BOEING

Boeing Research & Technology

Absolute Accuracy & Robot Calibration

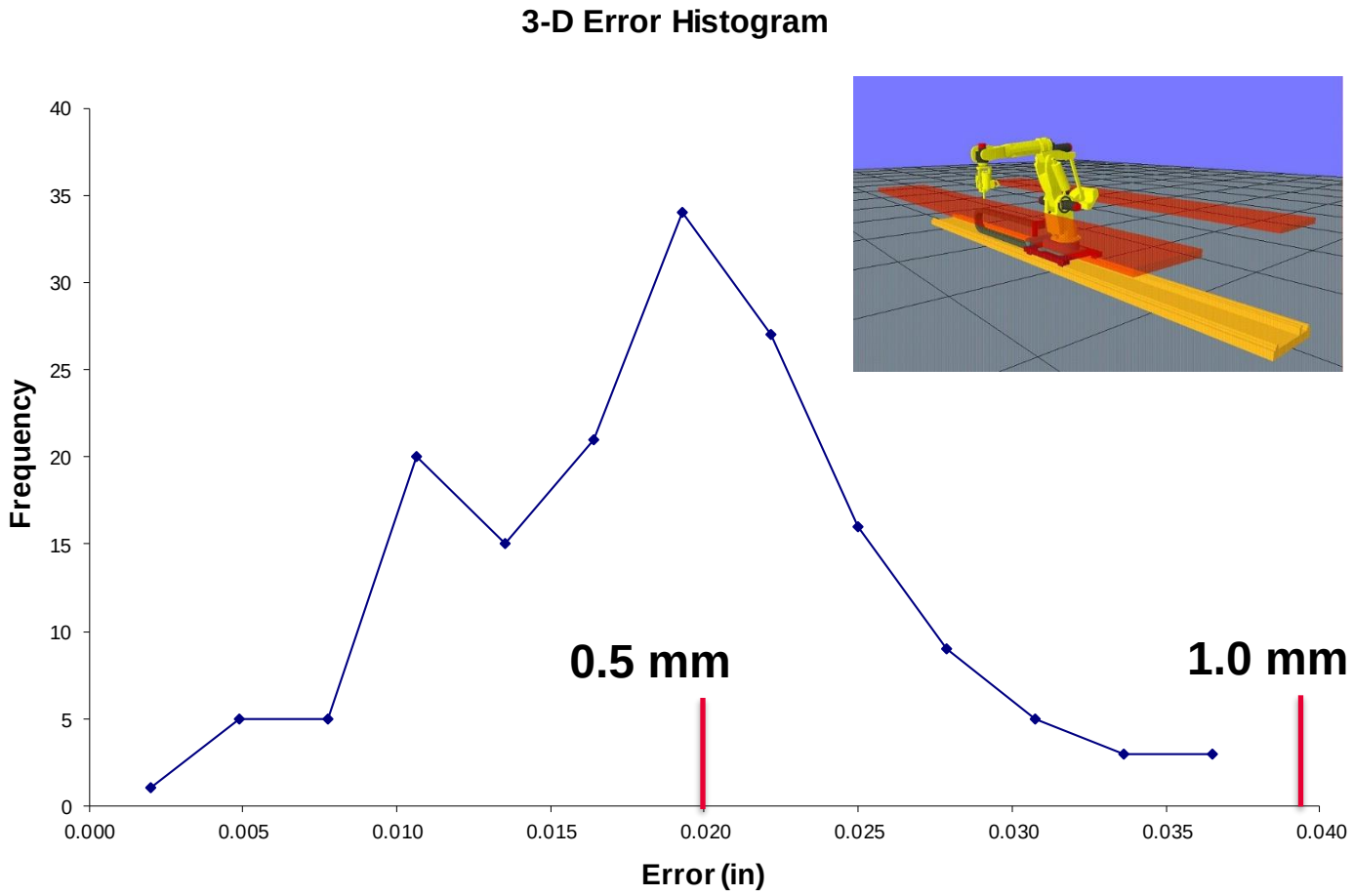
Phil Freeman

Senior Technical Fellow, Robotics & Automation

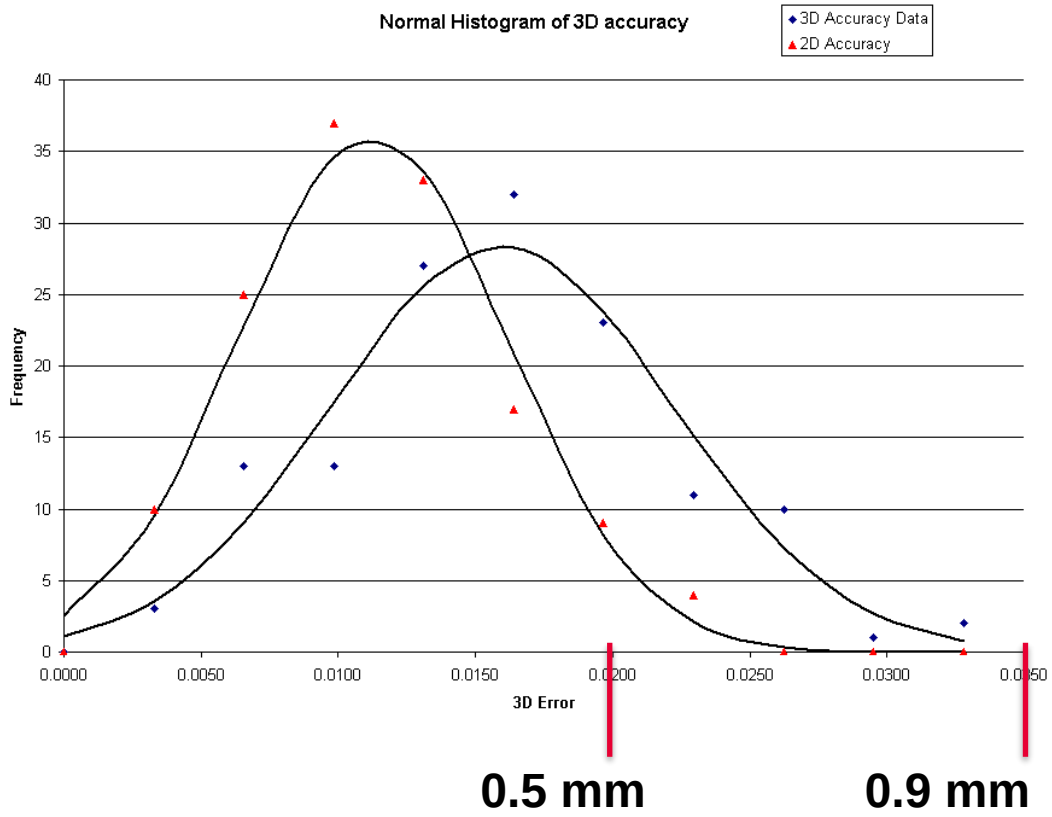
Boeing Research & Technology

March 11, 2025

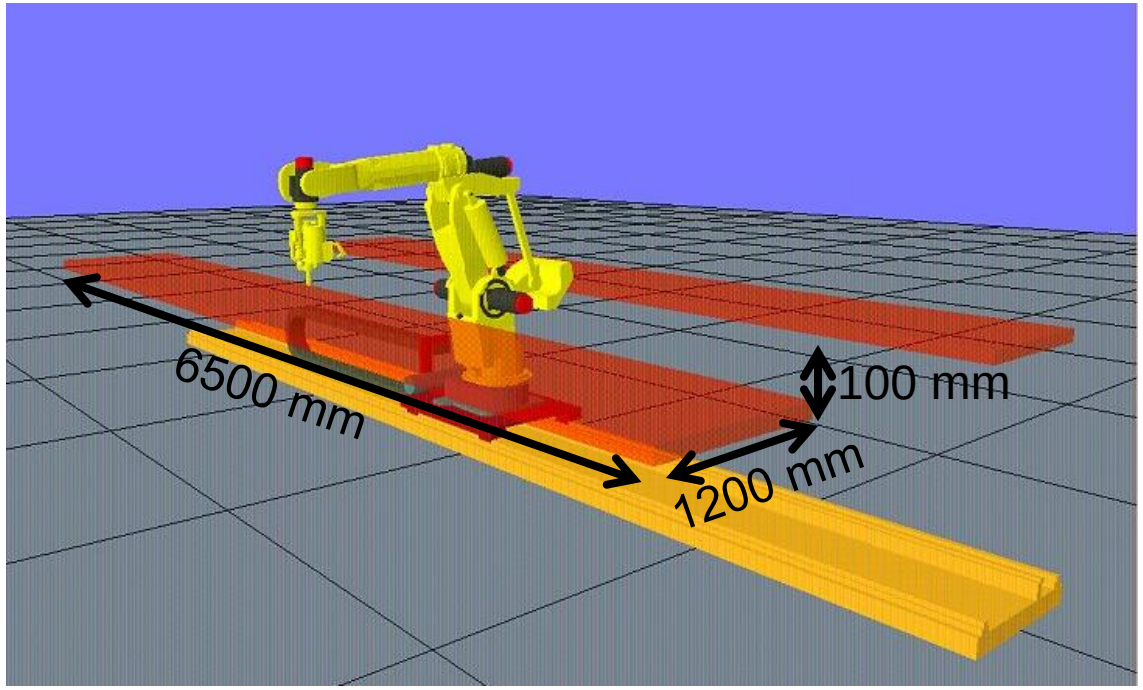
c. 1999

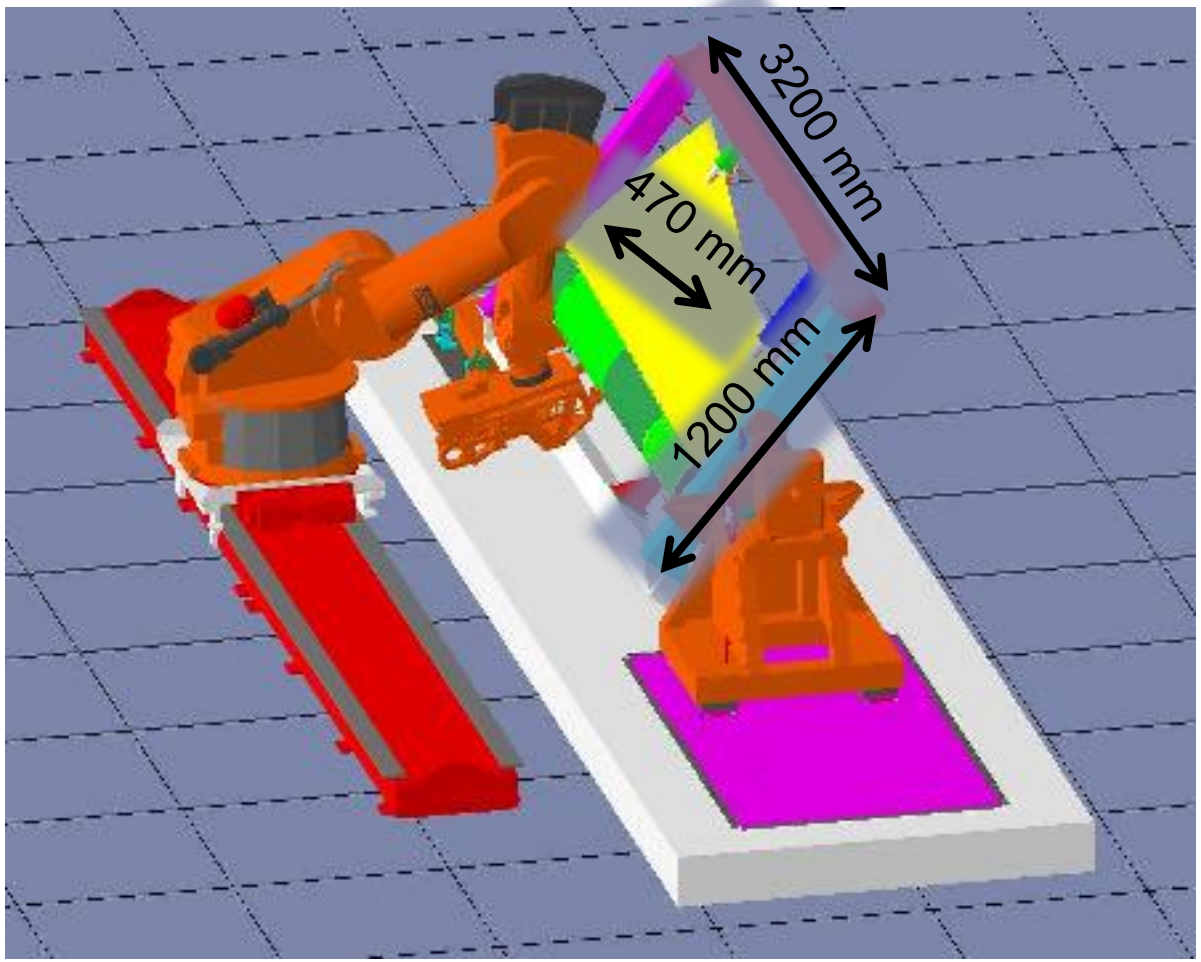


c. 2002

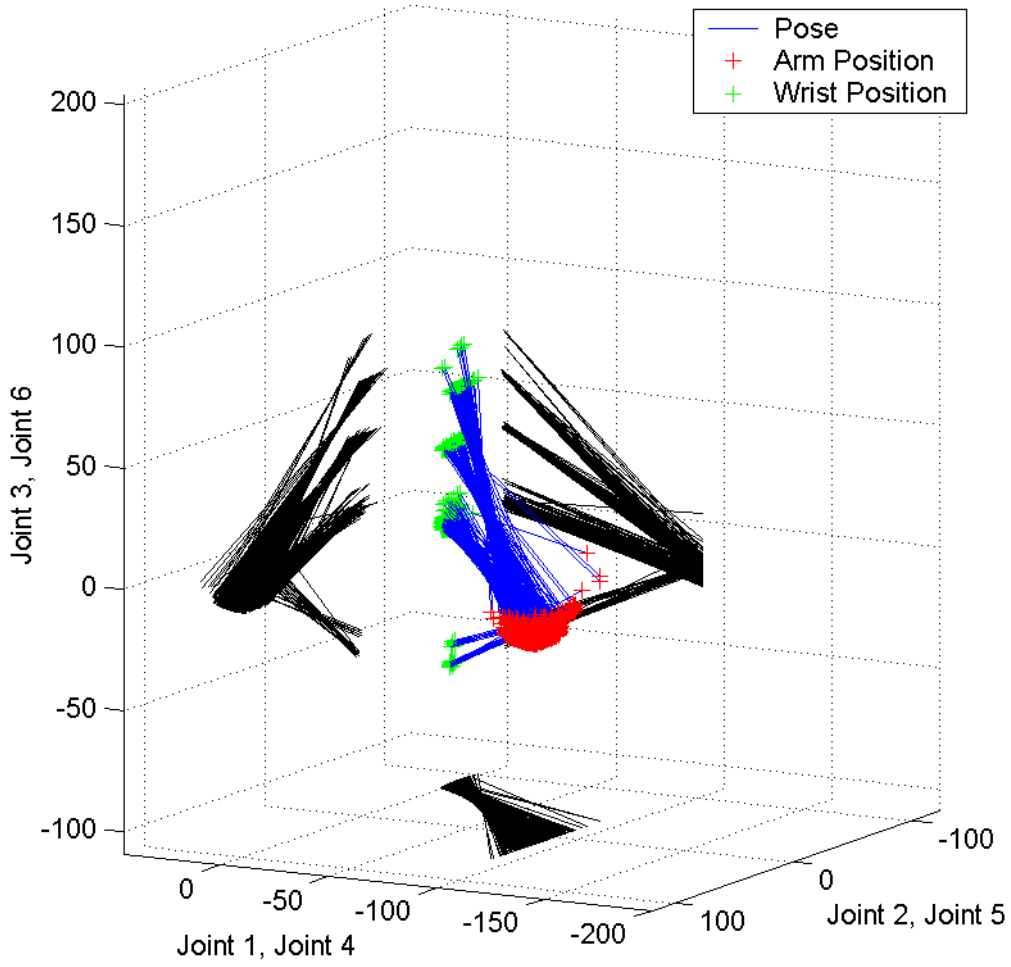


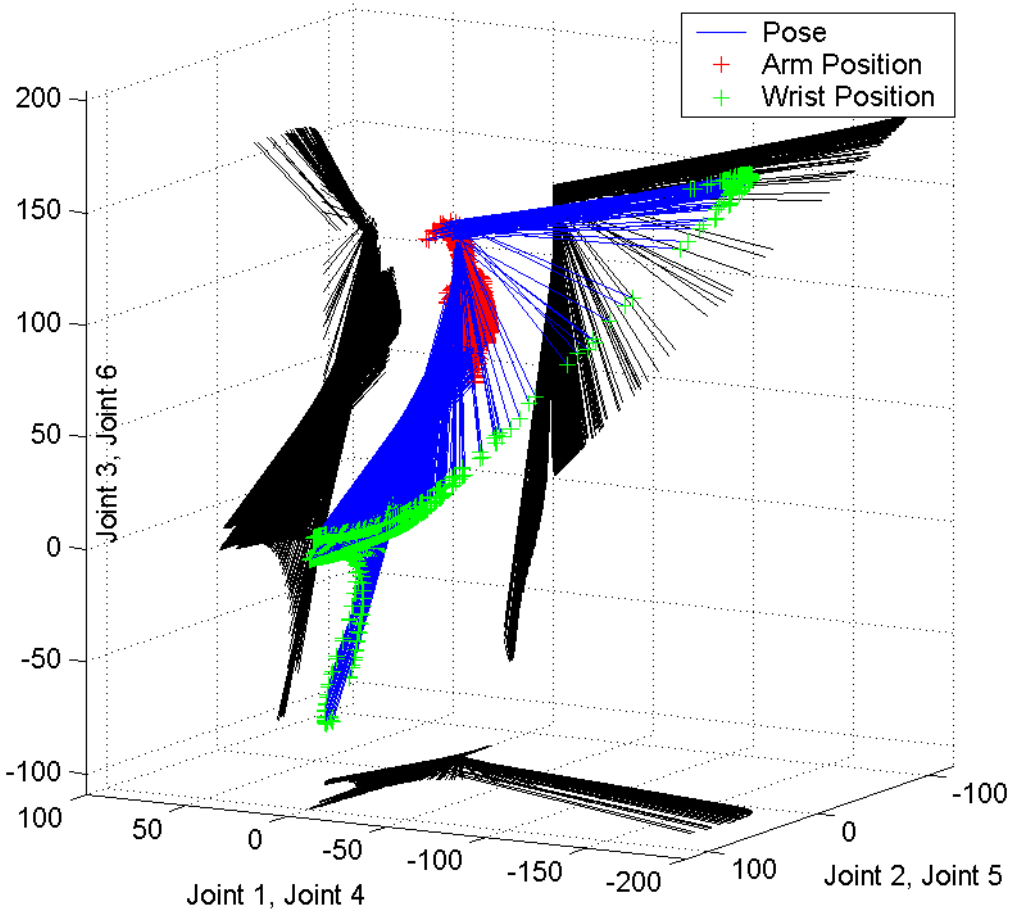
Comparable – But not really



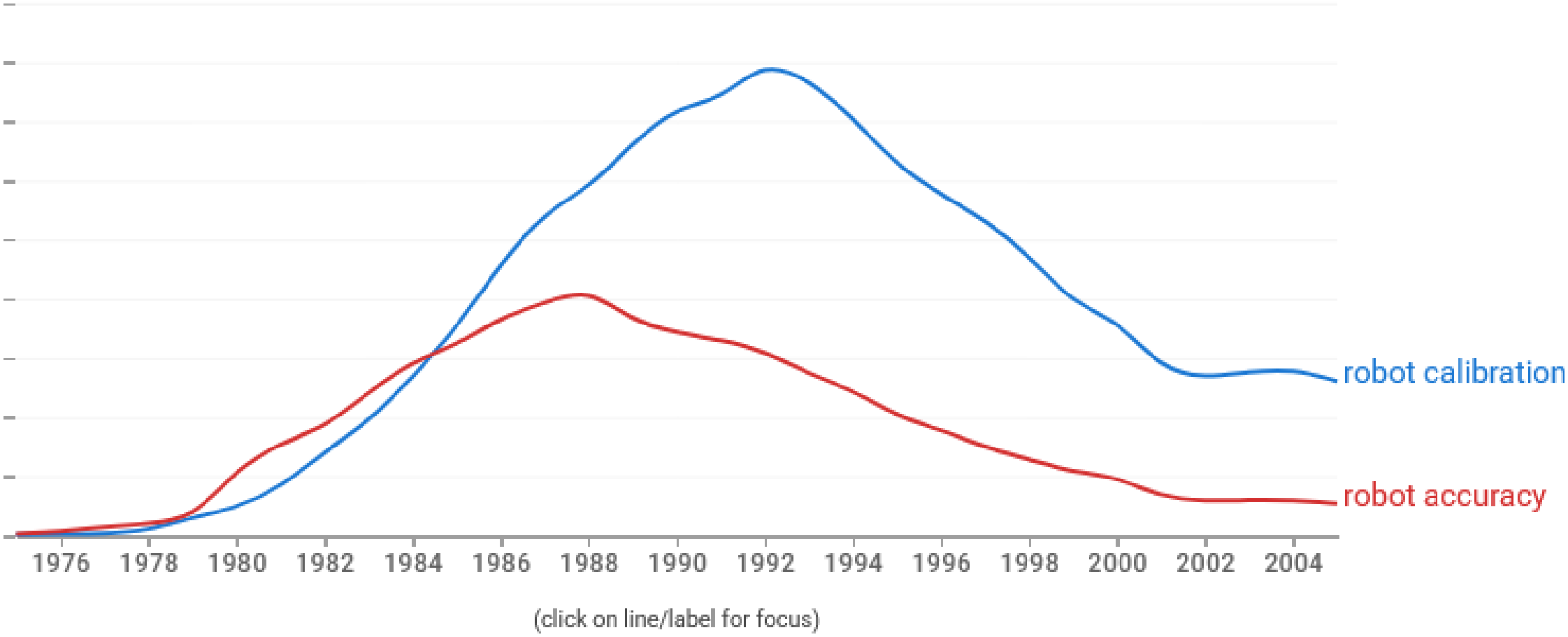


Comparable – But not really

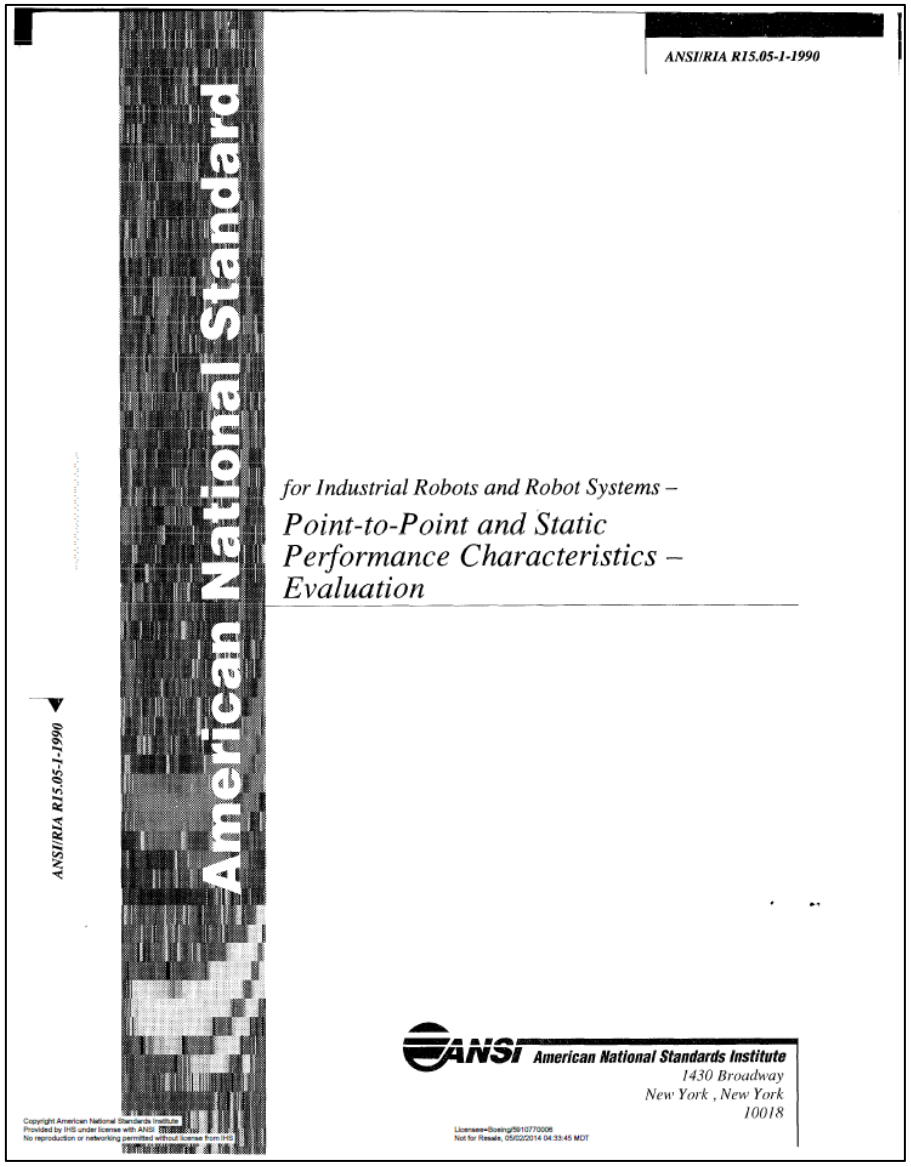


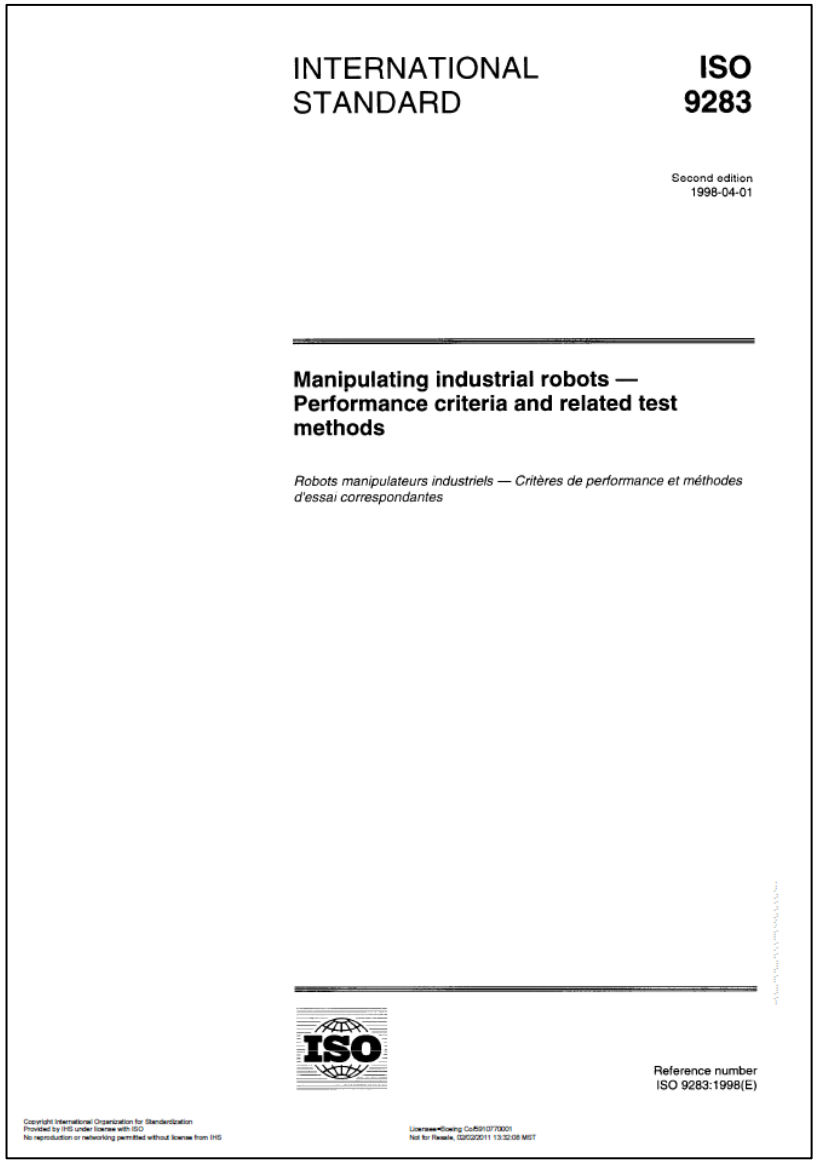


The golden age of robot accuracy?

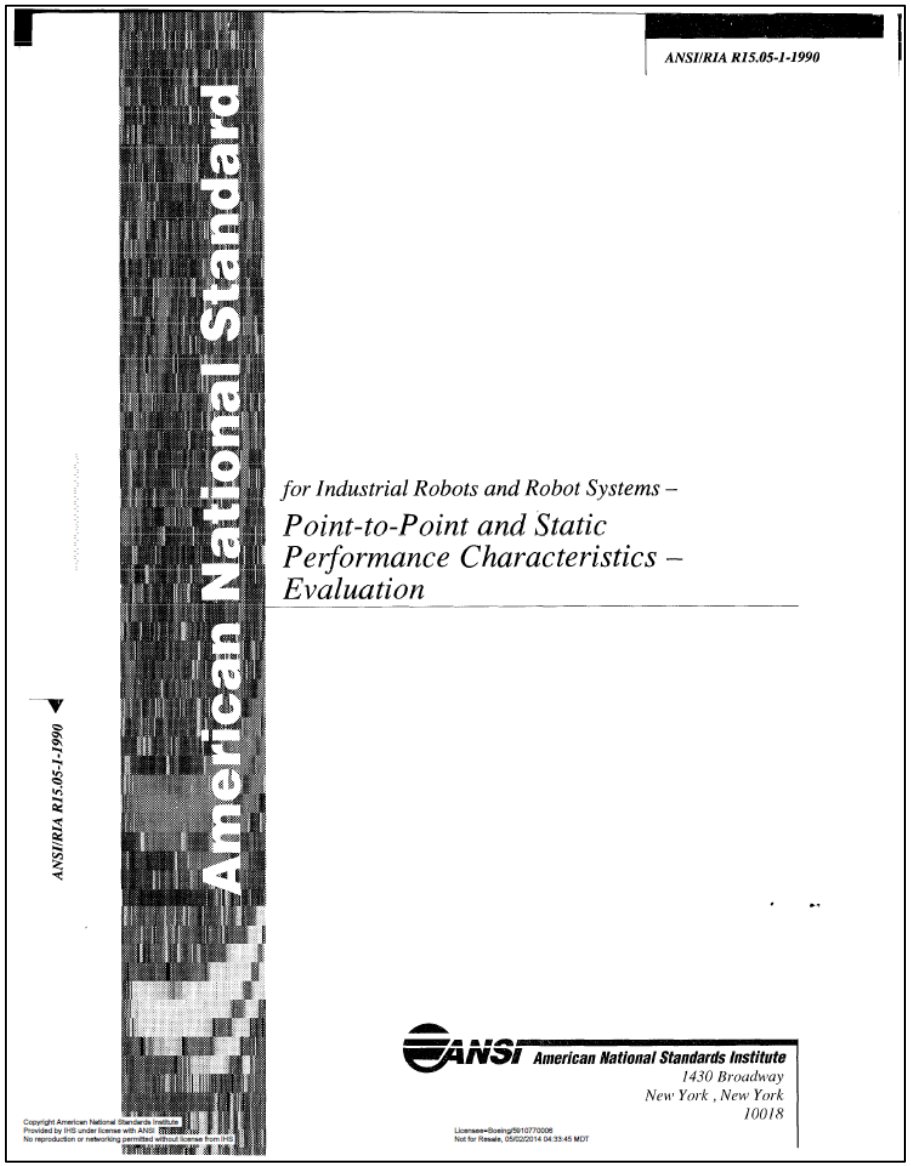


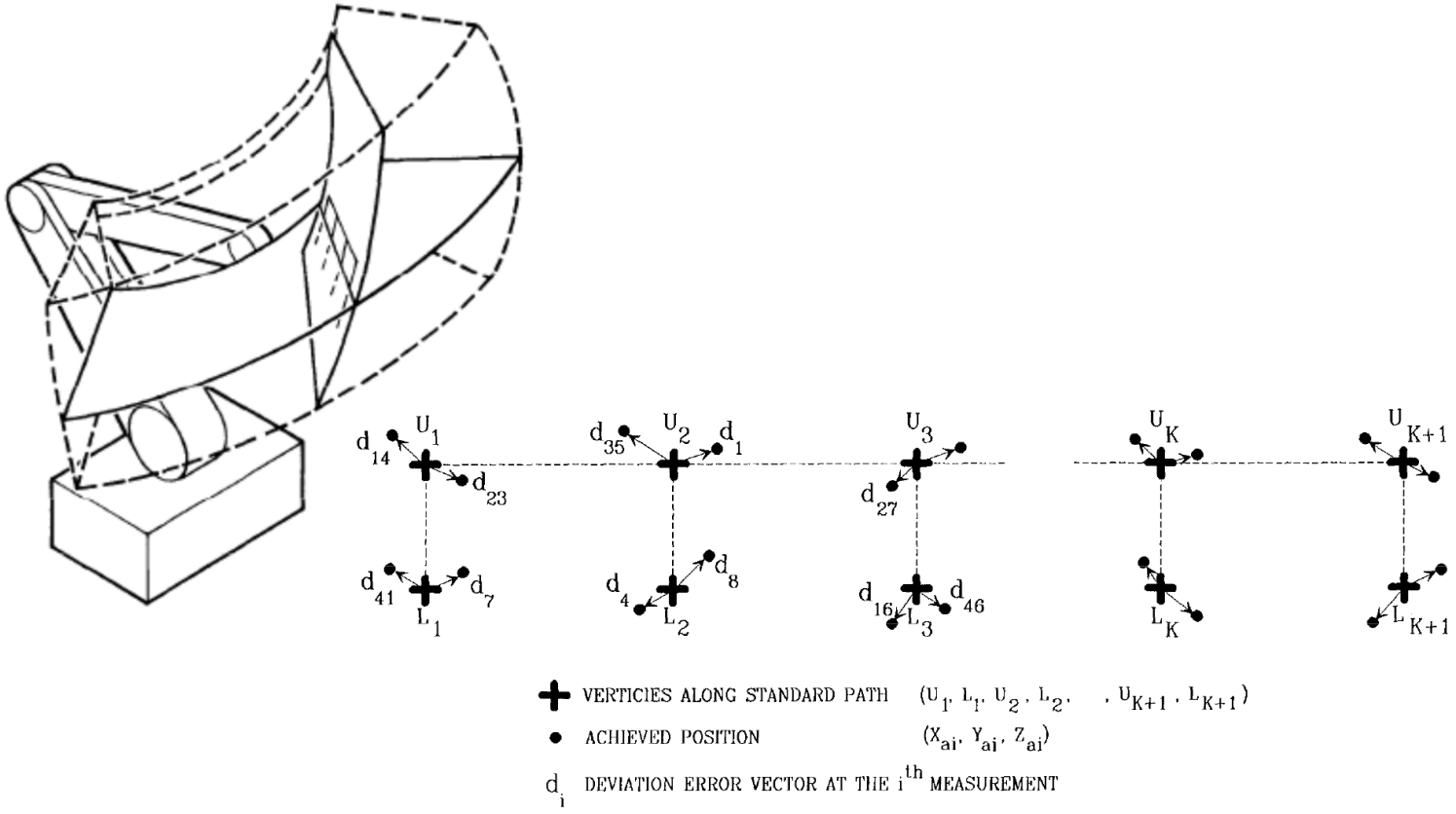
A tale of two standards





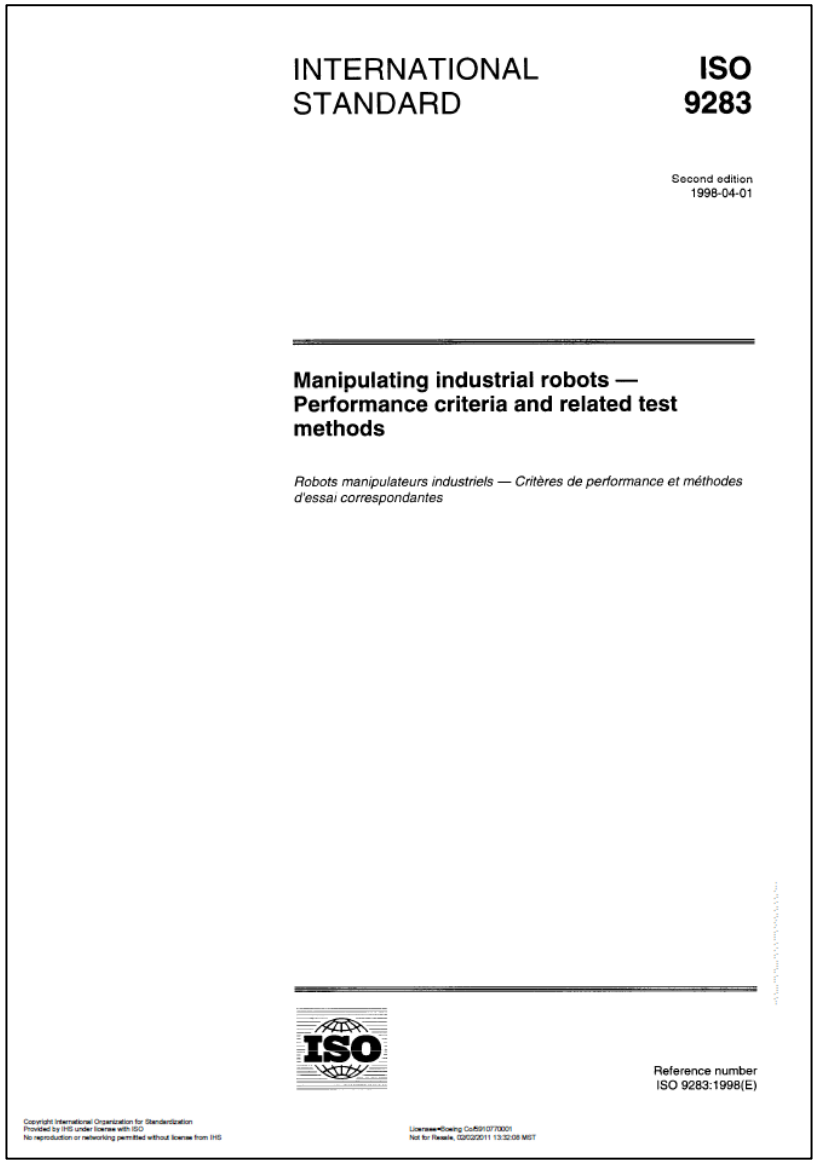
ANSI/RIA R15.05-1-1990 (R1999)





"Static position accuracy is a statistical measure of the spatial deviation between commanded and achieved robot positions. … Two statistics on positional accuracy are reported: mean and standard deviation." (Sec. 8.2.1.1)

ISO 9283:1998



INTERNATIONAL STANDARD

ISO 9283

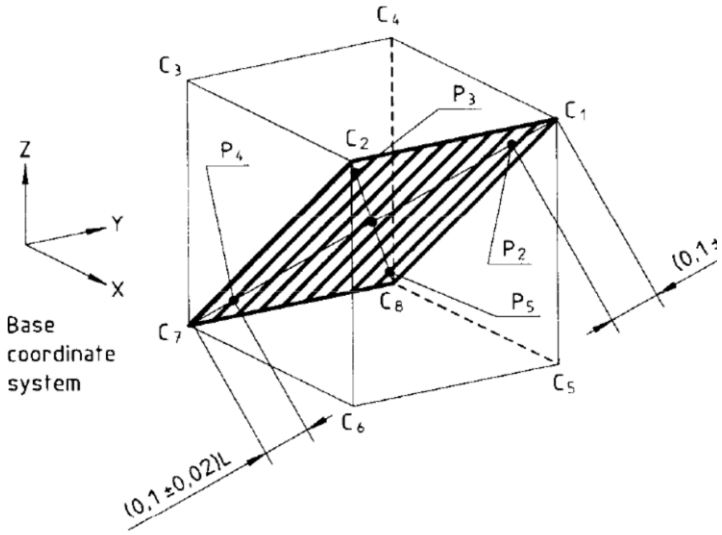
Second edition
1998-04-01

Manipulating industrial robots — Performance criteria and related test methods

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

ISO

Reference number
ISO 9283:1998(E)



L = length of diagonal
Example showing plane a) $C_1 - C_2 - C_7 - C_8$ with poses $P_1 - P_2 - P_3 - P_4 - P_5$

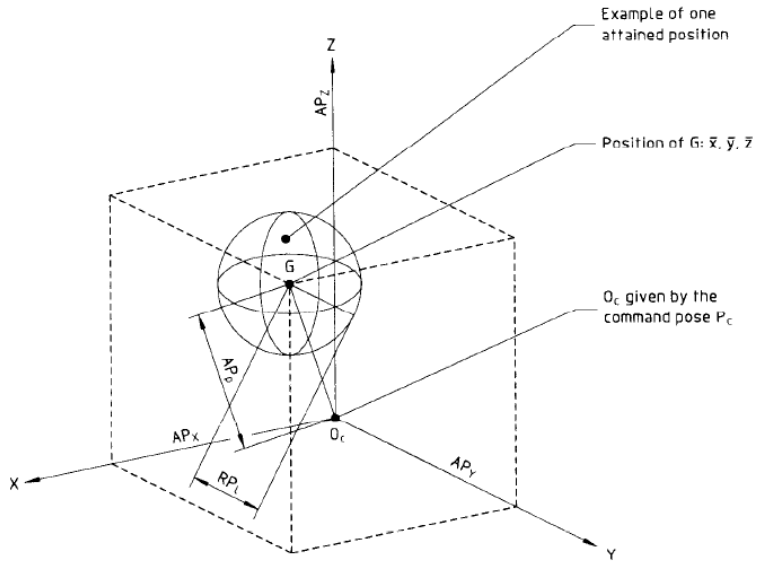
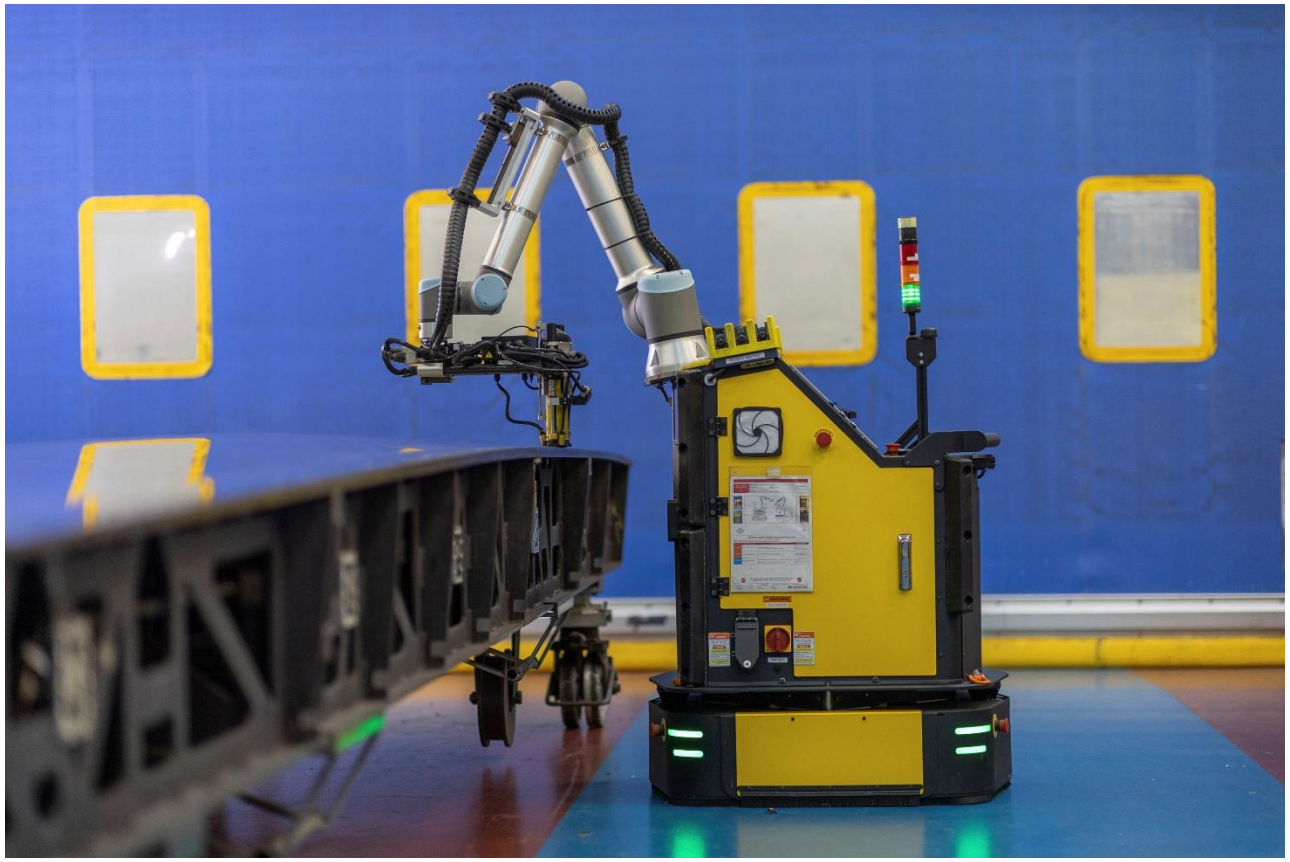


Figure 8 - Positioning accuracy and repeatability

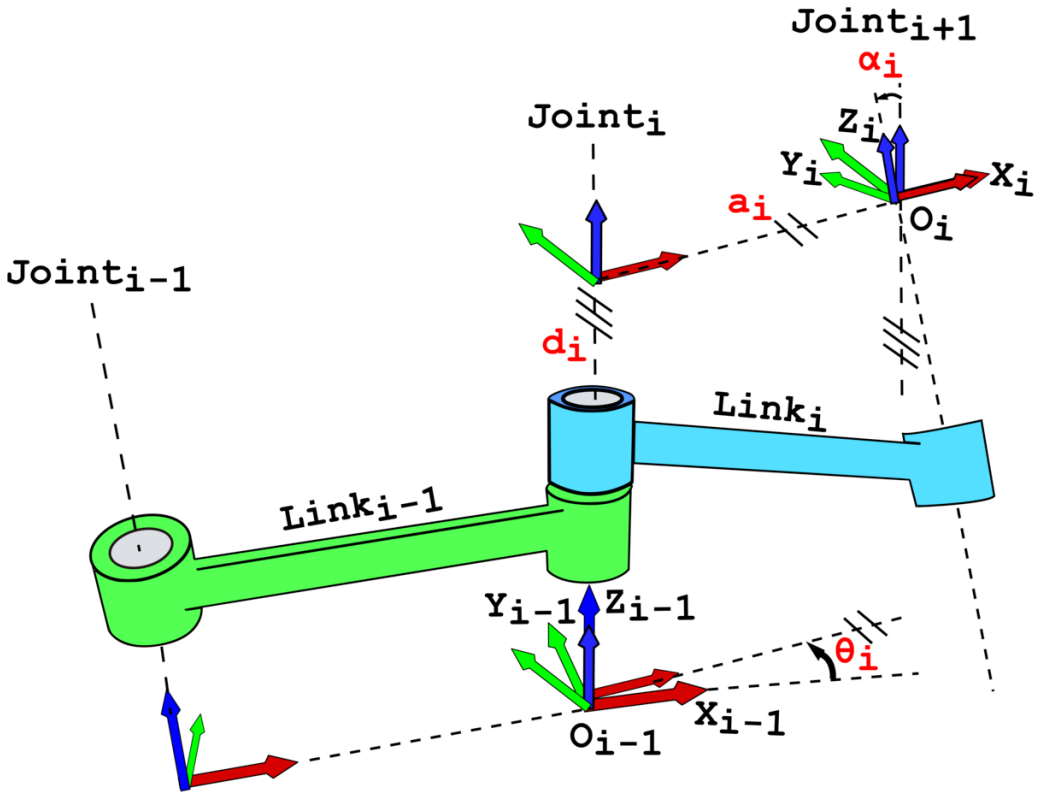
"*positioning accuracy:* the difference between the position of a **command pose** and the **barycentre** of the attained positions." (Sec 7.2.1 – bolded emphasis mine)

"The **commanded poses** for teach programmed robots are to be defined as the measurement point on the robot. … The coordinates **registered on the measuring system** are then used as "command pose" when calculating accuracy based on the consecutive attained poses." (Sec 7.1 – bolded emphasis mine)

Then vs. Now



Parametric Calibration



+ Stiffness

High accuracy robots

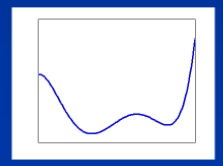
Complete Parametric Models

Axis Error Motion

$$\mathbf{K}_{forward} = \mathbf{E}_0\mathbf{A}_1\mathbf{E}_1\mathbf{A}_2\mathbf{E}_2\cdots\mathbf{A}_N\mathbf{E}_N$$

Nominal Axis Motion

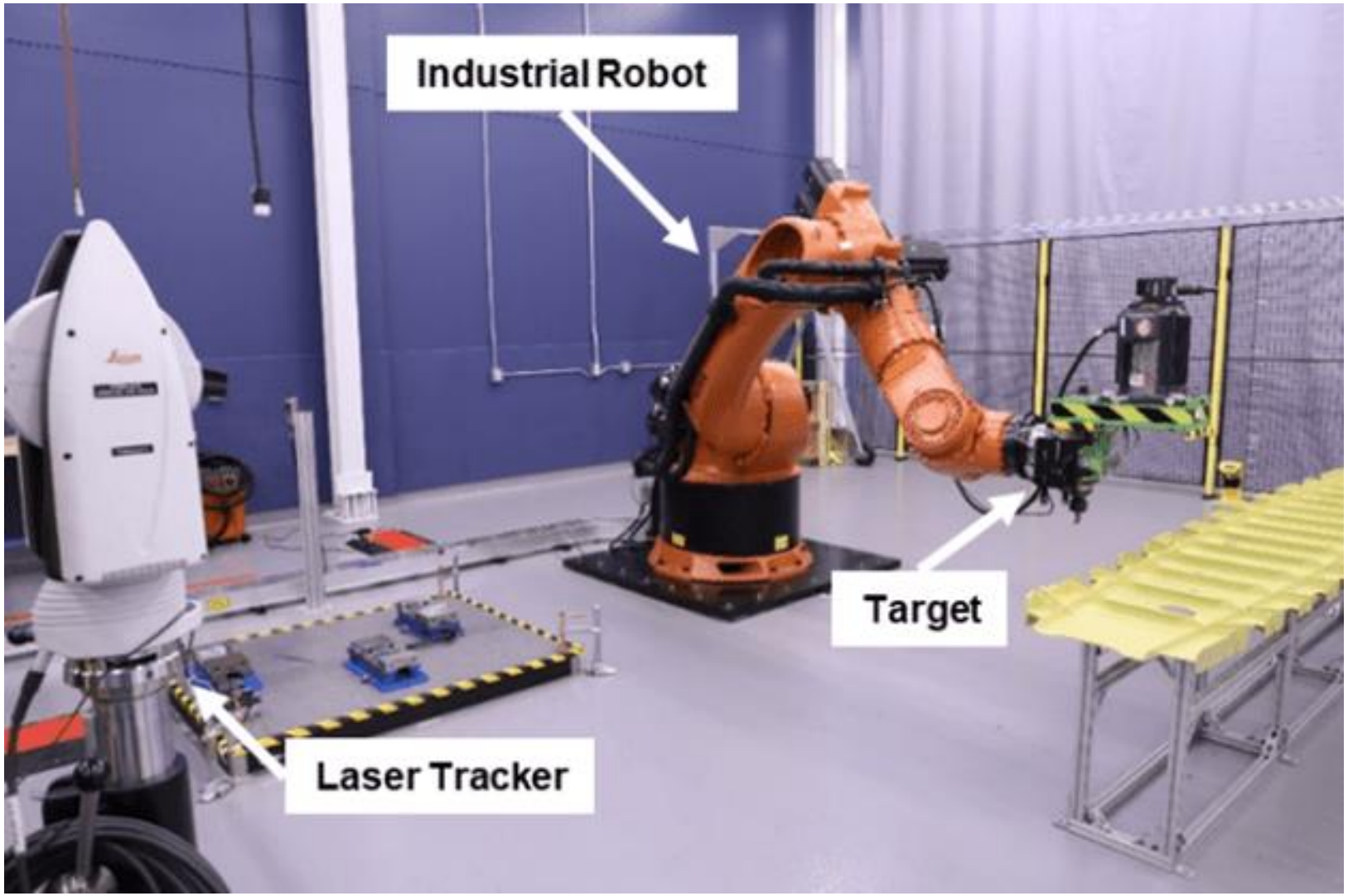
$$\begin{bmatrix} 1 & -\varepsilon_z(q) & \varepsilon_y(q) & \delta_x(q) \\ \varepsilon_z(q) & 1 & -\varepsilon_x(q) & \delta_y(q) \\ -\varepsilon_y(q) & \varepsilon_x(q) & 1 & \delta_z(q) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



Gantry (XYZCA)

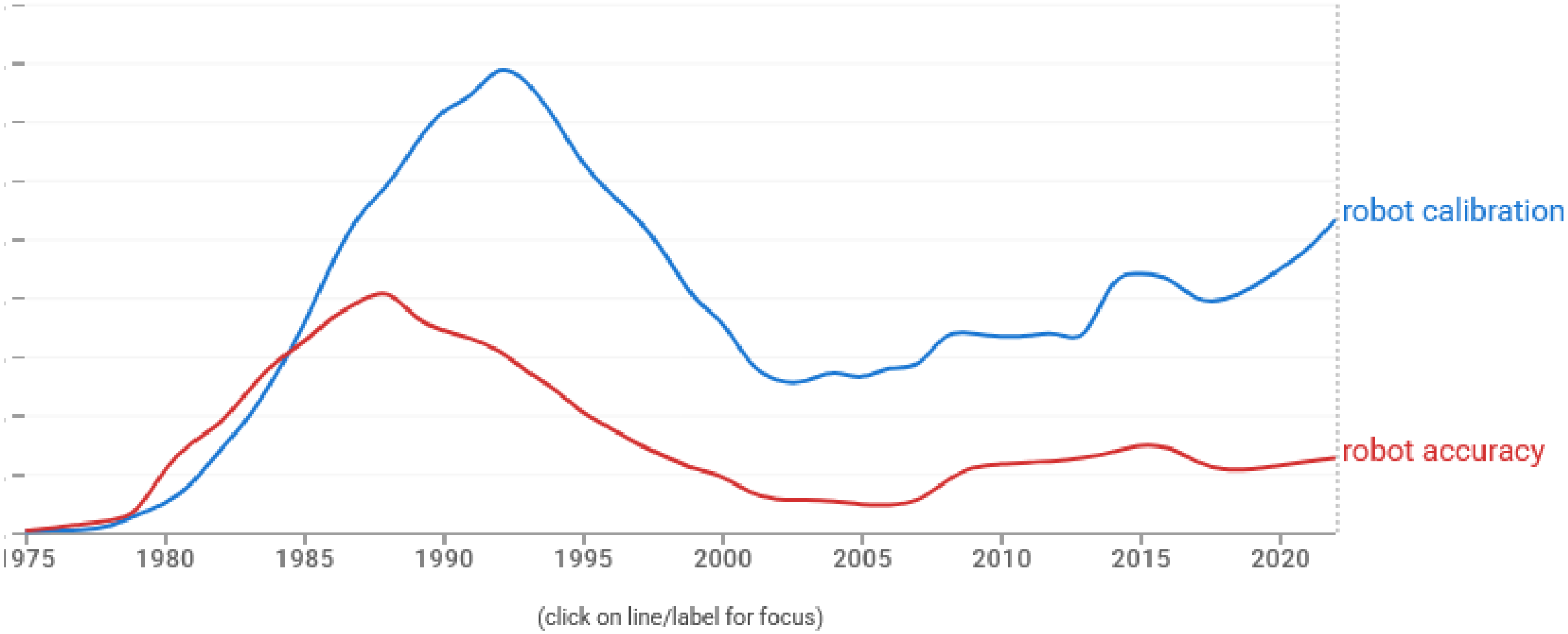
Accuracy (in)	Median	Max
Before	0.015	0.029
After	0.003	0.005

Dynamic control



Where should we go?

- A better definition of accuracy
- A better way to report accuracy
  - Accuracy compared to omni-directional repeatability
  - Accuracy compared to “distance”
- Non-parametric calibration
  - Error similarity measures
  - ML approaches
  - Something new?
- Accuracy for sensor driven robots
- Accuracy for program-free robots
- Registration/Alignment/Mapping



Parting thoughts

- Stop reporting “percent improvement”.
- Why do we seem to be stuck at 1 mm for COTS robots?
- Focus on the configuration space, not the task space.

Boeing Research & Technology