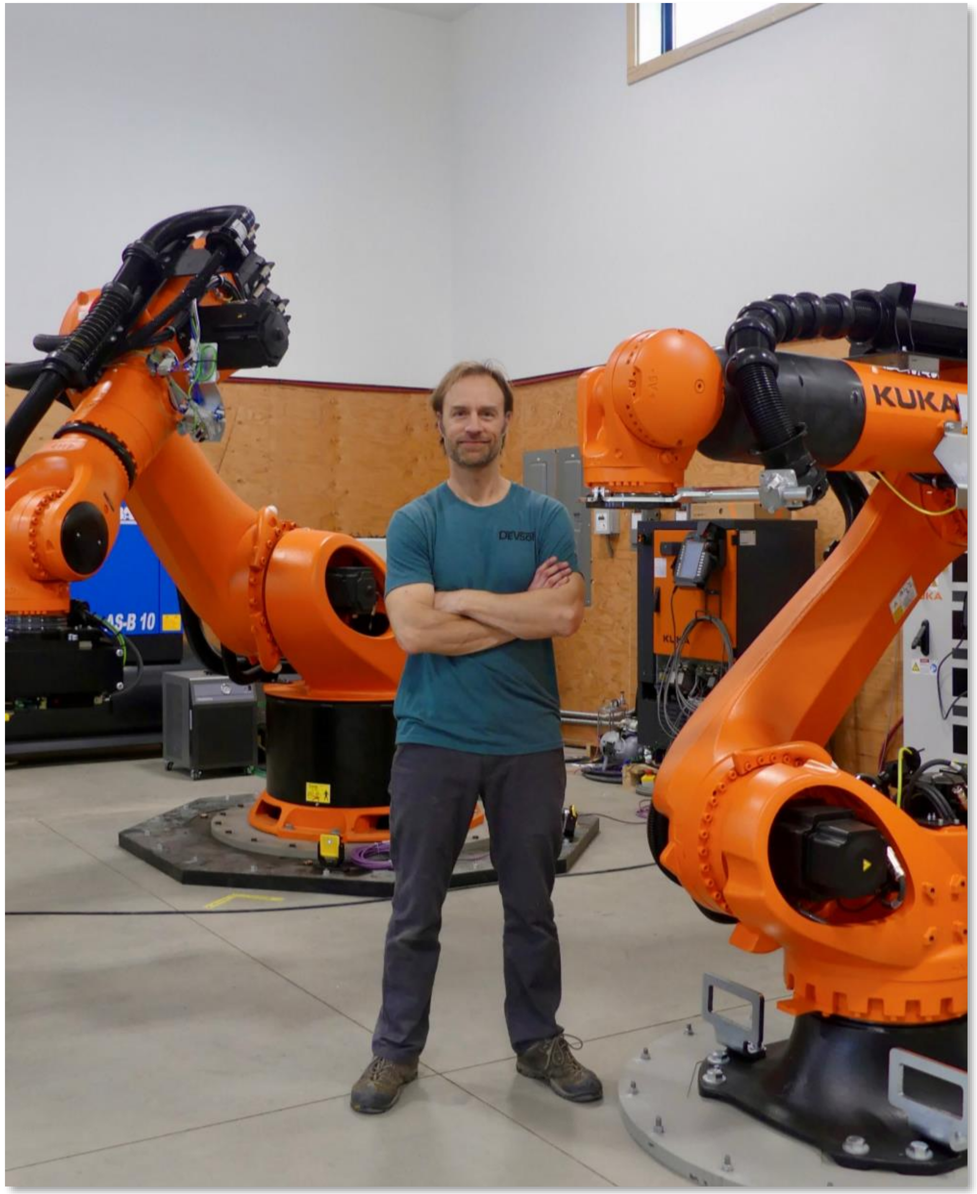
Open Loop Robot Accuracy - Observations and Lessons-Learned in Production Applications

Russ DeVlieg
DEVSON Engineering
11 March, 2025

Intro

- Working with robots for 25+ years
  - Director of Robotics when at Electroimpact
  - Co-Founder of DEVSON Engineering
- Mainly aerospace manufacturing
  - PTP drill/fasten (majority)
  - CONT path trim, mill, etc.
- Nearly 200 systems deployed
- Focus on improving positional accuracy



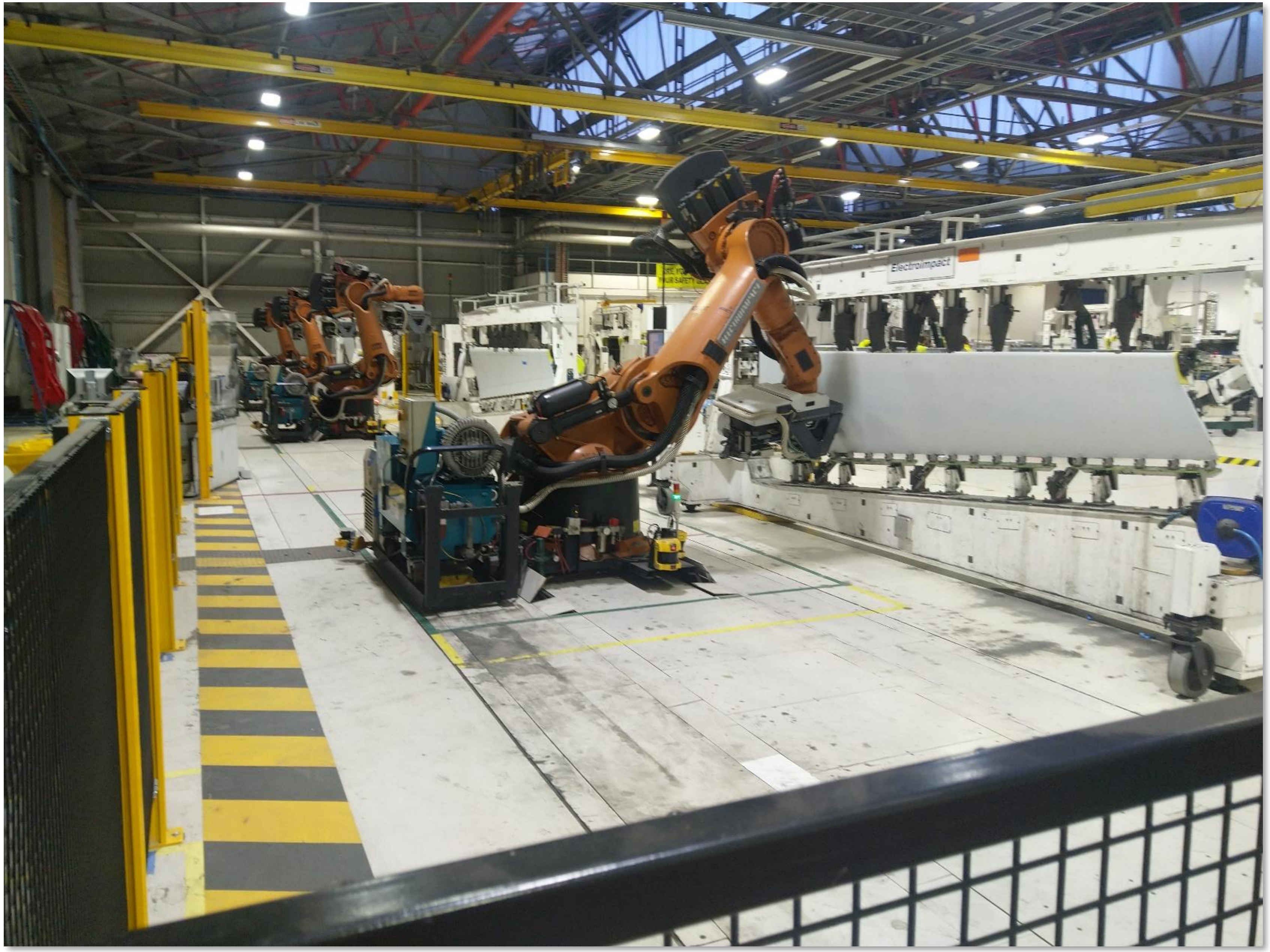
<u>Contents:</u>

- **Examples of Robots Delivered**
- **Methods Utilized in Practice for Accuracy Evaluation**
- **Observations and Considerations (Lessons-Learned)**
- **Sources of error that may warrant more attention**

Examples of Robots Delivered

Examples of Robots Delivered

Examples of Robots Delivered



Examples of Robots Delivered

Examples of Robots Delivered

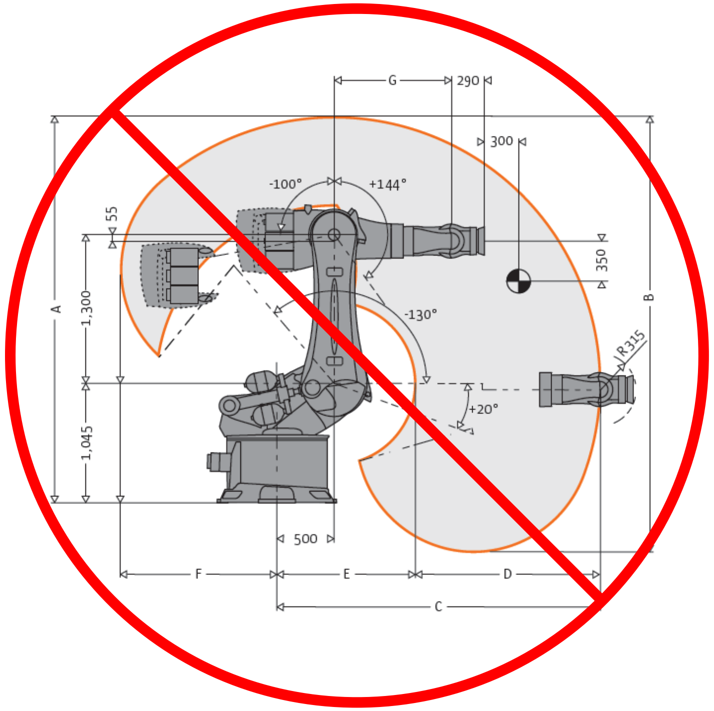
Typical Methods for Evaluating Robot Accuracy for Production Systems

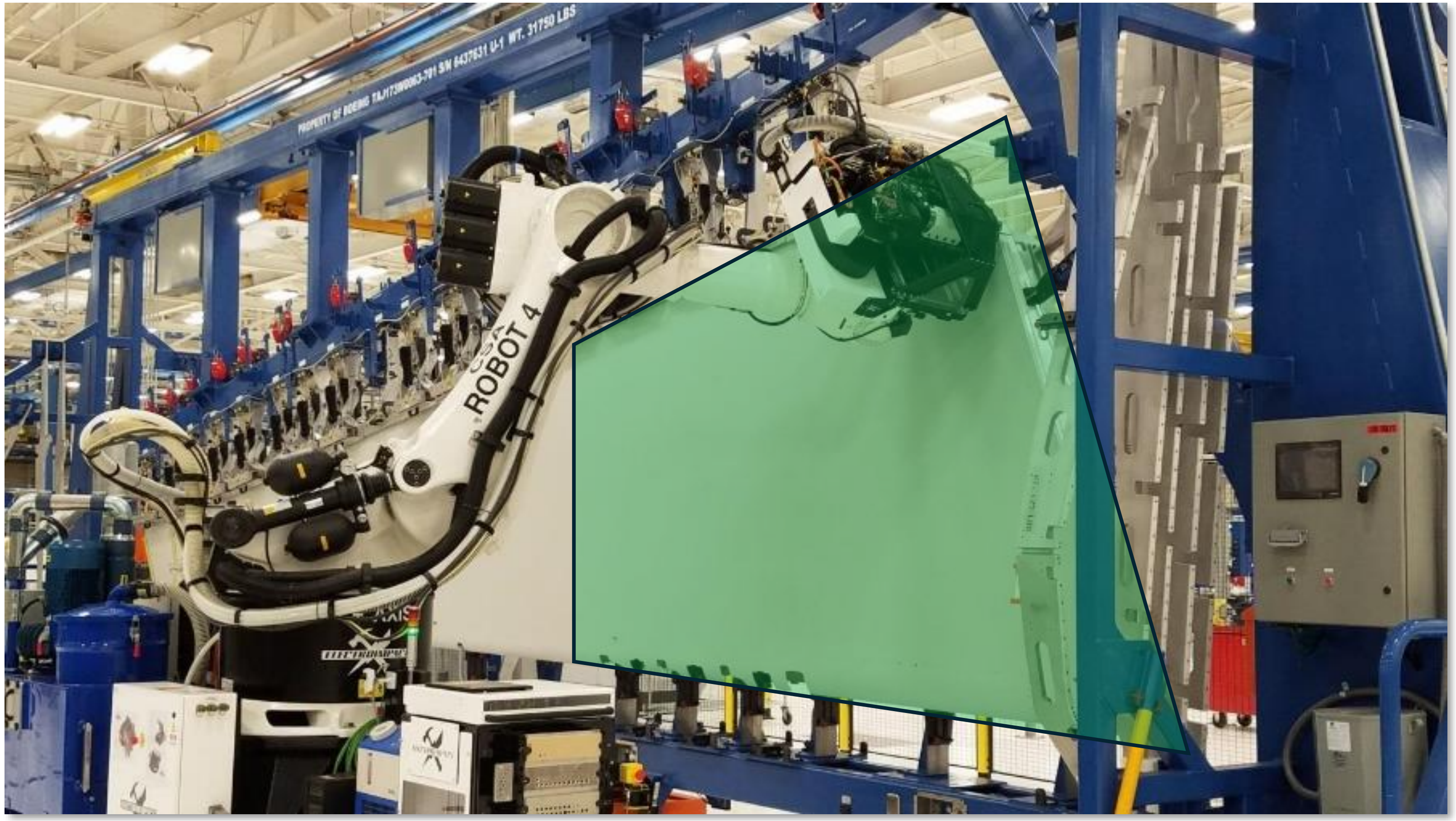
Typical Methods for Evaluating Robot Accuracy for Production Systems

Reflector ideally at nominal TCP

Default metrology device: **LASER TRACKER**

Typical Methods for Evaluating Robot Accuracy for Production Systems





Concerned with working volume and respective joint ranges, not entire robot envelope

Typical Methods for Evaluating Robot Accuracy for Production Systems

Off part (no process forces)

- ~100 poses forward and back
- Within working volume
- Random orientation
- Exercise joint ranges
- Alt – customer supplies NC programmed poses to simulate production application.

Typical Conditions

- Low speed
- Actual payload(s)
    - Often << rated payload especially for milling applications
- Trial duration minimized

Typical Methods for Evaluating Robot Accuracy for Production Systems

Statistics

- Assume normal distribution (found this is a good assumption)
- Best-fit nominal/actual to wash out error in base transform (though worth noting error)
- Optional results with best-fit TCP
- Accuracy → Average + 3 * STDEV error (99.7% confidence)

- Also reported:
  - Omni-directional repeatability
  - Vector accuracy reported if feasible
    - Move quill
    - Multiple tool lengths

	Pose						Nominal (commanded) Cartesian						Act (mm)			Error (mm)			
	A1	A2	A3	A4	A5	A6	Xn	Yn	Zn	A (rZ)	B (rY)	C (rX)	Xa	Ya	Za	dx	dy	dz	dr
P001	43.8	-53.4	111.9	161.2	39.4	-90.7	1830.36	-1322.78	1126.08	-85.87	-67.11	117.51	1830.37	-1322.84	1126.01	0.01	-0.06	-0.07	0.09
P002	29.6	-62.9	117.6	142.6	60.2	-73.2	1976.32	-954.12	1358.28	-145.10	-86.23	173.68	1976.38	-954.18	1358.39	0.07	-0.05	0.11	0.14
P003	11.4	-59.1	118.9	116.5	-68.2	-108.8	2006.08	59.69	1121.24	-65.78	55.67	110.17	2006.13	59.65	1121.36	0.05	-0.03	0.12	0.14
P004	26.5	-66.5	96.1	156.8	-79.3	-135.3	2061.75	-583.32	1341.62	-79.98	28.72	90.09	2061.79	-583.27	1341.70	0.04	0.05	0.08	0.10
P005	16.9	-62.4	100.9	170.9	-46.4	-144.4	2239.33	-422.64	1187.93	-77.08	3.03	97.99	2239.34	-422.56	1187.98	0.01	0.08	0.06	0.10
P006	28.4	-48.9	68.1	177.9	-72.2	-123.1	2392.63	-885.80	1252.41	-62.15	2.27	90.89	2392.70	-885.84	1252.51	0.06	-0.04	0.10	0.12
P007	42.1	-48.8	47.9	185.1	-74.6	-101.4	2158.30	-1446.00	1598.18	-52.56	-16.96	88.09	2158.31	-1446.12	1598.27	0.01	-0.12	0.09	0.15
P008	40.8	-62.5	52.2	203.4	-64.5	-102.8	2013.09	-1410.47	1931.79	-43.48	-38.54	70.65	2012.94	-1410.54	1931.69	-0.15	-0.07	-0.10	0.20
P009	29.3	-58.7	57.3	214.2	-61.8	-129.4	2360.37	-1161.40	1774.50	-54.99	-42.47	76.47	2360.39	-1161.40	1774.37	0.01	0.00	-0.13	0.13
P010	38.8	-60.5	95.7	222.6	-25.2	-145.7	1980.18	-1245.58	1210.45	-58.49	-38.71	85.23	1980.23	-1245.48	1210.42	0.05	0.10	-0.03	0.12
P011	10.6	-75	128.5	219.5	-27	-193.7	1856.42	-306.54	1138.42	-81.74	-20.93	98.15	1856.42	-306.44	1138.43	0.00	0.10	0.01	0.10
P012	-1.5	-64.2	105.9	192.5	-42.4	-197.8	2248.14	-58.85	1165.21	-97.98	-7.26	97.81	2248.15	-58.75	1165.14	0.01	0.09	-0.07	0.12
P013	-9	-60.2	84.3	191.8	-69.9	-206.2	2427.11	153.35	1328.13	-102.83	-11.61	90.81	2427.13	153.34	1328.18	0.02	-0.02	0.05	0.06
P014	-18.3	-63.9	103.2	144	-40.5	-194.2	2173.11	599.10	1153.96	-112.38	27.18	86.85	2173.11	599.06	1153.92	0.00	-0.04	-0.04	0.06
P015	-10.9	-60.2	90.6	129.2	-48.3	-169.9	2455.04	534.77	1359.43	-97.41	41.35	97.83	2455.04	534.79	1359.51	0.00	0.03	0.09	0.09
P016	-35.1	-52.9	92.3	31	-25.1	-110.9	2232.82	1182.37	1299.83	-119.26	72.53	101.87	2232.86	1182.34	1299.84	0.04	-0.03	0.01	0.05
P017	-26.6	-86.5	98.7	-37.2	59.3	-33.3	1827.05	818.67	1709.20	-114.52	37.76	79.50	1826.98	818.72	1709.12	-0.07	0.05	-0.08	0.12
P018	-16.3	-82.6	97.8	-39.4	65.3	-23	1985.63	578.63	1634.06	-114.73	36.34	77.69	1985.59	578.50	1633.98	-0.03	-0.13	-0.08	0.15
P019	-15.7	-67.6	70.4	-62.4	56.8	-28.2	2424.62	702.96	1884.51	-142.12	61.70	60.84	2424.62	703.02	1884.56	0.00	0.07	0.05	0.08
P020	-29.8	-50.4	63.3	-82.9	23.3	-6.2	2560.94	1202.97	1631.51	-144.92	74.59	71.97	2560.91	1202.94	1631.52	-0.03	-0.04	0.01	0.05
P021	-36	-51.5	85.9	-91.2	21.5	12.8	2238.04	1334.55	1220.91	-123.10	58.64	86.16	2238.00	1334.59	1220.81	-0.04	0.04	-0.10	0.12
P022	-32.9	-45.3	80.2	-124.5	17.5	42.5	2414.64	1201.22	1180.46	-130.88	66.05	90.44	2414.63	1201.24	1180.47	-0.01	0.01	0.01	0.02
P023	-41.2	-53.4	110.9	-156.6	45.2	88.4	1895.10	1294.33	1176.95	-83.12	72.08	127.41	1895.08	1294.43	1177.00	-0.01	0.10	0.04	0.11
P024	-9.8	-70	120.8	-136.5	-50.4	140	1965.39	74.71	1126.26	-89.34	-31.95	93.11	1965.38	74.71	1126.23	-0.02	-0.01	-0.03	0.04
P025	-21.8	-58.7	49.7	-214.3	-76.5	119.9	2417.82	847.50	1837.16	-136.87	35.06	67.61	2417.95	847.39	1837.15	0.13	-0.11	-0.01	0.17
P026	-27.2	-68.2	59.5	-217.7	-65	127.2	2231.75	1022.68	2018.63	-128.98	47.56	72.87	2231.75	1022.59	2018.54	0.01	-0.10	-0.09	0.13
P027	-10.9	-79.5	109.7	-232	-50	188.4	2047.11	460.04	1498.56	-100.40	42.85	94.43	2047.10	460.19	1498.60	-0.02	0.15	0.04	0.16
P028	10.3	-53.2	65.7	-139.1	-63.7	199.6	2684.34	-498.07	1477.95	-64.01	-40.30	83.28	2684.39	-498.08	1477.90	0.05	-0.01	-0.04	0.07
P029	35.7	-41.7	58.3	-157.8	-32.7	234.5	2485.73	-1404.22	1303.98	-58.43	-43.83	93.91	2485.71	-1404.25	1304.01	-0.02	-0.02	0.03	0.04
P030	31.4	-49.9	80.6	-98.4	-19.9	178.2	2396.49	-1166.46	1252.89	-50.95	-58.43	86.83	2396.51	-1166.44	1252.84	0.02	0.02	-0.05	0.05
P031	28.5	-41.8	72.8	-96.6	-16.1	164.8	2593.00	-1109.06	1206.22	-69.43	-56.55	108.70	2592.99	-1109.08	1206.27	-0.01	-0.02	0.05	0.06
P032	42.4	-62	87.2	-42.2	-16.3	134.2	2040.64	-1411.37	1580.71	-29.37	-76.08	66.45	2040.59	-1411.38	1580.56	-0.05	-0.01	-0.16	0.16
P033	23.3	-87.5	108.6	-71.8	-48.3	157.5	1899.01	-800.92	1878.25	7.62	-84.78	13.95	1898.99	-800.90	1878.30	-0.02	0.02	0.05	0.06
P034	-37	-65.5	115.6	-82.7	21	20.3	1806.97	1106.45	1129.84	-106.83	41.74	92.63	1806.97	1106.43	1129.87	0.01	-0.02	0.03	0.04
P035	2	-67.9	124.2	-32.7	21.8	31.2	2014.05	10.82	1106.09	-88.55	11.06	105.47	2014.12	10.69	1106.14	0.07	-0.13	0.05	0.15
P036	33	-67.8	111.6	-15.2	42	60.3	1878.07	-770.70	1196.61	-73.40	2.66	101.04	1878.11	-770.79	1196.73	0.04	-0.10	0.12	0.16
P037	41.8	-55.4	78.5	-0.9	50.7	79.2	2023.09	-1256.27	1315.47	-53.62	-15.74	93.96	2023.14	-1256.33	1315.58	0.06	-0.06	0.11	0.14
P038	38.7	-58.7	97.6	5.1	24.8	61.4	1999.00	-1134.13	1182.52	-65.27	-24.81	99.51	1999.01	-1134.10	1182.48	0.01	0.03	-0.04	0.05
P039	30.2	-58.8	76	33.4	46.9	47.6	2275.11	-1087.33	1426.28	-51.03	-36.69	78.02	2275.05	-1087.39	1426.11	-0.06	-0.06	-0.17	0.19

Stats		
mm	Metric	in
0.108	*Average*	0.0042
0.045	*stdev*	0.0018
0.196	*max*	0.0077
0.242	*avg+3stdev*	0.0095

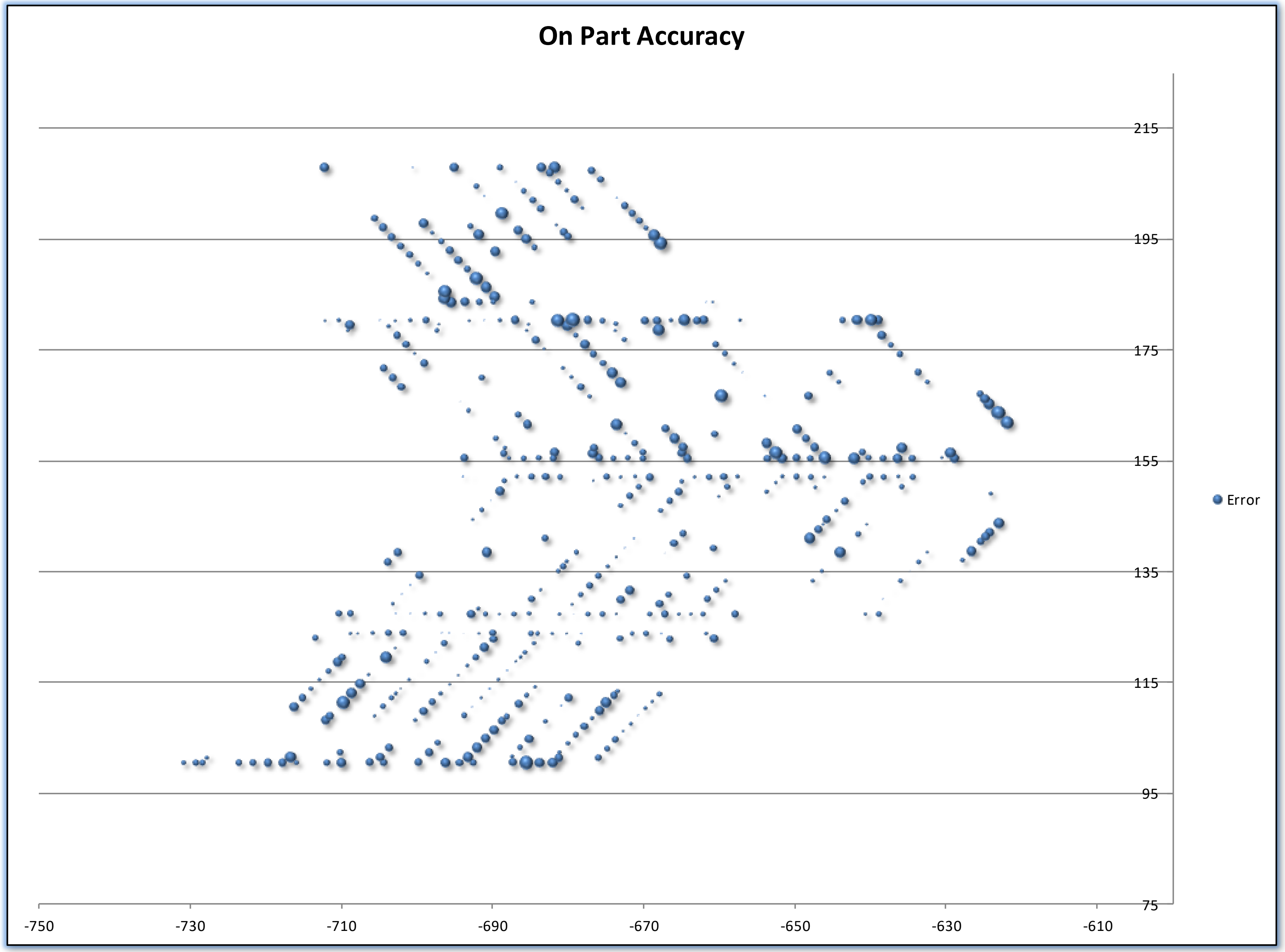
$$error_i = \sqrt{[(x_{ai} - x_{ni})^2 + (y_{ai} - y_{ni})^2 + (z_{ai} - z_{ni})^2]}$$

Typical Methods for Evaluating Robot Accuracy for Production Systems

<u>On part</u>

- Includes all error sources
  - Robot
  - Tool and base/part transforms
  - Process forces
  - Work piece deflection

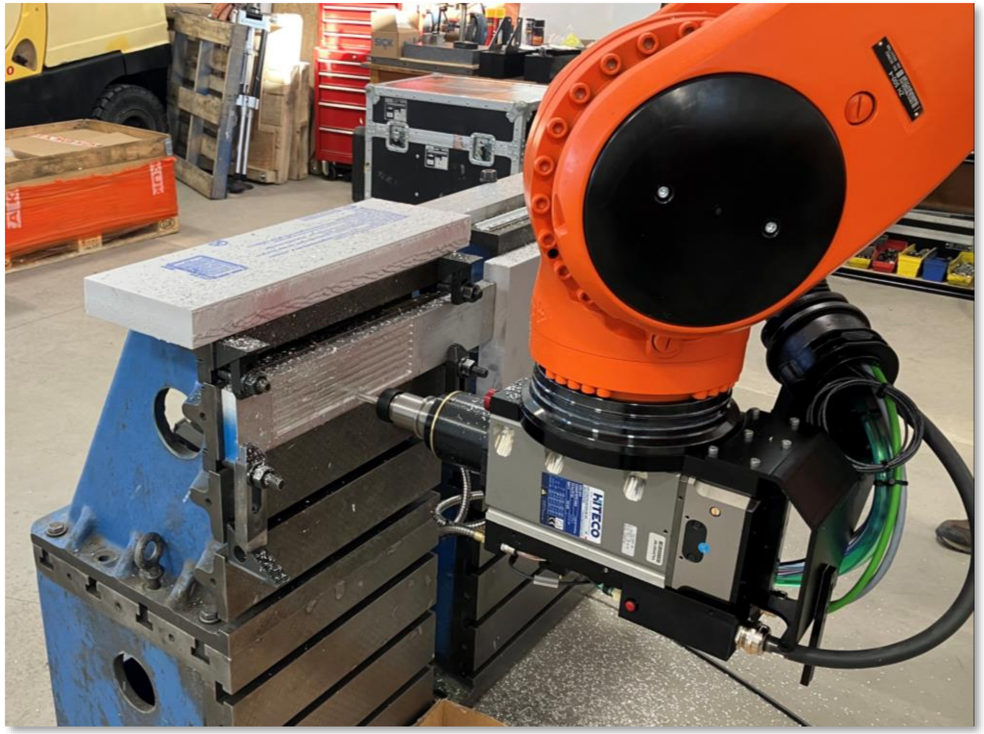
Typical Methods for Evaluating Robot Accuracy for Production Systems



<u>On part Statistics</u>

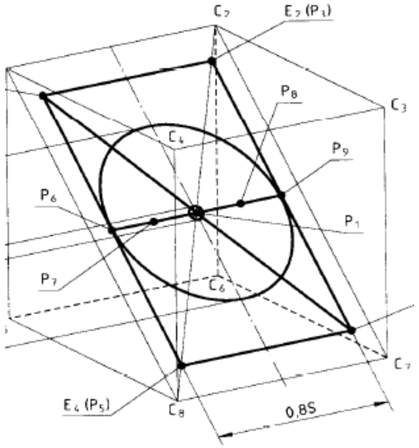
- Measured via best method (in this example, laser tracker)
- 2D deviation from nominal vector reported.
- Accuracy → Average + 3 * STDEV

Typical Methods for Evaluating Robot Accuracy for Production Syste



<u>Path-Related Processes (with external forces)</u>

- Quantify off-part accuracy as noted previously (static)
- General tuning and speed optimization can be performed using continuous motion tests similar to those noted in ISO9283, etc. Reflector in TCP, motion “in air”.
- Actual performance evaluated on part by producing product and measuring result (CMM, laser tracker, etc.)



Observations and Considerations – Notes from Production Implementations

Observations and Considerations – Notes from Production Implementations

Joint Space vs. Cartesian Space

- Working volume does not tell the whole story
- Joints range and TCP orientation must be exercised – unless specific application will not utilize
- Great test is to roll/pitch/yaw about TCP-mounted reflector – instant indicator of expected accuracy

SMALL Cartesian volume, significant orientation change, extreme joint range, DECREASED accuracy

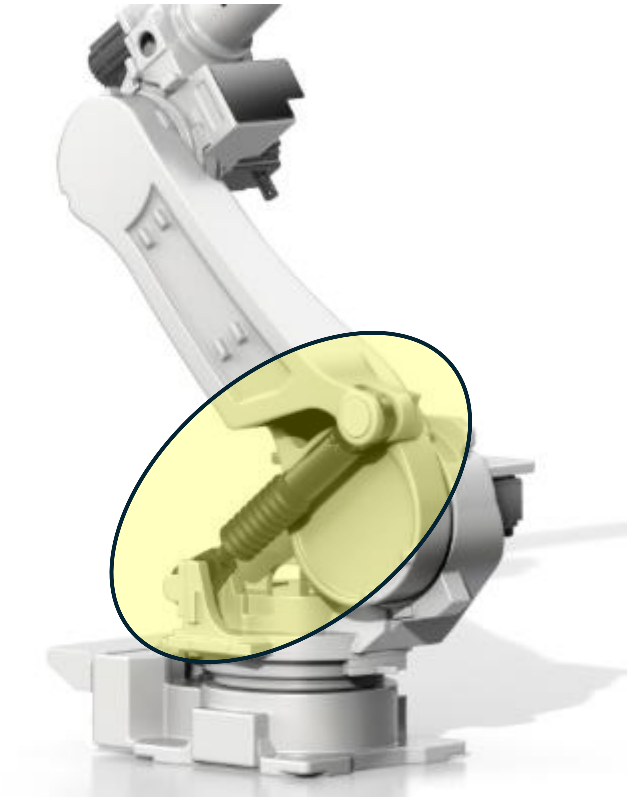
LARGE Cartesian volume, minimal orientation change, minimal joint range, INCREASED accuracy

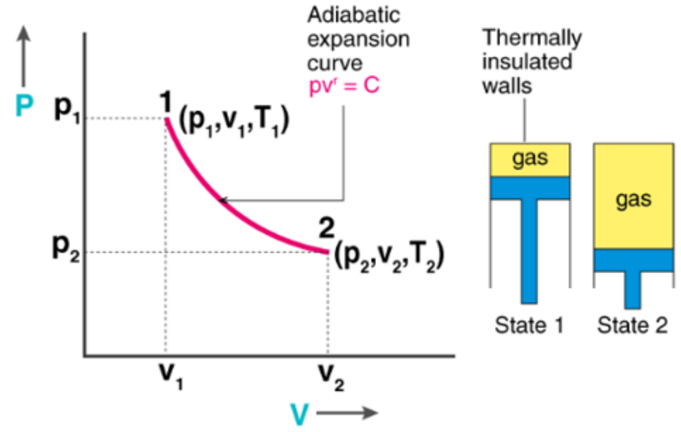
Observations and Considerations – Notes from Production Implementations

Drift of pose as related to mechanical construction

- Common source of drift is heat from motors (time dependent)
- Other sources may exist based on component selection (time AND position dependent)
    - Example: Counterbalances seen on joint 2 of various robots

- Hydro-pneumatic counterbalances exhibit variable force as the pressurized gas is heated/cooled.
- Large actuation results in rapid gas temperature change which slowly reaches equilibrium (1-2 minutes).
- During this time TCP drift is noted, and depending upon design, can drift in multiple directions





Observations and Considerations – Notes from Production Implementations

<u>Metrology Device Accuracy is Becoming More Significant</u>

- ISO 9283 (and others) specify the uncertainty of measurement shall not exceed 25% of the magnitude of the characteristic under test.
- Including ambient changes, reflector condition/precision, calibration – Laser tracker accuracy is good to about 0.03 to 0.05mm.

In practice, 0.03-0.05mm (0.001-0.002”)

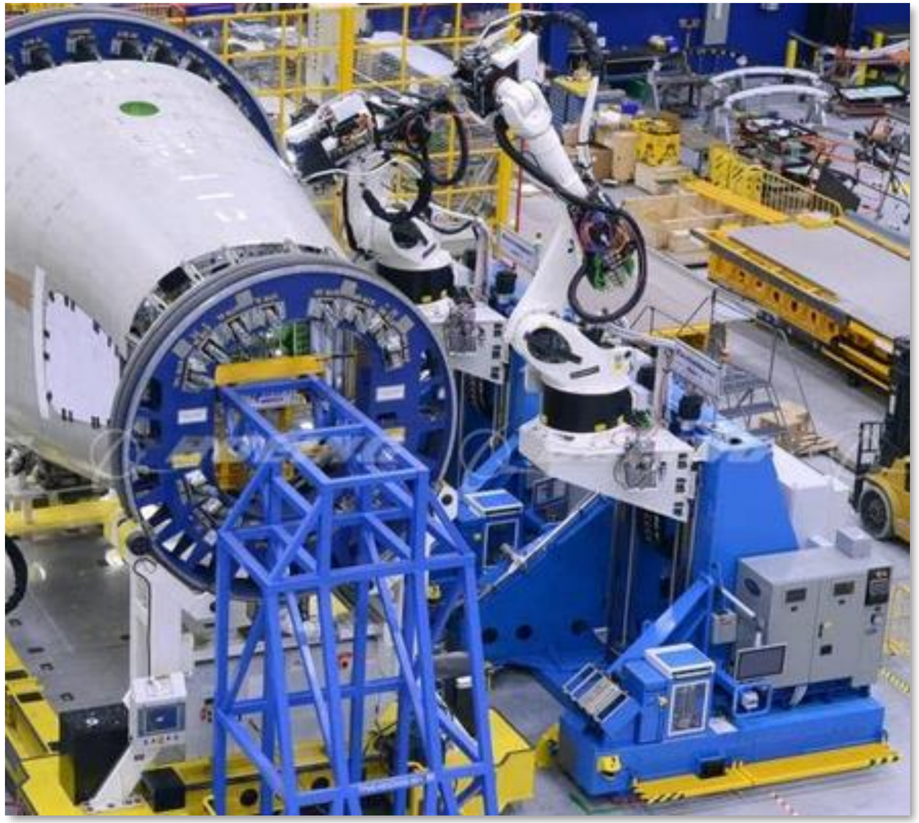
Verified accuracies < 0.12-0.15mm (0.005”-0.006”)

Significant Contributors to Positional Error Warranting More Attention in Standard(s)

Significant Contributors to Positional Error Warranting More Attention in Standard(s)

<u>Additional Kinematic Axes</u>

- Out of nearly 200 production system implementations, **96% utilize a 7th axis** to increase working range
    - Horizontal [most common] – robot rides on linear sled parallel to floor
    - Vertical – robot on elevator
    - Combinations thereof
- Error from linear axes is often amplified by the ratio of ArmReach:WheelBase/Track
- TCP deviations from external axes alone can easily exceed those exhibited solely by the robot
- External axes are servo-controlled and utilized as part of the kinematic chain, not positioned at discrete intervals



Significant Contributors to Positional Error Warranting More Attention in Standard(s)

Process Forces and Static Compliance

- One of the most critical characteristics for actual performance of the robot system
- Spring rates are pose-dependent, but can be 1mm or more per 100kg even for 500kg+ capacity robots.
- There are methods for dealing with the forces (predictive, sensed) but having a baseline for uncompensated performance would be extremely helpful
- We did extensive deflection evaluation across multiple makes to help select most rigid platform for given reach/payload capacity