A Robust and Efficient Ensemble of Diversified Evolutionary Computing Algorithms for Accurate Robot Calibration: Supplementary File

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This is the supplementary file for this paper. Additional tables and figures regarding the symbol appointment, model structure and experimental results are placed here.

I. Additional Tables

TABLE S.I. Symbol appointment.

Symbol	Explanation
A	Transformation matrix.
a, d, α, θ	Link length, link offset, link twist angle, joint angle.
$c\theta_i$, $s\theta_i$	$cos\theta$ and $sin\theta$.
$dA,\delta A$	Holomorphic differential matrix, error matrix.
dx, dy, dz	Differential translations.
δx, δy, δz	Differential rotations.
ΔS	Position error vector of the end-effector.
$\Delta\alpha$, Δa, Δd ,$\Delta\theta$	Vector of the D-H parameter deviations
L, $\hat{L}$	Measured length of the cable, nominal length of the cable.
N	The total number of samples.
f	Objective function.
S_0, $\hat{S}$	Fixed position of the cable encoder on the ground and nominal position.
f_c	Perceived magnitude.
$\hat{c}$	Sensory modality coefficient.
$\hat{a}$	Power exponent.
t	Current iteration.
n	Size of a population.
$\hat{d}$	Dimension of the position vector.
P^t_{Mk}	Population of the *k-th* expert's output value at *t-th* iteration.
k	Expert algorithm index.
g^*	Best position vector.
r, r_1, r_2	Random number.
$\tilde{p}$	Switching probability.
cumsum	Cumulative sum.
Iter	Max round of iteration.
$\tilde{r}$	The number of 0 or 1.
$l_{a,i}$, $l^t_{b,i}$, l^t_b	Lower limit of ALO.
$u_{a,i}$, $u^t_{b,i}$, u^t_b	Upper limit of ALO.
I	Unit vector.
R_v	Radius of random walks of ants.
$A^t_{tl,j}$	Positions vector of the *j-th* antlion at the *t-th* iteration.
R^t_A, R^t_E	Random walks.
$B^t_{1,i}$, $B^t_{2,i}$, $B^t_{3,i}$, $B^t_{4,i}$, $B^t_{5,i}$, C^t_j, Z^t_i O^t_i	Vectors of DA.
b_1, b_2, b_3, b_4, b_5	Weights of separation, alignment, cohesion, food, natural enemy and inertia for the dragonfly algorithm.
$Lévy(\cdot)$	Lévy flight.
$\tilde{\tau}$	Inertia.
$\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\eta}$	Leader wolves.
$\tilde{\varepsilon}$	An individual in the rest wolves.
D, $\hat{D}$, $\hat{D}_{best}$	Euclidean distance.
$\lvert\cdot\rvert$	Absolute value of a number
γ, μ	Coefficient vectors.
e^t	Convergence factor at *t-th* iteration.
R^t_i	Radius.
$\lVert\cdot\rVert_2$	L_2 norm of a vector.
ζ^t_i	Neighbors of $P^t_{M4,i\text{-}DLH}$
$\tilde{h}$, c'	Constant.
κ	A parameter of the I-WOA.
w, w_1, w_2	Nonlinear variable, maximum of w, minimum of w.
$\underline{m}$	Distance between the right and left antennas.
$\bar{d}$	Random unit vector.
$\mathrm{sign}(\cdot)$	Sign function.
χ_t	Exploration step.
υ	Constant.
$Sort\{\cdot\}$	Self-defined function of the non-inferior sort rule.
$\tilde{U}^t_{Mk}$	The set is based on the result of the $Sort\{\cdot\}$ function.
$Intercept\{\cdot\}$	Self-defined function for intercepting the selected agents.
$G_{\min}\{\cdot\}$	Self-defined function to select the best agent.
$\Gamma^{\mathrm{t}}_{\mathrm{Mk}}$	Contribution factor.
P^0	Initial D-H parameters.
q_i	Rotation angle.
ω	Dimension of q_i
K	Total number of expert algorithms.

TABLE XI S.II. CALIBRATION ACCURACY OF THE HOEs-TEST-BASED MODELS AND THEIR INVOLVED EXPERT ALGORITHMS (M1-8 AND M′1-7) ON D1-3.

Algorithm	D1			D2			D3		
	RMSE/mm	Mean/mm	Max/mm	RMSE/mm	Mean/mm	Max/mm	RMSE/mm	Mean/mm	Max/mm
M1	$0.791_{\pm 2.1E-2}$	$0.692_{\pm 1.8E-2}$	$1.496_{\pm 4.7E-2}$	$0.689_{\pm 3.1E-2}$	$0.579_{\pm 2.6E-2}$	$1.681_{\pm 4.1E-2}$	$0.642_{\pm 3.1E-2}$	$0.553_{\pm 3.7E-2}$	$1.421_{\pm 5.1E-2}$
M2	$0.767_{\pm 1.1E-2}$	$0.679_{\pm 9.5E-3}$	$1.375_{\pm 3.0E-2}$	$0.632_{\pm 4.6E-2}$	$0.533_{\pm 3.1E-2}$	$1.403_{\pm 5.1E-2}$	$0.553_{\pm 5.1E-2}$	$0.536_{\pm 4.0E-2}$	$1.337_{\pm 6.6E-2}$
M3	$1.060_{\pm 7.4E-2}$	$0.930_{\pm 7.4E-2}$	$1.740_{\pm 5.1E-2}$	$0.661_{\pm 8.3E-2}$	$0.560_{\pm 7.1E-2}$	$1.537_{\pm 8.6E-2}$	$0.675_{\pm 7.3E-2}$	$0.576_{\pm 6.1E-2}$	$1.526_{\pm 8.2E-2}$
M4	$0.673_{\pm 3.3E-2}$	$0.583_{\pm 4.6E-2}$	$1.100_{\pm 8.7E-2}$	$0.525_{\pm 2.1E-2}$	$0.422_{\pm 8.6E-3}$	$1.196_{\pm 1.8E-2}$	$0.525_{\pm 5.5E-2}$	$0.482_{\pm 3.2E-2}$	$0.826_{\pm 65E-2}$
M5	$0.652_{\pm 3.5E-2}$	$0.560_{\pm 6.5E-2}$	$1.031_{\pm 9.5E-3}$	$0.461_{\pm 3.3E-2}$	$0.372_{\pm 2.7E-2}$	$1.143_{\pm 6.1E-2}$	$0.505_{\pm 3.7E-2}$	$0.472_{\pm 2.9E-2}$	$0.791_{\pm 7.3E-2}$
M6	$0.905_{\pm 6.7E-3}$	$0.803_{\pm 6.0E-3}$	$1.629_{\pm 1.8E-2}$	$0.702_{\pm 6.1E-2}$	$0.565_{\pm 5.5E-2}$	$1.752_{\pm 2.2E-2}$	$0.635_{\pm 1.1E-2}$	$0.566_{\pm 8.5E-3}$	$1.481_{\pm 1.2E-2}$
M7	$1.012_{\pm 6.0E-2}$	$0.896_{\pm 2.2E-2}$	$1.844_{\pm 4.9E-2}$	$0.591_{\pm 7.3E-2}$	$0.492_{\pm 3.1E-2}$	$1.283_{\pm 5.1E-2}$	$0.993_{\pm 5.3E-2}$	$0.961_{\pm 2.5E-2}$	$1.373_{\pm 7.3E-2}$
M8	$0.867_{\pm 2.6E-2}$	$0.768_{\pm 1.6E-2}$	$1.543_{\pm 3.10E-2}$	$0.633_{\pm 5.1E-2}$	$0.533_{\pm 2.1E-2}$	$1.425_{\pm 6.1E-2}$	$0.622_{\pm 6.1E-2}$	$0.556_{\pm 3.1E-2}$	$1.283_{\pm 6.1E-2}$
M′1	$0.722_{\pm 5.6E-2}$	$0.621_{\pm 3.2E-2}$	$1.221_{\pm 1.7E-2}$	$0.615_{\pm 3.1E-2}$	$0.523_{\pm 5.1E-2}$	$1.303_{\pm 3.7E-2}$	$0.613_{\pm 3.0E-2}$	$0.546_{\pm 5.3E-2}$	$1.229_{\pm 6.1E-2}$
M′2	$0.681_{\pm 2.8E-2}$	$0.583_{\pm 1.6E-2}$	$1.166_{\pm 2.8E-2}$	$0.565_{\pm 4.6E-2}$	$0.460_{\pm 2.2E-2}$	$1.261_{\pm 1.1E-2}$	$0.591_{\pm 2.1E-2}$	$0.522_{\pm 3.3E-2}$	$1.052_{\pm 3.6E-2}$
M′3	$0.632_{\pm 3.7E-2}$	$0.536_{\pm 5.1E-2}$	$0.965_{\pm 6.2E-2}$	$0.512_{\pm 3.2E-2}$	$0.412_{\pm 3.9E-2}$	$1.186_{\pm 4.0E-2}$	$0.521_{\pm 5.3E-2}$	$0.453_{\pm 4.0E-2}$	$0.761_{\pm 5.3E-2}$
M′4	$0.579_{\pm 2.6E-2}$	$0.486_{\pm 2.6E-2}$	$0.896_{\pm 3.9E-2}$	$0.479_{\pm 2.3E-2}$	$0.383_{\pm 3.2E-2}$	$1.101_{\pm 5.5E-2}$	$0.502_{\pm 3.5E-2}$	$0.430_{\pm 3.6E-2}$	$0.736_{\pm 4.0E-2}$
M′5	$\mathbf{0.520_{\pm 9.7E-3}}$	$\mathbf{0.431_{\pm 1.9E-2}}$	$\mathbf{0.855_{\pm 2.0E-2}}$	$\mathbf{0.412_{\pm 3.6E-2}}$	$\mathbf{0.331_{\pm 3.7E-2}}$	$\mathbf{0.983_{\pm 3.5E-2}}$	$\mathbf{0.472_{\pm 8.2E-3}}$	$\mathbf{0.433_{\pm 7.5E-3}}$	$\mathbf{0.700_{\pm 1.1E-2}}$
M′6	$\mathbf{0.520_{\pm 1.6E-2}}$	$\mathbf{0.430_{\pm 1.9E-2}}$	$\mathbf{0.851_{\pm 2.5E-2}}$	$\mathbf{0.411_{\pm 3.0E-2}}$	$\mathbf{0.330_{\pm 1.9E-2}}$	$\mathbf{0.980_{\pm 3.2E-2}}$	$\mathbf{0.472_{\pm 2.8E-2}}$	$\mathbf{0.432_{\pm 2.5E-2}}$	$\mathbf{0.696_{\pm 3.7E-2}}$
M′7	$\mathbf{0.520_{\pm 1.3E-2}}$	$\mathbf{0.432_{\pm 1.9E-2}}$	$\mathbf{0.857_{\pm 1.9E-2}}$	$\mathbf{0.411_{\pm 4.1E-2}}$	$\mathbf{0.330_{\pm 3.1E-2}}$	$\mathbf{0.982_{\pm 4.6E-2}}$	$\mathbf{0.472_{\pm 5.8E-2}}$	$\mathbf{0.433_{\pm 6.5E-2}}$	$\mathbf{0.701_{\pm 6.0E-2}}$
M′7′	$\mathbf{0.520_{\pm 1.3E-2}}$	$\mathbf{0.432_{\pm 2.0E-2}}$	$\mathbf{0.857_{\pm 2.0E-2}}$	$\mathbf{0.411_{\pm 4.2E-2}}$	$\mathbf{0.330_{\pm 3.2E-2}}$	$\mathbf{0.982_{\pm 4.8E-2}}$	$\mathbf{0.472_{\pm 5.9E-2}}$	$\mathbf{0.433_{\pm 6.5E-2}}$	$\mathbf{0.701_{\pm 6.1E-2}}$

TABLE S.III. TOTAL TIME COSTS OF THE HOEs-TEST-BASED MODELS AND THEIR INVOLVED EXPERT ALGORITHMS (M1-8 AND M′1-7) ON D1-3.

Algorithm	D1		D2		D3	
	Iteration	Time/s	Iteration	Time/s	Iteration	Time/s
M1	$57.0_{\pm 1.0}$	$63.9_{\pm 1.16}$	$45.3_{\pm 1.6}$	$50.39_{\pm 1.95}$	$40.7_{\pm 2.5}$	$58.3_{\pm 2.83}$
M2	$28.6_{\pm 1.5}$	$33.9_{\pm 1.66}$	$31.7_{\pm 1.5}$	$37.25_{\pm 0.97}$	$25.6_{\pm 1.2}$	$30.4_{\pm 0.83}$
M3	$16.3_{\pm 1.5}$	$14.5_{\pm 1.08}$	$20.6_{\pm 2.5}$	$18.79_{\pm 1.35}$	$15.3_{\pm 2.8}$	$13.5_{\pm 1.58}$
M4	$44.6_{\pm 4.1}$	$53.3_{\pm 3.99}$	$50.9_{\pm 3.6}$	$60.76_{\pm 3.21}$	$50.5_{\pm 4.6}$	$58.6_{\pm 3.97}$
M5	$73.3_{\pm 6.7}$	$43.0_{\pm 4.13}$	$68.3_{\pm 6.7}$	$40.67_{\pm 4.07}$	$68.9_{\pm 5.3}$	$45.67_{\pm 4.62}$
M6	$35.0_{\pm 4.6}$	$10.3_{\pm 0.50}$	$36.7_{\pm 5.3}$	$12.36_{\pm 0.67}$	$39.4_{\pm 5.4}$	$9.62_{\pm 0.68}$
M7	$30.3_{\pm 1.5}$	$23.6_{\pm 0.72}$	$45.6_{\pm 1.9}$	$25.05_{\pm 0.98}$	$52.5_{\pm 1.8}$	$26.9_{\pm 0.76}$
M8	$90.7_{\pm 3.1}$	$55.9_{\pm 1.61}$	$86.9_{\pm 2.9}$	$53.65_{\pm 0.93}$	$70.7_{\pm 2.6}$	$50.5_{\pm 2.69}$
M′1	$24.3_{\pm 5.1}$	$60.2_{\pm 0.96}$	$24.4_{\pm 1.4}$	$50.8_{\pm 2.62}$	$20.5_{\pm 1.3}$	$49.33_{\pm 1.49}$
M′2	$18.6_{\pm 4.2}$	$42.3_{\pm 0.96}$	$16.3_{\pm 3.2}$	$46.3_{\pm 3.21}$	$17.3_{\pm 2.7}$	$53.27_{\pm 2.29}$
M′3	$12.2_{\pm 3.5}$	$50.1_{\pm 0.96}$	$13.2_{\pm 2.0}$	$52.3_{\pm 2.52}$	$15.2_{\pm 2.3}$	$58.23_{\pm 1.23}$
M′4	$9.3_{\pm 2.1}$	$40.6_{\pm 0.96}$	$8.5_{\pm 1.3}$	$36.2_{\pm 3.22}$	$12.8_{\pm 1.2}$	$52.91_{\pm 1.22}$
M′5	$\mathbf{5.1_{\pm 0.2}}$	$\mathbf{22.3_{\pm 0.96}}$	$\mathbf{5.1_{\pm 2.2}}$	$\mathbf{22.7_{\pm 4.42}}$	$\mathbf{7.5_{\pm 1.3}}$	$\mathbf{37.65_{\pm 1.22}}$
M′6	$5.3_{\pm 1.2}$	$30.1_{\pm 0.96}$	$5.2_{\pm 1.0}$	$27.9_{\pm 1.12}$	$7.2_{\pm 3.6}$	$43.25_{\pm 1.35}$
M′7	$5.2_{\pm 1.8}$	$36.3_{\pm 0.96}$	$5.6_{\pm 1.5}$	$33.1_{\pm 1.80}$	$7.3_{\pm 0.6}$	$46.31_{\pm 1.32}$
M′7′	$5.2_{\pm 1.7}$	$36.3_{\pm 0.93}$	$5.6_{\pm 1.5}$	$33.1_{\pm 1.86}$	$7.3_{\pm 0.6}$	$46.31_{\pm 1.40}$

TABLE S.IV. CALIBRATION ACCURACY OF M9-17 ON D1-3.

Algorithm	D1			D2			D3		
	RMSE/mm	Mean/mm	Max/mm	RMSE/mm	Mean/mm	Max/mm	RMSE/mm	Mean/mm	Max/mm
Before	2.56	2.45	4.51	2.09	2.0	3.36	2.73	2.72	3.09
M9	$0.675_{\pm 0.0E-0}$	$0.589_{\pm 0.0E-0}$	$1.162_{\pm 0.0E-0}$	$0.503_{\pm 0.0E-0}$	$0.416_{\pm 0.0E-0}$	$1.167_{\pm 0.0E-0}$	$0.523_{\pm 0.0E-0}$	$0.504_{\pm 0.0E-0}$	$0.796_{\pm 0.0E-0}$
M10	$1.213_{\pm 6.5E-2}$	$1.110_{\pm 5.6E-2}$	$2.232_{\pm 7.6E-2}$	$0.822_{\pm 5.1E-2}$	$0.728_{\pm 3.1E-2}$	$1.933_{\pm 7.1E-2}$	$1.375_{\pm 4.6E-2}$	$1.347_{\pm 3.5E-2}$	$2.461_{\pm 5.7E-2}$
M11	$1.383_{\pm 3.3E-2}$	$1.285_{\pm 3.8E-2}$	$2.621_{\pm 6.5E-2}$	$0.723_{\pm 5.1E-2}$	$0.635_{\pm 2.1E-2}$	$1.838_{\pm 6.8E-2}$	$1.302_{\pm 8.1E-2}$	$1.273_{\pm 6.1E-2}$	$2.235_{\pm 8.6E-2}$
M12	$0.981_{\pm 5.6E-2}$	$0.886_{\pm 5.0E-2}$	$1.820_{\pm 5.3E-2}$	$0.711_{\pm 3.3E-2}$	$0.578_{\pm 5.1E-2}$	$1.783_{\pm 3.9E-2}$	$1.648_{\pm 7.3E-2}$	$1.438_{\pm 8.3E-2}$	$1.887_{\pm 6.3E-2}$
M13	$0.836_{\pm 5.3E-2}$	$0.738_{\pm 3.8E-2}$	$1.632_{\pm 6.4E-2}$	$0.653_{\pm 3.9E-2}$	$0.552_{\pm 5.1E-2}$	$1.605_{\pm 6.1E-2}$	$0.972_{\pm 5.2E-2}$	$0.936_{\pm 4.0E-2}$	$1.502_{\pm 3.7E-2}$
M14	$0.557_{\pm 2.3E-2}$	$0.462_{\pm 2.1E-2}$	$0.897_{\pm 2.6E-2}$	$0.423_{\pm 5.2E-2}$	$0.348_{\pm 3.7E-2}$	$1.046_{\pm 5.0E-2}$	$0.506_{\pm 2.7E-2}$	$0.465_{\pm 2.1E-2}$	$0.757_{\pm 3.6E-2}$
M15	$0.526_{\pm 1.8E-2}$	$0.435_{\pm 9.2E-3}$	$0.858_{\pm 1.3E-2}$	$0.412_{\pm 5.7E-2}$	$0.325_{\pm 2.1E-2}$	$0.983_{\pm 1.1E-2}$	$0.473_{\pm 3.1E-2}$	$0.431_{\pm 2.6E-2}$	$0.713_{\pm 1.2E-2}$
M16	$0.563_{\pm 2.6E-2}$	$0.462_{\pm 1.5E-2}$	$0.891_{\pm 2.8E-2}$	$0.433_{\pm 3.1E-2}$	$0.353_{\pm 1.6E-2}$	$1.051_{\pm 2.2E-2}$	$0.512_{\pm 3.1E-2}$	$0.465_{\pm 1.1E-2}$	$0.751_{\pm 1.9E-2}$
M17	$\mathbf{0.520_{\pm 9.7E-3}}$	$\mathbf{0.431_{\pm 1.9E-2}}$	$\mathbf{0.855_{\pm 2.0E-2}}$	$\mathbf{0.412_{\pm 3.6E-2}}$	$\mathbf{0.331_{\pm 3.1E-2}}$	$\mathbf{0.983_{\pm 3.5E-2}}$	$\mathbf{0.472_{\pm 8.2E-3}}$	$\mathbf{0.433_{\pm 7.5E-3}}$	$\mathbf{0.700_{\pm 1.1E-2}}$

TABLE S.V. TOTAL TIME COSTS OF M9-17 ON D1-3.

Algorithm	D1		D2		D3	
	Iteration	Time/s	Iteration	Time/s	Iteration	Time/s
M9	$58.0_{\pm 0.00}$	$36.5_{\pm 0.28}$	$53.0_{\pm 0.00}$	$34.69_{\pm 0.15}$	$50.3_{\pm 0.00}$	$30.9_{\pm 0.12}$
M10	$13.0_{\pm 0.00}$	$13.6_{\pm 0.03}$	$10.0_{\pm 0.00}$	$10.67_{\pm 0.06}$	$12.7_{\pm 0.00}$	$13.5_{\pm 0.16}$
M11	$15.2_{\pm 1.23}$	$15.5_{\pm 1.86}$	$12.6_{\pm 1.50}$	$13.96_{\pm 1.90}$	$14.1_{\pm 1.63}$	$15.5_{\pm 1.57}$
M12	$11.7_{\pm 1.10}$	$29.2_{\pm 2.35}$	$9.5_{\pm 1.60}$	$19.98_{\pm 3.20}$	$10.2_{\pm 1.72}$	$22.3_{\pm 3.56}$
M13	$62.6_{\pm 3.05}$	$46.5_{\pm 1.61}$	$64.2_{\pm 2.95}$	$49.65_{\pm 0.93}$	$67.3_{\pm 3.67}$	$46.5_{\pm 2.69}$
M14	$5.3_{\pm 0.67}$	$35.1_{\pm 1.81}$	$5.5_{\pm 0.97}$	$40.92_{\pm 3.28}$	$7.9_{\pm 0.62}$	$50.2_{\pm 3.67}$
M15	$5.6_{\pm 0.30}$	$35.0_{\pm 2.07}$	$5.3_{\pm 0.46}$	$39.75_{\pm 2.50}$	$7.6_{\pm 0.75}$	$49.6_{\pm 4.60}$
M16	$5.1_{\pm 0.17}$	$26.2_{\pm 0.86}$	$5.2_{\pm 0.22}$	$30.86_{\pm 1.30}$	$8.2_{\pm 0.37}$	$38.7_{\pm 2.53}$
M17	$5.1_{\pm 0.23}$	$22.3_{\pm 0.96}$	$5.1_{\pm 0.33}$	$22.7_{\pm 1.60}$	$7.5_{\pm 0.31}$	$37.65_{\pm 2.20}$

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

Comparison	***R+***	***R-***	***p-value***
M17 vs. M9	45	0	0.002
M17 vs. M10	45	0	0.002
M17 vs. M11	45	0	0.002
M17 vs. M12	45	0	0.002
M17vs. M13	45	0	0.002
M17 vs. M14	45	0	0.002
M17 vs. M15	45	0	0.002
M17 vs. M16	45	0	0.002

*The highlighted significance level of acceptance is 0.05.

TABLE S.VII. THE CALIBRATION RESULTS OF THE D-H PARAMETERS DEVIATIONS ON D1-3.

Dataset	**Joint *i***	$\Delta\alpha_i$/°	Δa_i/mm	Δd_i/mm	$\Delta\theta_i$/°
D1	1	-0.1960	-0.3615	0.6391	0.1698
	2	-0.5361	-2.3644	-0.5903	-0.5987
	3	0.6073	3.7962	-0.1826	0.3161
	4	-0.0618	0.6569	3.8435	0.3668
	5	0.1094	-0.5389	0.1258	0.0396
	6	0.1205	-0.1536	-0.7375	0.9631
D2	1	0.2364	-5.3984	4.3259	-0.2366
	2	0.0035	-3.2165	-2.7589	-0.2698
	3	-0.7653	-0.3962	4.8632	-0.0659
	4	-0.8320	-0.2326	2.3654	-0.0836
	5	-0.0165	-4.2658	1.2369	-0.1265
	6	-0.3658	-0.2354	2.3698	-0.3659
D3	1	0.0562	-1.9678	2.3698	-0.0863
	2	0.0369	-0.0697	-1.5066	0.0532
	3	-0.1698	-2.9634	-0.5436	-0.0221
	4	0.0756	-1.2691	0.5396	0.5132
	5	-0.2689	1.7369	-0.1963	-0.1256
	6	-0.0235	-3.2692	0.2365	-0.3658

II. Additional Figures

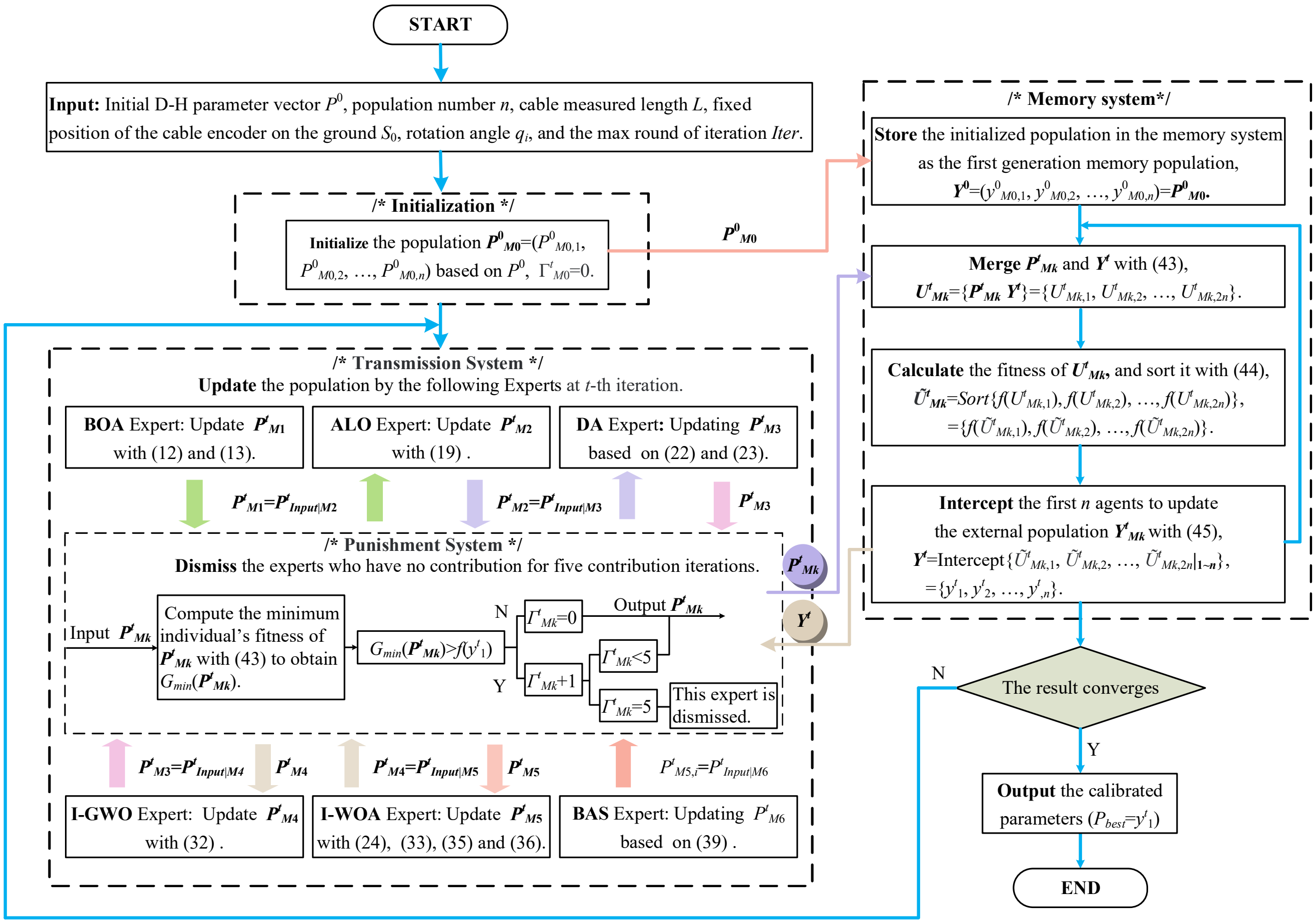


Fig. S.1. The flowchart of the HOEs model.

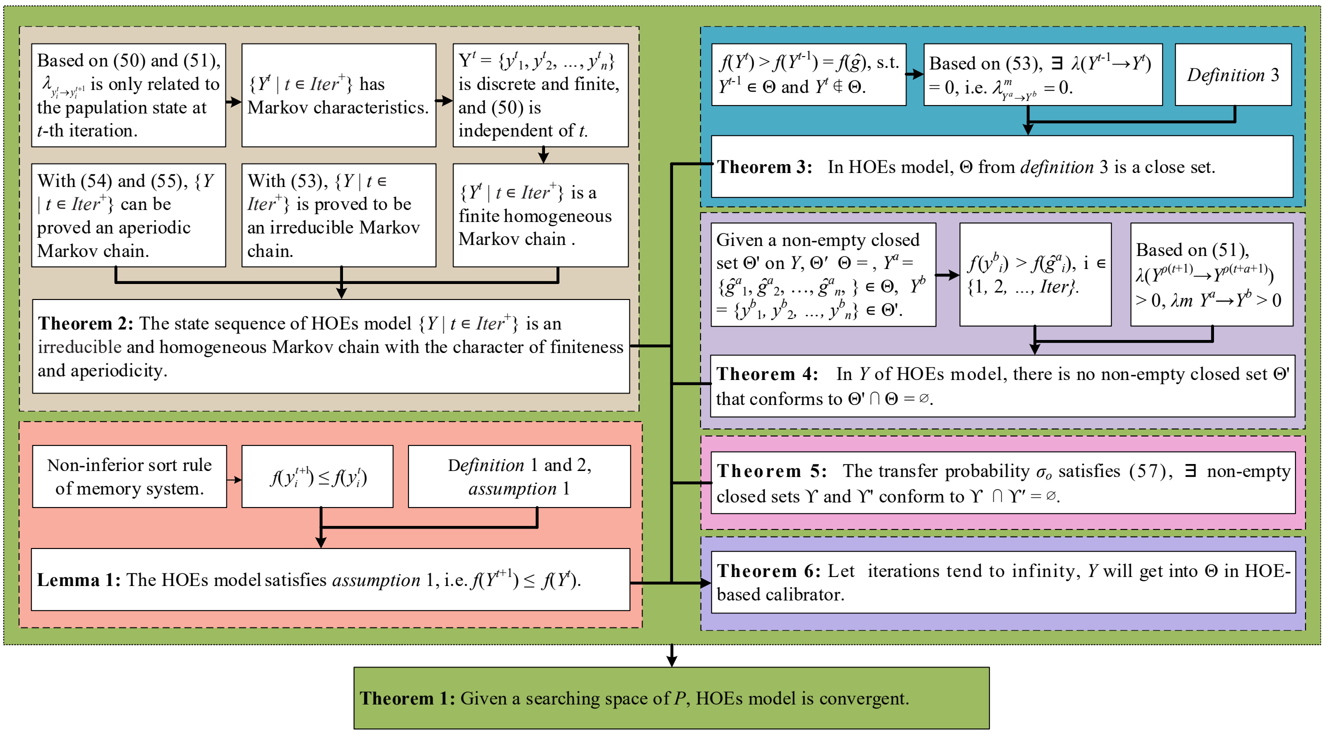


Fig. S.2. Proof sketch of HOEs model's convergence.

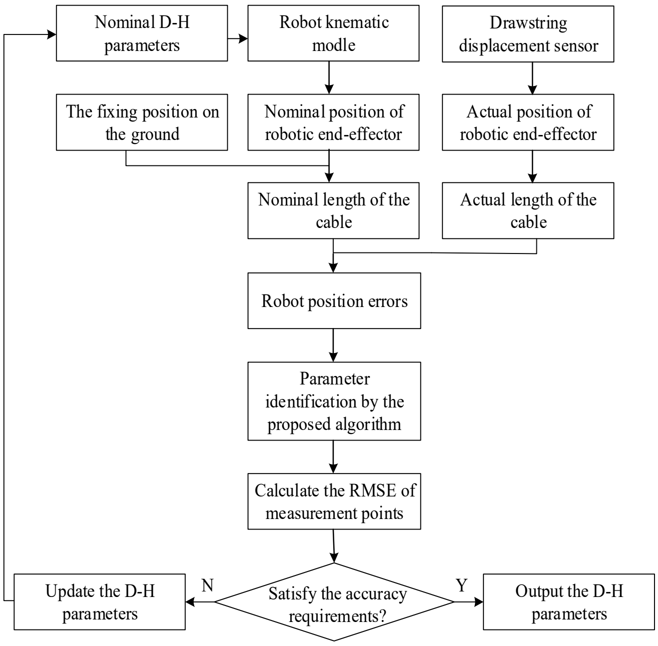
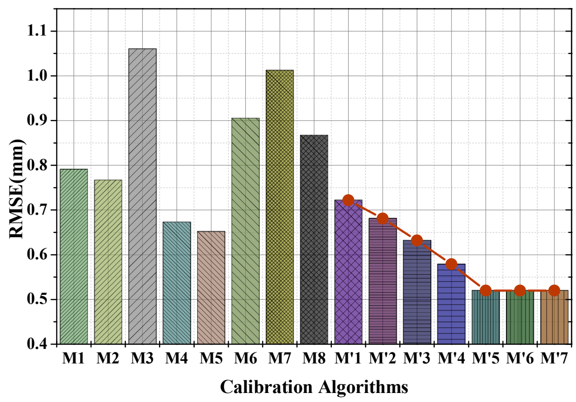
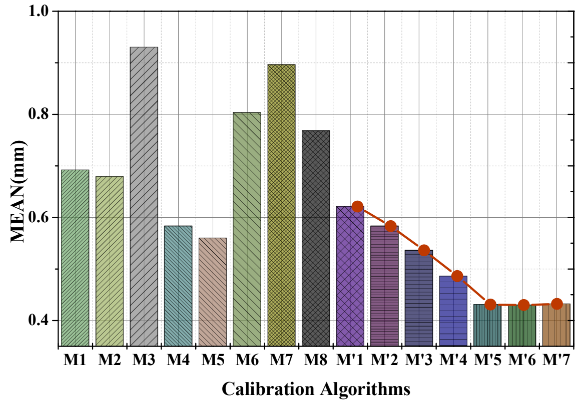


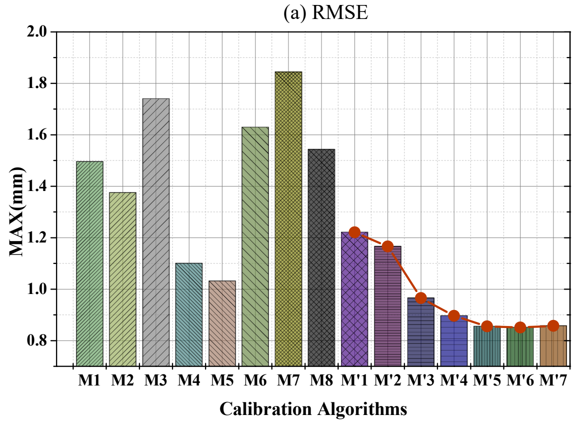
Fig. S.3. The industrial robot calibration process.



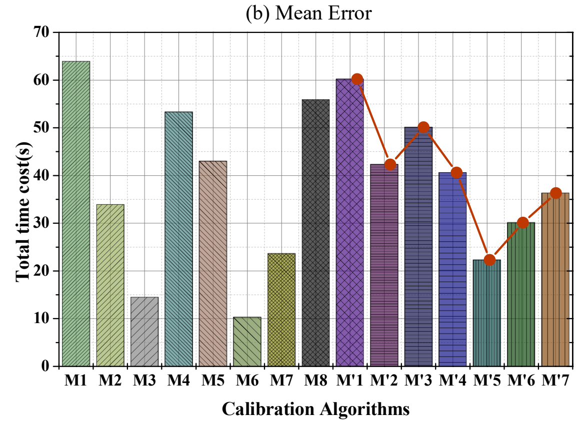
(a) RMSE



(b) Mean Error

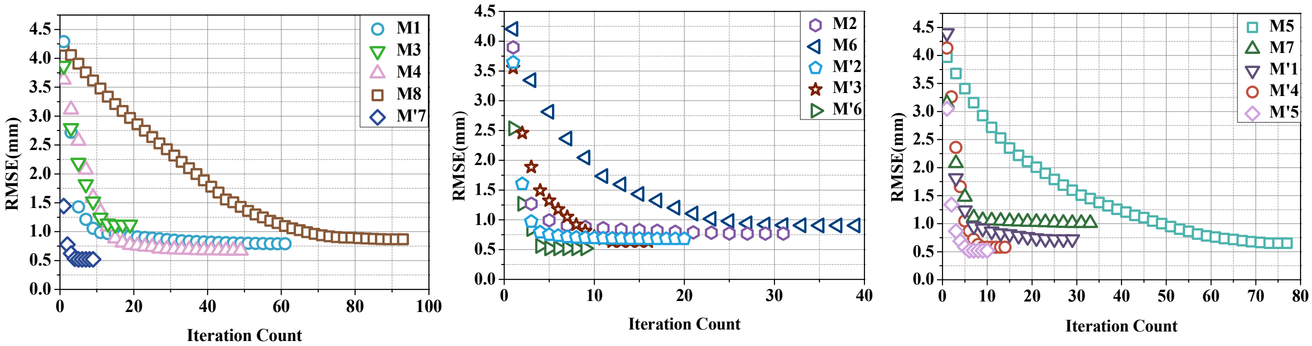


(c) Maximum Error



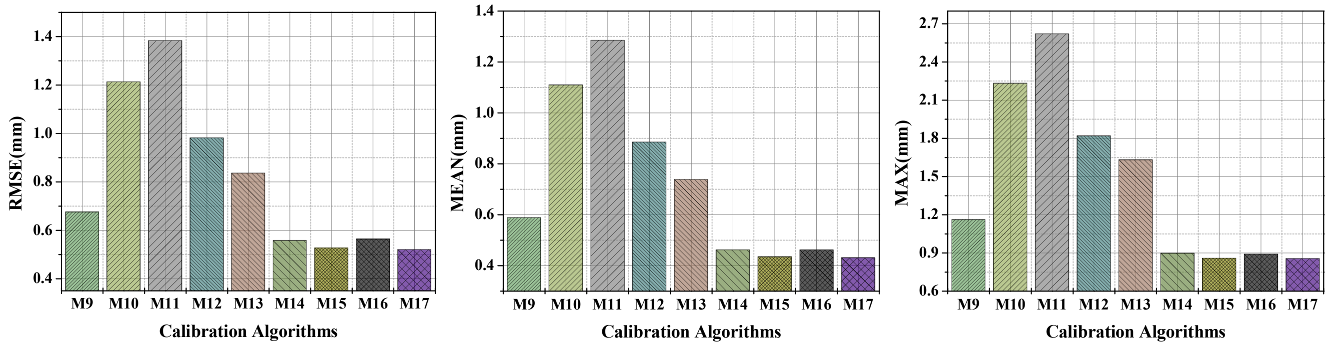
(d) Total time Cost

Fig. S.4. Calibration accuracy and total time cost of the HOEs-test-based models and its involved expert algorithms on D1.



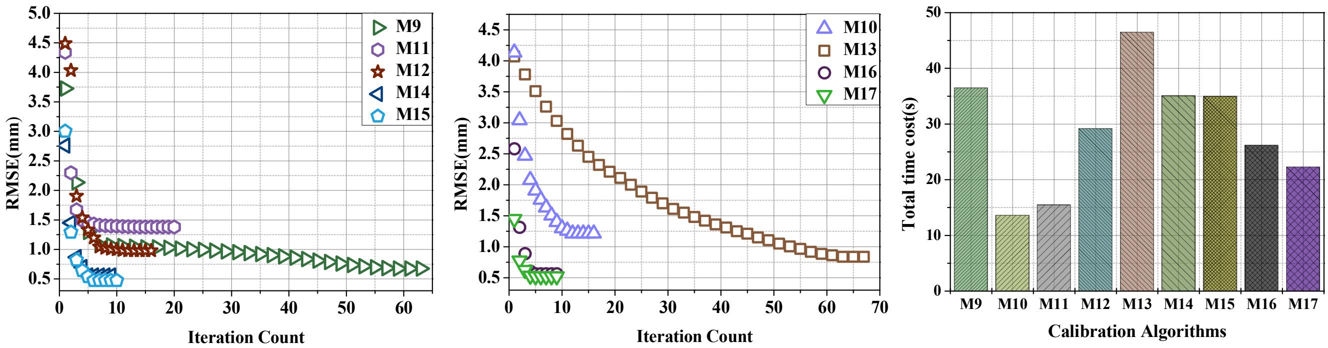
(a) M1, M3, M4, M8, M′7 (b) M2, M6, M′2, M′3, M′6 (c) M5, M7, M′1, M′4, M′5

Fig. S.5. Training curves of the HOEs-test-based models and its involved expert algorithms (M1-8, M′1-7) ON D1.



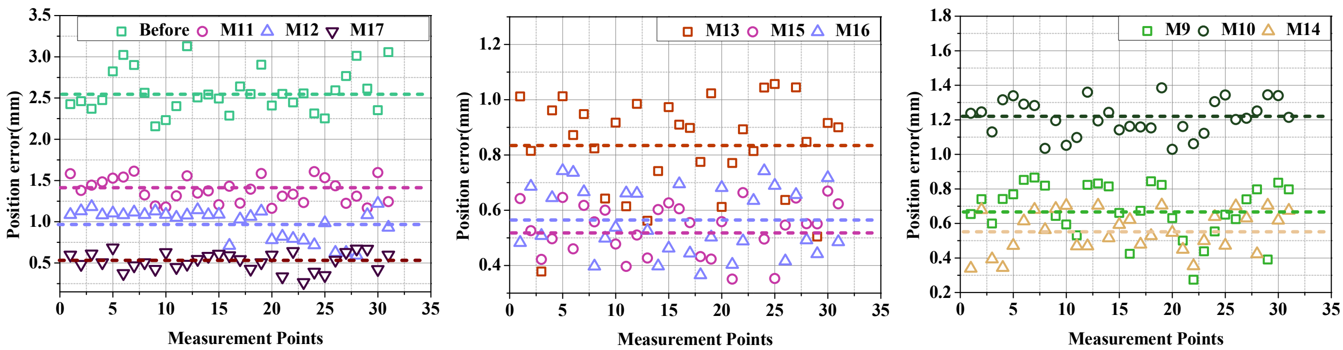
(a) RMSE (b) Mean Error (c) Maximum Error

Fig. S.6. Calibration accuracy of several state-of-the-art algorithms (M9-13) and the proposed HOEs model and its variant models (M14-17) on D1.



(a) M10, M13, M16, M17 (b) M9, M11, M12, M14 (c) Total time Cost of M9-17

Fig. S.7. Training curves and total time costs of several state-of-the-art algorithms (M9-13) and the proposed HOEs model and its variant models (M14-17) on D1.



(c) Before calibration, M11, M12, M17 (b) M13, M15, M16 (c) M9, M10, M14

Fig. S.8. The robot positioning errors after calibration through several state-of-the-art algorithms (M9-13) and the proposed HOEs model and its variant models (M14-17) on D1. It shows that the proposed model achieves the lowest calibration error.