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Enhanced hippopotamus optimization algorithm for tuning proportional–integral–derivative controllers

Key words: PID controllers; Parameter tuning; Hippopotamus optimization; Latin hypercube sampling; Adaptive lens reverse learning; Adaptive perturbation mechanism

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Motivation

1. Given the practical requirements of control engineering, the optimization and adjustment of proportional–integral–derivative (PID) controller parameters remain a long-standing core challenge, as it is difficult to achieve high efficiency and precision simultaneously.
2. Existing swarm intelligence optimization algorithms and other intelligent algorithms may have shortcomings in terms of global search capabilities, convergence speed, accuracy, and stability when solving such complex problems.
3. Considering the higher requirements for controller performance in complex practical applications, the ultimate goal of the research is to solve practical engineering problems.

Main idea

1. With enhanced hippopotamus optimization (EHO), population diversity is improved through Latin hypercube sampling (LHS) and adaptive lens reverse learning (ALRL), while an adaptive perturbation mechanism enhances global search in the exploration phase.
2. Compared with the original hippopotamus optimization (HO) and other intelligent algorithms, EHO demonstrates superior accuracy, convergence speed, and stability on the CEC2022 test suite and various PID tuning tasks.
3. To validate applicability, EHO is applied to cascade PID tuning for quadrotor unmanned aerial vehicle (UAV) trajectory tracking, achieving significantly lower time absolute error integrals than baseline methods.

Method

A novel initialization strategy for HO is designed, which combines LHS with ALRL. This strategy notably enhances the diversity of the initial population, and improves the global optimization performance of the algorithm. An adaptive perturbation mechanism is integrated into the position update formula during the exploration phase of HO. This mechanism dynamically adjusts perturbations to maintain population diversity and effectively avoid local optima, thereby improving the search accuracy of the algorithm.

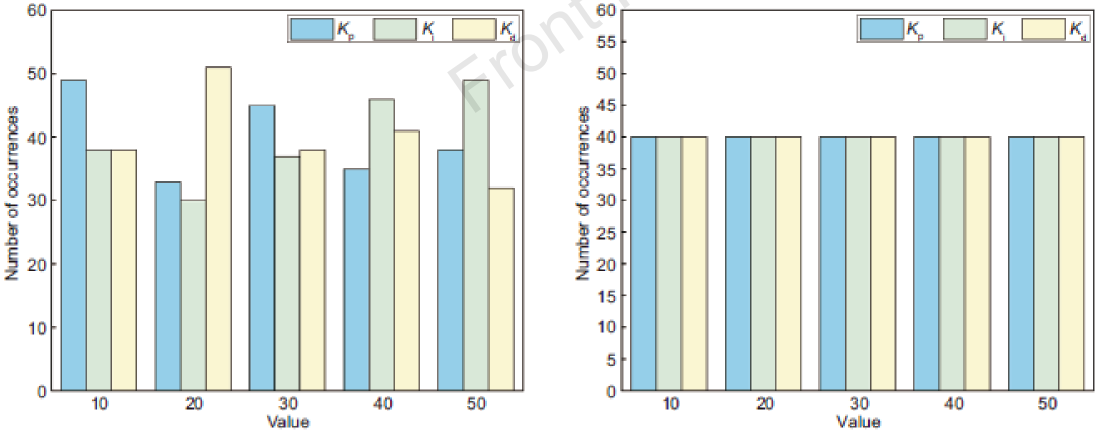


Fig. 3 Value distribution results of two initialization methods: (a) random initialization; (b) LHS initialization

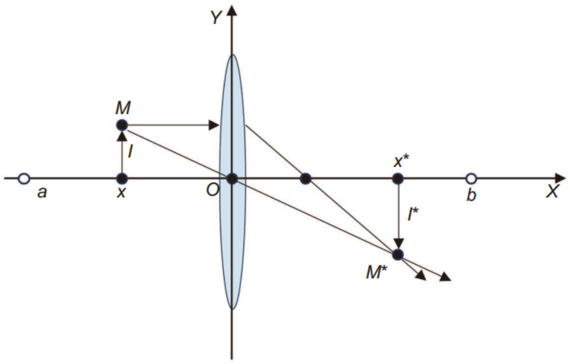
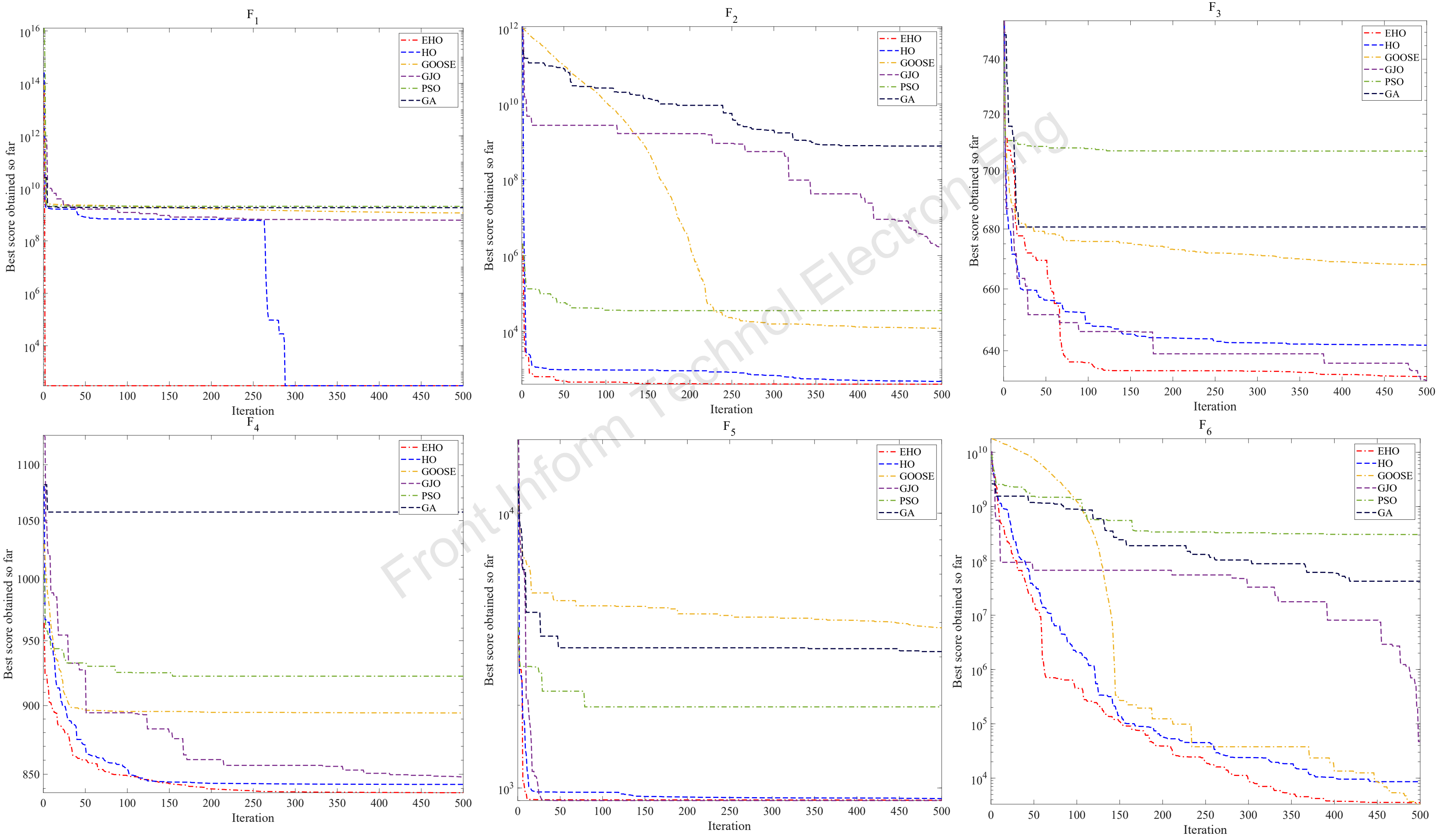


Fig. 4 Principle of adaptive lens reverse learning

Major results

CEC2022 benchmark functions



Major results (Cont'd)

CEC2022 benchmark functions

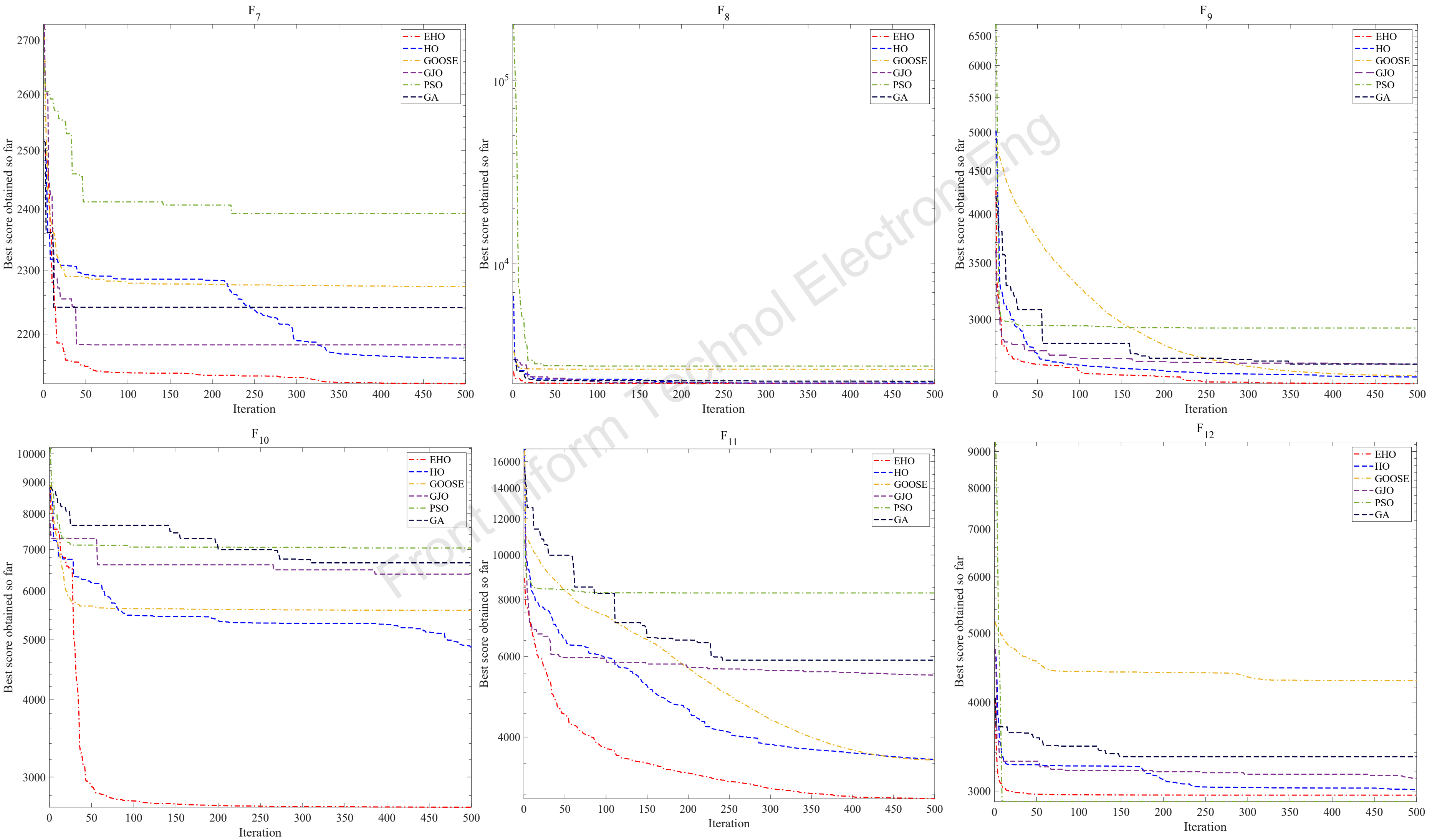
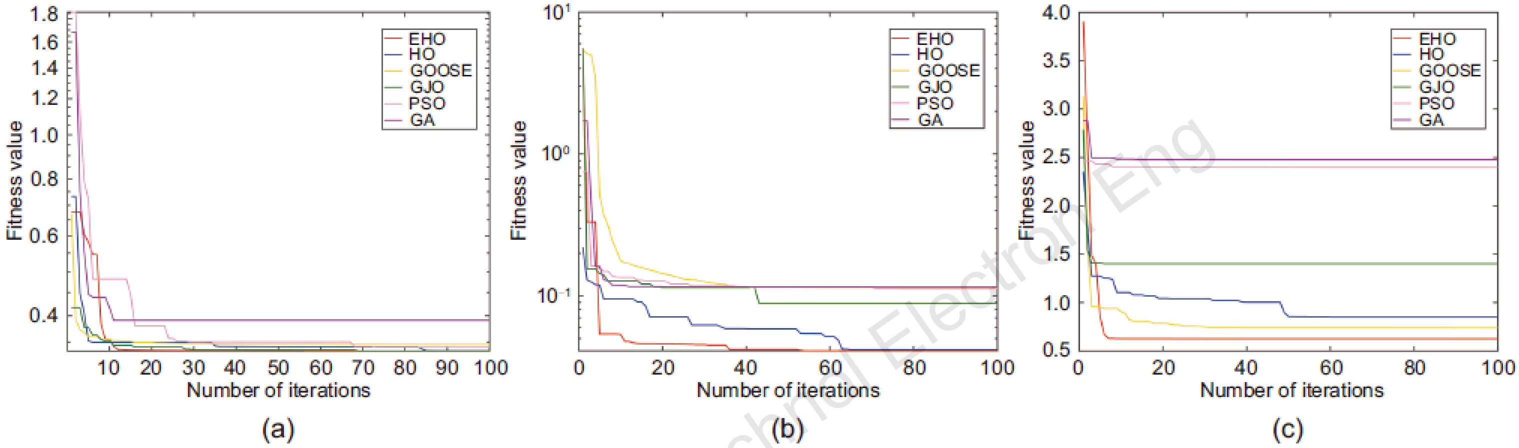


Fig. S1 Convergence curves of EHO and five comparison algorithms on the CEC2022 benchmark functions

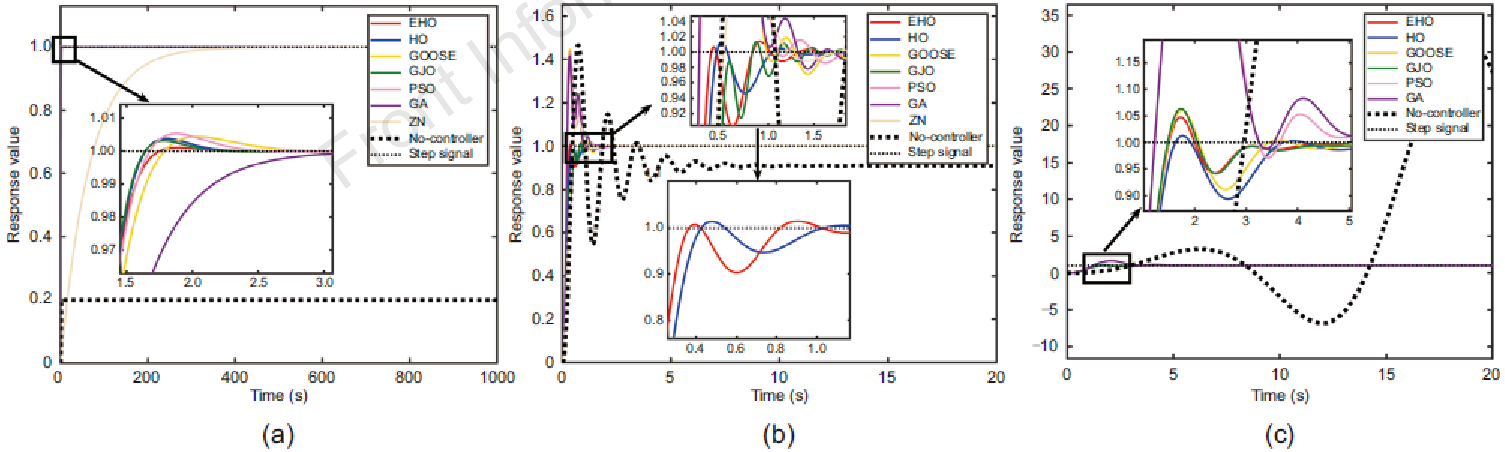
Major results (Cont'd)

Typical system simulation



(a) (b) (c)

Fig. 7 ITAE convergence curves of six algorithms for $G_1(s)$ (a), $G_2(s)$ (b), and $G_3(s)$ (c)

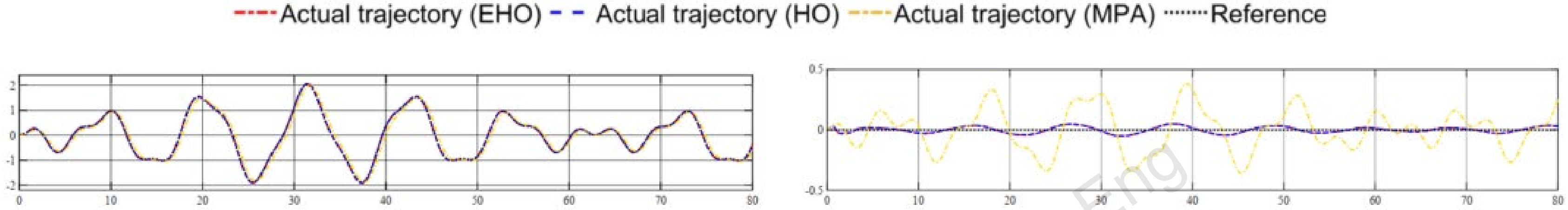


(a) (b) (c)

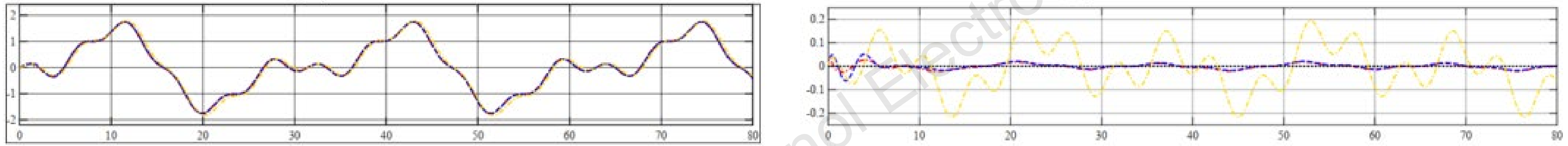
Fig. 8 Comparison of step responses using six algorithms and the ZN method for $G_1(s)$ (a), $G_2(s)$ (b), and $G_3(s)$ (c)

Major results (Cont'd)

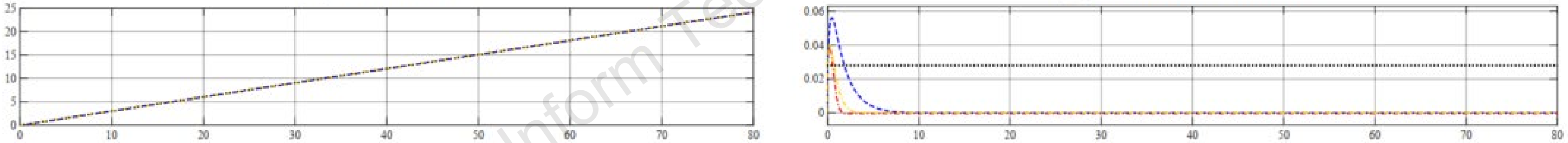
Trajectory tracking for quadrotor UAVs



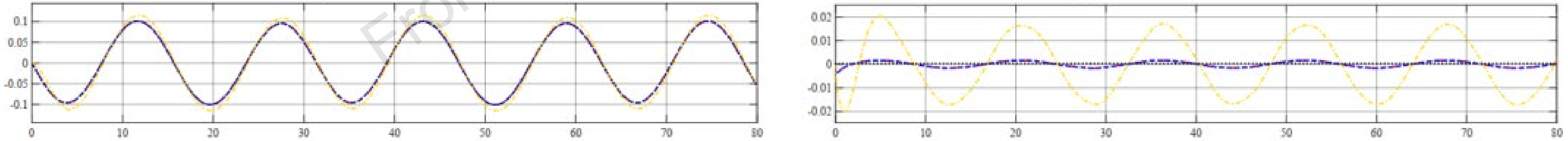
(a) Position x (b) Position x error



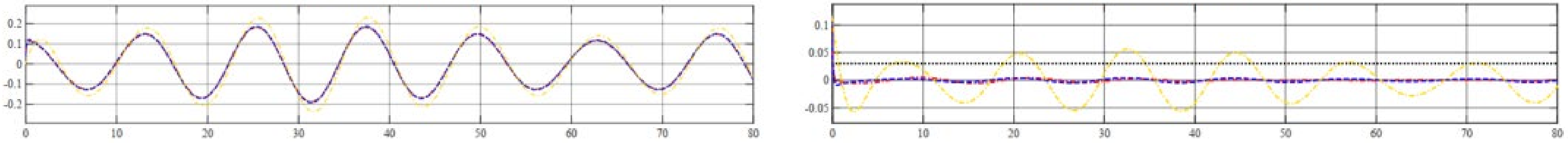
(c) Position y (d) Position y error



(e) Position z (f) Position z error



(g) Pitch angle φ (h) Pitch angle φ error



(i) Roll angle θ (j) Roll angle θ error

Fig. S3 Tracking effect of each channel

Major results (Cont'd)

Trajectory tracking for quadrotor UAVs

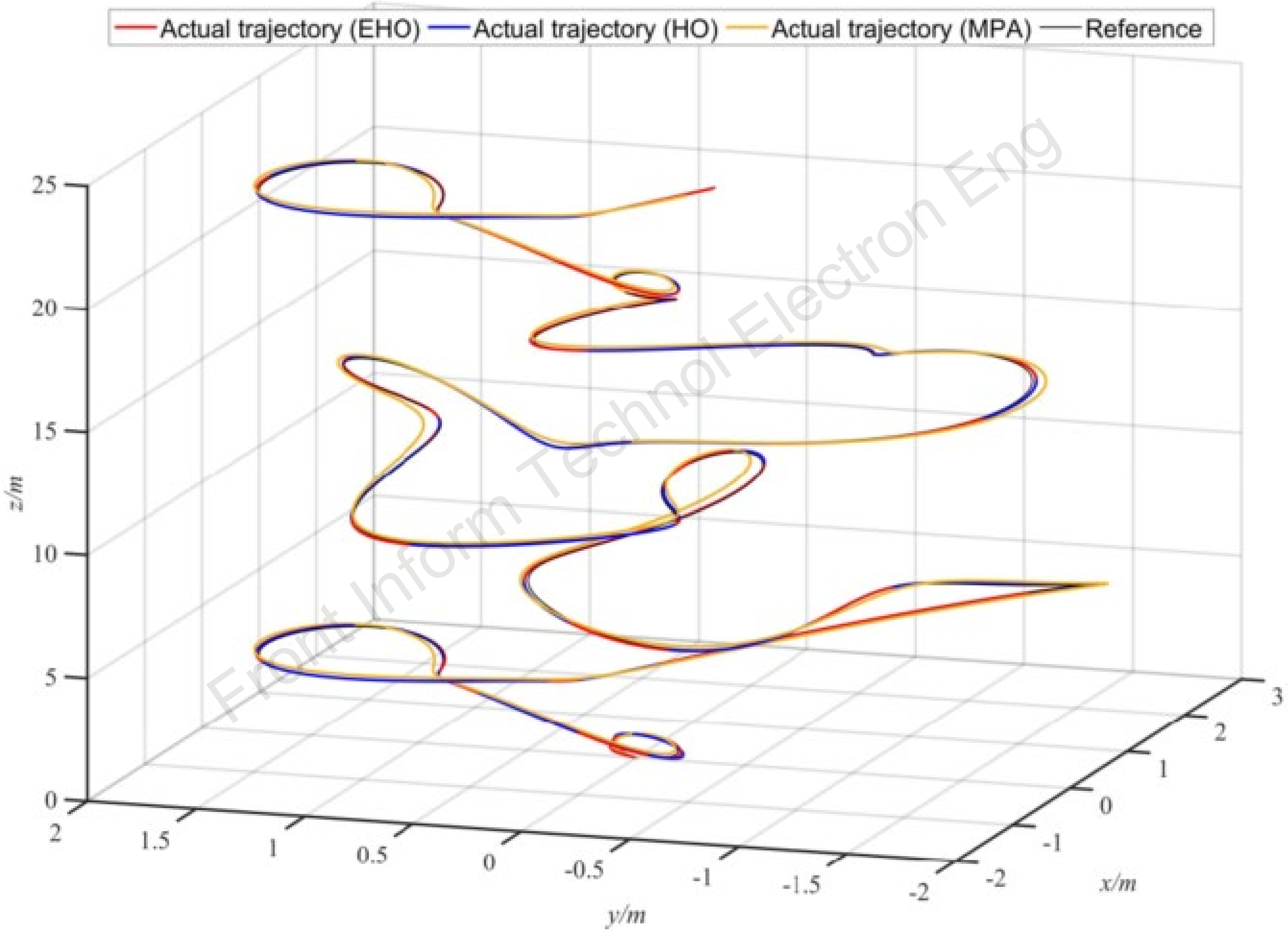


Fig. S4 3-D simulation results for the complex helical trajectory

Conclusions

1. Significant algorithmic improvement: The proposed EHO, incorporating LHS, ALRL, fitness value sorting, and an adaptive perturbation mechanism, effectively addresses the limitations of the original HO and achieves superior optimization accuracy, faster convergence, and stronger global search capability on the CEC2022 benchmark functions.

2. Validation on PID control: MATLAB/Simulink simulations on three typical systems demonstrate that EHO-tuned PID controllers consistently outperform competing algorithms in terms of control accuracy, stability, and dynamic response.

3. Practical application value: When applied to cascade PID controller optimization for a quadrotor UAV, EHO significantly enhances trajectory tracking performance, achieving the lowest integral of the time absolute error (ITAE) across all position channels and surpassing both HO and MPA, highlighting its strong engineering applicability.

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