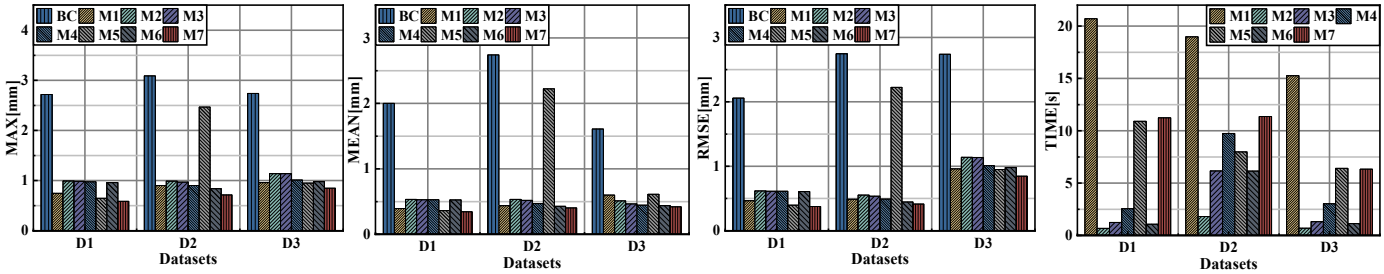
Highly-Accurate Manipulator Calibration via Extended Kalman Filter-Incorporated Residual Neural Network: Supplementary File

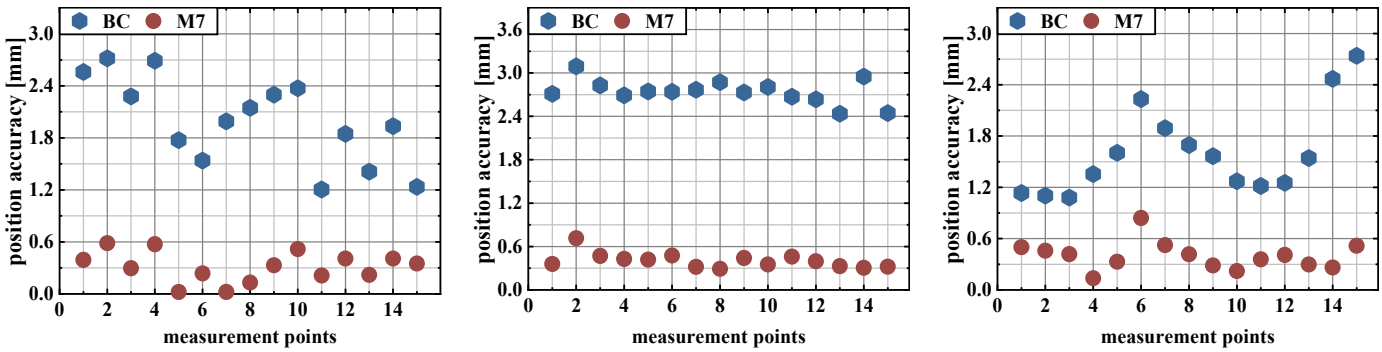
This is the supplementary file for the paper entitled *Highly-Accurate Manipulator Calibration via Extended Kalman Filter-Incorporated Residual Neural Network.* It mainly contains a) the evaluation metrics, position accuracy and convergence rates of experimental models on D1, D2, and D3, b) the practical experimental environment of a 6-DOF ABB IRB120 manipulator, and c) four supplementary tables recording the performance of the comparison models and calibration results.

PART. I. SUPPLEMENTARY FIGURES

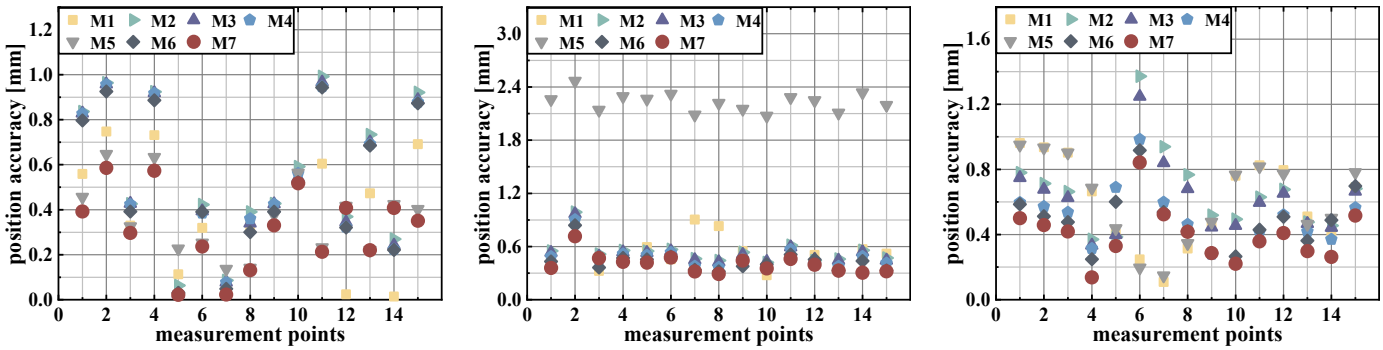


(a) MAX (b) MEAN (c) RMSE (d) TIME

Fig. S.1. The evaluation metrics of experimental results on D1, D2 and D3. Note that in panel (d), M1 takes 1.8, 1.6, and 2.4 times longer than M7 on D1, D2, and D3, respectively.

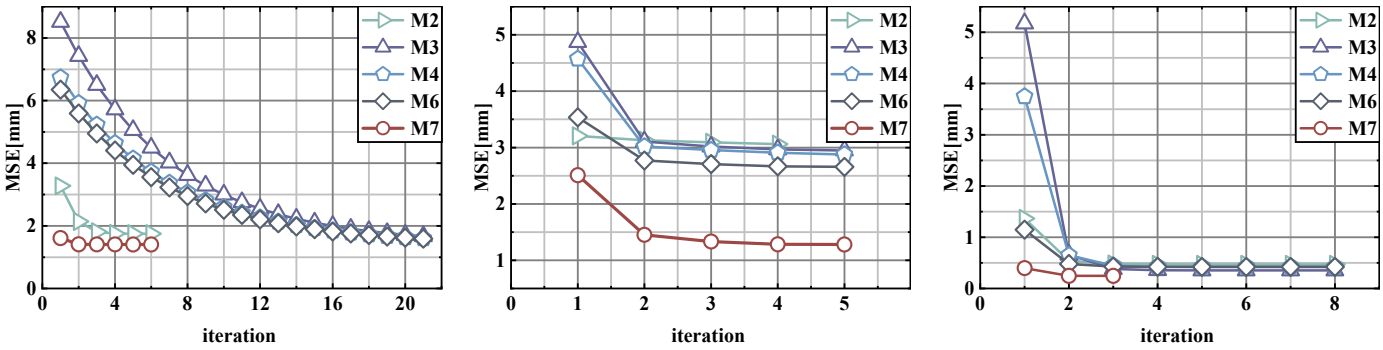


(a) Position accuracy of BC, M7 on D1 (b) Position accuracy of BC, M7 on D2 (c) Position accuracy of BC, M7 on D3



(d) Position accuracy of M1-7 on D1 (e) Position accuracy of M1-7 on D2 (f) Position accuracy of M1-7 on D3

Fig. S.2. The position accuracy of the measuring point on D1, D2, and D3 of each algorithm. (a), (b), and (c) Compared with BC (before calibration), the position accuracy of D-H parameters compensated by M7 is significantly optimized on D1, D2, and D3. (d), (e), and (f) Moreover, On D1, M7 performs better than other six algorithms 80% of the time on D2 and D3, and 86% of the time on D1.



(a) MSE on D1 (b) MSE on D2 (c) MSE on D2

Fig. S.3. MSE of algorithms with neural network (M2-4, M6-7) on D1, D2, and D3, M7 converges the fastest with the lowest MSE value.

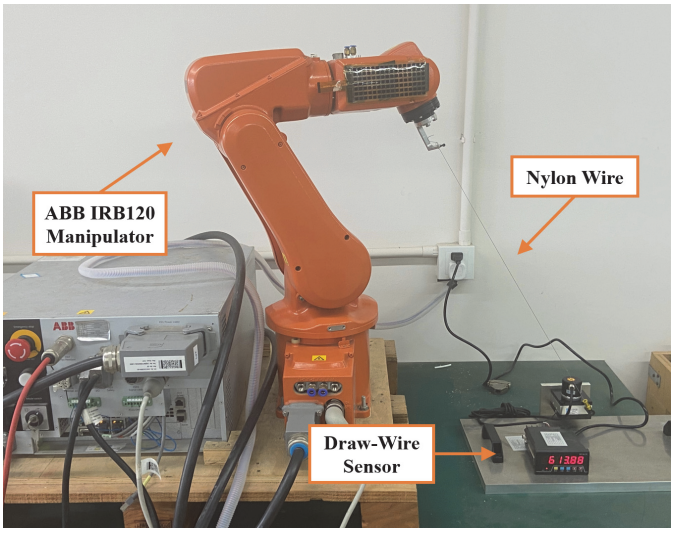


Fig. S.4. The practical experimental environment, including a 6-DOF ABB IRB120 manipulator, a nylon wire, and a draw-wire sensor. The two points of nylon wire are connected to the end-effector of the manipulator and the draw-wire sensor. The experimental data sets are obtained by changing the position of the manipulator to read the length of the draw-wire.

PART. II. SUPPLEMENTARY TABLES

TABLE S.I
THE COMPARATIVE TEST ERROR CALIBRATION RESULTS.

Dataset	Metric(mm)	BC	M1	M2	M3	M4	M5	M6	M7
D1	MEAN	2.000	0.394±5E-17	0.534±6E-03	0.529±2E-02	0.528±2E-02	0.363±0E-00	0.526±1E-02	0.345±3E-03
	RMSE	2.057	0.465±0E-00	0.618±7E-03	0.612±2E-02	0.612±2E-02	0.396±5E-17	0.608±1E-02	0.376±3E-03
	MAX	2.718	0.747±0E-00	0.992±2E-02	0.985±5E-02	0.977±5E-02	0.646±0E-00	0.962±1E-02	0.586±1E-02
D2	MEAN	2.741	0.439±5E-17	0.534±9E-08	0.519±2E-06	0.471±1E-06	2.221±0E-00	0.428±3E-06	0.403±8E-06
	RMSE	2.745	0.489±1E-16	0.552±8E-08	0.536±2E-06	0.491±1E-06	2.224±4E-16	0.446±3E-06	0.413±1E-05
	MAX	3.090	0.904±1E-16	0.987±1E-07	0.969±3E-06	0.902±3E-06	2.466±4E-16	0.839±4E-06	0.715±8E-06
D3	MEAN	1.610	0.599±0E-00	0.511±6E-03	0.465±2E-02	0.445±1E-02	0.611±0E-00	0.439±2E-02	0.422±8E-02
	RMSE	1.685	0.653±1E-16	0.565±1E-02	0.546±8E-02	0.505±3E-02	0.662±1E-16	0.501±3E-02	0.498±8E-02
	MAX	2.738	0.961±0E-00	1.140±7E-02	1.137±3E-02	1.010±2E-02	0.950±0E-00	0.980±2E-02	0.847±9E-02

TABLE S.II
TIME COST OF METHODS M1-M6 ON RMSE.

Dataset	Item	M1	M2	M3	M4	M5	M6	M7
D1	Iteration	50	5	20	20	20	20	5
	Time(s)	20.707±2.202	0.681±0.054	1.247±0.059	2.555±0.069	10.918±2.250	1.082±0.066	11.248±0.078*
D2	Iteration	30	5	5	5	20	5	5
	Time(s)	18.979±3.071	1.821±0.305	6.171±0.307	9.751±0.331	7.985±3.032	6.160±0.320	11.360±0.376*
D3	Iteration	30	8	8	8	20	8	3
	Time(s)	15.271±2.168	0.697±0.0725	1.319±0.072	3.032±0.103	6.418±2.221	1.139±0.103	6.327±0.089*

**Note that the base model of M7 is trained serially. Therefore, its time cost is determined by the model superposition of its two combinations.*

TABLE S.III
RESULTS OF THE WILCOXON SIGNED-RANKS TEST ON MEAN/RMSE/MAX OF TABLE S.I.

Comparison	R+	R-	p-value
M7 vs. M1	45	0	0.002
M7 vs. M2	45	0	0.002
M7 vs. M3	45	0	0.002
M7 vs. M4	45	0	0.002
M7 vs. M5	45	0	0.002
M7 vs. M6	45	0	0.002

TABLE S.IV
D-H PARAMETER DEVIATIONS AFTER CALIBRATION ON THE THREE DATASETS.

	D1				D2				D3			
Joint	$\Delta\alpha_{i-1}$/°	Δa_{i-1}/mm	$\Delta\theta_{i-1}$/°	Δd/mm	$\Delta\alpha_{i-1}$/°	Δa_{i-1}/mm	$\Delta\theta_{i-1}$/°	Δd/mm	$\Delta\alpha_{i-1}$/°	Δa_{i-1}/mm	$\Delta\theta_{i-1}$/°	Δd/mm
1	0.040	0.389	0.097	-0.965	1.052	-4.436	0.016	-0.971	-0.026	-0.097	-1.248	0.390
2	-0.075	-1.043	-0.069	-0.272	1.053	0.447	1.991	-0.286	0.148	0.355	-0.424	0.129
3	-0.083	0.000	0.620	-0.272	-7.002	-0.553	1.369	-0.286	-0.151	0.000	-0.919	0.129
4	0.001	0.000	-0.352	0.199	5.991	-5.063	0.995	-0.286	0.022	0.000	-1.752	-0.358
5	-0.000	0.000	0.617	-0.013	0.205	-0.484	0.097	1.028	0.027	0.000	0.266	-0.138
6	0.000	-0.097	0.094	0.000	-9.997	-0.485	0.050	3.128	0.000	0.024	-0.588	0.000