



Supplementary materials for

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Table S1 Description of CEC2022 benchmark functions

Type	No.	Name	Range	f_{\min}
Unimodal	F_1	Shifted and full Rotated Zakharoy Function	$[-100, 100]$	300
Basic multimodal	F_2	Shifted and full Rotated Rosenbrock's Function	$[-100, 100]$	400
	F_3	Shifted and full Rotated Expanded Schaffer's f_6 Function	$[-100, 100]$	600
	F_4	Shifted and full Rotated Non-Continuous Rastrigin's Function	$[-100, 100]$	800
	F_5	Shifted and full Rotated Levy Function	$[-100, 100]$	900
Hybrid	F_6	Hybrid Function 1 ($N = 3$)	$[-100, 100]$	1800
	F_7	Hybrid Function 2 ($N = 6$)	$[-100, 100]$	2000
	F_8	Hybrid Function 3 ($N = 5$)	$[-100, 100]$	2200
Composition	F_9	Composition Function 1 ($N = 5$)	$[-100, 100]$	2300
	F_{10}	Composition Function 2 ($N = 4$)	$[-100, 100]$	2400
	F_{11}	Composition Function 3 ($N = 5$)	$[-100, 100]$	2600
	F_{12}	Composition Function 4 ($N = 6$)	$[-100, 100]$	2700

Table S2 Parameter settings of six algorithms

Algorithm	Parameter
EHO	$I_1 \in [1, 2]$ and $I_2 \in [1, 2]$ are random integers, $b \in [2, 4]$, $c \in [1, 1.5]$, $d \in [2, 3]$, and $l \in [-2\pi, 2\pi]$ are random numbers
HO	$I_1 \in [1, 2]$ and $I_2 \in [1, 2]$ are random integers, $b \in [2, 4]$, $c \in [1, 1.5]$, $d \in [2, 3]$, and $l \in [-2\pi, 2\pi]$ are random numbers
GOOSE	$S_S = 343.2$
GJO	$\beta = 1.5$, $\alpha = 1.5$
PSO	$v_{max} = 10$, $v_{min} = -10$, $\omega = 0.9$, $c_1 = 2$, $c_2 = 2$
GA	$p_c = 0.8$, $p_m = 0.05$

Table S3 Optimization results of EHO and five comparison algorithms on CEC2022 benchmark functions

No.	Item	EHO	HO	GOOSE	GJO	PSO	GA
F1	Best	3.00E+02	3.00E+02	8.22E+03	9.12E+03	2.82E+04	5.63E+04
	Worst	3.00E+02	3.02E+02	5.38E+04	4.08E+04	6.37E+04	1.30E+05
	Mean	3.00E+02	3.01E+02	2.60E+04	1.76E+04	3.94E+04	8.87E+04
	Std	0.00E+00	4.05E-01	1.11E+04	6.03E+03	8.95E+03	2.01E+04
	Times/s	9.97E-01	8.86E-01	5.44E-02	7.45E-02	2.76E-02	3.94E-02
F2	Best	4.61E+02	4.70E+02	4.75E+02	5.07E+02	9.57E+02	6.91E+02
	Worst	6.08E+02	6.37E+02	6.65E+02	8.40E+02	2.89E+03	1.83E+03
	Mean	5.21E+02	5.47E+02	5.27E+02	6.28E+02	1.79E+03	1.15E+03
	Std	4.39E+01	5.17E+01	3.92E+01	8.79E+01	5.07E+02	3.44E+02
	Times/s	1.03E+00	9.11E-01	4.14E-02	9.36E-02	2.79E-02	4.09E-02
F3	Best	6.35E+02	6.30E+02	6.48E+02	6.09E+02	6.55E+02	6.80E+02
	Worst	6.72E+02	6.72E+02	6.93E+02	6.68E+02	7.02E+02	7.41E+02
	Mean	6.57E+02	6.50E+02	6.75E+02	6.30E+02	6.87E+02	7.04E+02
	Std	9.98E+00	1.26E+01	1.03E+01	1.11E+01	1.16E+01	1.53E+01
	Times/s	1.15E+00	1.02E+00	7.48E-02	1.70E-01	6.23E-02	7.73E-02
F4	Best	8.73E+02	8.57E+02	8.89E+02	8.55E+02	9.30E+02	9.58E+02
	Worst	9.01E+02	9.04E+02	1.04E+03	9.47E+02	9.90E+02	1.08E+03
	Mean	8.88E+02	8.82E+02	9.43E+02	9.01E+02	9.62E+02	1.01E+03
	Std	7.07E+00	1.18E+01	4.37E+01	2.40E+01	1.41E+01	3.35E+01
	Times/s	1.15E+00	9.27E-01	5.37E-02	1.12E-01	3.92E-02	5.20E-02
F5	Best	1.74E+03	1.66E+03	2.30E+03	1.33E+03	3.01E+03	2.36E+03
	Worst	2.73E+03	2.76E+03	6.20E+03	2.80E+03	5.11E+03	6.68E+03
	Mean	2.39E+03	2.32E+03	3.64E+03	2.09E+03	3.87E+03	4.52E+03
	Std	2.52E+02	2.74E+02	1.23E+03	4.20E+02	5.07E+02	1.11E+03
	Times/s	1.20E+00	1.15E+00	5.62E-02	7.57E-02	4.03E-02	5.63E-02
F6	Best	2.67E+03	2.49E+03	2.15E+03	1.37E+05	2.19E+07	2.98E+05
	Worst	1.70E+04	2.70E+04	1.93E+04	1.92E+08	2.20E+09	1.75E+08
	Mean	4.41E+03	8.87E+03	6.62E+03	3.39E+07	7.12E+08	3.09E+07
	Std	2.62E+03	6.83E+03	4.83E+03	3.64E+07	6.29E+08	4.11E+07
	Times/s	1.04E+00	9.00E-01	4.35E-02	7.36E-02	2.96E-02	4.38E-02
F7	Best	2.07E+03	2.07E+03	2.07E+03	2.07E+03	2.13E+03	2.13E+03
	Worst	2.19E+03	2.20E+03	2.59E+03	2.30E+03	2.54E+03	2.47E+03
	Mean	2.14E+03	2.15E+03	2.34E+03	2.15E+03	2.26E+03	2.30E+03
	Std	2.60E+01	3.26E+01	1.39E+02	4.84E+01	8.94E+01	8.73E+01
	Times/s	1.33E+00	1.06E+00	9.19E-02	1.10E-01	7.31E-02	9.56E-02
F8	Best	2.23E+03	2.23E+03	2.23E+03	2.23E+03	2.26E+03	2.26E+03
	Worst	2.26E+03	2.35E+03	2.90E+03	2.37E+03	4.82E+03	3.76E+03
	Mean	2.24E+03	2.25E+03	2.62E+03	2.27E+03	2.65E+03	2.57E+03
	Std	6.00E+00	2.26E+01	1.84E+02	5.04E+01	4.65E+02	3.21E+02
	Times/s	1.35E+00	1.29E+00	1.02E-01	1.36E-01	8.50E-02	1.01E-01
F9	Best	2.48E+03	2.51E+03	2.49E+03	2.50E+03	2.72E+03	2.67E+03
	Worst	2.59E+03	2.67E+03	2.95E+03	2.68E+03	3.78E+03	3.40E+03
	Mean	2.54E+03	2.56E+03	2.60E+03	2.58E+03	3.10E+03	2.96E+03
	Std	2.71E+01	3.59E+01	8.80E+01	4.32E+01	2.68E+02	1.86E+02
	Times/s	1.25E+00	1.06E+00	1.04E-01	1.39E-01	7.80E-02	9.70E-02
F10	Best	2.50E+03	2.50E+03	2.50E+03	2.51E+03	2.61E+03	2.57E+03
	Worst	5.49E+03	5.51E+03	6.36E+03	7.43E+03	7.53E+03	7.81E+03
	Mean	3.94E+03	4.34E+03	5.01E+03	4.45E+03	6.56E+03	6.05E+03
	Std	1.16E+03	9.34E+02	9.91E+02	1.81E+03	1.13E+03	1.28E+03
	Times/s	1.21E+00	1.02E+00	7.79E-02	1.09E-01	6.30E-02	8.08E-02
F11	Best	2.62E+03	2.92E+03	3.26E+03	3.47E+03	5.26E+03	4.86E+03
	Worst	3.83E+03	7.21E+03	1.31E+04	6.28E+03	8.88E+03	1.02E+04
	Mean	3.22E+03	3.30E+03	4.95E+03	4.62E+03	7.87E+03	7.00E+03
	Std	2.45E+02	7.68E+02	2.16E+03	6.65E+02	8.40E+02	1.57E+03
	Times/s	1.33E+00	1.54E+00	1.15E-01	1.94E-01	9.81E-02	1.22E-01
F12	Best	2.96E+03	2.97E+03	3.20E+03	2.96E+03	2.90E+03	3.33E+03
	Worst	3.19E+03	3.55E+03	4.46E+03	3.23E+03	2.90E+03	4.42E+03
	Mean	3.06E+03	3.11E+03	3.67E+03	3.04E+03	2.90E+03	3.78E+03
	Std	5.88E+01	1.23E+02	2.72E+02	6.17E+01	8.01E-05	2.82E+02
	Times/s	1.49E+00	1.25E+00	1.49E-01	1.83E-01	1.07E-01	1.34E-01
Average Rank		2.3542	2.7708	3.5000	3.1667	4.4583	4.7500
Total Rank		1	2	4	3	5	6

Best result is in bold.

Table S4 Comparison results of the original HO and its improved variants

No.	Item	HO	LHO	AHO	LAHO	THO	EHO
F1	Best	3.00E+02	3.00E+02	3.00E+02	3.00E+02	3.00E+02	3.00E+02
	Worst	3.02E+02	3.00E+02	3.00E+02	3.00E+02	3.00E+02	3.00E+02
	Mean	3.01E+02	3.00E+02	3.00E+02	3.00E+02	3.00E+02	3.00E+02
	Std	4.05E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
F2	Best	4.70E+02	4.67E+02	4.66E+02	4.64E+02	4.69E+02	4.61E+02
	Worst	6.37E+02	6.11E+02	6.20E+02	6.70E+02	6.35E+02	6.08E+02
	Mean	5.47E+02	5.29E+02	5.23E+02	5.35E+02	5.36E+02	5.21E+02
	Std	5.17E+01	4.45E+01	4.62E+01	4.86E+01	5.12E+01	4.39E+01
F8	Best	2.23E+03	2.23E+03	2.23E+03	2.23E+03	2.23E+03	2.23E+03
	Worst	2.35E+03	2.34E+03	2.26E+03	2.34E+03	2.26E+03	2.26E+03
	Mean	2.25E+03	2.25E+03	2.24E+03	2.25E+03	2.24E+03	2.24E+03
	Std	2.26E+01	2.06E+01	7.56E+00	2.18E+01	7.48E+00	6.00E+00
F9	Best	2.51E+03	2.49E+03	2.50E+03	2.50E+03	2.48E+03	2.48E+03
	Worst	2.67E+03	2.65E+03	2.59E+03	2.66E+03	2.60E+03	2.59E+03
	Mean	2.56E+03	2.55E+03	2.54E+03	2.56E+03	2.54E+03	2.54E+03
	Std	3.59E+01	4.36E+01	2.63E+01	3.83E+01	2.99E+01	2.71E+01
F11	Best	2.92E+03	2.86E+03	2.63E+03	2.62E+03	2.71E+03	2.62E+03
	Worst	7.21E+03	6.11E+03	3.91E+03	5.31E+03	3.91E+03	3.83E+03
	Mean	3.30E+03	3.23E+03	3.23E+03	3.37E+03	3.27E+03	3.22E+03
	Std	7.68E+02	5.97E+02	3.05E+02	5.55E+02	2.88E+02	2.45E+02
F12	Best	2.97E+03	2.97E+03	2.97E+03	2.97E+03	2.96E+03	2.96E+03
	Worst	3.55E+03	3.40E+03	3.54E+03	3.34E+03	3.33E+03	3.19E+03
	Mean	3.11E+03	3.09E+03	3.17E+03	3.10E+03	3.09E+03	3.06E+03
	Std	1.23E+02	1.02E+02	1.67E+02	9.35E+01	9.06E+01	5.88E+01

Best result is in bold.

Table S5 PID controller parameter optimization results by EHO using different fitness functions

Fitness function	K_p	K_i	K_d	Overshoot	Peak time	Settling time	Steady state error	Average
ITAE	9.9409	0.7613	0.0008	7.2%	0.049s	0.265s	2.07E-08	1.82E-03
ITSE	9.7393	0.7295	0.0124	7.3%	0.049s	0.265s	4.40E-07	1.83E-03
IAE	9.9997	0.6768	0.0476	3.1%	0.06s	0.273s	2.00E-07	2.16E-02
ISE	10.0000	0.6609	0.0658	2.1%	0.064s	0.276s	1.90E-05	2.16E-02

Best result is in bold.

Table S6 Parameters of the quadrotor UAV

Symbol	Description	Value	Unit
l	Body radius	0.225	m
m	Mass	1.400	kg
J_x	x -axis moment of inertia	$2.110 \cdot 10^{-2}$	$\text{kg} \cdot \text{m}^2$
J_y	y -axis moment of inertia	$2.190 \cdot 10^{-2}$	$\text{kg} \cdot \text{m}^2$
J_z	z -axis moment of inertia	$3.660 \cdot 10^{-2}$	$\text{kg} \cdot \text{m}^2$
c_T	Tension coefficient	$1.105 \cdot 10^{-5}$	$(\text{N} \cdot \text{s}^2)/\text{rad}^2$
c_M	Moment coefficient	$1.779 \cdot 10^{-7}$	$(\text{N} \cdot \text{m} \cdot \text{s}^2)/\text{rad}^2$
g	gravity acceleration	9.800	$(\text{N} \cdot \text{s}^2)/\text{rad}^2$

Table S7 PID controller parameters for outer loop

Method	Variable	x -inner loop	y -inner loop	z -inner loop	φ -inner loop	θ -inner loop
EHO	K_p	9.9996	10.0000	5.3757	10.0000	9.9824
	K_i	10.0000	10.0000	10.0000	10.0000	9.9988
	K_d	0.0000	0.0007	0.0000	0.0000	0.0000
HO	K_p	10.0000	10.0000	4.3658	10.0000	10.0000
	K_i	10.0000	10.0000	2.3995	10.0000	10.0000
	K_d	0.0000	5.4733	0.0000	0.0000	0.0000
MPA	K_p	2.5843	2.5755	0.6374	8.0495	8.0495
	K_i	0.5334	0.7101	2.6135	10.0000	10.0000
	K_d	2.2307	2.2582	0.0067	0.2009	0.2009

Table S8 PID controller parameters for inner loop

Method	Variable	x -inner loop	y -inner loop	z -inner loop	φ -inner loop	θ -inner loop
EHO	K_p	2.4172	1.5547	9.9980	9.3642	0.1144
	K_i	8.1097	9.8592	9.9934	5.3300	2.2327
	K_d	2.6673	5.5995	5.2024	9.7993	9.9725
HO	K_p	2.3672	1.6914	5.1748	9.6335	7.5508
	K_i	8.9485	4.1481	2.3995	5.2556	10.0000
	K_d	3.0132	1.7645	0.0000	10.0000	0.0000
MPA	K_p	2.3650	2.3858	6.6651	0.5083	0.4898
	K_i	0.6138	0.6221	6.6651	5.9080	5.6924
	K_d	1.8030	1.8169	0.0124	0.0076	0.0074

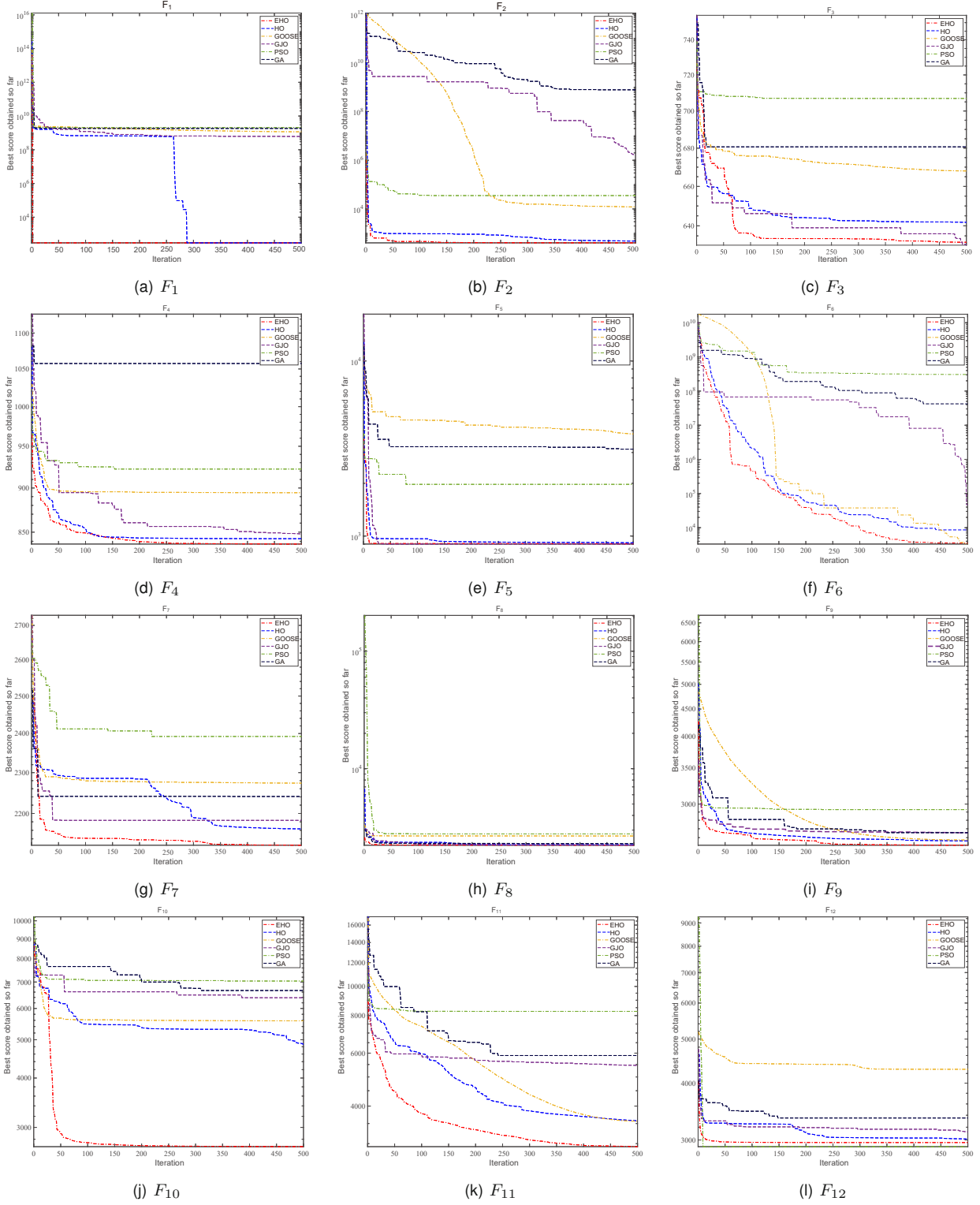


Fig. S1 Convergence curves of EHO and five compared algorithms on CEC2022 benchmark functions

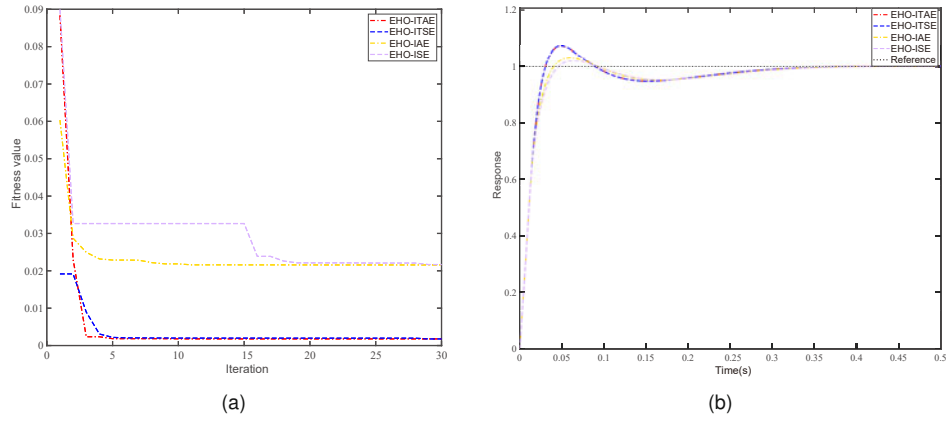


Fig. S2 Convergence curves of EHO and step responses of the system using different fitness functions

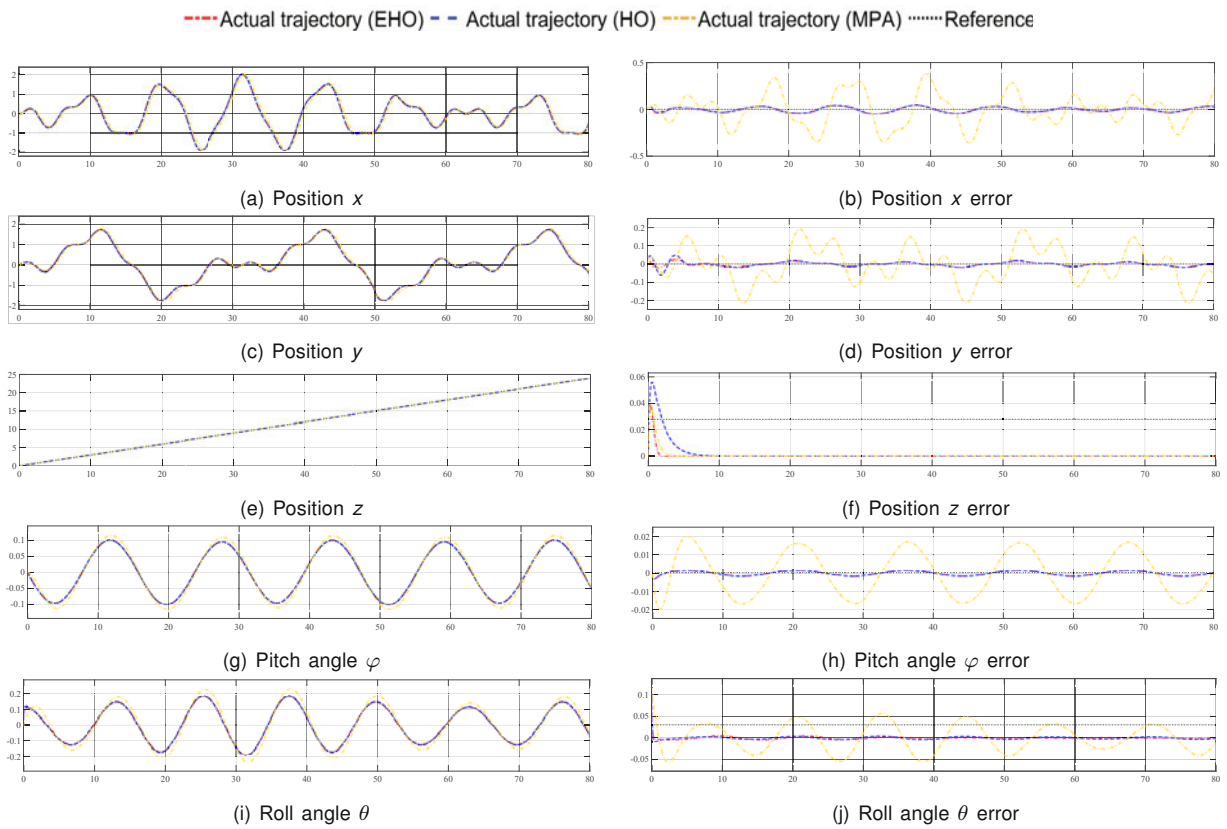


Fig. S3 Tracking effect of each channel

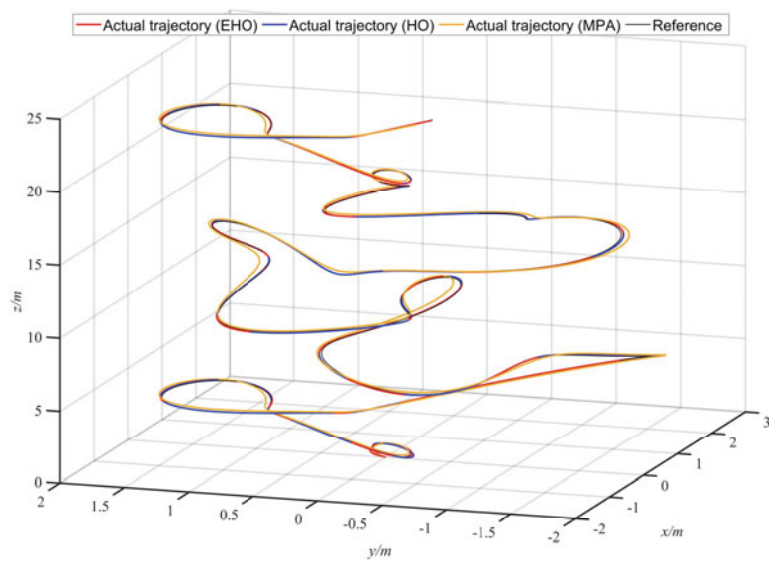


Fig. S4 3D simulation results for the complex helical trajectory