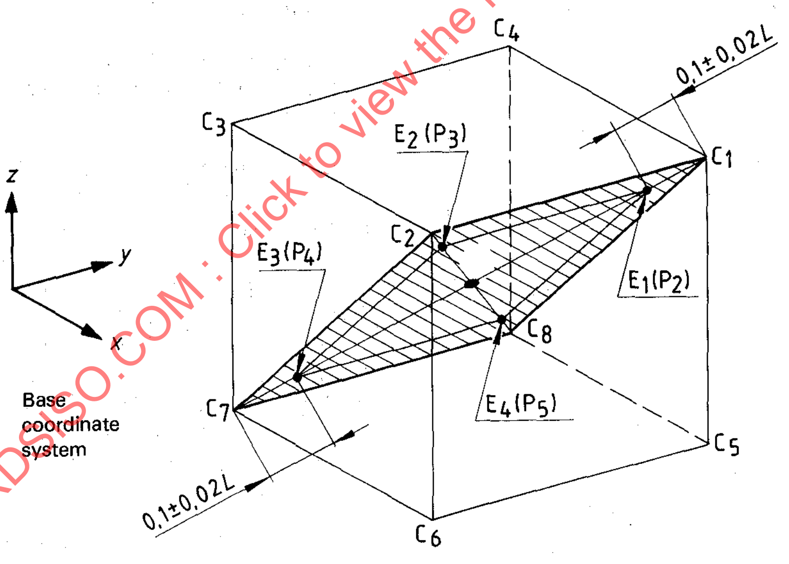
For the circular path test, two different circles shall be tested. For the large circle the path shall be inside the defined plane and as large as possible.

The diameter of the large circle shall be at least 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 largest circle in the plane or 20 mm, whichever figure is the least. The centre of the circle shall be P_1.

The path shall be programmed so that a minimum number of command points are used and that each command point is located along the path. The number and location of the command points and the method of 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 4 in which P_2, P_3, P_4 and P_5 coincide with E_1, E_2, E_3 and E_4 respectively.



L = length of diagonal

Figure 4 — Example showing a rectangular path

6.9 Number of cycles

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

Table 5 — Number of cycles

Characteristic to be tested	Minimum number of cycles
Unidirectional pose accuracy and pose repeatability	30
Multi-directional pose accuracy variation	30
Distance accuracy and distance repeatability	30
Pose stabilization time	3
Pose overshoot	3
Drift of pose characteristics	Continuous cycling during 8 h
Path accuracy and path repeatability	10
Cornering deviations	3
Path velocity characteristics	10
Minimum positioning time	3

The confidence level is increased if more measurements are carried out.

6.10 Test procedure

The sequence of testing has no influence on the results. Tests for stabilization time, 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 control and path characteristics shall be tested under path control.

The determination of the path accuracy 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 shall 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.

7 Pose characteristics

7.1 General description

Command pose (see figure 5): Pose specified through teach programming, manual data input or explicit programming.

Attained pose (see figure 5): 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 deviations which occur between a command and an 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.)

A command pose can be specified by teach programming, manual data input or, where a robot has the appropriate facilities, by explicit programming.

If the command pose is specified by teach programming, the relationship (i.e. distance and orientation) between different command poses is unimportant and need not be known.

If the command pose is specified by explicit programming, 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 accuracy and repeatability characteristics (see 7.3).

NOTE 3 For the measurement of pose characteristics using explicit programming, the position of the measurement system needs to be known relative to the base coordinate system.

Since the accuracy and repeatability characteristics of the robot are dependent on which method is used to specify the command pose, the method used shall be clearly stated in the data sheet or test report.

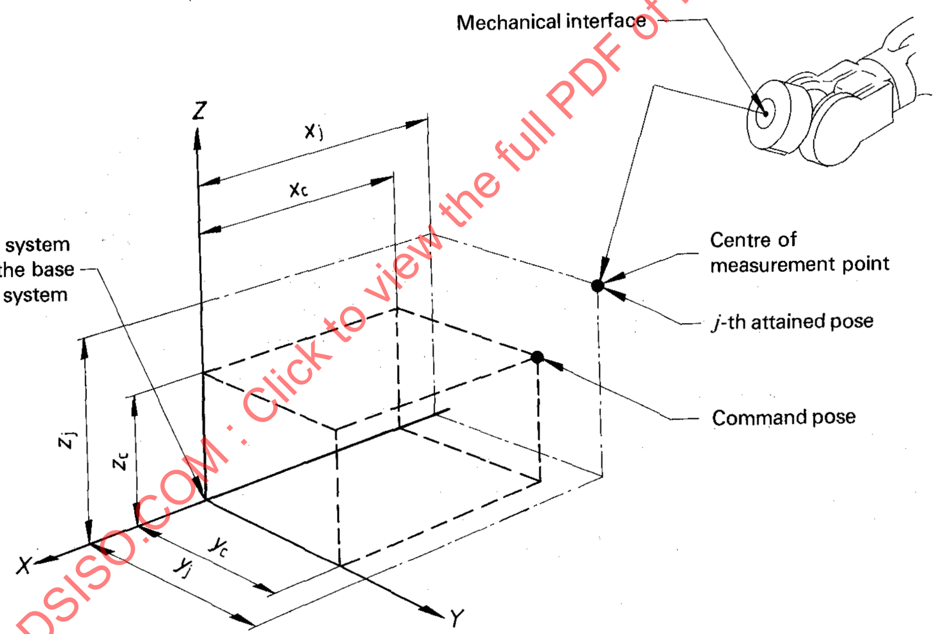


Figure 5 — Relation between command and attained pose (figure 6 and figure 7 also show this relationship)

7.2 Pose accuracy and pose repeatability

7.2.1 Unidirectional pose accuracy (AP)

Unidirectional 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. Unidirectional pose accuracy is divided into

a) the difference between a command pose and the barycentre of the cluster of attained points (i.e. unidirectional positioning accuracy), see figure 6;

b) the difference between command angular orientation and the average of the attained angular orientation (i.e. unidirectional orientation accuracy), see figure 7.

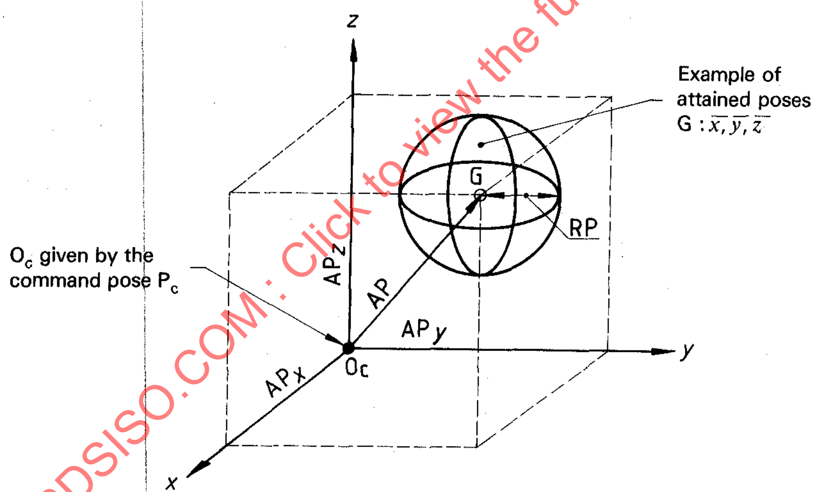


Figure 6 — Unidirectional positioning accuracy and repeatability

The unidirectional pose accuracy is calculated as follows:

Unidirectional positioning accuracy	$\mathrm{AP} = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2 + (\bar{z} - z_c)^2}$

$$\mathrm{AP}_x = (\bar{x} - x_c)$$

$$\mathrm{AP}_y = (\bar{y} - y_c)$$

$$\mathrm{AP}_z = (\bar{z} - z_c)$$

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.

Unidirectional orientation accuracy	$\mathrm{AP}_a = (\bar{a} - a_c)$ $\mathrm{AP}_b = (\bar{b} - b_c)$ $\mathrm{AP}_c = (\bar{c} - c_c)$

with

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

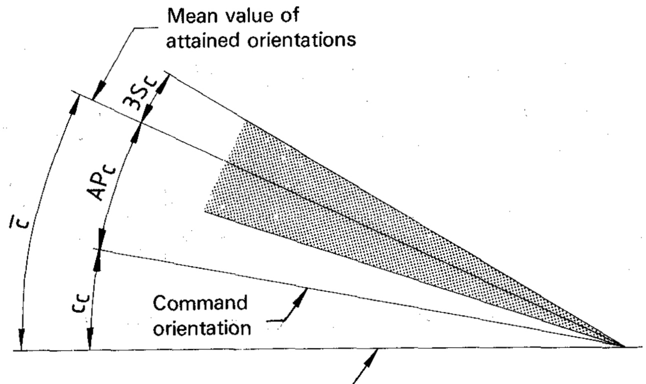
$$\bar{b} = \frac{1}{n} \sum_{j=1}^{n} b_j;$$

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

These values are the mean values of the orientation 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.



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

Figure 7 — Unidirectional orientation accuracy and repeatability

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

— 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 8. Paths used during the test shall be similar to those used when programming.

— For each pose, unidirectional positioning accuracy (AP) and orientation accuracy (AP_a, AP_b, AP_c) are calculated.

Table 6 — Summary of test conditions for unidirectional pose accuracy

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

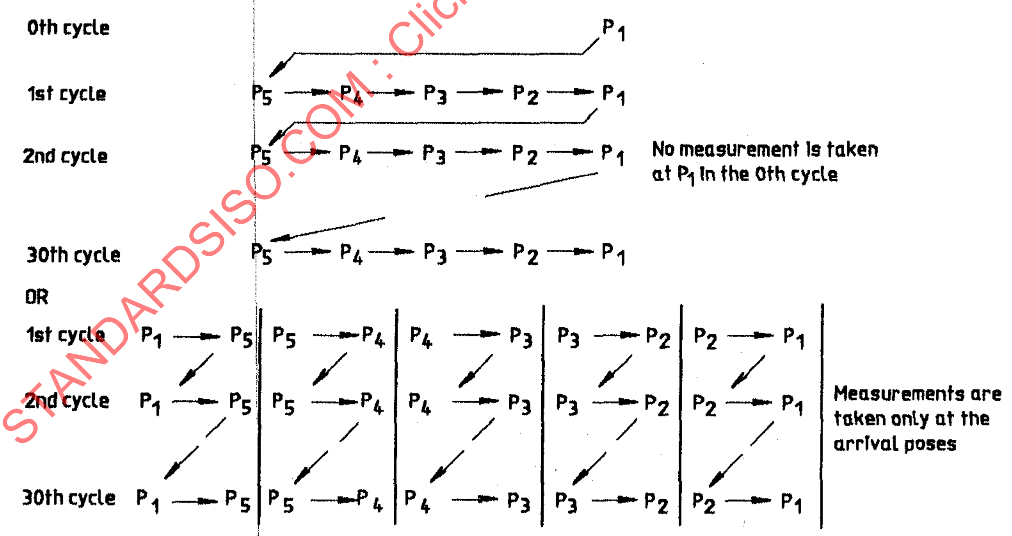


Figure 8 — Illustration of possible cycles

7.2.2 Unidirectional pose repeatability (RP)

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

For a given pose, it is expressed by

— the value of RP, which is the radius of the sphere whose centre is the barycentre and which is calculated as below;

— 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.

where

$$\mathrm{RP} = \bar{l} + 3S_l$$

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.

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

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

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

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

NOTE 4 This criterion can be calculated even if the distances are not normally distributed.

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

— 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.

Table 7 — Summary of test conditions for unidirectional pose repeatability

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

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 perpendicular directions (see figure 9).

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

— vAP_a, vAP_b and vAP_c are the maximum deviations between the mean values of the angles attained at the end of different paths.

Multi-directional pose accuracy variation is calculated as follows:

$$vAP = \max_{h,k=1}^{3} \left| \vec{AP}_h - \vec{AP}_k \right|$$

where $\vec{AP}$ (positioning accuracy vector) is calculated as follows:

$$\vec{AP} = (\bar{x} - x_c)\vec{u} + (\bar{y} - y_c)\vec{v} + (\bar{z} - z_c)\vec{w}$$

Three is the number of approaching paths.

$$vAP_a = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{a}_h - \bar{a}_k) \right| \right]$$

$$vAP_b = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{b}_h - \bar{b}_k) \right| \right]$$

$$vAP_c = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{c}_h - \bar{c}_k) \right| \right]$$

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

— 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 figure 9 and figure 10). If this is not possible, the approach directions used shall be as specified by the manufacturer and shall be reported.

— For each pose vAP, vAP_a, vAP_b, vAP_c are calculated.

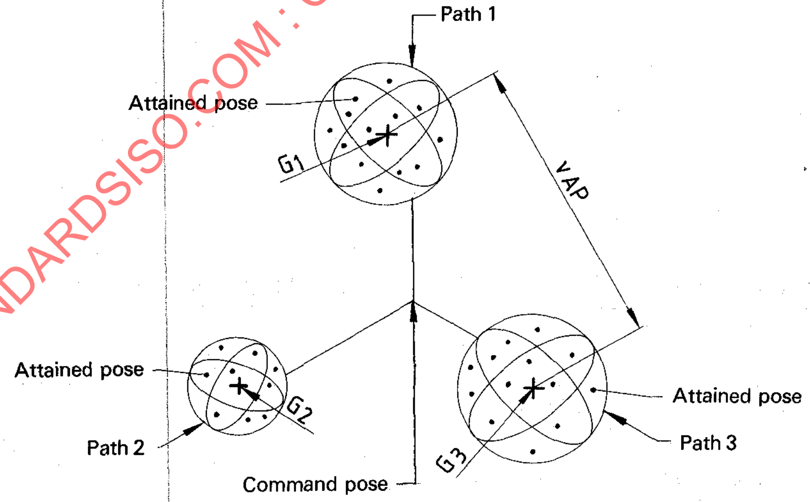


Figure 9 — Multi-directional pose accuracy variation

7.2.2 Unidirectional pose repeatability (RP)

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

For a given pose, it is expressed by

- the value of RP, which is the radius of the sphere whose centre is the barycentre and which is calculated as below;
- 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.

where

$$\mathrm{RP} = \bar{l} + 3S_l$$

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.

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

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

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

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

NOTE 4 This criterion can be calculated even if the distances are not normally distributed.

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

- 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.

Table 7 — Summary of test conditions for unidirectional pose repeatability

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

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 perpendicular directions (see figure 9).

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

— vAP_a, vAP_b and vAP_c are the maximum deviations between the mean values of the angles attained at the end of different paths.

Multi-directional pose accuracy variation is calculated as follows:

$$vAP = \max_{h,k=1}^{3} \left| \vec{AP}_h - \vec{AP}_k \right|$$

where $\vec{AP}$ (positioning accuracy vector) is calculated as follows:

$$\vec{AP} = (\bar{x} - x_c)\vec{u} + (\bar{y} - y_c)\vec{v} + (\bar{z} - z_c)\vec{w}$$

Three is the number of approaching paths.

$$vAP_a = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{a}_h - \bar{a}_k) \right| \right]$$

$$vAP_b = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{b}_h - \bar{b}_k) \right| \right]$$

$$vAP_c = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{c}_h - \bar{c}_k) \right| \right]$$

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

— 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 figure 9 and figure 10). If this is not possible, the approach directions used shall be as specified by the manufacturer and shall be reported.

— For each pose vAP, vAP_a, vAP_b, vAP_c are calculated.

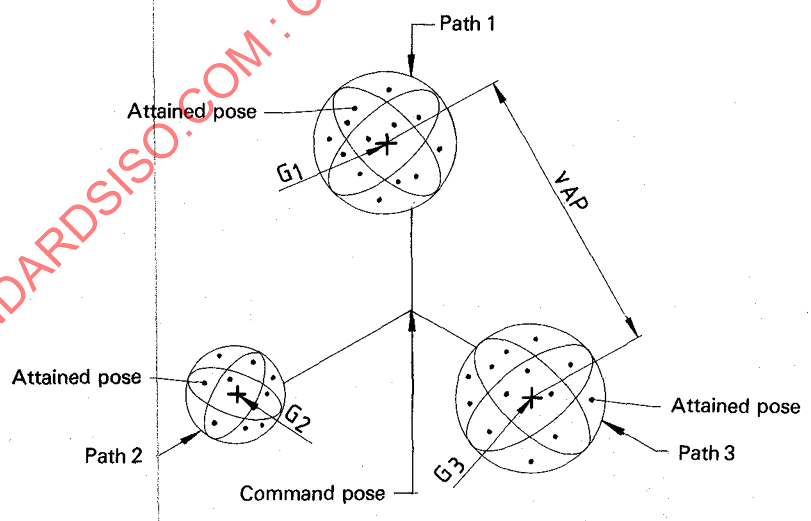


Figure 9 — Multi-directional pose accuracy variation

7.2.2 Unidirectional pose repeatability (RP)

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

For a given pose, it is expressed by

- the value of RP, which is the radius of the sphere whose centre is the barycentre and which is calculated as below;
- 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.

where

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

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.

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

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

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

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

NOTE 4 This criterion can be calculated even if the distances are not normally distributed.

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

- 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.

Table 7 — Summary of test conditions for unidirectional pose repeatability

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

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 perpendicular directions (see figure 9).

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

— vAP_a, vAP_b and vAP_c are the maximum deviations between the mean values of the angles attained at the end of different paths.

Multi-directional pose accuracy variation is calculated as follows:

$$vAP = \max_{h,k=1}^{3} \left| \vec{AP}_h - \vec{AP}_k \right|$$

where $\vec{AP}$ (positioning accuracy vector) is calculated as follows:

$$\vec{AP} = (\bar{x} - x_c)\vec{u} + (\bar{y} - y_c)\vec{v} + (\bar{z} - z_c)\vec{w}$$

Three is the number of approaching paths.

$$vAP_a = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{a}_h - \bar{a}_k) \right| \right]$$

$$vAP_b = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{b}_h - \bar{b}_k) \right| \right]$$

$$vAP_c = \max_{h=1}^{3}\left[\max_{k=1}^{3} \left| (\bar{c}_h - \bar{c}_k) \right| \right]$$

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

— 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 figure 9 and figure 10). If this is not possible, the approach directions used shall be as specified by the manufacturer and shall be reported.

— For each pose vAP, vAP_a, vAP_b, vAP_c are calculated.

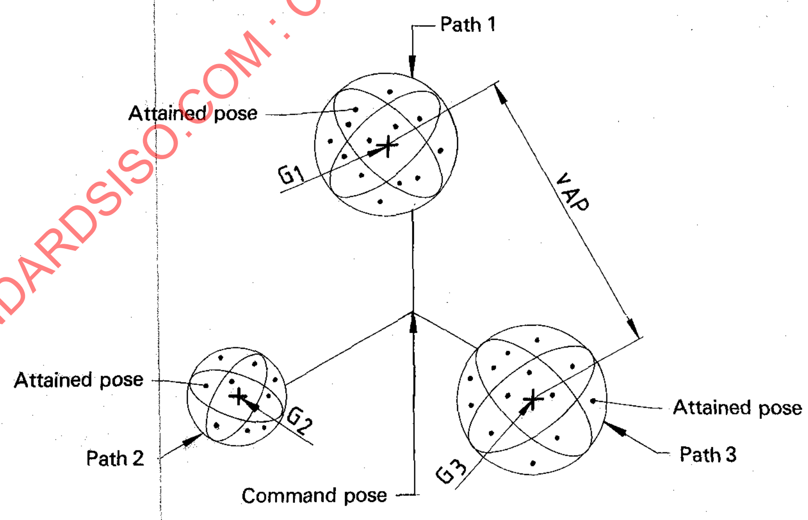


Figure 9 — Multi-directional pose accuracy variation

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 % and/or 10 % (optional)	$P_1 - P_2 - P_4$	30
The mass of rated load reduced to 50 % (optional)	100 % of rated velocity (optional) 50 % and/or 10 % (optional)		

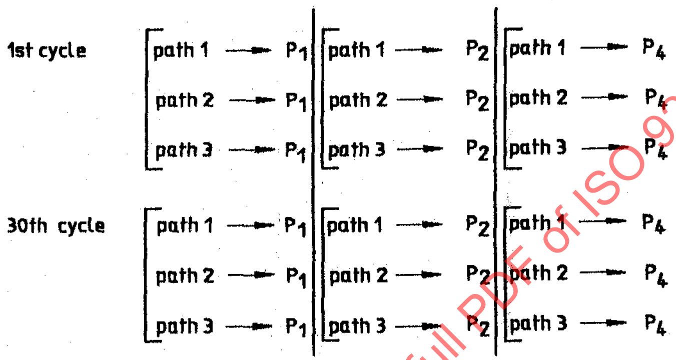


Figure 10 — Illustration of the cycle

7.3 Distance accuracy and repeatability

(applicable only to robots with the facility for explicit programming)

7.3.1 General

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

Where the unidirectional pose accuracy and repeatability characteristics in 7.2 have been measured using explicit programming to command each pose it is possible to calculate the distance accuracy and repeatability between each two successive command poses by processing the data already collected by using the formulae in 7.3.2 and 7.3.3. In this case the results obtained for each pair of successive poses should be recorded.

Where the unidirectional pose accuracy and repeatability characteristics in 7.2 have been measured using teach programming to command each pose it is sufficient to make a limited test in which distance accuracy and repeatability are measured between two poses only. In this case the distance accuracy and repeatability can be measured by commanding the pose in one of two ways:

a) by commanding both poses using explicit programming;

b) by commanding one pose by teach and programming a distance.

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 11) and the distance being repeated n times.

The positioning distance accuracy AD is calculated as follows:

$$\mathrm{AD} = D_c - \overline{D}$$

where

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

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

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

with

- x_{c1}, y_{c1} and z_{c1} as the coordinates of P_{c1} available in the robot computer;
- x_{c2}, y_{c2} and z_{c2} as the coordinates of P_{c2} available in the robot computer;
- 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:

$$\mathrm{AD}_x = D_{cx} - \overline{D}_x$$
$$\mathrm{AD}_y = D_{cy} - \overline{D}_y$$
$$\mathrm{AD}_z = D_{cz} - \overline{D}_z$$

where

$$D_{cx} = |x_{c1} - x_{c2}|$$
$$D_{cy} = |y_{c1} - y_{c2}|$$
$$D_{cz} = |z_{c1} - z_{c2}|$$

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

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

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

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

$$\mathrm{AD}_a = D_{ca} - \overline{D}_a$$
$$\mathrm{AD}_b = D_{cb} - \overline{D}_b$$
$$\mathrm{AD}_c = D_{cc} - \overline{D}_c$$

where

$$D_{ca} = |a_{c1} - a_{c2}|$$
$$D_{cb} = |b_{c1} - b_{c2}|$$
$$D_{cc} = |c_{c1} - c_{c2}|$$

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

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

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

with

- a_{c1}, b_{c1} and c_{c1} as the orientations of P_{c1} available in the robot computer;
- a_{c2}, b_{c2} and c_{c2} as the orientations of P_{c2} available in the robot computer;
- 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 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 % and/or 10 % (optional)	$P_1 - P_2 - P_4$	30
The mass of rated load reduced to 50 % (optional)	100 % of rated velocity (optional) 50 % and/or 10 % (optional)		

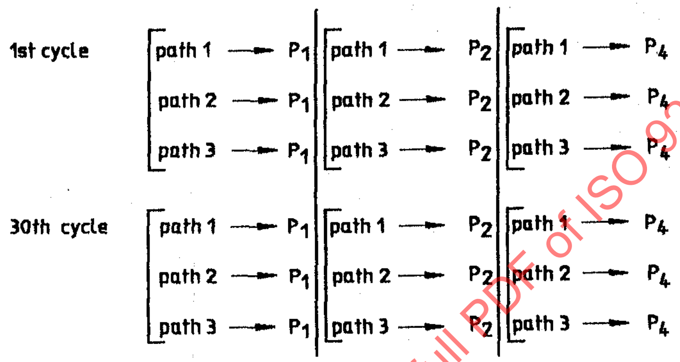


Figure 10 — Illustration of the cycle

7.3 Distance accuracy and repeatability (applicable only to robots with the facility for explicit programming)

7.3.1 General

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

Where the unidirectional pose accuracy and repeatability characteristics in 7.2 have been measured using explicit programming to command each pose it is possible to calculate the distance accuracy and repeatability between each two successive command poses by processing the data already collected by using the formulae in 7.3.2 and 7.3.3. In this case the results obtained for each pair of successive poses should be recorded.

Where the unidirectional pose accuracy and repeatability characteristics in 7.2 have been measured using teach programming to command each pose it is sufficient to make a limited test in which distance accuracy and repeatability are measured between two poses only. In this case the distance accuracy and repeatability can be measured by commanding the pose in one of two ways:

a) by commanding both poses using explicit programming;

b) by commanding one pose by teach and programming a distance.

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 11) and the distance being repeated n times.

The positioning distance accuracy AD is calculated as follows:

$$\mathrm{AD} = D_c - \overline{D}$$

where

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

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

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

with

x_{c1}, y_{c1} and z_{c1} as the coordinates of P_{c1} available in the robot computer;

x_{c2}, y_{c2} and z_{c2} as the coordinates of P_{c2} available in the robot computer;

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:

$$\mathrm{AD}_x = D_{cx} - \overline{D}_x$$
$$\mathrm{AD}_y = D_{cy} - \overline{D}_y$$
$$\mathrm{AD}_z = D_{cz} - \overline{D}_z$$

where

$$D_{cx} = |x_{c1} - x_{c2}|$$
$$D_{cy} = |y_{c1} - y_{c2}|$$
$$D_{cz} = |z_{c1} - z_{c2}|$$

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

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$$\mathrm{AD}_a = D_{ca} - \overline{D}_a$$
$$\mathrm{AD}_b = D_{cb} - \overline{D}_b$$
$$\mathrm{AD}_c = D_{cc} - \overline{D}_c$$

where

$$D_{ca} = |a_{c1} - a_{c2}|$$
$$D_{cb} = |b_{c1} - b_{c2}|$$
$$D_{cc} = |c_{c1} - c_{c2}|$$

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

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

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

with

a_{c1}, b_{c1} and c_{c1} as the orientations of P_{c1} available in the robot computer;

a_{c2}, b_{c2} and c_{c2} as the orientations of P_{c2} available in the robot computer;

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

Load	Velocity	Poses	Number of cycles
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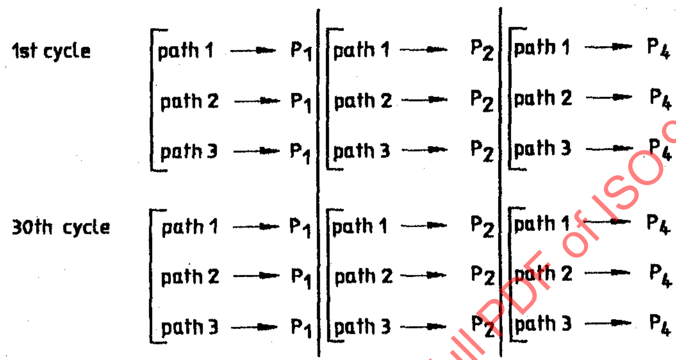

Figure 10 — Illustration of the cycle

7.3 Distance accuracy and repeatability (applicable only to robots with the facility for explicit programming)

7.3.1 General

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

Where the unidirectional pose accuracy and repeatability characteristics in 7.2 have been measured using explicit programming to command each pose it is possible to calculate the distance accuracy and repeatability between each two successive command poses by processing the data already collected by using the formulae in 7.3.2 and 7.3.3. In this case the results obtained for each pair of successive poses should be recorded.

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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 11) and the distance being repeated n times.

The positioning distance accuracy AD is calculated as follows:

$$\mathrm{AD} = D_c - \overline{D}$$

where

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

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

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

with

- x_{c1}, y_{c1} and z_{c1} as the coordinates of P_{c1} available in the robot computer;
- x_{c2}, y_{c2} and z_{c2} as the coordinates of P_{c2} available in the robot computer;
- 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:

$$\mathrm{AD}_x = D_{cx} - \overline{D}_x$$
$$\mathrm{AD}_y = D_{cy} - \overline{D}_y$$
$$\mathrm{AD}_z = D_{cz} - \overline{D}_z$$

where

$$D_{cx} = |x_{c1} - x_{c2}|$$
$$D_{cy} = |y_{c1} - y_{c2}|$$
$$D_{cz} = |z_{c1} - z_{c2}|$$

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

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

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

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

$$\mathrm{AD}_a = \mathrm{D}_{ca} - \overline{D}_a$$
$$\mathrm{AD}_b = \mathrm{D}_{cb} - \overline{D}_b$$
$$\mathrm{AD}_c = \mathrm{D}_{cc} - \overline{D}_c$$

where

$$D_{ca} = |a_{c1} - a_{c2}|$$
$$D_{cb} = |b_{c1} - b_{c2}|$$
$$D_{cc} = |c_{c1} - c_{c2}|$$

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

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

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

with

- a_{c1}, b_{c1} and c_{c1} as the orientations of P_{c1} available in the robot computer;
- a_{c2}, b_{c2} and c_{c2} as the orientations of P_{c2} available in the robot computer;
- 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.

— 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 12).

— At least as a minimum, the value of AD is given.

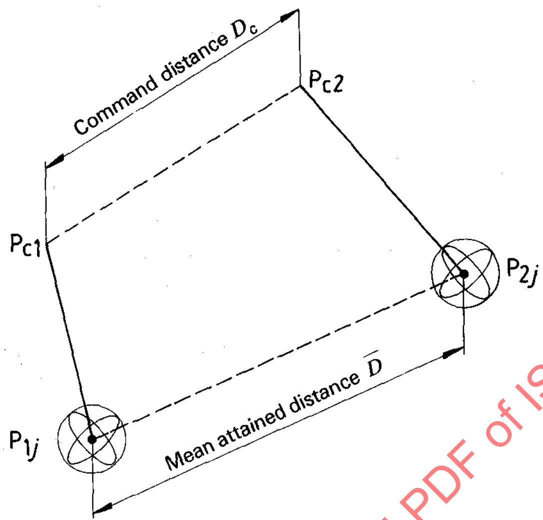


Figure 11 — Distance accuracy

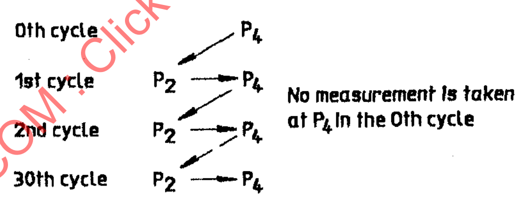


Figure 12 — Illustration of the cycle

Table 9 — Summary of test conditions for distance accuracy

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % and/or 10 % (optional)	$P_2 - P_4$	30

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 applies:

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

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

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

with the different variables as defined in 7.3.2.

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

— Same procedure as in 7.3.2. The value of RD is given.

7.4 Pose stabilization time

The stabilization time is the period of time which elapses between the instant at which the robot gives the attained pose signal and the instant at which the damped oscillatory motion or the damped motion of the mechanical interface falls within a limit as specified by the manufacturer (see figure 13).

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

Table 10 — Summary of test conditions for distance repeatability

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % and/or 10 % (optional)	$P_2 - P_4$	30

Table 11 — Summary of test conditions for pose stabilization time

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % and/or 10 % (optional)	$P_1 - P_2 - P_3$ $P_4 - P_5$	3
The mass of rated load reduced to 50 % (optional)	100 % of rated velocity (optional) 50 % and/or 10 % (optional)		

— The cycles are the same as in 7.2.1 (see figure 8). For each pose, position and orientation of the mechanical interface are recorded from the time the robot gives the attained pose signal.

  The time at which the oscillatory response of the mechanical interface falls within the limit as specified by the manufacturer, is recorded on the resulting graph (see figure 13).

— For each pose, the mean value t of the three cycles is calculated.

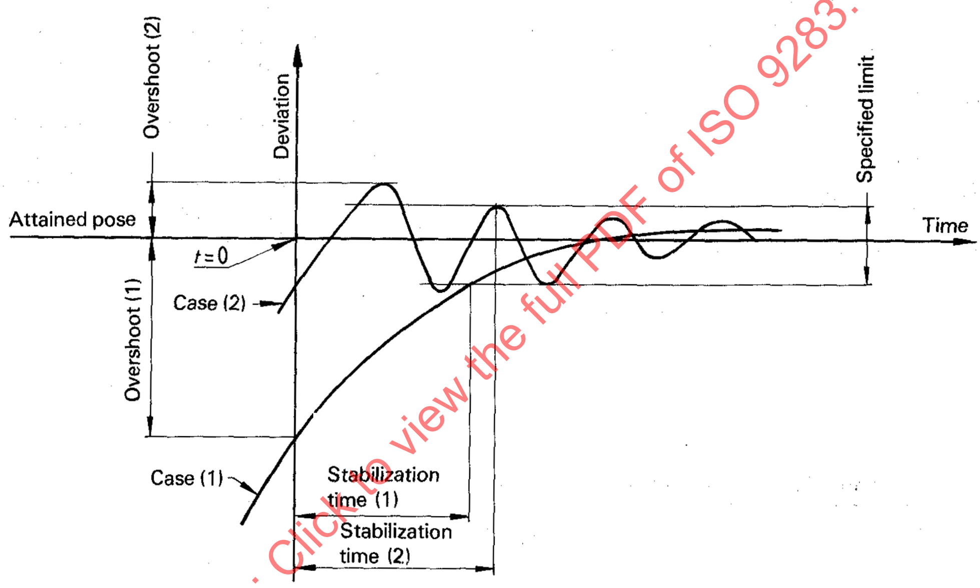
7.5 Pose overshoot

Pose overshoot is the maximum deviation between the approach path and the attained pose after the robot has given the attained pose signal.

This is shown in figure 13 for case 1 as a negative deviation (negative overshoot), and for case 2 as a positive deviation (positive overshoot).

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

— The mean deviation of the three cycles is calculated for each pose.



NOTE — Time t = 0 corresponds to the time when the attained pose signal occurs. The two cases (1) and (2) shown in the above figure correspond to two different approaches.

Figure 13 — Stabilization time and pose overshoot

Table 12 — Summary of test conditions for pose overshoot

Load	Velocity	Poses	Number of cycles
100 % of rated load	100 % of rated velocity 50 % and/or 10 % (optional)	$P_1 - P_2 - P_3$ $P_4 - P_5$	3
The mass of rated load reduced to 50 % (optional)	100 % of rated velocity (optional) 50 % and/or 10 % (optional)		

7.6 Drift of pose characteristics

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

$$dAP = |AP_{t=0} - AP_{t=T}|$$

$$dAP_a = |AP_{at=0} - AP_{at=T}|$$

$$dAP_b = |AP_{bt=0} - AP_{bt=T}|$$

$$dAP_c = |AP_{ct=0} - AP_{ct=T}|$$

where AP is defined in 7.2.1.

The maximum values should be reported.

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

$$dRP = |RP_{t=0} - RP_{t=T}|$$

$$dRP_a = |RP_{at=0} - RP_{at=T}|$$

$$dRP_b = |RP_{bt=0} - RP_{bt=T}|$$

$$dRP_c = |RP_{ct=0} - RP_{ct=T}|$$

where RP is defined in 7.2.2.

The maximum value should be reported.

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

- Drift measurements should begin from cold (immediately after actuation of the main power) and continued over several hours in the warmed-up state.
- 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 (see figure 14).
- The measurements can be stopped before 8 h if the rate of change of the drift for five continuous sets is less than 10 % of the largest rate of change during the first hour. These measurements are used to calculate unidirectional pose accuracy and repeatability (see 7.2.1 and 7.2.2). These results are plotted on a graph as a function of time. The time between the measurements shall be 10 min (see figure 15).

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

Load	Velocity	Pose	Number of cycles
100 % of rated load	100 % of rated velocity	P_1	8 h continuous cycling

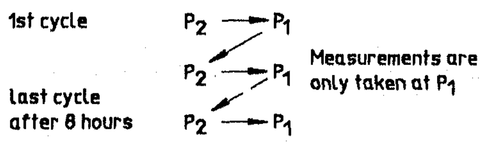
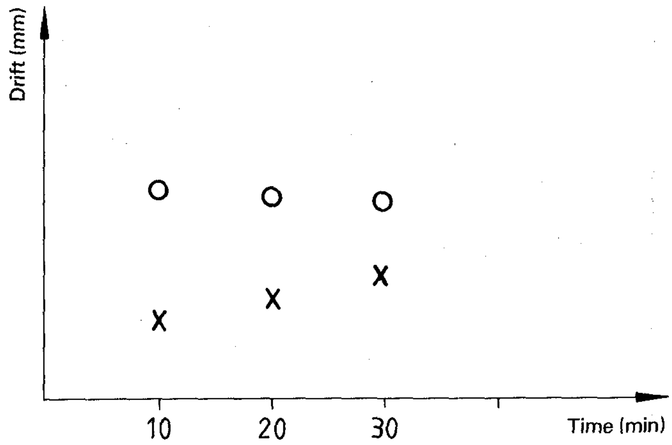


Figure 14 — Illustration of the cycle



X = Unidirectional pose accuracy: AP
O = Unidirectional pose repeatability: RP

Figure 15 — Example of graph for drift of pose characteristics

8 Path characteristics

8.1 General

Path accuracy and repeatability definitions are independent of the shape of the command path. Two examples of different shapes of command path are shown in figure 16 and figure 17.

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, and n times in the opposite direction.

Path accuracy is determined by the two factors:

- the difference between a command path and the barycentre line of the cluster of the obtained paths (i.e. positioning path accuracy, AT, in figure 16);
- the difference between command angular orientation and the average of the attained angular orientation (i.e. orientation path accuracy).

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

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

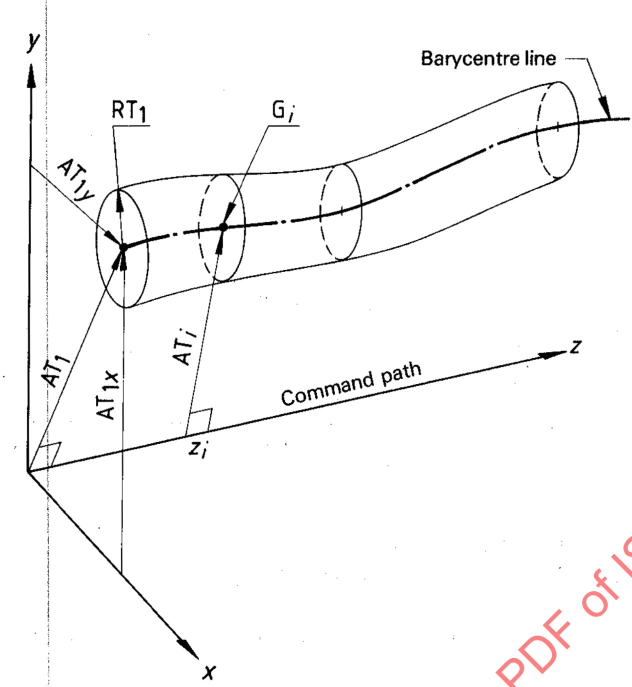


Figure 16 — Path accuracy and path repeatability for a command linear path

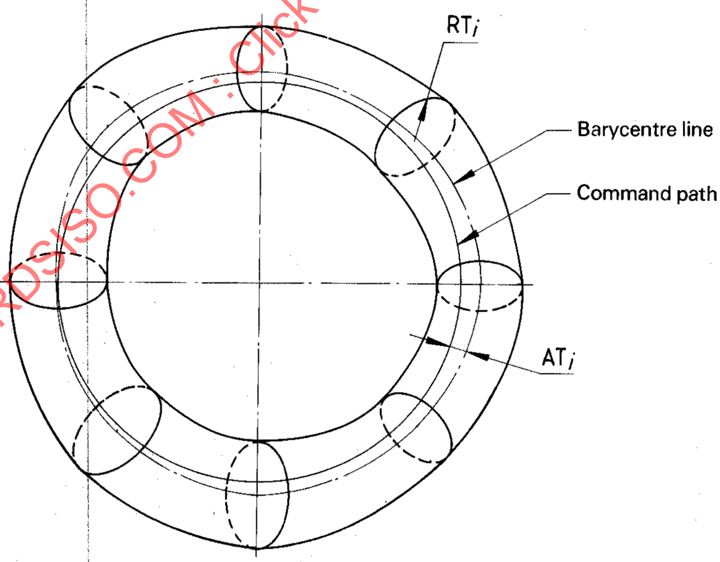


Figure 17 — Path accuracy and path repeatability for a command circular path

If the command path is defined as the Z-axis, the positioning path accuracy is calculated as follows:

$$\mathrm{AT} = \max_{i=1}^{m} \sqrt{(x_{ci} - \bar{x}_i)^2 + (y_{ci} - \bar{y}_i)^2}$$

$$\mathrm{AT}_x = \max_{i=1}^{m} |(x_{ci} - \bar{x}_i)|$$

$$\mathrm{AT}_y = \max_{i=1}^{m} |(y_{ci} - \bar{y}_i)|$$

where

$$\bar{x}_i = \frac{1}{n} \sum_{j=1}^{n} x_{ij}$$

$$\bar{y}_i = \frac{1}{n} \sum_{j=1}^{n} y_{ij}$$

x_{ci} and y_{ci} are the coordinates of a point on the command path corresponding to measurement point z_i;

x_{ij} and y_{ij} are the coordinates of the point of the attained path corresponding to the measurement point z_i for the j-th replication.

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

$$\mathrm{AT}_a = \max_{i=1}^{m} |a_{ci} - \bar{a}_i|$$

$$\mathrm{AT}_b = \max_{i=1}^{m} |b_{ci} - \bar{b}_i|$$

$$\mathrm{AT}_c = \max_{i=1}^{m} |c_{ci} - \bar{c}_i|$$

where

$$\bar{a}_i = \frac{1}{n} \sum_{j=1}^{n} a_{ij}$$

$$\bar{b}_i = \frac{1}{n} \sum_{j=1}^{n} b_{ij}$$

$$\bar{c}_i = \frac{1}{n} \sum_{j=1}^{n} c_{ij}$$

a_{ci}, b_{ci} and c_{ci} are the command angles at the measurement point z_i;

a_{ij}, b_{ij} and c_{ij} are the attained angles at the measurement point z_i for the j-th replication.

Table 14 gives a summary of test conditions for path accuracy.

Whilst the definition of path accuracy shows path accuracy as a distance dependent quantity, measurement of the attained path may be carried out as a function of either distance or time.

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.

Table 14 — Summary of test conditions for path accuracy

Load	Velocity	Example of path	Number of cycles
100 % of rated load	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity	Linear path $E_1 - E_3$ and $E_3 - E_1$	10
The mass of rated load reduced to 50 % (optional)	100 % of rated velocity 50 % of rated velocity 10 % of rated velocity		

The start point shall lie outside the chosen test plane. The tests shall be bidirectional.

The results to be given, as a minimum, are for each load and velocity condition:

	+ z direction		− z direction	
Path accuracy:	AT =	mm	AT =	mm
	AT_a =	°	AT_a =	°
	AT_b =	°	AT_b =	°
	AT_c =	°	AT_c =	°

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

— the maximum value of RT which is the radius of the circle whose centre is on the barycentre line and with the z-value z_i;

— the maximum of the spread of angles about the mean value at the different z_i positions.

If the command path is defined as the Z-axis, the path repeatability is calculated as follows:

$$\mathrm{RT} = \max_{i=1}^{m}\left[\bar{l}_i + 3S_{li}\right]$$

where

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

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

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

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

$$\mathrm{RT}_a = \max_{i=1}^{m}\left[3\sqrt{\frac{\sum_{j=1}^{n}(a_{ij}-\bar{a}_i)^2}{n-1}}\right]$$

$$\mathrm{RT}_b = \max_{i=1}^{m}\left[3\sqrt{\frac{\sum_{j=1}^{n}(b_{ij}-\bar{b}_i)^2}{n-1}}\right]$$

$$\mathrm{RT}_c = \max_{i=1}^{m}\left[3\sqrt{\frac{\sum_{j=1}^{n}(c_{ij}-\bar{c}_i)^2}{n-1}}\right]$$

with $\bar{a}_i$, $\bar{b}_i$, $\bar{c}_i$, 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.

The results to be given, as a minimum, are for each load and velocity condition:

	+ z direction		− z direction	
Path repeatability:	RT =	mm	RT =	mm
	RT_a =	°	RT_a =	°
	RT_b =	°	RT_b =	°
	RT_c =	°	RT_c =	°

8.4 Cornering deviations

8.4.1 Cornering overshoot (CO) and cornering round-off error (CR) are deviations between a command path and the actual path when the command path consists of two lines perpendicular to each other (see figure 18).

Cornering round-off error is defined as the minimum distance between the corner point (x_e, y_e, z_e in figure 18) and the attained path. For the j-th path this is calculated as follows:

$$\mathrm{CR}_j = \min_{i=1}^{m}\left(\sqrt{(x_i-x_e)^2+(y_i-y_e)^2+(z_i-z_e)^2}\right)$$

where

m	is the number of measurement points along the path;
x_e, y_e and z_e	are the coordinates of the corner point;
x_i, y_i and z_i	are the coordinates of the attained path pose corresponding to the measurement point i.

Cornering overshoot is defined as the maximum deviation from the command path after the robot started on the second path without delay time and with programmed constant path velocity.

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:

$$CO = \max_{i=1}^{m} \sqrt{(x_i - x_{ci})^2 + (y_i - y_{ci})^2}$$

where

x_{ci} and y_{ci} are the coordinates of the command path pose corresponding to measurement point z_{ci};

x_i and y_i are the coordinates of the attained path pose 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.

Table 15 gives a summary of test conditions for cornering deviations.

The start position shall be half-way between E_1 and E_4. Continuous path programming shall be used to command the corner path. Any automatic reduction in velocity when executing the path shall be as specified by the manufacturer.

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

Cornering overshoot can be calculated from measuring the deviation from the corner point and each path measured. The position of the corner point can be either measured during teaching in the case of teach programming or known in the case of explicit programming.

The mean cornering overshoot error CO is calculated as the arithmetic mean of all overshoot errors recorded in three passes.

The mean cornering round-off error CR is calculated as the arithmetic mean of all path distance errors recorded in three passes.

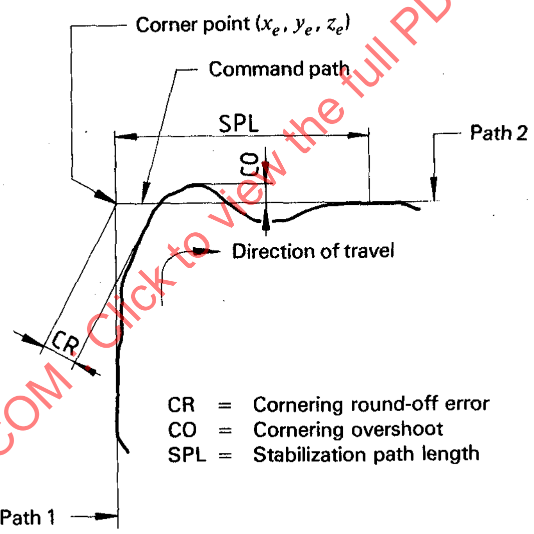


Figure 18 — Cornering overshoot and cornering round-off error

Table 15 — 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 4, 6.8.6.2)	3