Energy-Efficient Nonlinear Controller Tuning for Mobile Robots via Metaheuristic Optimization

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INTRODUCTION & AIM

Mobile robots are increasingly deployed in autonomous navigation tasks where both tracking performance and energy efficiency are critical requirements. Conventional controller tuning methods generally focus on minimizing tracking errors without considering energy consumption, which may reduce the operational autonomy of battery-powered platforms. This work proposes an energy-aware tuning framework for a nonlinear backstepping controller applied to a two-wheeled mobile robot. The controller gains are optimized using the Cuckoo Search Algorithm (CSA) under three different strategies: accuracy-oriented optimization, energy-aware optimization, and an adaptive switching approach. The objective is to investigate the trade-off between trajectory tracking precision and electrical energy consumption while maintaining stable robot motion.

METHOD

Input: Weight coefficients w_E, w_P (energy / error), bounds $[k_1^{\min}, k_1^{\max}]$, $[k_2^{\min}, k_2^{\max}]$, population size $N = 15$, max generations $G = 20$, discovery probability $p_a = 0.25$.

Output: Optimal gains (k_1^*, k_2^*).

Initialization: N nests (k_1, k_2) randomly sampled in $[0.1, 5.0]^2$.
Evaluate each nest via robot simulation (unicycle model, backstepping control):

$$J = w_E \frac{E}{E_{\text{ref}}} + w_P \frac{\text{RMSE}}{\text{RMSE}_{\text{ref}}}$$

$(k_1^{\text{best}}, k_2^{\text{best}}) \leftarrow$ nest with smallest J.
for $g = 1$ **to** G **do**
  for $i = 1$ **to** N **do**
    Generate a new nest using Lévy flight: $(k_1^i, k_2^i)_{\text{new}} = (k_1^i, k_2^i) + \alpha \cdot \text{Levy}(2) \cdot ((k_1^i, k_2^i) - (k_1^{\text{best}}, k_2^{\text{best}}))$
    Clip to bounds.
    Evaluate J_{new}^i.
  end for
  Selection: if $J_{\text{new}}^i < J_{\text{old}}^i$, replace old nest.
  Abandonment: each nest has probability p_a to be replaced by a random one.
  Update $(k_1^{\text{best}}, k_2^{\text{best}})$.
end for
return (k_1^*, k_2^*).

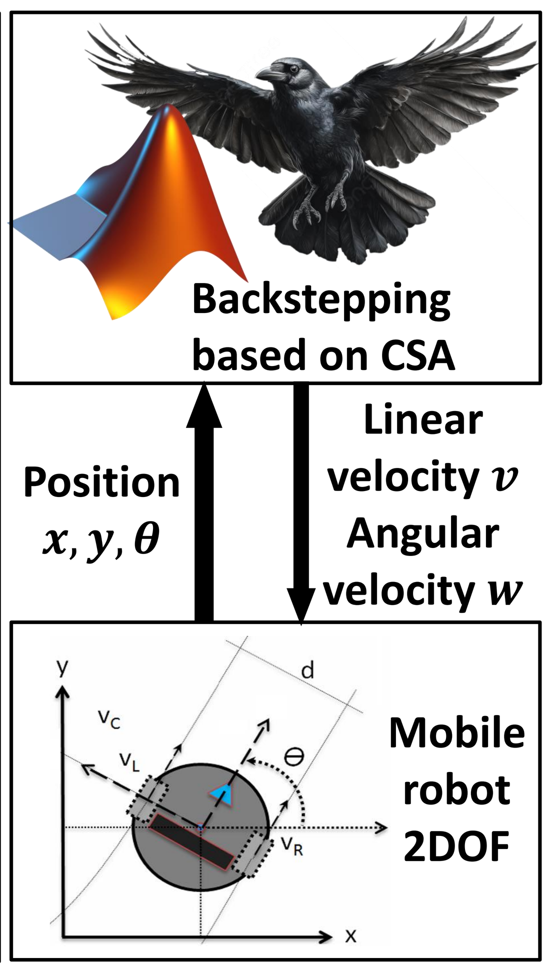

Figure 1: Flowchart of the Crow Search Algorithm applied to Backstepping controller of the 2DOF mobile robot

A nonlinear backstepping controller is designed to regulate the linear and angular velocities of the mobile robot. The controller gains are optimized using the Cuckoo Search Algorithm (CSA), a population-based metaheuristic inspired by the brood parasitism behavior of cuckoo birds. Three optimization strategies are evaluated:

1st Strategy: minimization of trajectory tracking error (RMSE) only.

2nd Strategy: multi-objective optimization combining tracking accuracy and energy consumption, with a dominant energy weight (85%).

3rd Strategy: adaptive switching between the two optimized gain sets according to the instantaneous tracking error. The performance is assessed on circular and lemniscate trajectories under realistic velocity constraints using tracking accuracy, energy consumption, and power demand as evaluation criteria.

RESULTS & DISCUSSION

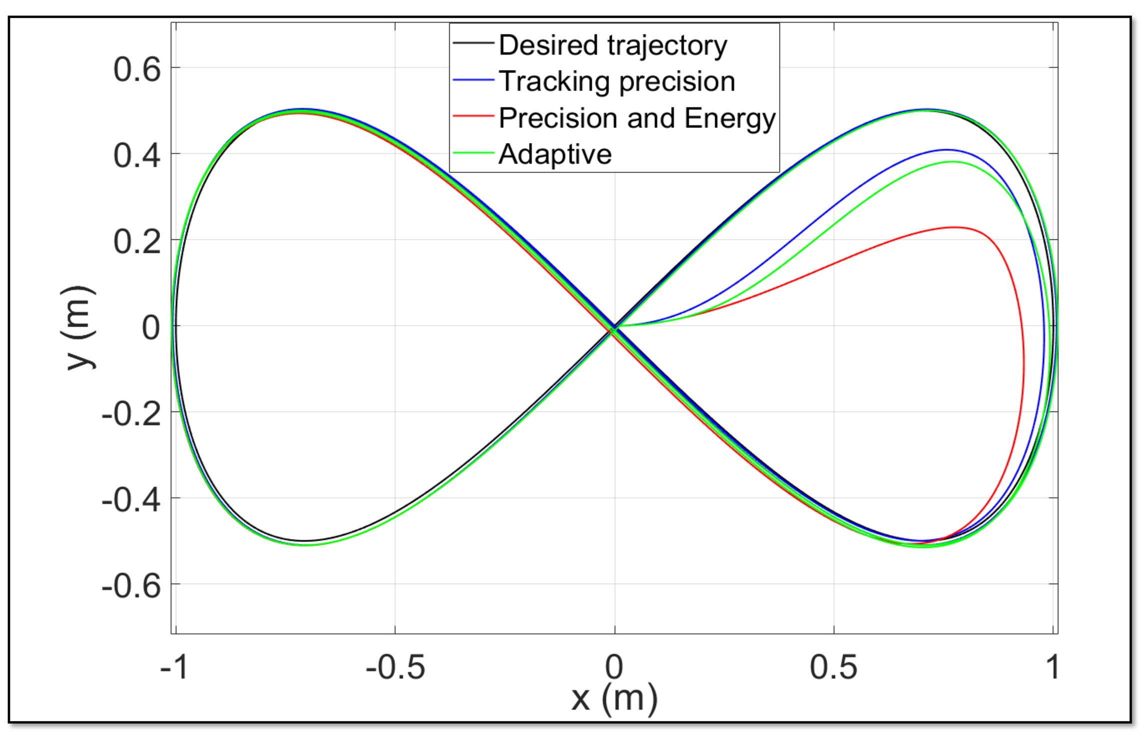

Figure 2: Lemniscate trajectory tracking in 2D presentation

Figure 2 compares the lemniscate trajectory tracking performance obtained with the three CSA-optimized controller configurations. The tracking-precision strategy follows the reference path most accurately, maintaining a close overlap with the desired trajectory throughout the maneuver. The precision-and-energy strategy exhibits the largest deviation, particularly along the right loop of the lemniscate, where the trajectory becomes noticeably contracted due to the reduction of control effort imposed by the energy-oriented optimization criterion. The adaptive strategy achieves an intermediate behavior, remaining significantly closer to the reference path than the energy-oriented solution while still benefiting from reduced control activity. These results clearly illustrate the trade-off between trajectory accuracy and energy efficiency. While prioritizing energy consumption leads to a degradation in tracking performance, the adaptive approach successfully balances both objectives, preserving acceptable path-following accuracy while reducing the energetic demand of the robot.

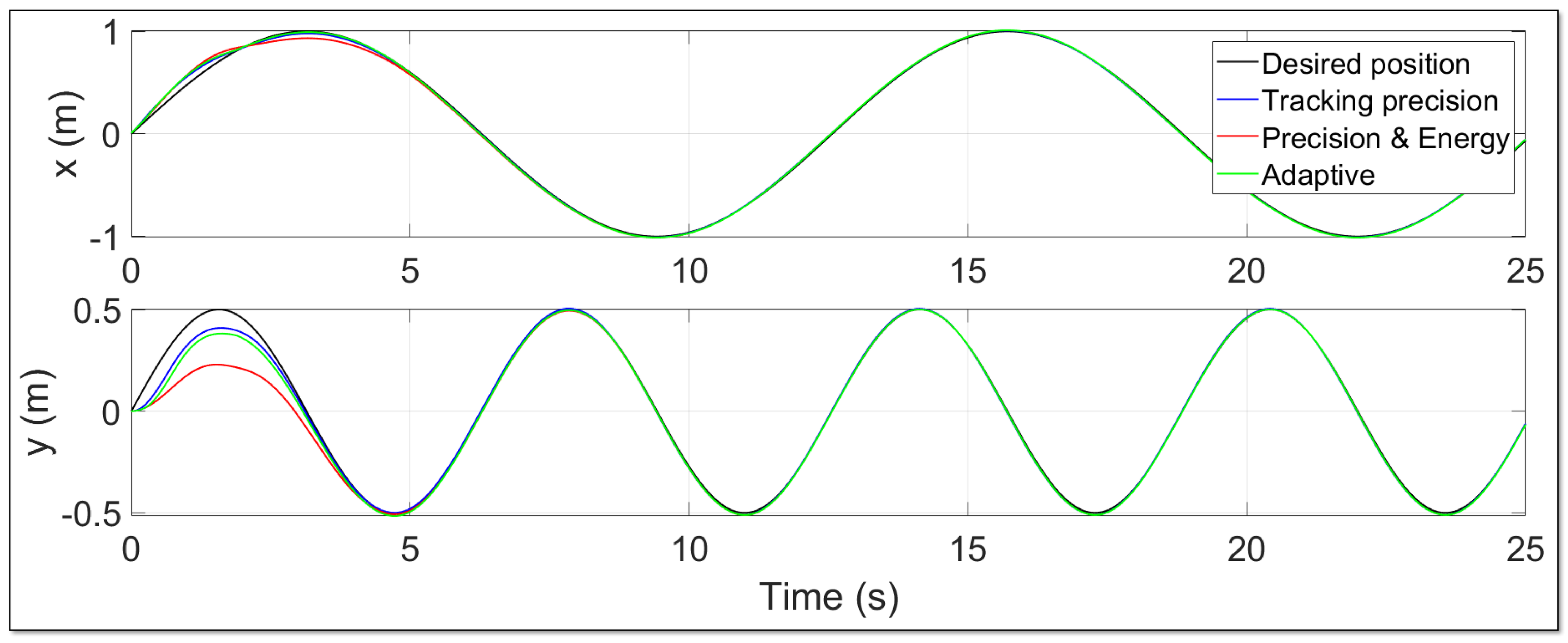

Figure 3: X & Y positions tracking

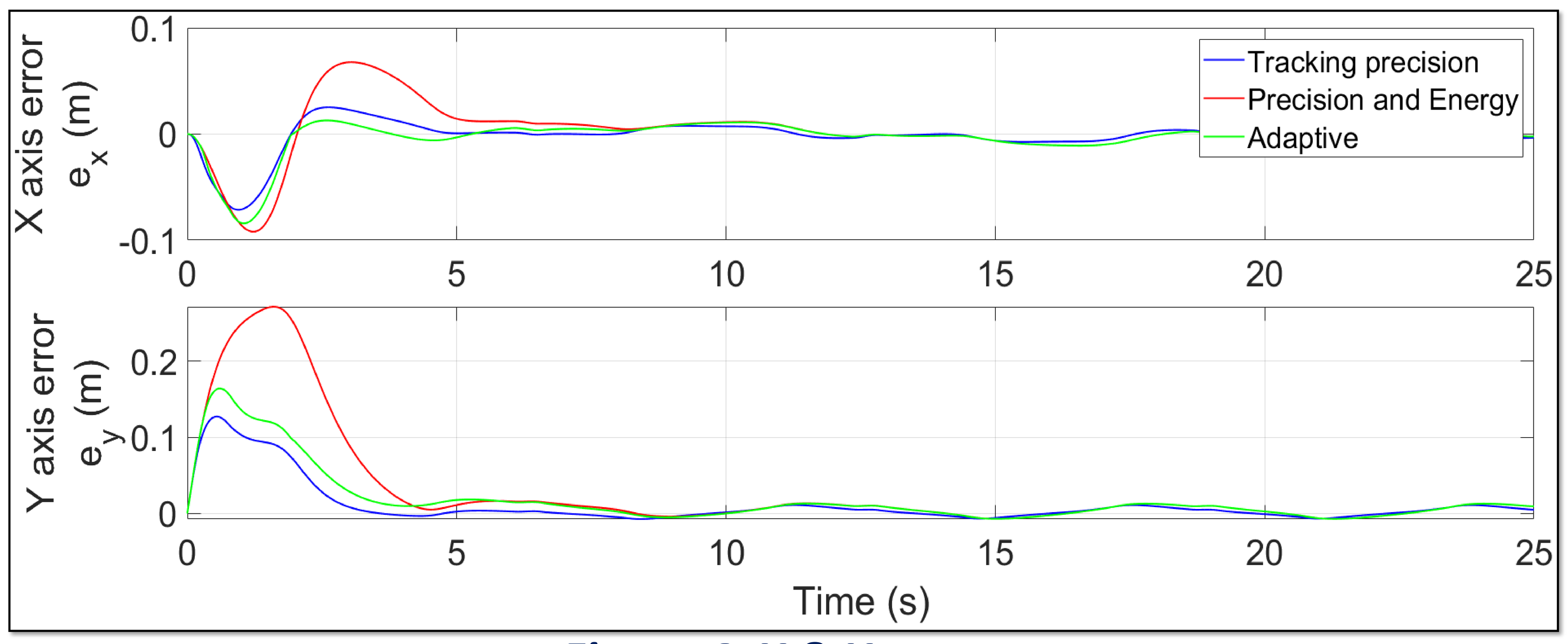

Figure 4: X & Y errors

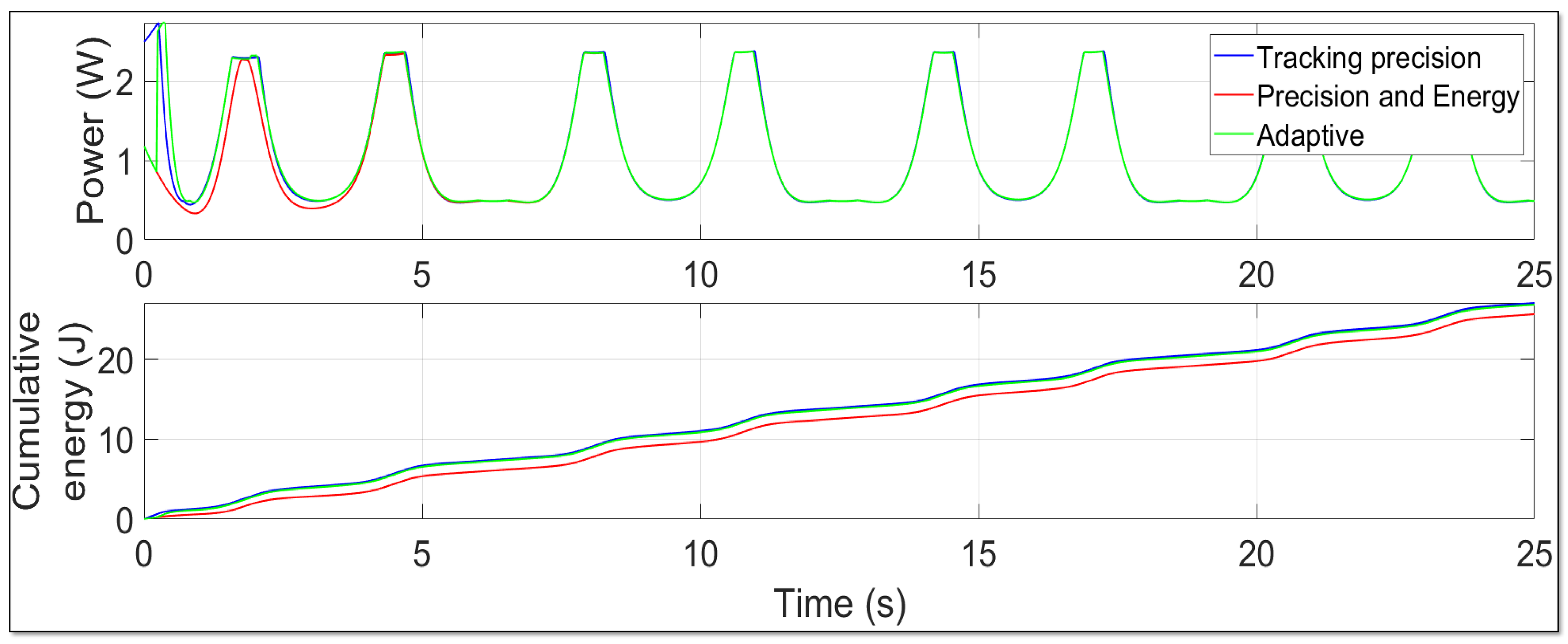

Figure 5: Energy consumption

Figures 3–5 provide a quantitative comparison of the three optimization strategies in terms of tracking accuracy and energy consumption. The position responses in Figure 3 show that all controllers successfully follow the reference trajectory, although the precision-and-energy configuration exhibits larger transient deviations, particularly during the initial stages of motion. This behavior is confirmed by the tracking errors shown in Figure 4, where the energy-oriented strategy produces the highest peak errors in both the x and y directions. In contrast, the tracking-precision strategy achieves the smallest errors, while the adaptive approach maintains intermediate error levels. Regarding energy performance, Figure 5 indicates that the energy-oriented controller consistently requires less cumulative energy and lower power demand than the accuracy-oriented solution. The adaptive strategy preserves part of these energy savings while significantly reducing the tracking degradation. Overall, the results demonstrate that energy-aware optimization effectively decreases control effort, whereas the adaptive switching mechanism offers a practical compromise between trajectory accuracy and energy efficiency.

CONCLUSIONS

This work presented a CSA-based optimization framework for tuning a nonlinear backstepping controller of a two-wheeled mobile robot under tracking and energy constraints. The results demonstrated that prioritizing energy efficiency reduces power demand and cumulative energy consumption at the expense of tracking accuracy. Conversely, the accuracy-oriented strategy achieved the best trajectory-following performance but required higher control effort. The adaptive switching approach provided the most balanced solution, combining acceptable tracking precision with reduced energy consumption. These findings highlight the potential of metaheuristic optimization for designing energy-aware control systems suitable for autonomous mobile robotic applications.

FUTUR WORK

Future work will focus on the experimental validation of the proposed CSA-based backstepping controller on a real mobile robot platform. The objective is to evaluate its robustness and energy-saving capabilities under real-world operating conditions.