Journal of Computer Science and Artificial Intelligence
ISSN: 3078-8242 (Print), ISSN: 3078-2309 (Online) | Vol. 7, No. 3, 2026

Extended Horizon Model Predictive Control for Cooperative Encirclement of Unmanned Surface Vehicle Swarm

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Abstract: Cooperative encirclement of moving targets using unmanned surface vehicle (USV) swarms plays a vital role in maritime patrol, active interception, and autonomous cluster confrontation missions. Conventional finite-horizon model predictive control strategies often suffer from short-sighted control decisions and gradual performance degradation in long-duration cooperative tasks, which may cause unstable formation evolution and potential constraint violations. To address these limitations, this paper proposes an extended horizon model predictive control (EH-MPC) method for USV swarm cooperative encirclement. By extending the optimization prediction horizon, the proposed method endows the controller with long-term decision-making capability, effectively optimizing the swarm formation evolution while strictly maintaining multiple physical constraints, including inter-vehicle safety distance and formation centroid tracking. Comprehensive numerical simulations demonstrate that the EH-MPC strategy can achieve smooth and stable encirclement trajectory evolution, sustained collision-free performance, and high-precision centroid tracking during long-time marine missions. The results verify that the proposed method possesses excellent stability, constraint adaptability, and cooperative consistency for USV swarm encirclement applications.

Keywords: Unmanned surface vehicle, model predictive control, cooperative encirclement, extended horizon control.

1. Introduction

With the rapid development of intelligent marine equipment and autonomous cluster technology, unmanned surface vehicle swarms have been widely applied in complex ocean scenarios, including maritime surveillance, target interception, water area defense, and intelligent cruise missions. Cooperative encirclement represents one of the most essential and challenging cooperative behaviors, which requires multiple distributed USVs to dynamically adjust their positions, gradually form a closed formation around a moving evader, and maintain stable cluster coordination throughout the entire task duration.

Figure 1. Formation cruising process of the USV swarm

Model predictive control (MPC) has become a dominant optimization-based control technique for multi-agent cooperative systems due to its inherent advantages in explicit constraint handling and rolling optimization capability. Different from traditional static feedback control methods, MPC optimizes control sequences within a finite time horizon at each sampling moment, which enables the system to actively cope with dynamic target movements and time-varying marine environments. Nevertheless, conventional MPC adopts a relatively short prediction horizon to reduce computational consumption, which inevitably leads to local optimal and short-sighted control behaviors in long-duration encirclement tasks. In practical long-time cluster operations, short-horizon optimization cannot fully consider future formation evolution trends, easily resulting in insufficient formation stability, periodic position jitter, and subtle constraint trespassing phenomena.

To overcome the short-sightedness of conventional finite-horizon optimization, this paper develops an extended horizon model predictive control framework for USV swarm cooperative encirclement. The core innovation lies in the extension of the prediction horizon while retaining efficient rolling optimization characteristics. The extended prediction window enables the controller to perceive long-term formation variation trends, thereby generating more reasonable and continuous control commands. Meanwhile, comprehensive optimization objectives involving trajectory tracking, collision avoidance, and centroid stabilization are integrated into the rolling optimization process, ensuring that the USV swarm can complete progressive encirclement and maintain long-term stable formation constraints.

The main contributions of this work are summarized as follows: Firstly, an extended horizon MPC framework is established to enhance the long-term optimization capability of USV cooperative encirclement, effectively solving the performance degradation problem caused by finite short-horizon optimization. Secondly, a multi-objective rolling optimization cost function and systematic constraint sets are constructed, which simultaneously guarantee trajectory tracking accuracy, inter-vehicle collision avoidance, and swarm centroid stability. Thirdly, long-time numerical simulations covering the entire encirclement evolution process are performed, and multi-dimensional quantitative and qualitative analyses fully validate the superior practicability and stability of the proposed EH-MPC method.

2. System Modeling and Problem Formulation

2.1. USV Kinematic Model

Consider a swarm consisting of N homogeneous unmanned surface vehicles operating in a two-dimensional horizontal plane. The kinematic model of the i-th USV is established based on the standard marine vehicle motion description:

$$\dot{\mathbf{x}}_i = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\psi}_i \end{bmatrix} = \begin{bmatrix} u_i \cos\psi_i - v_i \sin\psi_i \\ u_i \sin\psi_i + v_i \cos\psi_i \\ r_i \end{bmatrix}$$

Where $\mathbf{x}_i = [x_i, y_i, \psi_i]^T$ denotes the state vector of the i-th USV, x_i and y_i represent the horizontal position coordinates in the global coordinate frame, and ψ_i is the heading angle. u_i and v_i denote the surge and sway velocities, respectively, and r_i is the yaw angular velocity. The control inputs of the USV are surge acceleration and yaw acceleration, which are constrained by the physical actuator limits:

$$\dot{u}_i \in [\dot{u}_{min}, \dot{u}_{max}], \dot{r}_i \in [\dot{r}_{min}, \dot{r}_{max}]$$

2.2. Cooperative Encirclement Problem Definition

The cooperative encirclement task requires the USV swarm to form and maintain a stable closed circular formation around a dynamically moving evader. Three critical constraints must be satisfied throughout the whole mission:

(1) Inter-vehicle safety distance constraint: To avoid cluster collision risks, the spatial distance between any two USVs must always exceed the predefined safety threshold d_{safe}:

$$\| \mathbf{p}_i(t) - \mathbf{p}_j(t) \| \geq d_{\text{safe}}, \forall i \neq j, \forall t \in [0, T]$$

Where $\mathbf{p}_i(t) = [x_i(t), y_i(t)]^T$ represents the position vector of the i-th USV, and T is the total mission duration.

(2) Circular formation constraint: The USV swarm is required to surround the evader with a fixed expected encirclement radius R after the formation convergence stage:

$$\| \mathbf{p}_i(t) - \mathbf{p}_e(t) \| = R, \forall i, \forall t \in [t_{\text{enc}}, T]$$

Where $\mathbf{p}_e(t)$ is the real-time position of the moving evader, and t_{enc} denotes the time when the encirclement formation is stably formed.

(3) Swarm centroid tracking constraint: The geometric centroid of the USV swarm must synchronously track the evader's trajectory to ensure overall formation coordination:

$$\mathbf{p}_c(t) = \frac{1}{N} \sum_{i=1}^{N} \mathbf{p}_i(t) \to \mathbf{p}_e(t), \forall t \in [0, T]$$

3. Proposed Extended Horizon MPC Framework

3.1. Fundamental MPC Optimization Formulation

Model predictive control solves a finite-horizon constrained optimization problem at each sampling instant. The controller generates an optimal control sequence by minimizing the predefined cost function, and only the first control action is executed in real time. The standard finite-horizon optimization problem is formulated as:

$$\min_{\mathbf{u}_i(\cdot)} J_i(\mathbf{x}_i(t), \mathbf{u}_i(\cdot)) = \sum_{k=0}^{N_p-1} L(\mathbf{x}_i(t+k|t), \mathbf{u}_i(t+k|t)) + V_f(\mathbf{x}_i(t+N_p|t))$$

s.t.

$$\begin{cases} \mathbf{x}_i(t+k+1|t) = f(\mathbf{x}_i(t+k|t), \mathbf{u}_i(t+k|t)), & k = 0,1,\ldots,N_p-1 \\ \mathbf{u}_i(t+k|t) \in \mathcal{U}, & k = 0,1,\ldots,N_p-1 \\ \mathbf{x}_i(t+k|t) \in \mathcal{X}, & k = 0,1,\ldots,N_p \end{cases}$$

Where N_p is the conventional prediction horizon, $L(\cdot)$ represents the stage cost function for instantaneous state optimization, $V_f(\cdot)$ is the terminal cost function ensuring endpoint stability, $\mathcal{U}$ and $\mathcal{X}$ denote the feasible sets of control inputs and system states, respectively.

3.2. Extended Horizon Optimization Mechanism

Different from conventional short-horizon MPC, the proposed EH-MPC extends the original prediction horizon N_p to a longer horizon N_p' ($N_p' \gg N_p$). The extended optimization window enables the controller to fully predict the long-term evolution trend of swarm formation, effectively eliminating short-sighted optimization defects. The improved multi-objective cost function is constructed as follows:

$$J_i^{\text{EH}} = \sum_{k=0}^{N_p'-1} \alpha \|\mathbf{p}_i(t+k|t) - \mathbf{p}_d(t+k|t)\|^2 + \sum_{k=0}^{N_p'-1} \beta(\| \mathbf{p}_i(t+k|t) - \mathbf{p}_j(t+k|t) \| - d_{\text{safe}})^2 + \gamma \|\mathbf{p}_c(t+N_p'|t) - \mathbf{p}_e(t+N_p'|t)\|^2$$

The cost function consists of three core components: trajectory tracking cost, inter-vehicle collision avoidance cost, and terminal centroid stabilization cost. $\mathbf{p}_d(t+k|t)$ is the dynamic desired position calculated according to the evader's motion state and expected encirclement formation. α, β, and γ are positive weight coefficients that balance the priority of different optimization objectives.

The complete constraints of the EH-MPC optimization problem are defined as:

$$\begin{cases} \mathbf{x}_i(t+k+1|t) = f(\mathbf{x}_i(t+k|t), \mathbf{u}_i(t+k|t)) \\ \dot{u}_i(t+k|t) \in [\dot{u}_{min}, \dot{u}_{max}] \\ \dot{r}_i(t+k|t) \in [\dot{r}_{min}, \dot{r}_{max}] \\ \| \mathbf{p}_i(t+k|t) - \mathbf{p}_j(t+k|t) \| \geq d_{\text{safe}} \end{cases}$$

By solving the extended-horizon optimization problem at each time step, the system obtains the optimal control sequence. The rolling updating mechanism ensures that the USV swarm can always adapt to the real-time motion state of the evader and dynamically adjust the encirclement formation throughout the long-duration mission.

4. Simulation Results and Analysis

To fully verify the effectiveness and long-term stability of the proposed EH-MPC method, numerical simulations of USV swarm cooperative encirclement are implemented in a 2D marine motion scenario. The simulation platform contains four pursuing USVs and one intelligent evader with flexible maneuvering characteristics. Key simulation parameters are listed in Table 1.

Table 1. Key Simulation Parameters

Parameter	Value	Description
N	4	Number of pursuing USVs
d_{safe}	1.5 m	Safety distance threshold
R	5 m	Expected encirclement radius
N_p'	20	Extended prediction horizon
α	1.0	Tracking cost weight
β	10.0	Collision avoidance weight
γ	5.0	Centroid tracking weight
T	200 s	Total simulation time

4.1. Spatio-Temporal Encirclement Evolution Performance

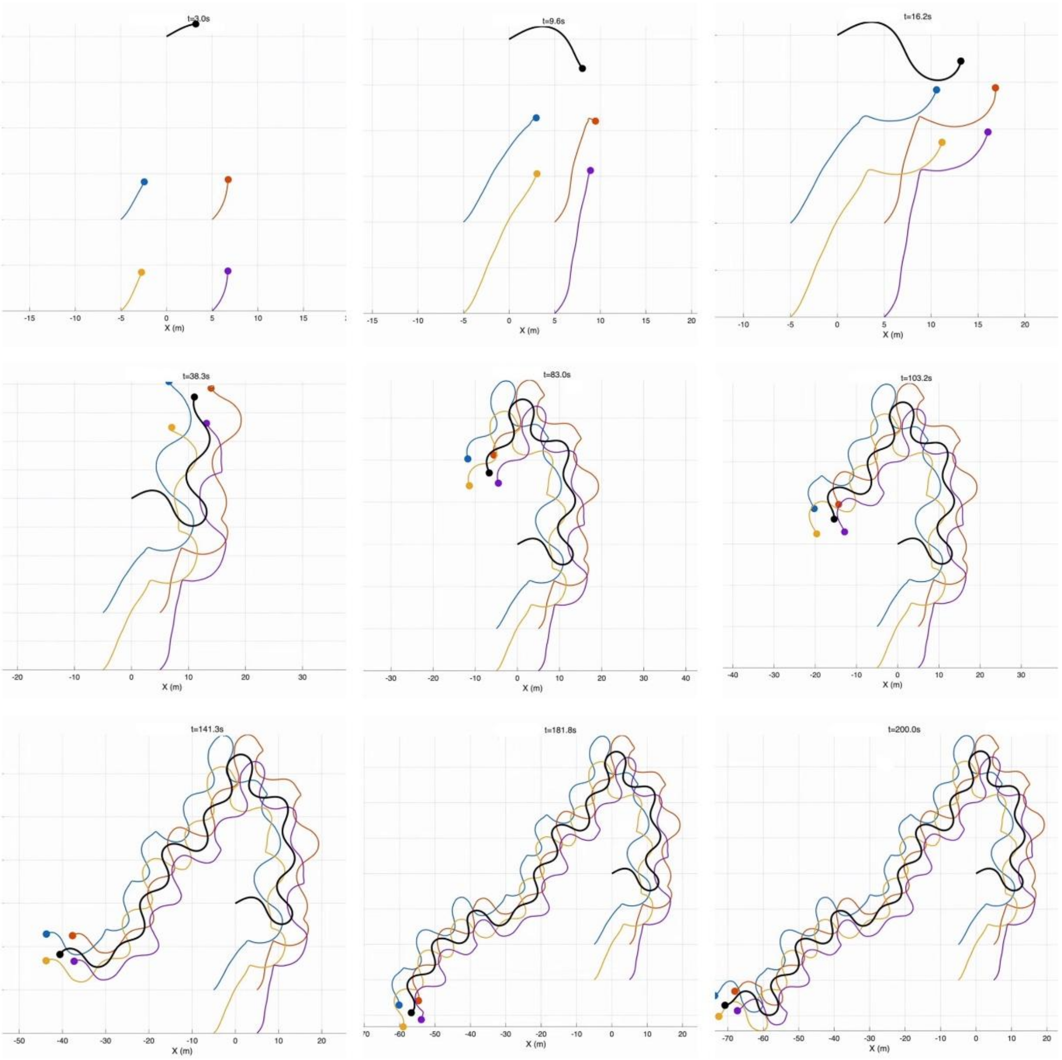

Figure 2. Time-varying encirclement trajectories of USV swarm at typical moments under EH-MPC

The temporal and spatial evolution process of USV swarm encirclement under the EH-MPC strategy is illustrated in Figure 2. The nine-group time-series snapshots intuitively reflect the complete formation convergence process from discrete distribution to stable closed encirclement. In the initial stage (3.0 s–16.2 s), the USVs start from scattered initial positions and continuously approach the evader while adjusting their relative spatial layout. During the mid-term stage (38.3 s–103.2 s), the swarm gradually converges toward the target, forming a preliminary surrounding trend with uniform spatial distribution. In the later stable stage (141.3 s–200.0 s), the USV swarm finally forms a complete and stable circular encirclement formation, and the relative positional relationship between each USV and the evader remains highly stable.

Benefiting from the extended prediction horizon, the controller possesses long-term prediction capability, which avoids the local optimization limitation of conventional short-horizon strategies. The entire evolution process is smooth and continuous without abnormal jitter or formation divergence, proving that EH-MPC can effectively guide the progressive and stable construction of swarm encirclement formation.

4.2. Global Trajectory Tracking Performance

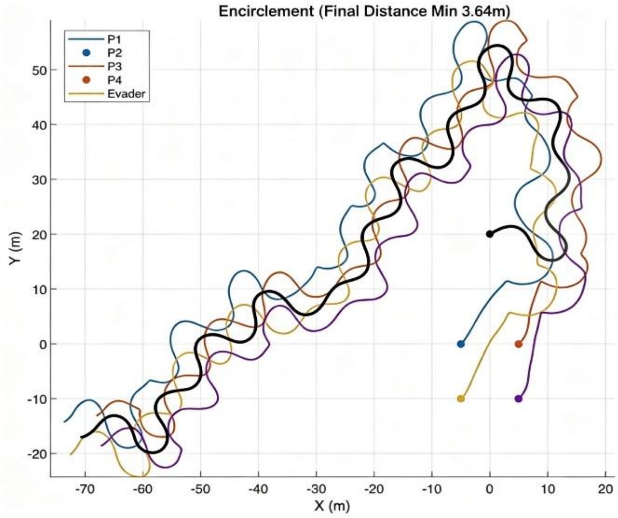

Figure 3. Global trajectories of four pursuing USVs and the evader over the full 200-second simulation duration

The full-period motion trajectories of four pursuing USVs and the evader within 200 seconds are depicted in Figure 3. It can be observed that all pursuing USVs achieve continuous and effective tracking of the maneuvering evader throughout the mission. The overall trajectories are smooth and continuous without sudden jumps or violent oscillations. At the end of the simulation, the minimum distance between the pursuing swarm and the evader reaches 3.64 m, which is within the preset ideal encirclement radius range, verifying that the proposed method can steadily complete the dynamic encirclement task for continuously moving targets.

The long-horizon optimization mechanism enables the controller to generate gentle and continuous control outputs, which fundamentally guarantees the smoothness and stability of long-time trajectory evolution and adapts to the continuous maneuvering changes of marine targets.

4.3. Inter-Vehicle Safety Distance Maintenance

The variation curves of inter-vehicle distances between all pursuing USV pairs are presented in Figure 4. Throughout the entire 200-second simulation process, all inter-agent distances are consistently maintained above the safety threshold of 1.5 m, and no constraint violation or collision risk occurs. In the initial convergence stage, the inter-vehicle distances decrease moderately as the swarm gathers toward the target. After the formation is formed, the distances quickly stabilize within a safe range of 6–10 m, with only tiny fluctuations caused by the evader's maneuvering and fine formation adjustment.

This phenomenon fully demonstrates that the embedded collision avoidance cost and hard constraints in the EH-MPC framework can strictly guarantee swarm safety. Even in the dynamic formation adjustment process, the cooperative strategy can always maintain reliable inter-vehicle spacing, which is essential for the stable operation of USV swarm systems in complex marine environments.

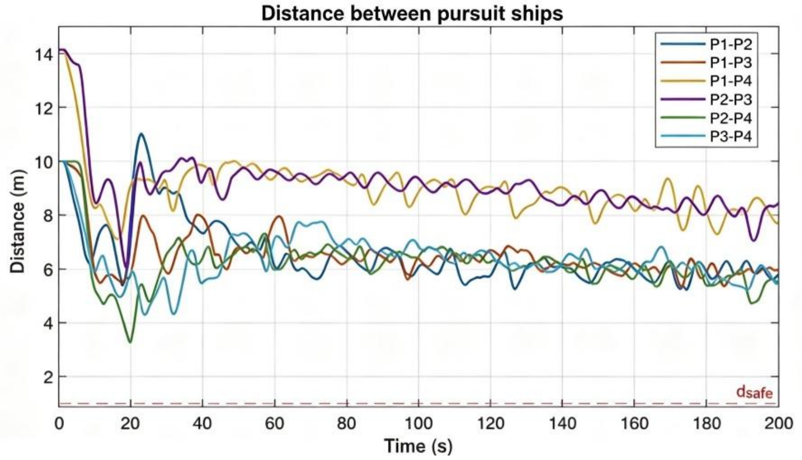

Figure 4. Inter-vehicle distance variation curves of the USV swarm during the entire encirclement process

4.4. Swarm Centroid Cooperative Tracking Performance

The tracking comparison between the swarm geometric centroid and the evader trajectory is shown in Figure 5. The centroid trajectory of the pursuing swarm maintains a high degree of coincidence with the evader's motion trajectory throughout the whole task. The tracking error gradually decreases with the formation convergence and finally remains within a tiny stable range. The accurate centroid synchronization capability ensures that the overall swarm position can always follow the dynamic target, preventing formation deviation, lagging, or dispersion during long-term pursuit and encirclement.

The long-horizon optimization design endows the controller with global cooperative awareness, which effectively guarantees the overall coordination and structural stability of the USV swarm in long-duration dynamic encirclement missions.

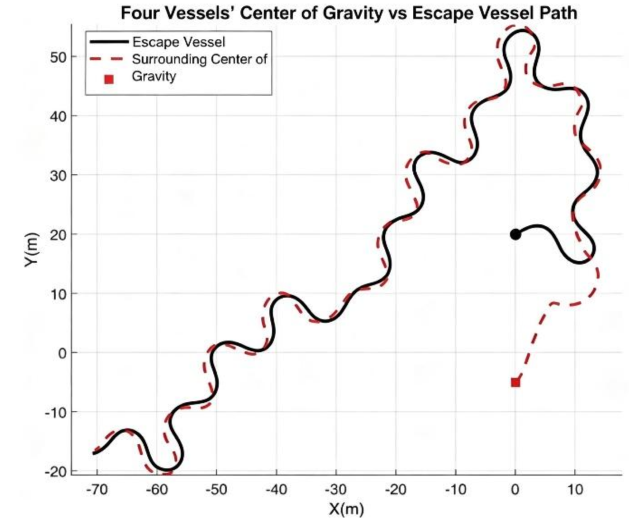

Figure 5. Tracking performance between USV swarm centroid and evader trajectory

5. Discussion

The comprehensive simulation results validate the superior performance of the proposed EH-MPC method in long-duration USV swarm cooperative encirclement tasks. Different from conventional short-horizon optimization control, the extended prediction horizon mechanism significantly enhances the long-term decision-making ability of the controller, enabling the system to balance instantaneous control performance and long-term formation stability. The multi-objective optimization function integrates trajectory tracking, collision avoidance, and centroid coordination requirements, realizing multi-constraint synchronous satisfaction in dynamic marine scenarios.

The EH-MPC strategy exhibits three prominent advantages in practical swarm encirclement applications. Firstly, it eliminates the short-sighted optimization defect of finite short-horizon control, ensuring stable formation evolution in ultra-long-time tasks. Secondly, the explicit constraint processing mechanism strictly guarantees inter-vehicle safety without collision risks during formation convergence and dynamic adjustment. Thirdly, the swarm centroid tracking optimization realizes high-consistency cooperative motion, which greatly improves the overall robustness of the encirclement system against target maneuvering disturbances.

6. Conclusion and Future Work

This paper proposes an extended horizon model predictive control method for USV swarm cooperative encirclement against maneuvering targets. By extending the prediction optimization horizon, the proposed method overcomes the performance limitation of conventional short-horizon control strategies in long-duration cooperative tasks. The designed multi-objective rolling optimization cost function and systematic constraint system simultaneously ensure trajectory smoothness, inter-vehicle safety, and swarm centroid coordination. Sufficient numerical simulations verify that EH-MPC can achieve stable progressive encirclement formation evolution, persistent safety constraint satisfaction, and high-precision dynamic tracking for moving targets.

Future research will focus on improving the environmental adaptability of the algorithm. The communication delay, data packet loss, and complex ocean disturbance factors will be integrated into the control framework to make the method more suitable for practical marine engineering applications. In addition, further research on adversarial evasion target strategies will be carried out to enhance the anti-interference and confrontation performance of the swarm encirclement system.

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