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

Anonymous

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	$0.608_{\pm 1.0E-2}$	$0.510_{\pm 9.0E-3}$	$1.006_{\pm 8.9E-3}$	$0.482_{\pm 7.6E-3}$	$0.380_{\pm 1.1E-2}$	$1.061_{\pm 9.0E-3}$	**$0.495_{\pm 9.2E-3}$**	**$0.473_{\pm 7.4E-3}$**	**$0.881_{\pm 8.2E-3}$**
p=6	**$0.599_{\pm 1.1E-2}$**	**$0.499_{\pm 8.9E-3}$**	**$0.922_{\pm 9.5E-3}$**	**$0.453_{\pm 1.3E-2}$**	**$0.353_{\pm 9.1E-3}$**	**$0.959_{\pm 7.1E-3}$**	$0.530_{\pm 6.3E-3}$	$0.510_{\pm 8.0E-3}$	$0.963_{\pm 5.9E-3}$
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	$13.6_{\pm 1.25}$	$14.3_{\pm 1.63}$	$13.8_{\pm 0.91}$	$12.5_{\pm 2.03}$	$14.5_{\pm 1.07}$	**$11.6_{\pm 0.96}$**	$13.9_{\pm 2.36}$	$16.1_{\pm 1.72}$	$16.2_{\pm 1.74}$	$14.9_{\pm 1.64}$
D2	Iteration	15	14	13	14	16	**11**	13	14	15	15
	Time/s	$16.4_{\pm 0.93}$	$14.2_{\pm 0.91}$	$13.7_{\pm 2.13}$	$15.9_{\pm 1.82}$	$16.8_{\pm 1.24}$	**$11.8_{\pm 0.93}$**	$14.0_{\pm 1.79}$	$16.2_{\pm 2.82}$	$16.4_{\pm 1.93}$	$16.6_{\pm 1.53}$
D3	Iteration	13	14	14	13	**11**	12	11	15	15	12
	Time/s	$13.2_{\pm 0.98}$	$14.3_{\pm 0.75}$	$14.5_{\pm 0.96}$	$13.6_{\pm 0.75}$	**$10.3_{\pm 0.91}$**	$12.2_{\pm 1.43}$	$11.8_{\pm 1.79}$	$15.2_{\pm 1.64}$	$14.9_{\pm 1.34}$	$13.1_{\pm 1.23}$

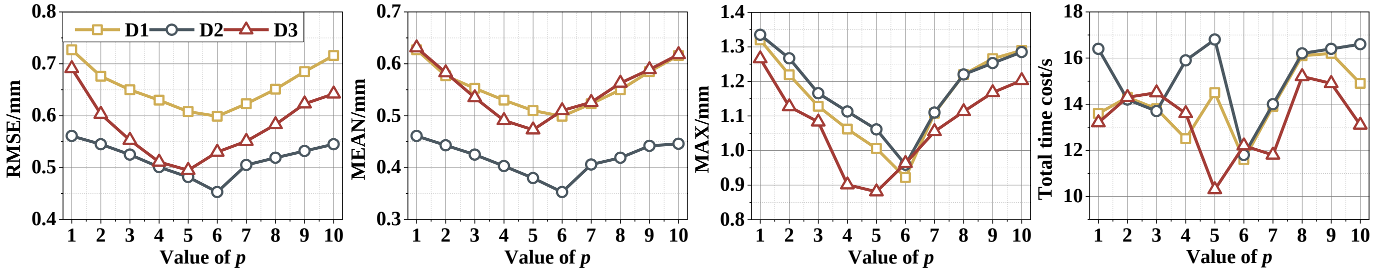
TABLE S.III. Calibration accuracy of M1-8 on D1-3.

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	$0.610_{\pm 7.6E-3}$	$0.510_{\pm 5.1E-3}$	$0.941_{\pm 6.9E-3}$	$0.453_{\pm 5.8E-3}$	$0.358_{\pm 6.2E-3}$	$0.961_{\pm 4.6E-3}$	**$0.482_{\pm 1.0E-2}$**	**$0.441_{\pm 1.2E-2}$**	**$0.816_{\pm 1.2E-2}$**
M5	**$0.549_{\pm 8.5E-3}$**	**$0.450_{\pm 9.6E-3}$**	**$0.853_{\pm 9.7E-3}$**	**$0.437_{\pm 1.7E-2}$**	**$0.334_{\pm 1.2E-2}$**	**$0.830_{\pm 1.0E-2}$**	**$0.482_{\pm 9.8E-3}$**	**$0.441_{\pm 1.3E-2}$**	**$0.816_{\pm 8.5E-3}$**
M6	**$0.549_{\pm 8.1E-3}$**	**$0.450_{\pm 9.9E-3}$**	**$0.853_{\pm 8.8E-3}$**	**$0.437_{\pm 6.6E-3}$**	**$0.334_{\pm 5.1E-3}$**	**$0.830_{\pm 4.3E-3}$**	**$0.482_{\pm 4.9E-3}$**	**$0.441_{\pm 4.9E-3}$**	**$0.816_{\pm 4.6E-3}$**
M7	**$0.549_{\pm 9.1E-3}$**	**$0.450_{\pm 5.9E-3}$**	**$0.853_{\pm 7.8E-3}$**	**$0.437_{\pm 7.2E-3}$**	**$0.334_{\pm 1.0E-2}$**	**$0.830_{\pm 5.2E-3}$**	**$0.482_{\pm 3.2E-3}$**	**$0.441_{\pm 3.5E-3}$**	**$0.816_{\pm 3.7E-3}$**
M8	**$0.549_{\pm 7.1E-3}$**	**$0.450_{\pm 6.0E-3}$**	**$0.853_{\pm 8.0E-3}$**	**$0.437_{\pm 5.3E-3}$**	**$0.334_{\pm 8.6E-3}$**	**$0.830_{\pm 6.3E-3}$**	**$0.482_{\pm 5.5E-3}$**	**$0.441_{\pm 5.6E-3}$**	**$0.816_{\pm 6.1E-3}$**

TABLE S.IV. Time costs and training iteration counts of M1-8 on D1-3.

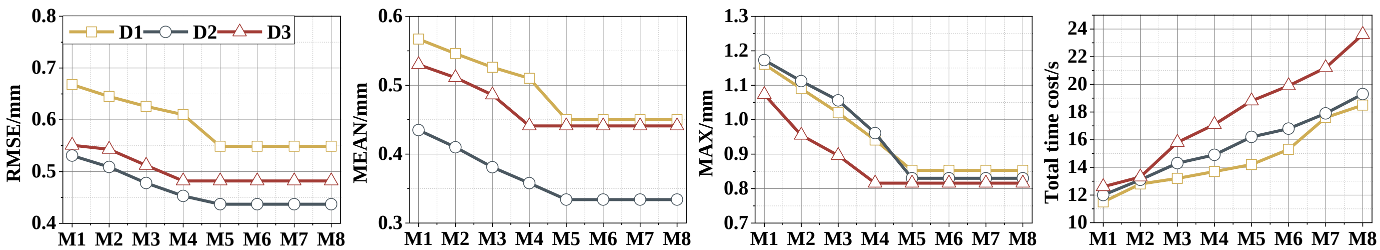
No.	**Item**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**
D1	Iteration	12	12	11	10	9	9	11	12
	Time/s	$16.1_{\pm 1.36}$	$18.4_{\pm 1.72}$	$19.3_{\pm 1.22}$	$20.1_{\pm 1.21}$	$21.2_{\pm 1.23}$	$23.4_{\pm 1.12}$	$30.9_{\pm 1.81}$	$34.6_{\pm 0.81}$
D2	Iteration	13	12	12	11	11	10	10	11
	Time/s	$17.0_{\pm 1.25}$	$17.9_{\pm 1.53}$	$20.2_{\pm 1.56}$	$21.8_{\pm 0.81}$	$22.9_{\pm 0.93}$	$24.7_{\pm 1.02}$	$26.8_{\pm 1.53}$	$31.9_{\pm 1.53}$
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



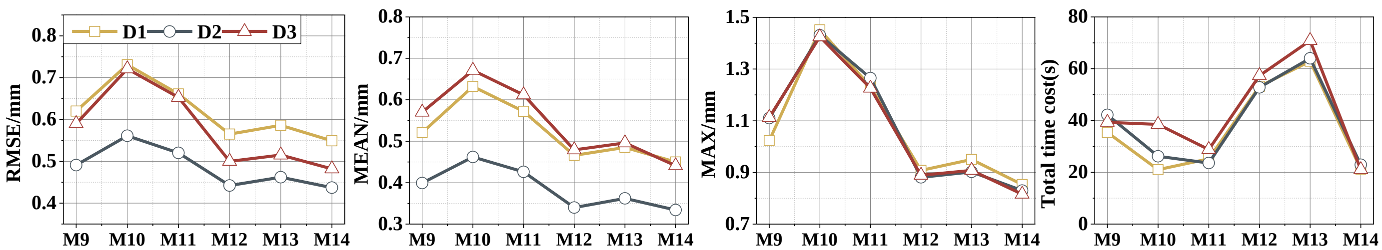
(a) RMSE (b) MEAN (c) MAX (d) Time cost

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.



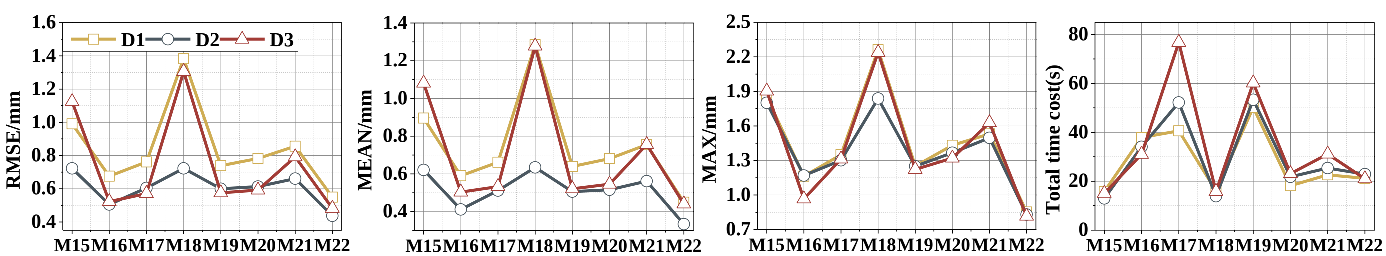
(a) RMSE (b) MEAN (c) MAX (d) Time cost

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



(a) RMSE (b) MENA (c) MAX (d) Time cost

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



(a) RMSE (b) MENA (c) MAX (d) Time cost

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

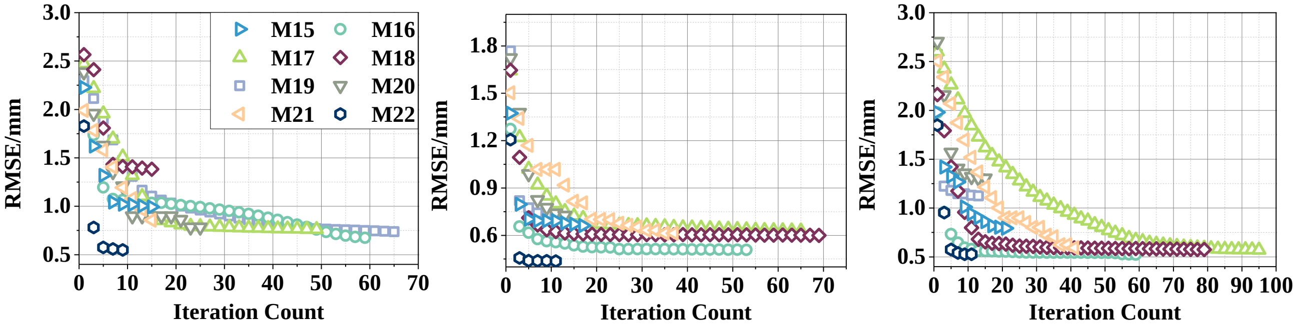
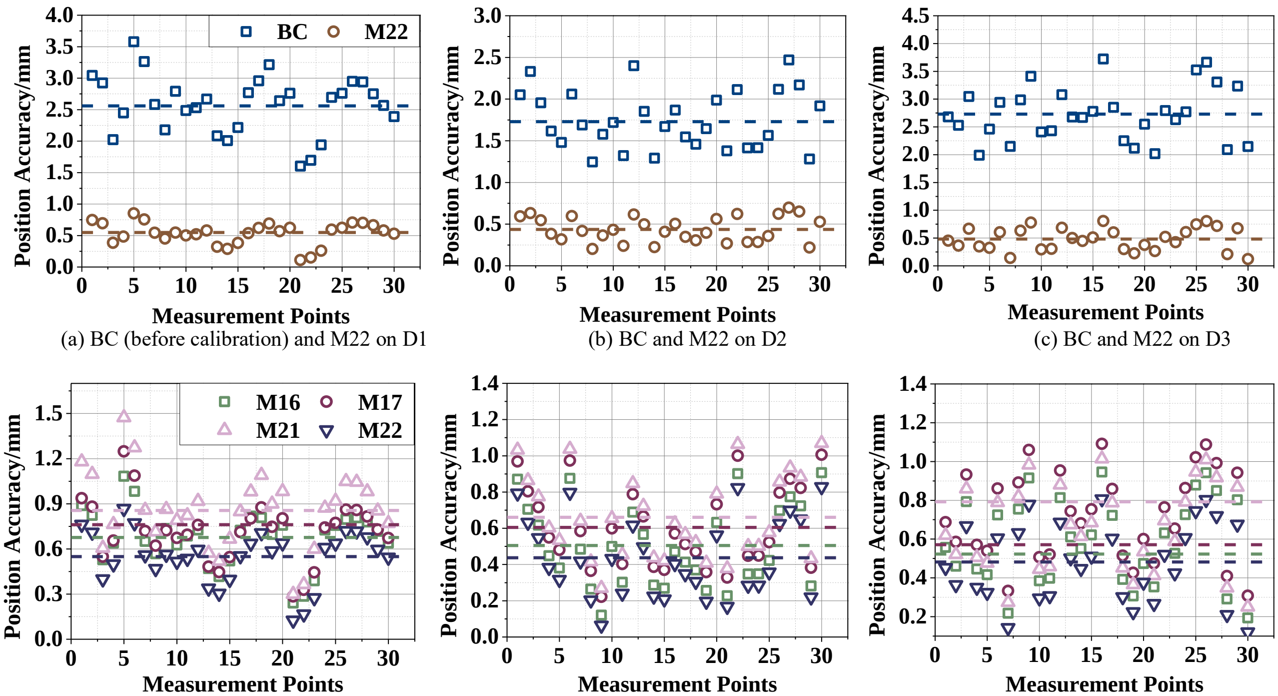


Fig. S.5. Training process of M15-22 on D1-3. The legend displayed in panel (a) applies to all other panels.



(a) BC (before calibration) and M22 on D1
(b) BC and M22 on D2
(c) BC and M22 on D3
(d) M16, M17, M21 and M22 on D1
(e) M16, M17, M21 and M22 on D2
(f) M16, M17, M21 and M22 on D3

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).