

An Adaptive p -Norms-based Kinematic Calibration Model for Industrial Robot Positioning Accuracy Promotion: Supplementary File

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This is the supplementary file for this paper. Additional tables and figures regarding the experimental results are placed here.

I. ADDITIONAL TABLES

TABLE S.I. CALIBRATION ACCURACY OF TEN L_p -KC MODELS ON D1-3.

L_p -KC Models	D1			D2			D3		
	RMSE/mm	MEAN/mm	MAX/mm	RMSE/mm	MEAN/mm	MAX/mm	RMSE/mm	MEAN/mm	MAX/mm
$p=1$	0.727 \pm 2.1E-2	0.627 \pm 1.8E-2	1.320 \pm 1.6E-2	0.561 \pm 2.6E-2	0.461 \pm 1.7E-2	1.335 \pm 1.2E-2	0.691 \pm 1.8E-2	0.631 \pm 1.9E-2	1.266 \pm 2.0E-2
$p=2$	0.676 \pm 2.2E-2	0.577 \pm 1.5E-2	1.219 \pm 1.8E-2	0.545 \pm 9.9E-3	0.443 \pm 2.8E-2	1.267 \pm 2.0E-2	0.603 \pm 1.9E-2	0.583 \pm 1.5E-2	1.127 \pm 2.2E-2
$p=3$	0.650 \pm 1.5E-2	0.553 \pm 2.2E-2	1.128 \pm 2.1E-2	0.525 \pm 1.9E-2	0.425 \pm 2.2E-2	1.166 \pm 2.6E-2	0.553 \pm 3.0E-2	0.535 \pm 2.3E-2	1.083 \pm 2.0E-2
$p=4$	0.630 \pm 2.1E-2	0.530 \pm 1.2E-2	1.062 \pm 1.7E-2	0.501 \pm 1.2E-2	0.403 \pm 1.8E-2	1.113 \pm 1.0E-2	0.511 \pm 1.6E-2	0.491 \pm 1.5E-2	0.901 \pm 1.2E-2
$p=5$	0.608 \pm 1.0E-2	0.510 \pm 9.0E-3	1.006 \pm 8.9E-3	0.482 \pm 7.6E-3	0.380 \pm 1.1E-2	1.061 \pm 9.0E-3	0.495\pm9.2E-3	0.473\pm7.4E-3	0.881\pm8.2E-3
$p=6$	0.599\pm1.1E-2	0.499\pm8.9E-3	0.922\pm9.5E-3	0.453\pm1.3E-2	0.353\pm9.1E-3	0.959\pm7.1E-3	0.530 \pm 6.3E-3	0.510 \pm 8.0E-3	0.963 \pm 5.9E-3
$p=7$	0.623 \pm 1.1E-2	0.523 \pm 1.7E-2	1.108 \pm 8.9E-3	0.505 \pm 1.6E-2	0.406 \pm 1.2E-2	1.110 \pm 1.2E-2	0.551 \pm 1.1E-2	0.526 \pm 6.8E-3	1.055 \pm 8.8E-3
$p=8$	0.651 \pm 2.1E-2	0.550 \pm 2.0E-2	1.220 \pm 2.0E-2	0.519 \pm 1.8E-2	0.419 \pm 1.8E-2	1.220 \pm 1.9E-2	0.583 \pm 2.1E-2	0.563 \pm 1.7E-2	1.113 \pm 2.1E-2
$p=9$	0.685 \pm 1.6E-2	0.585 \pm 2.1E-2	1.266 \pm 2.1E-2	0.532 \pm 1.6E-2	0.442 \pm 1.9E-2	1.253 \pm 1.9E-2	0.623 \pm 2.3E-2	0.589 \pm 2.6E-2	1.168 \pm 2.9E-2
$p=10$	0.716 \pm 2.2E-2	0.616 \pm 3.6E-2	1.290 \pm 3.0E-2	0.545 \pm 3.1E-2	0.446 \pm 2.8E-2	1.285 \pm 3.2E-2	0.642 \pm 1.6E-3	0.618 \pm 2.8E-2	1.203 \pm 2.0E-2

TABLE S.II. TIME COSTS AND TRAINING ITERATION COUNTS OF TEN L_p -KC MODELS ON D1-3.

No.	Item	$p=1$	$p=2$	$p=3$	$p=4$	$p=5$	$p=6$	$p=7$	$p=8$	$p=9$	$p=10$
D1	Iteration	13	14	13	12	14	11	13	15	15	14
	Time/s	13.6 \pm 1.25	14.3 \pm 1.63	13.8 \pm 0.91	12.5 \pm 2.03	14.5 \pm 1.07	11.6\pm0.96	13.9 \pm 2.36	16.1 \pm 1.72	16.2 \pm 1.74	14.9 \pm 1.64
D2	Iteration	15	14	13	14	16	11	13	14	15	15
	Time/s	16.4 \pm 0.93	14.2 \pm 0.91	13.7 \pm 2.13	15.9 \pm 1.82	16.8 \pm 1.24	11.8\pm0.93	14.0 \pm 1.79	16.2 \pm 2.82	16.4 \pm 1.93	16.6 \pm 1.53
D3	Iteration	13	14	14	13	11	12	11	15	15	12
	Time/s	13.2 \pm 0.98	14.3 \pm 0.75	14.5 \pm 0.96	13.6 \pm 0.75	10.3\pm0.91	12.2 \pm 1.43	11.8 \pm 1.79	15.2 \pm 1.64	14.9 \pm 1.34	13.1 \pm 1.23

TABLE S.III. CALIBRATION ACCURACY OF M1-8 ON D1-3.

Models	D1			D2			D3		
	RMSE/mm	MEAN/mm	MAX/mm	RMSE/mm	MEAN/mm	MAX/mm	RMSE/mm	MEAN/mm	MAX/mm
M1	0.668 \pm 2.6E-2	0.567 \pm 1.9E-2	1.161 \pm 1.2E-2	0.531 \pm 4.0E-2	0.435 \pm 3.3E-2	1.173 \pm 1.5E-2	0.551 \pm 1.3E-2	0.530 \pm 1.7E-2	1.073 \pm 1.0E-2
M2	0.645 \pm 1.2E-2	0.546 \pm 1.3E-2	1.090 \pm 1.1E-2	0.509 \pm 9.2E-3	0.410 \pm 8.8E-3	1.112 \pm 7.0E-3	0.543 \pm 5.3E-3	0.510 \pm 3.5E-3	0.955 \pm 4.1E-3
M3	0.626 \pm 6.7E-2	0.526 \pm 5.1E-3	1.020 \pm 4.6E-3	0.478 \pm 5.1E-3	0.381 \pm 5.8E-2	1.056 \pm 5.2E-3	0.512 \pm 4.2E-3	0.486 \pm 5.3E-3	0.896 \pm 3.6E-3
M4	0.610 \pm 7.6E-3	0.510 \pm 5.1E-3	0.941 \pm 6.9E-3	0.453 \pm 5.8E-3	0.358 \pm 6.2E-3	0.961 \pm 4.6E-3	0.482\pm1.0E-2	0.441\pm1.2E-2	0.816\pm1.2E-2
M5	0.549\pm8.5E-3	0.450\pm9.6E-3	0.853\pm9.7E-3	0.437\pm1.7E-2	0.334\pm1.2E-2	0.830\pm1.0E-2	0.482\pm9.8E-3	0.441\pm1.3E-2	0.816\pm8.5E-3
M6	0.549\pm8.1E-3	0.450\pm9.9E-3	0.853\pm8.8E-3	0.437\pm6.6E-3	0.334\pm5.1E-3	0.830\pm4.3E-3	0.482\pm4.9E-3	0.441\pm4.9E-3	0.816\pm4.6E-3
M7	0.549\pm9.1E-3	0.450\pm5.9E-3	0.853\pm7.8E-3	0.437\pm7.2E-3	0.334\pm1.0E-2	0.830\pm5.2E-3	0.482\pm3.2E-3	0.441\pm3.5E-3	0.816\pm3.7E-3
M8	0.549\pm7.1E-3	0.450\pm6.0E-3	0.853\pm8.0E-3	0.437\pm5.3E-3	0.334\pm8.6E-3	0.830\pm6.3E-3	0.482\pm5.5E-3	0.441\pm5.6E-3	0.816\pm6.1E-3

TABLE S.IV. TIME COSTS AND TRAINING ITERATION COUNTS OF M1-8 ON D1-3.

No.	Item	M1	M2	M3	M4	M5	M6	M7	M8
D1	Iteration	12	12	11	10	9	9	11	12
	Time/s	16.1 \pm 1.36	18.4 \pm 1.72	19.3 \pm 1.22	20.1 \pm 1.21	21.2 \pm 1.23	23.4 \pm 1.12	30.9 \pm 1.81	34.6 \pm 0.81
D2	Iteration	13	12	12	11	11	10	10	11
	Time/s	17.0 \pm 1.25	17.9 \pm 1.53	20.2 \pm 1.56	21.8 \pm 0.81	22.9 \pm 0.93	24.7 \pm 1.02	26.8 \pm 1.53	31.9 \pm 1.53
D3	Iteration	12	11	11	11	10	12	12	14
	Time/s	15.6 \pm 1.26	16.7 \pm 1.36	18.7 \pm 1.55	20.5 \pm 0.82	21.0 \pm 1.02	25.0 \pm 1.11	27.8 \pm 0.99	35.5 \pm 1.25

II. ADDITIONAL FIGURES

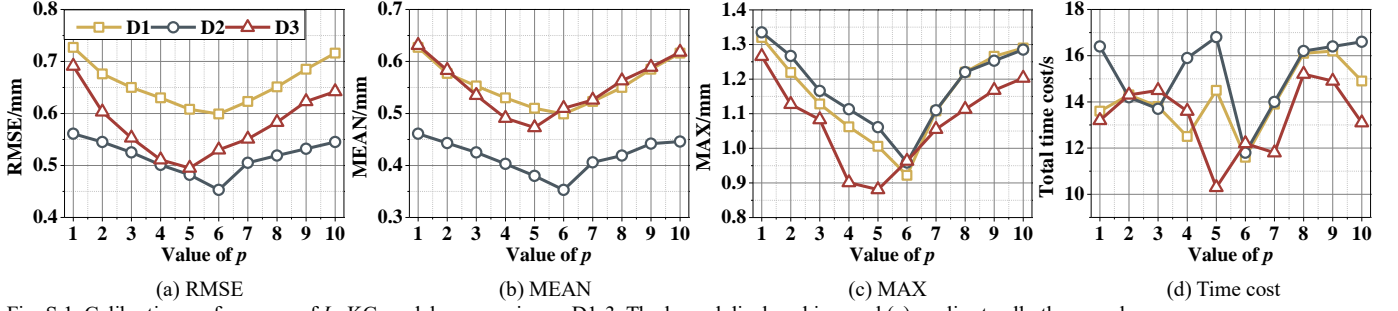


Fig. S.1. Calibration performance of L_p -KC models as p varies on D1-3. The legend displayed in panel (a) applies to all other panels.

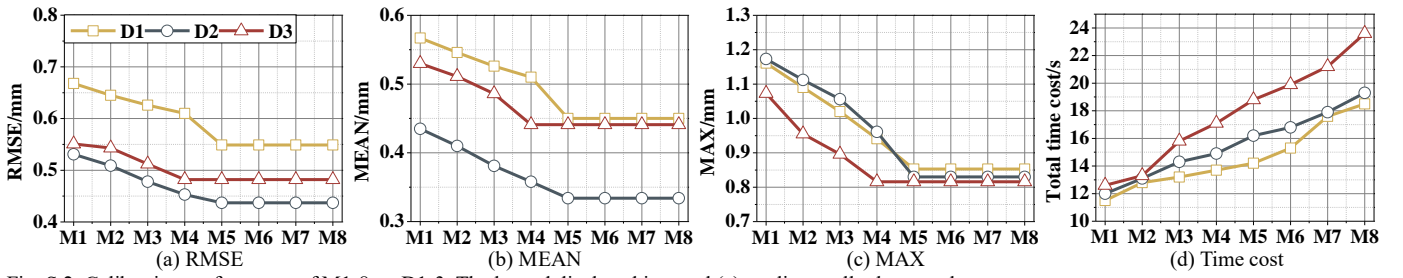


Fig. S.2. Calibration performance of M1-8 on D1-3. The legend displayed in panel (a) applies to all other panels.

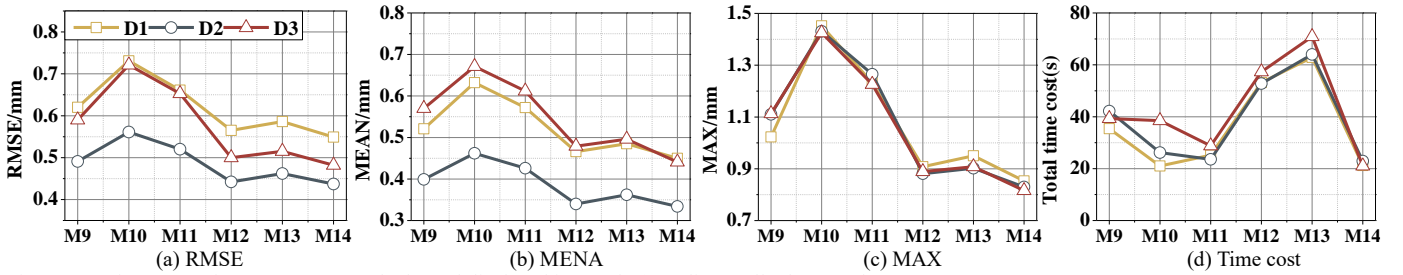


Fig. S.3. Performance of M9-14 on D1-3. The legend displayed in panel (a) applies to all other panels.

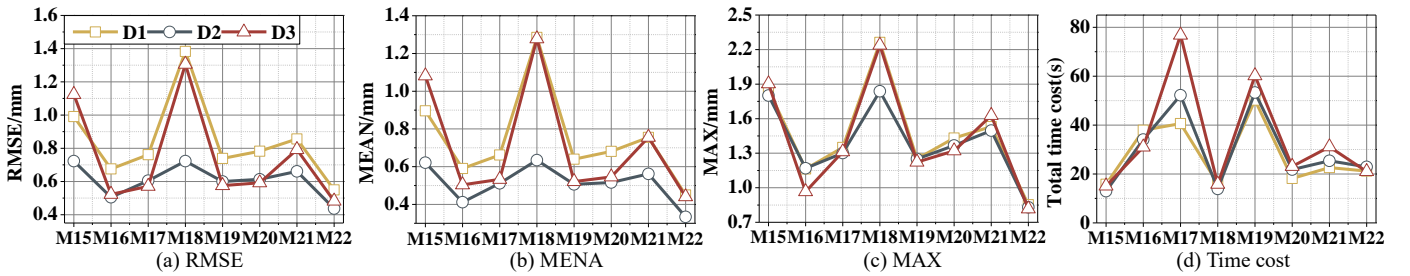


Fig.S.4. Performance of M15-22 on D1-3. The legend displayed in panel (a) applies to all other panels.

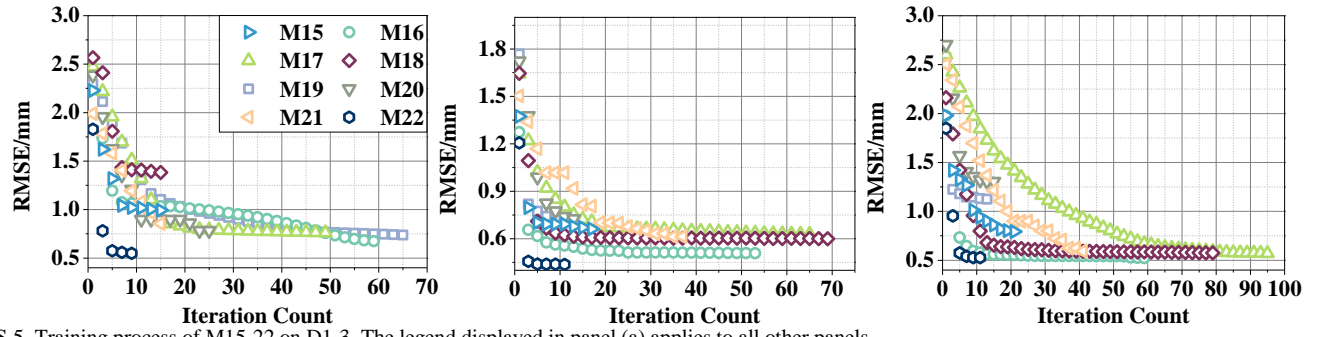


Fig. S.5. Training process of M15-22 on D1-3. The legend displayed in panel (a) applies to all other panels.

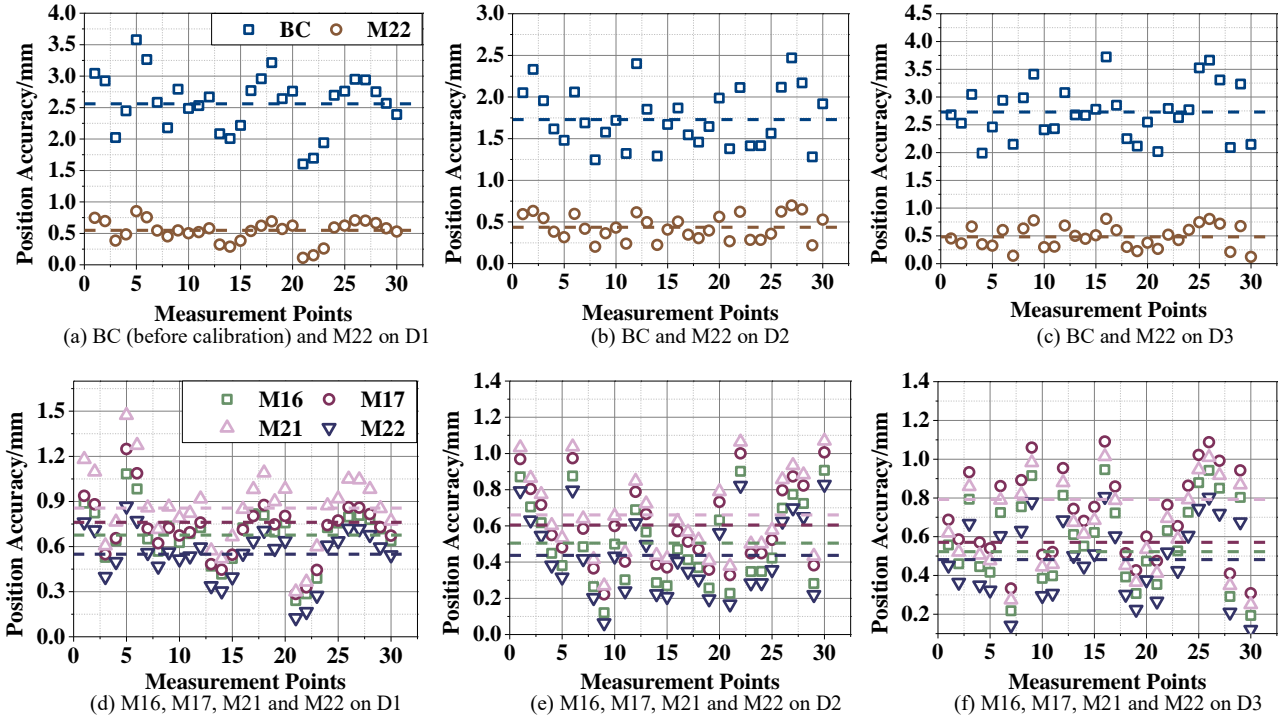


Fig. S.6. Position accuracy of measurement points by M16, M17, M21 and M22 on D1-3. Notably, the dashed lines are the mean values. Panels (a)-(c) compare the position accuracy on D1-3 before calibration (BC), and after calibration by M22. Panels (d)-(f) illustrate the position accuracy comparison among M16, M17, M21 and M22 on D1-3. The above results show that the calibrator M22 has evidently outperformed its peers in position accuracy. The legends displayed in panels (a) and (d) respectively apply to panels (a)-(b) and panels (e)-(f).