Chapter 15
Accuracy and Repeatability of Industrial Manipulators

In this chapter we shall briefly consider performance criteria and the methods for testing of industrial robot manipulators as described in the ISO 9283 standard. Before addressing accuracy and repeatability of industrial manipulators we will summarize basic information about robot manipulators.

The basic robot data typically includes a schematic drawing of the robot mechanical structure:

- cartesian robot (Fig. 15.1 left),
- cylindrical robot (Fig. 15.1 right),
- polar (spherical) robot (Fig. 15.2 left),
- anthropomorphic robot (Fig. 15.2 right),
- SCARA robot (Fig. 15.3).

In all drawings the degrees of freedom of the robot mechanism must be marked. The drawing must include also the base coordinate frame and the mechanical interface frame which are determined by the manufacturer.

Of special importance is the diagram showing the boundaries of the workspace (Fig. 15.4). The maximal reach of the robot arm must be clearly shown in at least two planes. The range of motion for each robot axis (degree of freedom) must be indicated. The manufacturer must specify also the center of the workspace c_w, where most of the robot activities take place.

The robot data must be accompanied by the characteristic loading parameters, such as mass (kg), torque (Nm), moment of inertia (kgm^2), and thrust (N). The maximal velocity must be given at a constant rate, when there is no acceleration or deceleration. The maximal velocities for particular robot axes must be given with the load applied to the end-effector. The resolution of each axis movement (mm or °), description of the control system and the programming methods must also be presented.

The three most relevant robot coordinate frames (right-handed) are shown in Fig. 15.5. First is the world coordinate frame x_0–y_0–z_0. The origin of the frame is defined by the user. The z_0 axis is parallel to the gravity vector, however in the opposite direction. Second is the base coordinate frame x_1–y_1–z_1, whose origin is defined by the manufacturer. Its axes are aligned with the base segment of the robot.

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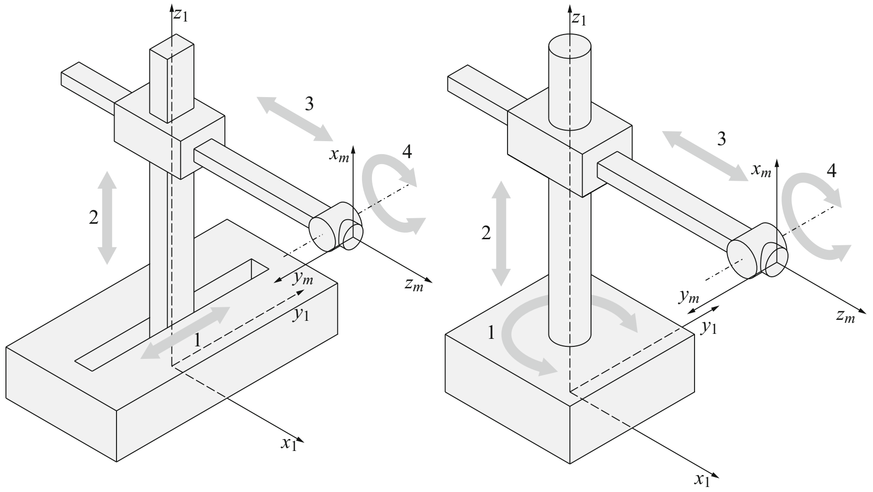

Fig. 15.1 Mechanical structures of the cartesian robot (left) and the cylindrical robot (right)

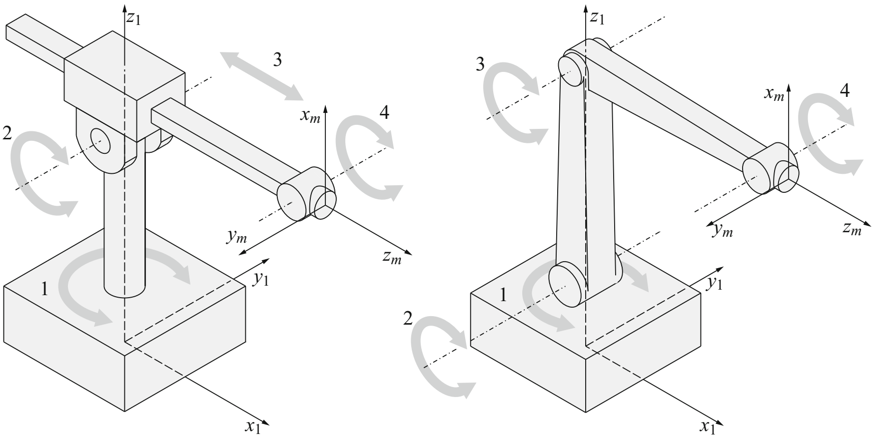

Fig. 15.2 Mechanical structure of the polar robot (left) and the anthropomorphic robot (right)

The positive z_1 axis is pointing perpendicularly away from the base mounting surface. The x_1 axis passes through the projection of the center of the robot workspace c_w. The frame x_m–y_m–z_m is called the mechanical interface coordinate frame. Its origin is placed in the center of the mechanical interface (robot palm) connecting the robot arm with the gripper. The positive z_m axis points away from the mechanical interface toward the end-effector. The x_m axis is located in the plane defined by the interface, which is perpendicular to the z_m axis.

The positive directions of robot motions, specified as the translational and rotational displacements are shown in Fig. 15.6.

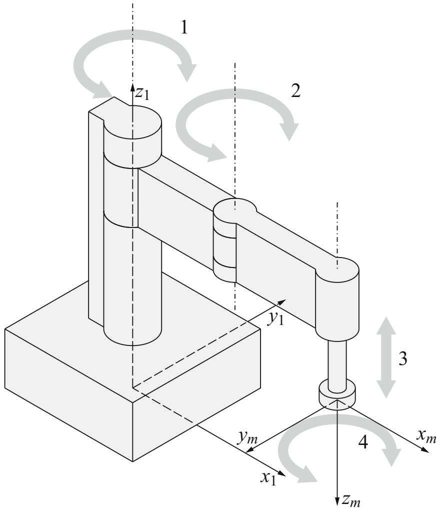

Fig. 15.3 Mechanical structure of the SCARA robot

The ISO 9283 standard deals with criteria and methods for testing of industrial robot manipulators. This is the most important standard as it facilitates the dialogue between manufacturers and users of the robot systems. It defines the way by which particular performance characteristics of a robot manipulator should be tested. The tests can be performed during the robot acceptance phase or in various periods of robot usage in order to check the accuracy and repeatability of the robot motions. The robot characteristics, which significantly affect the performance of a robot task, are the following:

- pose accuracy and repeatability (pose is defined as position, and orientation of a particular robot segment, usually end-effector),
- distance accuracy and repeatability,
- pose stabilization time,
- pose overshoot,
- drift of the pose accuracy and repeatability.

These performance parameters are important in the point-to-point robot tasks. Similar parameters are defined for cases when the robot end-effector moves along a continuous path. These parameters will not be considered in this book and can be found in the original documents.

When testing the accuracy and repeatability of a robot mechanism, two terms are important, namely the cluster and the cluster barycenter. The cluster is defined as a set of attained end-effector poses, corresponding to the same command pose. The barycenter is a point whose coordinates are the mean values of the x, y and z coordinates of all the points in the cluster. The measured position and orientation data must be expressed in a coordinate frame parallel to the base frame.

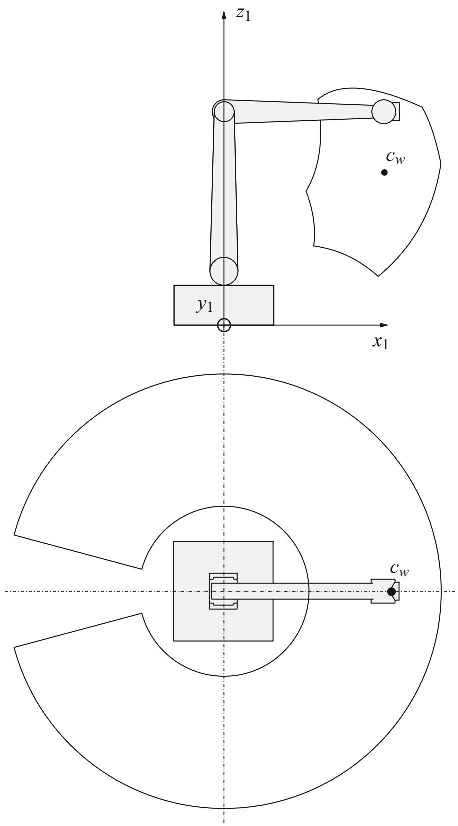

Fig. 15.4 Robot workspace

The measurement point should lie as close as possible to the origin of the mechanical interface frame. Contact-less optical measuring methods are recommended. The measuring instrumentation must be adequately calibrated. The robot accuracy and repeatability tests must be performed with maximal load at the end-effector and maximal velocity between the specified points.

The standard defines the poses which should be tested. The measurements must be performed at five points, located in a plane which is placed diagonally inside a cube (Fig. 15.7). Also specified is the pose of the cube in the robot workspace. It should be located in that portion of the workspace where most of the robot activities are anticipated. The cube must have maximal allowable volume in the robot workspace and its edges should be parallel to the base coordinate frame. The point P_1 is located in the intersection of the diagonals in the center of the cube. The points P_2 – P_5 are located at a distance from the corners of the cube equal to 10% ± 2% of the length of the diagonal L. The standard also determines the minimum number of cycles to be performed when testing each characteristic parameter:

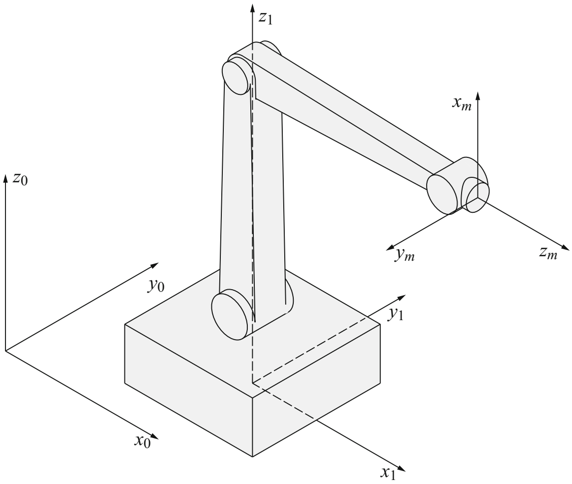

Fig. 15.5 The coordinate frames of the robot manipulator

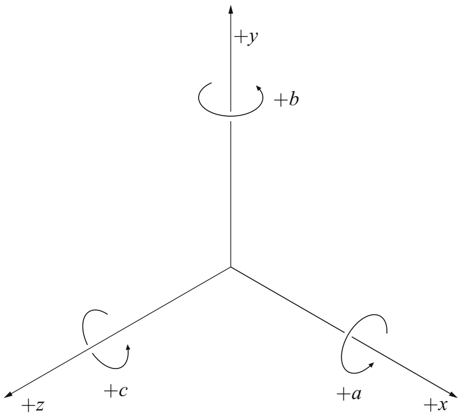

Fig. 15.6 Positive directions of translational and rotational displacements

- pose accuracy and repeatability: 30 cycles,
- distance accuracy and repeatability: 30 cycles,
- pose stabilization time: 3 cycles,
- pose overshoot: 3 cycles,
- drift of pose accuracy and repeatability: continuous cycling during 8 h.

When testing the accuracy and repeatability of the end-effector poses we must distinguish between the so-called command pose and the attained pose (Fig. 15.8).

The command pose is the desired pose, specified through robot programming or manual input of the desired coordinates using a teach pendant. The attained pose is the actually achieved pose of the robot end-effector in response to the command

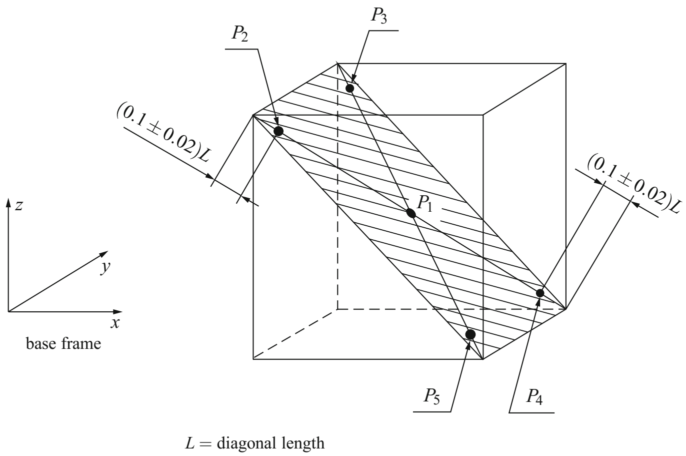

Fig. 15.7 The cube with the points to be tested

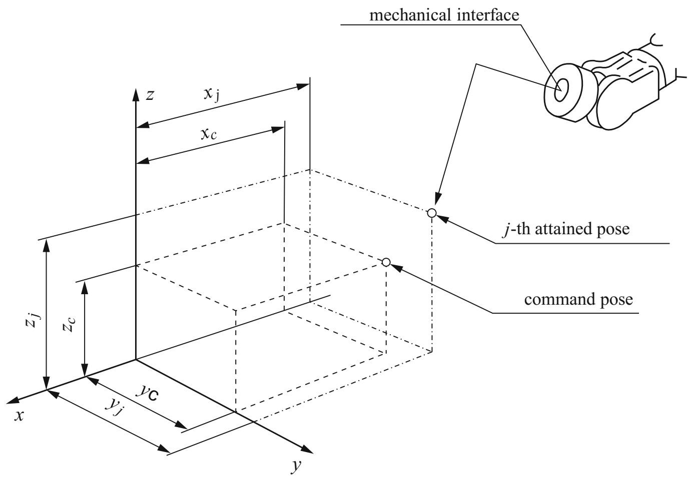

Fig. 15.8 The command pose and the attained end-effector pose

pose. The pose accuracy evaluates the deviations, which occur between the command and the attained pose. The pose repeatability estimates the fluctuations in the attained poses for a series of repeated visits to the same command pose. The pose accuracy and repeatability are, therefore, very similar to the accuracy and repeatability of repetitive shooting at a target. The reasons for the deviations are: errors caused by the control algorithm, coordinate transformation errors, differences between the dimensions of the robot mechanical structure and the robot control model, mechanical faults, such as hysteresis or friction, and external influences such as temperature.

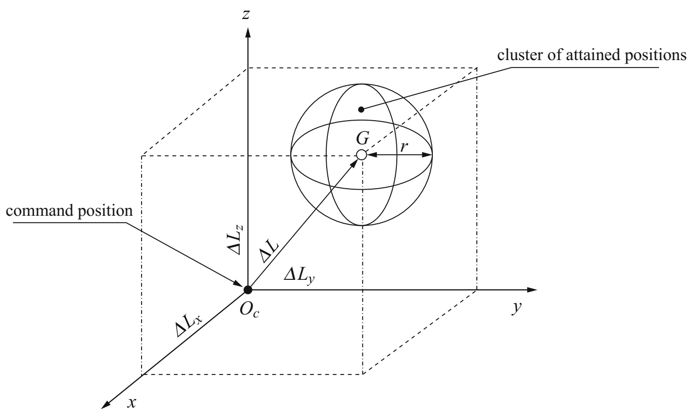

Fig. 15.9 The position accuracy and repeatability

The pose accuracy is defined as the deviation between the command pose and the mean value of the attained poses when the end-effector was approaching the command pose from the same direction. The position and orientation accuracy are treated separately. The position accuracy is determined by the distance between the command pose and the barycenter of the cluster of attained poses (Fig. 15.9). The position accuracy $\Delta L = [\Delta L_x \; \Delta L_y \; \Delta L_z]^T$ is expressed by the following equation

$$\Delta L = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2 + (\bar{z} - z_c)^2}, \tag{15.1}$$

where $(\bar{x}, \bar{y}, \bar{z})$ are the coordinates of the cluster barycenter, obtained by averaging the 30 measurement points, assessed when repeating the motions into the same command pose O_c with the coordinates (x_c, y_c, z_c).

The orientation accuracy is the difference between the commanded angular orientation and the average of the attained angular orientations. It is expressed separately for each axis of the base coordinate frame. The orientation accuracy around the z axis has the following form

$$\Delta L_c = \bar{C} - C_c, \tag{15.2}$$

where $\bar{C}$ is the mean value of the orientation angles around the z axis, obtained in 30 measurements when trying to reach the same command angle C_c. Similar equations are written for the orientation accuracy around the x and y axes.

The standard exactly defines also the course of the measurements. The robot starts from point P_1 and moves into points P_5, P_4, P_3, P_2, P_1. Each point is always reached from the same direction

$$
\begin{array}{ll}
0 \;\; \text{cycle} & \qquad\qquad\quad P_1 \\
1^{st} \; \text{cycle} & P_5 \rightarrow P_4 \rightarrow P_3 \rightarrow P_2 \rightarrow P_1 \\
2^{nd} \; \text{cycle} & P_5 \rightarrow P_4 \rightarrow P_3 \rightarrow P_2 \rightarrow P_1 \\
 & \qquad\qquad\quad \vdots \\
30^{th} \; \text{cycle} & P_5 \rightarrow P_4 \rightarrow P_3 \rightarrow P_2 \rightarrow P_1
\end{array}
$$

For each point the position accuracy ΔL and the orientation accuracies ΔL_a, ΔL_b and ΔL_c are calculated.

For the same series of measurements also the pose repeatability is to be determined. The pose repeatability expresses the closeness of the positions and orientations of the 30 attained poses when repeating the robot motions into the same command pose. The position repeatability (Fig. 15.9) is determined by the radius of the sphere r whose center is the cluster barycenter. The radius is defined as

$$
r = \bar{D} + 3S_D. \tag{15.3}
$$

The calculation of the radius r according Eq. (15.3) is further explained by the following equations

$$
\begin{aligned}
\bar{D} &= \frac{1}{n}\sum_{j=1}^{n} D_j \\
D_j &= \sqrt{(x_j - \bar{x})^2 + (y_j - \bar{y})^2 + (z_j - \bar{z})^2} \\
S_D &= \sqrt{\frac{\sum_{j=1}^{n}(D_j - \bar{D})^2}{n-1}}.
\end{aligned} \tag{15.4}
$$

In the above equations we again select $n = 30$, while (x_j, y_j, z_j) are the coordinates of the j-th attained position.

The orientation repeatability for the angle around the z axis is presented in Fig. 15.10. The orientation repeatability expresses how dispersed are the 30 attained angles around their average for the same command angle. It is described by the threefold standard deviations. For the angle around the z axis we have

$$
r_c = \pm 3S_c = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(C_j - \bar{C})^2}{n-1}}. \tag{15.5}
$$

In Eq. (15.5) C_j represents the angle measured at the j-th attained pose. The course of the measurements is the same as in testing of the accuracy. The radius r and the angular deviations r_a, r_b and r_c are calculated for each pose separately.

The distance accuracy and repeatability are tested in a similar way. The distance accuracy quantifies the deviations which occur in the distance between two command positions and two sets of the mean attained positions. The distance repeatability

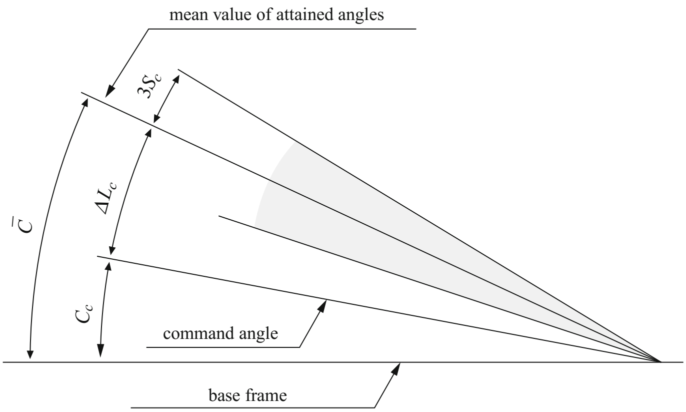

Fig. 15.10 The orientation accuracy and repeatability

determines the fluctuations in distances for a series of repeated robot motions between two selected points. The distance accuracy is defined as the deviation between the command distance and the mean of the attained distances (Fig. 15.11). Assuming that P_{c1} and P_{c2} are the commanded pair of positions and P_{1j} and P_{2j} are the j-th pair from the 30 pairs of the attained positions, the distance accuracy ΔB is defined as

$$\Delta B = D_c - \bar{D}. \tag{15.6}$$

where

$$D_c = \left|P_{c_1} - P_{c_2}\right| = \sqrt{(x_{c_1} - x_{c_2})^2 + (y_{c_1} - y_{c_2})^2 + (z_{c_1} - z_{c_2})^2}$$

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

$$D_j = \left|P_{1_j} - P_{2_j}\right| = \sqrt{(x_{1_j} - x_{2_j})^2 + (y_{1_j} - y_{2_j})^2 + (z_{1_j} - z_{2_j})^2}.$$

In the above equations describing the distance accuracy $P_{c_1} = (x_{c_1}, y_{c_1}, z_{c_1})$ and $P_{c_2} = (x_{c_2}, y_{c_2}, z_{c_2})$ represent the pair of desired positions while $P_{1_j} = (x_{1_j}, y_{1_j}, z_{1_j})$ and $P_{2_j} = (x_{2_j}, y_{2_j}, z_{2_j})$ are the pair of attained positions. The distance accuracy test is performed at maximal loading of the robot end-effector, which must be displaced 30 times between points P_2 and P_4 of the measuring cube. The distance repeatability R_B is defined as

$$R_B = \pm 3\sqrt{\frac{\sum_{j=1}^{n}(D_j - \bar{D})^2}{n-1}}. \tag{15.7}$$

Let us consider another four characteristic parameters which should be tested in industrial robots moving from point to point. The first is the pose stabilization

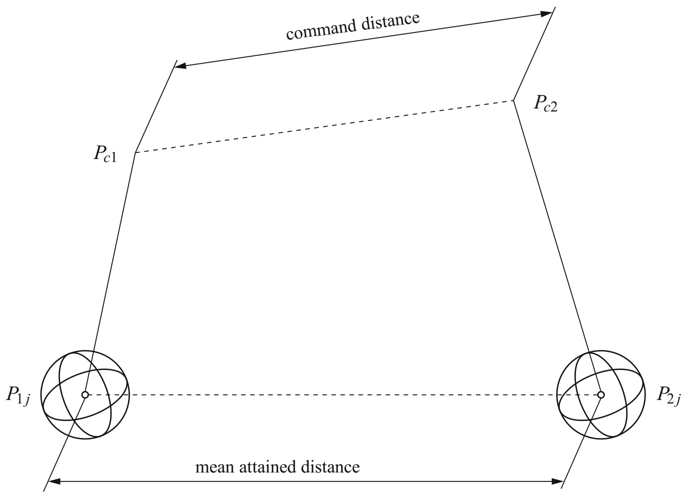

Fig. 15.11 Distance accuracy

time. The stabilization time is the time interval between the instant when the robot gives the "attained pose" signal and the instant when either oscillatory or damped motion of the robot end-effector falls within a limit specified by the manufacturer. The definition of the pose stabilization time is evident from Fig. 15.12. The test is performed at maximal loading and velocity. All five measuring points are visited in the following order $P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4 \rightarrow P_5$. For each pose the mean value of three cycles is calculated.

A similar parameter is the pose overshoot, also shown in Fig. 15.12. The pose overshoot is the maximum deviation between the approaching end-effector trajectory and the attained pose after the robot has given the "attained pose" signal. In Fig. 15.12 a negative overshoot is shown in the first example and a positive overshoot in the second example. The instant $t = 0$ is the time when the "attained pose" signal was delivered. The measuring conditions are the same as when testing the stabilization time.

The last two parameters to be tested in the industrial robot manipulator moving from point to point are drift of the pose accuracy and the drift of the pose repeatability. The drift of the position accuracy L_{DR} is defined as

$$L_{DR} = |\Delta L_{t=0} - \Delta L_{t=T}|, \tag{15.8}$$

where $\Delta L_{t=0}$ and $\Delta L_{t=T}$ are the position accuracy values at time $t = 0$ and time t=T, respectively. The drift of the orientation accuracy L_{DRC} is equal to

$$L_{DRC} = \left|\Delta L_{c,t=0} - \Delta L_{c,t=T}\right|, \tag{15.9}$$

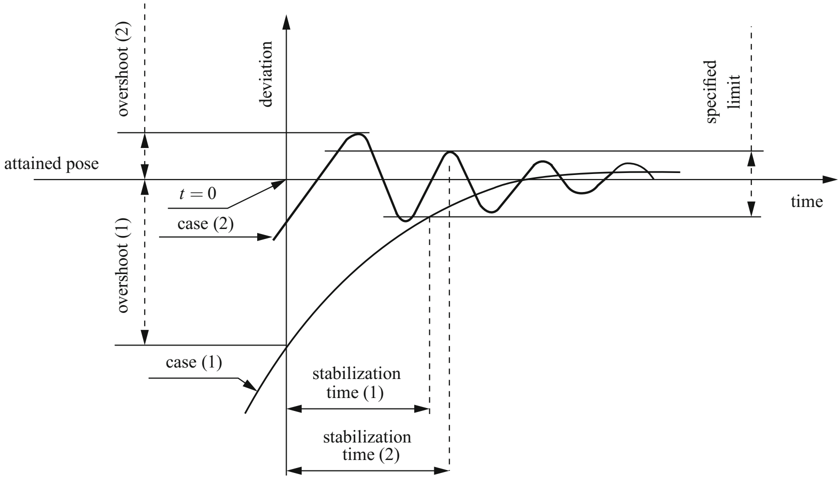

Fig. 15.12 Pose stabilization time and overshoot

where $\Delta L_{c,t=0}$ and $\Delta L_{c,t=T}$ are the orientation accuracy values at time $t = 0$ and time t=T, respectively. The drift of the position repeatability is defined by the following equation

$$r_{DR} = r_{t=0} - r_{t=T}, \tag{15.10}$$

where $r_{t=0}$ and $r_{t=T}$ are the position repeatability values at time $t = 0$ and time t=T, respectively. The drift of the orientation repeatability is for the rotation around the z axis defined as

$$r_{DRC} = r_{c,t=0} - r_{c,t=T}, \tag{15.11}$$

where $r_{c,t=0}$ and $r_{c,t=T}$ are the orientation repeatability values at time $t = 0$ and time t=T, respectively. The measurements are performed at maximal robot loading and velocity. The robot is cyclically displaced between points P_4 and P_2. The cyclic motions last for eight hours. Measurements are only taken in point P_4.