Accuracy

Accuracy seems to be an easy concept. However, since accurate is always a relative term and we are often dealing with discrete devices, accuracy can be a rather vague term. The concepts in this portion apply to many mechanical and electrical systems. The vagueness open doors to different interpolations. People often use the interpretation to their advantage.
1. Basic concepts

In order to discuss accuracy in more rigorous terms, we need to define several terms.

Definitions

Pose: position and orientation of a robot. A taught point results in a post.

Point: x, y and z coordinate of the tool center point.

Measuring or reference coordinate system: a coordinate system considered error free or traceable with less error than the robot.

Target point: where we want to the robot to go. It is may or may be specified in robot or reference coordinate system.

Commanded point: Taught point in robot coordinate system.

Achieved position: where robot actually reaches in measuring coordinate system.

Resolution: The closest commanded nominal locations. Angular or linear.

Repeatability: The errors between successive achieved positions for the same commanded position.

Position accuracy: the difference between commanded and achieved point.

Common sense accuracy: Difference between achieved and target.

Static error: the error measured after robot stops. Like put a key in the key hole.

Dynamic error: the error measured during robot motion, like throw a basketball into a basket.

In 1-D, the target, achieved and commanded points are shown in Figure 1.

![Figure 2.1. The relationship between various coordinate and points.](image-url)
2. Robot control mechanism and resolution

Robot construction has limited accuracy. The errors can in the encoder, drive train, scales of a joint or out of squared between connecting links. What is important is the difference between the achieved point and target point in the same coordinate system.

2.1 Robot Drive and position sensing system

Robot uses motors and sensors to achieve motion, speed and position control. The following figure shows a typical DC servo drive train. The power can be Hydraulic, AC motors, Stepping motors, or Pneumatic drives. Most robot modern sensors are discrete devices.

![Servo drive system of a joint.](image)

2.2 Position Sensing:

Analog vs. digital, we believe we have analog. Robots mostly digital (discrete).

Absolute vs. incremental odometer vs. tripometer:

- Revolvers: proportional to angles.
- Incremental encoders: digital, incremental

For example, an encoder can have a glass disk with alternate transparent and opaque stripes. A photo-transmitter is used to project light through the disk. A photo sensor on the other side of the disk can be used to count the light intensity changes. An encoders is commonly attached to the motor.

- Single sensor: no directional capabilities
- Dual sensor: can detect direction. Two are positioned such that 90° out of phase.

White = 1
clockwise: 10 - 11 - 01 - 00 - 11
c. clockwise: 10 - 00 - 01 - 11 - 10

States: $2^2 *$ lines
Encoders: absolute. Use of multiple tracks. It will only work in one circle. Not common in robots.

States = \(2^2 \times 2^n\), where \(n\) is number of rings.

Even when an incremental encoder is used, you can still record absolute positions by using limit switches and memory. The CRS uses 1000/rev absolute (microchip recording) encoder.

### 2.3 Resolution of a joint
Smallest distance between consecutive commanded positions in a joint. It is the distance changed in a link corresponds to an encoder change.

- Rotational joint: constant angular separation \(\alpha\)
- CRS: 600 pulses / deg.
- Linear joint: Distance between consecutive addressible locations.
- This is sometimes called basic length unit or BLU.

\[
\text{Rotational joint has approximate linear resolution: } \alpha R,
\]

where \(R\) is the length of the link.

CRS F3

- Encoder: 1000 states/ rev
- Joint 1: 600 positions / degree
Calculation of resolution

Linear resolution is affected by encoder resolution, gear ratio, length of arm, pitch in lead screw and constrained by position word length

Notations and relationships (3.8)

Resolution of the encoder (angular):

- $N_e$: number of states in a circle of an encoder.
- $\alpha_e$: angular resolution of encoder. rad/state or degrees/state $= \frac{2\pi}{N_e} = \frac{360}{N_e}$
- $\alpha_{arm}$: angular resolution of the arm.
- $\alpha$: linear resolution of a rotational joint $= \alpha_{enc} \cdot R$ ($\alpha$ is in radians)

![Diagram](image)

- $N_m$: number of teeth on the motor gear
- $N_{arm}$: number of teeth on the arm gear
- $n = \frac{N_m}{N_{arm}}$: The gear ratio
- $\alpha_{arm}$: angular res. of arm.
- $\alpha_{arm} = \alpha_e \cdot n$

Linear resolution of a rotational joint

$\alpha_L = \alpha_{arm} \cdot R$

![Diagram](image)

Lead screw mechanism

Pitch / $N_{screw}$

Where $N_{screw}$ is the number of partitions on the screw in 1 revolution.

E.g. An arm is 5 m. $N_e = 2^B$, $N_m = 10$, $N_{arm} = 30$. The location memory variable has 16 bits and total travel is 300 degrees. What is the linear resolution at the end of the arm.

![Diagram](image)
Angular resolution encoder: $\alpha_e = 2\pi / N_e = 0.02454 \text{ rad} = 1.406^\circ$

Angular resolution arm: $\alpha_e = \alpha_e \times n = \alpha_e 	imes 10 / 30 = 0.00818 = .468^\circ$

Min linear resolution $\alpha_L = R \times \alpha_e = 4.09 \text{ mm} = .16''$

No. of required positions $= 300 / \alpha_e \text{ (in degrees)} = 640.1$

Maximum recordable positions in 16 bits $= 2^{16} = 65536$. OK

ANSWER: The linear resolution of this rotational joint is 0.16''

Resolution grid pattern
Cartesian

Note that the linear resolution of a spherical, cylindrical or articulated arm is not a constant in its envelop. What is constant? The angular resolution for each joint is.

SCARA robot example

The arm and forearm $L_1$ and $L_2$ in an articulated robot are 300 mm long. The angular resolutions of shoulder and elbow are 0.01°. Please find the tangential $L_C$ and radial $L_R$ resolutions when $\theta_2 = -60^\circ$ and $\theta_2 = -120^\circ$ (hint: the following figure offers the easiest pose for calculation). The angular velocity of the joints are $v_{\theta_1} = v_{\theta_2} = 180^\circ / \text{ second}$.

Without loosing generality, we consider the end point is on x axis (any radial line is O.K.), $\theta_1 = -0.5\theta_2$. 
\[ x = 2 L_1 \cos \left( \frac{\theta_2}{2} \right) , \]
\[ y = 2 L_1 \cos \left( \frac{\theta_2}{2} \right) \theta_1 \]
\[ \frac{dx}{d\theta_2} = -2 L_1 \sin \left( \frac{\theta_2}{2} \right) \frac{1}{2} = -2 L_1 \sin \left( \frac{\theta_2}{2} \right) \quad \text{At any point, } \theta_1 \text{ is irrelevant} \]
\[ \frac{dy}{d\theta_1} = 2 L_1 \cos \left( \frac{\theta_2}{2} \right) \quad \text{At any position, } \theta_2 \text{ is irrelevant} \]

Note that you must convert \( d\theta_1 \) and \( d\theta_2 \) into radians. The conversion is \( \pi / 180 \). Therefore,

The angular resolution \( d\theta_2 = 0.01 \times \pi / 180 = 0.0001745 \) radians.

<table>
<thead>
<tr>
<th>( \theta_2 )</th>
<th>( dx )</th>
<th>( dy )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( dx = 0 )</td>
<td>( dy = 2 L_1 \cdot d\theta_1 = 600 \cdot 0.01 \times \pi / 180 = 0.1047 ) mm</td>
</tr>
<tr>
<td>60</td>
<td>( dx = -0.090 )</td>
<td>( dy = 0.0524 )</td>
</tr>
<tr>
<td>120</td>
<td>( dx = -0.090 )</td>
<td>( dy = 0.090 )</td>
</tr>
<tr>
<td>180</td>
<td>( dx = -0.1047 )</td>
<td>( dy = 0.090 )</td>
</tr>
</tbody>
</table>

Radial Speed can

\[ V_x = \frac{dx}{dt} = \frac{dx}{d\theta_2} \cdot d\theta_2 / dt = -2 L_1 \sin \left( \frac{\theta_2}{2} \right) v_0 \]
\[ V_y = \frac{dy}{dt} = \frac{dy}{d\theta_1} \cdot d\theta_1 / dt = 2 L_1 \cos \left( \frac{\theta_2}{2} \right) v_0 \]

\[ 2 L_1 v_0 = 600 \times \pi / 180 \times 180 = 1,884 \text{ mm} \]

<table>
<thead>
<tr>
<th>( \theta_2 )</th>
<th>( v_x )</th>
<th>( v_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( V_x = 0 )</td>
<td>( V_y = 2 L_1 \cdot d\theta_1 = 600 \times \pi / 180 \times 180 = 1,884 ) mm</td>
</tr>
<tr>
<td>60</td>
<td>( V_x = 942 \text{ mm} )</td>
<td>( V_y = 1632 \text{ mm} )</td>
</tr>
<tr>
<td>120</td>
<td>( V_x = 1,632 \text{ mm} )</td>
<td>( V_y = 942 \text{ mm} )</td>
</tr>
<tr>
<td>180</td>
<td>( V_x = 1,884 \text{ mm} )</td>
<td>( V_y = 0 ).</td>
</tr>
</tbody>
</table>
Resolution trend for SCARA robot

The above resolution and speed analysis can be extended to any radial or tangential direction. The radial resolution becomes coarser when $2\theta_2$ goes from $0 \rightarrow 180$. It follows a sine function.

When the resolution is too coarse, the ability to reach a specific target point is poor. When the resolution is too fine, the speed will be limited. Either case, it is not good. The best case is tangential and radial resolutions are moderate. In a SCARA robot, this means that it is best when the arm is not fully extended or retracted. This part range is called "sweet region". An important concept when you deal with non-Cartesian robots.

E.g. a linear joint with a DC servo/encoder directly attached to a leadscrew. Pitch $P = 0.1''$, one thread. $N_e = 100$ states / circle. What is the linear resolution $\lambda$ or BLU?

The angular resolution in the encoder or lead screw

$$\alpha_e = \frac{2 \pi}{N_e} = 0.06283 \text{ radians/line}$$

The linear resolution in the joint

$$\lambda = \text{BLU} = P \times 2 \pi / N_e = 0.1 \times 2 \pi / 0.06283 = 0.001'' / \text{line}$$

In cylindrical or spherical, the grid is not uniform but have simple pattern. In RR, it is not simple.
2.4 Effect of resolution on accuracy
The resolution will affect the ability for a robot to stop at a specific position.

If you teach a point around the target, the best commanded point is the one closest to the target. If we assume that the best possible point is taught and the resolution is uniform, the maximum error due to the resolution is .5 of the resolution.

If you do off-line programming, you will instruct the robot to the closest position based on the computer model, normally related to reference coordinate system. Then, the error can actually be larger.

This is simple in Cartesian robot since linear resolution is uniform. In motion involving rotational joints, the constant is the angular resolution. The linear will depends on the post.

3 Other sources of errors
There are many other sources of errors. Some are systematic while others are random. Here are some examples:

- Length of a link
- Eccentricity of the encoder, gears,
- Calibration
- Thermal expansion
- Elastic deformation
- Backlash
These are more difficult to quantify than that of resolution. RIA has developed some standard measures that capture some of these errors.

4 Standards measures for errors

In order to provide good guidance to the buyers, the RIA defined some standard measures for robot accuracy. ANSI / RIA R15.05 Performance. PTP and static performance defined 2 measures: repeatability and position accuracy.

4.1 Standard development as experiment design problem

For each measure, the standard must provide measurement specifics for the values to be consistent. The first question is the experiment design. The objective is to provide some simple numbers that really capture the robot accuracy that requires minimum effort to achieve.

Repeatability: important in applications in which all important points are taught.

Position accuracy: important if relative movement are used or in off-line programming.

Repeatability

If the robot only uses taught points in an application, the position accuracy is not very important. In fact, we are not even concerned with the readings of the taught point. What is important is whether the robot can go back to the taught point with tolerable errors. Here, we care variation in achievable position for the same commanded point. Repeatability is a parameter intended to capture this type of errors.

The experiment design intended to capture various factors such as

- Speed and approach direction variation
- Various commanded points. It is important to select points that represent different part of the work envelope.
- Number of point at each commanded point.
• Temperature, load, start up, etc.
• Requirements:

The key specifications of the standard include the following.

• Standard loads, as related to the payload in specification, provided in a table.

• 3 locations (j = 1, 2, 3) on Standard plane: (L, 0, 0), (0, L, 0) and (0, 0, -L). The three points should spread almost to the boundary of the envelope. This is intended to use small number of locations that spread the work envelop.

• 500 times each location, (i = 1, ..., 500) repetitions at three (j = 1, 2, 3) specified positions

All points are the measurements of the achieved positions.

\[
r_j = \sqrt{(x_j - \bar{x}_j)^2 + (y_j - \bar{y}_j)^2 + (z_j - \bar{z}_j)^2}, \quad j = 1, 2, 3
\]

\[
\frac{r_{REP}}{\text{N}} = \frac{\sum_{j=1}^{3} \sum_{i=1}^{N} r_j}{3N}
\]

\[
S_{REP} = \sqrt{\frac{\sum_{j=1}^{3} \sum_{i=1}^{N} (r_j - r_{REP})^2}{3N - 1}}
\]

Here, there will be three sets of averages. Each is the center of over 500 achieved positions. If the errors are not directional, the achieved positions will form three spheres about these centers. The \( r_{REP} \) is the average radius of the sphere. If the errors are directional along three orthogonal directions, it can be an ellipse.
E.g. Let’s try a simplified example with three repeated measures at three points for on the standard plane \((0, 10, 0), (5, 0, -5), (10, -10, -10)\). The measurements and calculations are shown on a spreadsheet. The numbers in normal font are given. The numbers in bold face are calculated. Where \(Xc, Yc\) and \(Zc\) are commanded positions, \(Xa, Ya\) and \(Za\) are achievable positions, -24, 10.171, etc are average of 3 achieved positions. \(Dx^2\) are the squares of the differences between the achieved and averages.

### Repeatability

**Three measurements at the first commanded point \((0, 10, 0)\)**

<table>
<thead>
<tr>
<th>Xc1</th>
<th>Xa1</th>
<th>Dx^2</th>
<th>Yc1</th>
<th>Ya1</th>
<th>Dy^2</th>
<th>Zc1</th>
<th>Za1</th>
<th>Dz^2</th>
<th>r_ij</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.500</td>
<td><strong>0.0652</strong></td>
<td>10</td>
<td>9.950</td>
<td><strong>0.0488</strong></td>
<td>0</td>
<td>-0.500</td>
<td><strong>4.251E-05</strong></td>
<td>0.3376</td>
</tr>
<tr>
<td>0</td>
<td>-0.11</td>
<td><strong>0.0195</strong></td>
<td>10</td>
<td>10.353</td>
<td><strong>0.0332</strong></td>
<td>0</td>
<td>-0.4911</td>
<td><strong>5.856E-06</strong></td>
<td>0.2296</td>
</tr>
<tr>
<td>0</td>
<td>-0.13</td>
<td><strong>0.0134</strong></td>
<td>10</td>
<td>10.210</td>
<td><strong>0.0015</strong></td>
<td>0</td>
<td>-0.4899</td>
<td><strong>1.681E-05</strong></td>
<td>0.122</td>
</tr>
</tbody>
</table>

**Three measurements at the second commanded point \((5, 0, -5)\)**

<table>
<thead>
<tr>
<th>Xc2</th>
<th>Xa2</th>
<th>Dx^2</th>
<th>Yc2</th>
<th>Ya2</th>
<th>Dy^2</th>
<th>Zc2</th>
<th>Za2</th>
<th>Dz^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.510</td>
<td><strong>0.0652</strong></td>
<td>0</td>
<td>-0.05</td>
<td><strong>0.0067</strong></td>
<td>-5</td>
<td>-5.500</td>
<td><strong>9.05E-05</strong></td>
</tr>
<tr>
<td>5</td>
<td>4.905</td>
<td><strong>0.0195</strong></td>
<td>0</td>
<td>0.156</td>
<td><strong>0.0154</strong></td>
<td>-5</td>
<td>-5.4876</td>
<td><strong>8.565E-06</strong></td>
</tr>
<tr>
<td>5</td>
<td>4.881</td>
<td><strong>0.0134</strong></td>
<td>0</td>
<td>-0.01</td>
<td><strong>0.0018</strong></td>
<td>-5</td>
<td>-5.4839</td>
<td><strong>4.338E-05</strong></td>
</tr>
</tbody>
</table>

**Three measurements at the third commanded point \((10, -10, -10)\)**

<table>
<thead>
<tr>
<th>Xc3</th>
<th>Xa3</th>
<th>Dx^2</th>
<th>Yc3</th>
<th>Ya3</th>
<th>Dy^2</th>
<th>Zc3</th>
<th>Za3</th>
<th>Dz^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9.915</td>
<td><strong>0.0195</strong></td>
<td>-10</td>
<td>-10.05</td>
<td><strong>0.0533</strong></td>
<td>-10</td>
<td>-10.500</td>
<td><strong>7.248E-05</strong></td>
</tr>
<tr>
<td>10</td>
<td>9.891</td>
<td><strong>0.0134</strong></td>
<td>-10</td>
<td>-9.827</td>
<td><strong>5E-05</strong></td>
<td>-10</td>
<td>-10.488</td>
<td><strong>1.161E-05</strong></td>
</tr>
<tr>
<td>10</td>
<td>9.520</td>
<td><strong>0.0652</strong></td>
<td>-10</td>
<td>-9.581</td>
<td><strong>0.0567</strong></td>
<td>-10</td>
<td>-10.486</td>
<td><strong>2.608E-05</strong></td>
</tr>
</tbody>
</table>

**r_rep** 0.2225  
**S_rep** 0.0858
5. Position accuracy

One type of error is the inherent in the robot coordinate system. This is systematic error due to the scale, orientation and origin. The sources can be scales in absolute encoders or mechanism errors in the incremental encoder.\(360^\circ\) can not be wrong itself. This is important in off-line programming. How do we capture that?

Position accuracy error = achieved - commanded

Note that this is different from common sense of Accuracy = achieved - target

This has to be done throughout the working envelope. Standard requires \(N \geq 50\) points evenly spaced in a line in the standard plane.

\[
d_i = \sqrt{(x_{ai} - x_{ci})^2 + (y_{ai} - y_{ci})^2 + (z_{ai} - z_{ci})^2}
\]

\[
\overline{d_{PA}} = \frac{1}{N} \sum N d_i
\]

\[
S_{PAi} = \sqrt{\frac{\sum N (d_i - \overline{d_{PA}})^2}{N - 1}}
\]

Standard plane: \((L, 0, 0), (0, L, 0)\) and \((0, 0, -L)\).

The standard plane is specified for each type of robot configuration.

Let's look at an example in which we let \(N = 3\).

E.g. If we only do three points. \((0, 10, 0), (5, 5, -5), (10, 0, -10)\)

Position Accuracy Calculation based on 3 point (50 in standard)

<table>
<thead>
<tr>
<th>Xc</th>
<th>Xa</th>
<th>Dx^2</th>
<th>Yc</th>
<th>Ya</th>
<th>Dy^2</th>
<th>Zc</th>
<th>Za</th>
<th>Dz^2</th>
<th>Dvect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.433</td>
<td>0.187</td>
<td>10</td>
<td>10.06</td>
<td>0.004</td>
<td>0</td>
<td>-0.481</td>
<td>0.231</td>
<td>0.65</td>
</tr>
<tr>
<td>5</td>
<td>4.864</td>
<td>0.018</td>
<td>5</td>
<td>5.32</td>
<td>0.102</td>
<td>-5</td>
<td>-5.492</td>
<td>0.242</td>
<td>0.603</td>
</tr>
<tr>
<td>10</td>
<td>9.87</td>
<td>0.017</td>
<td>0</td>
<td>0.171</td>
<td>0.029</td>
<td>-10</td>
<td>-10.5</td>
<td>0.246</td>
<td>0.54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position Accuracy</th>
<th>r_pa</th>
<th>0.598</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S_pa</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Normally, the position accuracy is higher than repeatability. It may not be important if all the important points are taught on-line.

Usage of repeatability and position accuracy

In the book, the repeatability is defined as \(r\).
The relationships between \( r \) and \( r_{REP} \) depends on distribution and dof.

In 1-D and uniform distribution,

\[ r = 2 r_{REP} \]

In 3-D and uniform distribution

\[ r_{REP} = \frac{1}{4} \pi r^3 \int \int \int r^2 \sin \theta d\theta d\phi d\psi = \frac{3}{4} r \]

Or, \( r = \frac{4}{3} r_{REP} = 1.333 r_{REP} \)

If position accuracy error = 0 or all points are taught,

The maximum possible error \( \approx \frac{1}{2} \) resolution + \( r \)

If Repeatability = \( r_{REP} \), what is the value of \( r \)?

In 1-D with uniform distribution, \( r = 2 r_{REP} \)

In other cases, you have to calculate.

E.g. If resolution is .1 mm (0.004") \( r_{REP} = .015 \), target is 10.58 in robot coordinates. \( r_{PA} = 0.5 \).

a). How do you estimate maximum possible error for any target point if the point is taught?

b). What is the maximum error at this target point if a closest point is taught?

c). What is the probability that the position error > .04 for this target point if the error follows a uniform distribution with zero mean?

d) What is the maximum error at any position if the robot is taught off-line.
a) 
Max Error due to resolution = .05
Max Error due to repeatability = .03
Max Error = .08.

b) 
The closest point to be taught is 0.6, the max error is 0.05

c).
Assume the repeatability has zero mean and follow a uniform distribution. If we specify the position 10.60, The probability the error is > .04 is in the shaded area.

\[ P(\text{error} < .04) = P(x < .62) \]

\[ \int_{10.57}^{10.62} \frac{1}{0.06} \, dx = 0.8333 = 83\% \]

Often, the distribution is unknown. Uniform is assumed.
\( r_{PA} = 0.5 \text{ mm (very large).} \) The robot program is done off-line. The target is at 10.58 in reference coordinates. How do you estimate the maximum error at this target?

This is a very rough estimate. One can adjust the taught point after testing. Then, the error can be reduced to eliminate the effect of position accuracy. For example, after test run, the taught point can be moved to 10.10.

Relationships between resolution and repeatability in a robot

Repeatability is listed in a spec sheet.
Resolution may or may not be listed in spec sheet. It is often given in the manual.

If \( r >> L \), we have

The resolution do not mean much

If \( L >> r \), we have

waste of resources.

It is cheaper to get higher resolution, more difficult to get good repeatability.

Repeatability of homing or same home: a study in the lab.

Put a .75" part in a chuck of .8". Resolution at the location point = .01".
The maximum possible error = .005 + .005 = .01"

It is also possible to define a position one unit away due to eyeball, 0.02". This can still be O.K. But in reality, the robot miss the feed whenever rehoming.

Homing error = .03"

6. Dynamic accuracy

Baby control dynamics (3.3): rubber band example and tranparency on control (p 83)

Rising time:

    time to reach the desired position, or from 10% to 90% desired position.

Settling time:

    time to settle at within some prespecified range.

Steady state error:  \( \pm \delta \)

PID controller in Laplace domain

\[
G_c(s) = K_p + K_Ds + \frac{K_I}{s}
\]

\( K_p \): amplification of the error

\( K_D \): amplification of the rate of change in error

\( K_I \): amplification of the cummulative error
$K_p \uparrow, K_v \uparrow$: shorter rising time, low oscillation

$K_i \uparrow$: smaller steady state error

It takes time to reach a point at robot resolution. In applications, speed is very important. In many applications such as printing, glue application, spot welding, the path accuracy is not critical.

We discussed the accuracy associated with an addressable position. This applies when you stop the robot at a point.

However, in many applications, the point not checked with exact encoder count are of importance in terms of accuracy.

On a continuous path in continuous path control.

- Arc welding
- Deburring

On a path in PTP control.

- Investment casting

The dynamic accuracy is rarely given quantitatively. It is often a lot worse than static accuracy. It differs greatly between robots.

7. Robot speed

Robot speed is actually a complex issue. To a user, what he cares is how quickly a robot can finish tasks with acceptable accuracy.

7.1 Cycle time

RIA defined a standard cycle time specification in ANSI/RIA R15-1. The motion in the cycle includes 1" up, 12" over, 1" down and 12" back in a specific plane.

Robot must carry standard rated loads (over 50% of maximum) with continuous path control.

Sweet region
References

Point-to-point and static performance characteristics - Evaluation. ANSI/RIA standard R15.05-1, 1990.


Both are available on CD in reference section in Georgia Tech library.