Optimal Coverage-based Cooperative Guidance for Inferior Vehicles Against a Maneuvering Target*

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Abstract— **An optimal cooperative guidance law for multiple vehicles with weak maneuverability against a superior target is studied in this paper. Firstly, the range of zero-effort-miss distance under the relative-frame-based optimal guidance law is derived by considering the acceleration limitation. Secondly, by adopting the concept of a joint maneuver domain that encompasses the escape area, the reachable sets with bias for each vehicle are devised through the establishment of time-varying virtual aiming points. Then, the guidance command for is obtained by minimum energy consumption optimization. Moreover, the relations among the number of vehicles, the coverage area of the target's large maneuver and the coefficient of guidance law are analyzed by designing a non-overlapping coverage strategy. Finally, simulation results demonstrate the feasibility and performance of the proposed method with bias term, which can realize the perfect interception of the weak multi-vehicles against the strong maneuvering target.**

I. INTRODUCTION

With the increasing defensive confrontation, the implementation of precise strike on maneuvering target has become the focus of research. The strategy of cooperative interception enables multiple vehicles intercept a high-maneuverability target successfully through their numerical superiority. In order to meet the demand for simultaneous interception, the core of cooperative guidance is to ensure the final impact time of each vehicles in the swarm needs to be constrained, divided into two categories: individual homing and cooperative homing.

In the individual homing, each vehicle is equipped with the same attack time before the mission. Under the linear assumption, Jeon et al. [1] firstly adds a time-related feedback term into the proportional navigation guidance (PNG) loop according to the optimal control theory. In addition to these studies utilizing the optimal control theory [2]-[4], individual homing can be also realized by polynomial guidance [5]-[7] and sliding mode control (SMC) [8]-[10].

In the cooperative homing, each vehicle exchange its motion information through network communication to achieve simultaneous attack. In [11], a distributed cooperative protocol to guarantee the fixed-time consensus of impact time is designed. The author in [12] derived a finite-time consensus protocol with adaptive super-twisting algorithm and integral sliding mode and requires no information on target maneuver. Furthermore, there are still many studies that apply the consensus algorithm to the design of cooperative homing guidance law, demonstrating promising interception capabilities [13]-[15].

Although some of the above guidance laws can achieve salvo attack on maneuvering target, they all assume that the vehicles has better maneuverability than the target. When the maneuvering ability of vehicles is weaker than target's, it will be unable to achieve cooperative interception because of saturation of acceleration commands.

In recent years, the idea of covering the escape region of high maneuvering target through the combined reachable area has been put forward, named coverage-based cooperative guidance (CBCG). CBCG ensures that at least one vehicle can intercept the maneuvering target without exceeding its own acceleration limit. For cooperative interception of high-maneuvering targets by vulnerable groups, the target's escape region is covered by the union of multiple interception domains, which are biased through the design of virtual target points. Reference [16] designs the virtual aiming point with the biased zero effort miss distance (*ZEM*) related to the time-to-go and a constant *B* on the basis of true proportional navigation (TPN) guidance, where *B* is solved by analyzing the trend of acceleration command. The author in [17] proposes a desired *ZEM* considering a adaptive coverage strategy and make full use of maneuverability to force the vehicle to satisfy its own current reachable set. Xiao et al.[18] introduces a relatively straight standard ballistic trajectory by minimizing the energy consumption at the initial and interception time with pre-set uniform coverage strategy. The concept of a standard ballistic trajectory, which is widely used in [19]-[22], exhibits variations in terms of coverage mode for two-dimensional scenario. Reference [19] designs the coverage allocation by evenly distributing overlapping areas. Bai et al. [20] eliminates the coverage overlapping area through selecting appropriate navigation parameters. However, the optimization index of guidance law and the non-overlapping coverage mode are not considered in the above research.

Motivated by aforementioned observations, this paper firstly analyses the feasible area under the optimal guidance law based on relative frame with maneuverability limitation. Then, an optimal coverage-based cooperative guidance with a bias ZEM term is designed by minimizing energy consumption. Meanwhile, by solving the guidance parameters

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with nonlinear precision algorithm, the strategy of non-overlapping combining maneuvering domain to cover target evasion region can ensure that at least one vehicle precisely intercept a strong maneuvering target.

The remainder of this paper is organized as follows: Section II presents problem statements under acceleration bound. The details of the optimal biased guidance law design and coverage area allocation strategy for inferior vehicle are given in Section III, followed by the simulation results of various engagements and comparison with existing study in Sec. IV. Finally, conclusions are discussed in Sec. V.

II. Problem Statement

A. Engagement geometry

This section introduces the relative kinematics between the vehicle and target in a reference frame required to design the proposed guidance law. At first, the inertial coordinate frame is depicted in Fig. 1, named XOY. It is assumed that the maneuvering target and vehicle are both particle models with constant speed, that is, there are only acceleration commands a perpendicular to the directions of velocity V to change the direction of velocities.The flight-path angle and the leading angle are expressed as σ and η,respectively. The subscripts M and T represent the vehicle and target, respectively. The variable r denotes the relative distance and q is the line-of-sight (LOS) angle.

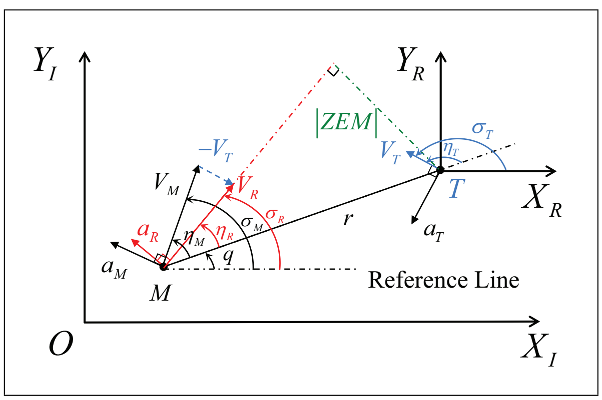


Fig. 1. Relative kinematics in inertial and reference frame

In order to reduce the nonlinear degree of the relative motion caused by the maneuverability of target, a relative coordinate system $X_R T Y_R$ with the target as the origin is constructed. The relative velocity V_R can be calculated as

$$V_R = \sqrt{V_M^2 + V_T^2 - 2V_M V_T \cos(\sigma_M - \sigma_T)} \tag{1}$$

Therefore, the relative motion equations in reference frame can be written as

$$\dot{r} = -V_R \cos\eta_R = -V_R \cos(\sigma_R - q) \tag{2}$$

$$r\dot{q} = -V_R \sin\eta_R = -V_R \sin(\sigma_R - q) \tag{3}$$

$$\dot{\sigma}_R = \frac{a_P}{V_R} \tag{4}$$

where σ_R and η_R denote the relative flight path angle and relative leading angle, which can be obtained from

$$\sigma_R = \tan^{-1}\frac{\sin\sigma_M - K\sin\sigma_T}{\cos\sigma_M - K\cos\sigma_T} \tag{5}$$

$$\eta_R = \eta_M - \cos^{-1}\frac{V_M^2 + V_R^2 - V_T^2}{2V_M V_R} \tag{6}$$

where $K = \frac{V_T}{V_M}$, and

$$a_P = a_M \cos(\sigma_R - \sigma_M) - a_T \cos(\sigma_R - \sigma_T) \tag{7}$$

B. Optimal guidance law based on relative frame

In order to achieve the mission requirements of interception under the guidance command a_P in relative frame, the zero effort miss distance (ZEM) is first formulated as

$$ZEM = -r\sin\eta_R \tag{8}$$

and the terminal desired state is

$$ZEM(r_f = 0) = 0 \tag{9}$$

Thus, the differentiation of ZEM with respect to r can be written as

$$\frac{dZEM}{dr} = ru \tag{10}$$

where

$$u = \frac{a_p}{V_R^2} \tag{11}$$

For 2-D interception scenario, the optimal guidance law based on relative frame (OGR) for zero miss distance is developed in [23] as

$$a_P = N V_R \dot{q} \tag{12}$$

where $N \geq 3$ is the user-selected guidance gain.

Remark 1: In order to ensure that the relative distance is always monotonically decreasing and $ZEM = 0$ is satisfied at the end, the initial state of guided interception needs to meet the conditions that $K<1$ and $|\eta_{M0}|<\pi/2$.

Remark 2: Since V_R varies within a small range during the engagement, it is assumed to be constant.

To analyze the variation range of guidance command throughout the whole process, (12) is rewritten as

$$a_p = \frac{N \cdot ZEM \cdot V_R^2}{r^2} \tag{13}$$

where ZEM can be expressed as $ZEM = ZEM_0\left(\frac{r}{r_0}\right)^N$ by solving the differential equation (10). The subscript 0 denotes the initial state. Therefore, the OGR command is a monotonic function with respect r, i.e.,

$$a_p = \frac{N \cdot ZEM_0 \cdot V_R^2}{r_0^N} r^{N-2} \tag{14}$$

Rewriting (7), the guidance command can be obtained as

$$a_M = \frac{a_P + a_T\cos(\sigma_R - \sigma_T)}{\cos(\sigma_R - \sigma_M)} \tag{15}$$

and

$$|a_M| \leq \left|\frac{a_P}{\cos(\sigma_R - \sigma_M)}\right| + \left|\frac{a_T \cos(\sigma_R - \sigma_T)}{\cos(\sigma_R - \sigma_M)}\right| \tag{16}$$

It can be seen from Fig. that $\sigma_{Rf} - \sigma_{Mf}$ is less than 45° because the condition for $K<1$ mentioned in *Remark 1*. Therefore, the upper bound for absolute value is

$$\left|\frac{\cos(\sigma_{Rf} - \sigma_{Tf})}{\cos(\sigma_{Rf} - \sigma_{Mf})}\right| \leq 1 \tag{17}$$

In order to meet the requirement of the acceleration limit, it is necessary to ensure that the initial and final value do not exceed the maximum. Here we assume that a_T is constant. Thus, substituting (13) into (16) under the consideration of angle variations can get

$$|ZEM_0| \leq \frac{|a_{M,\max}| - |a_T|) r_0^2}{\sqrt{2} N \left(V_M + V_T\right)^2} \tag{18}$$

since the vehicle is highly maneuvering than target. It indicates that the capture ability of OGR is determined by the maximum acceleration of vehicle and target. Meanwhile, ZEM_0, that is, the lead angle and relative distance at the initial moment, also determines whether it will exceed its acceleration limit during guidance.

III. Optimal Coverage-based Cooperative Guidance Design

A. *Optimal biased guidance law design*

The acceleration limitation will affect the terminal interception accuracy, especially intercepting highly maneuvering target with inferior vehicle. Thus, the strategy of collaborative interception is adopted to make up for the lack of overload capability through numerical advantages, that is, the maneuvering area of multiple interceptor covers the target evasion region to ensure that at least one vehicle can achieve interception. Inspired by [17], the virtual aiming point for each inferior vehicle to cover the segment of target maneuvering range is designed in this section. The virtual aiming point about biased term for ZEM is formulated as

$$ZEM_{bias} = B(r) r^2 \tag{19}$$

where $B(r)$ is a variable related to relative distance. Thus, substituting (19) into (10), the differential equation can be rewritten as

$$\frac{dZEM}{dr} = \frac{N}{r} ZEM(r) - NB(r) r \tag{20}$$

and the relative acceleration command for each vehicle yields

$$a_p(r) = N V_R^2 \left(\frac{ZEM(r)}{r^2} - B(r)\right) \tag{21}$$

Let $u = B(r)$ be the control input. In order to ensure the optimality of the acceleration instruction, the optimal control problems concerning the whole energy consumption and the terminal homing are constructed as follows:

$$\begin{aligned} &\min_u J = C_\lambda \cdot |ZEM| + \frac{1}{2}\int_{r_0}^{0} a_P^2 dr \\ &s.t. \quad \frac{dZEM}{dr} = \frac{N}{r} ZEM - Nur \\ &\qquad ZEM(r = r_0) = ZEM_0 \\ &\qquad ZEM(r = 0) = 0 \\ &\qquad |a_M| \leq a_{M,max} \end{aligned} \tag{22}$$

Define that $C = C_\lambda \cdot sgn(ZEM)$. Thus, the Lagrangian function with inequality constraint can be obtained as

$$\psi = H + \theta\left(a_{M,\max}^2 - a_M^2\right) \tag{23}$$

where

$$H = \frac{1}{2} {a_p}^2 + \lambda\left(\frac{N}{r} ZEM - Nur\right) \tag{24}$$

By solving problem (22) based on the optimal control theory, the solution of u is derived as

$$u = br + d \tag{25}$$

where

$$b = \frac{(3-N)C}{3V_R^4}, d = \frac{(N-2)\theta a_{M,c}}{V_R^2 \cos(\sigma_R - \sigma_M)} \tag{26}$$

Note that the symbol $a_{M,c}$ is the calculated magnitude of the acceleration in the derivation process for solving θ. Please refer to Appendix A for detailed solution of (25).

B. *Cooperative coverage area strategy*

In this section, we aim to construct a cooperative coverage area strategy against highly maneuvering target. Firstly, based on the aforementioned optimal guidance command, the coverage interval of the vehicle that can be realized under the restricted conditions is analyzed. In order to achieve complete coverage of the escape area of high maneuvering target, the number of vehicle required is obtained. Finally, by adjusting the value of C, the maneuvering domain coverage without overlapping is realized.

In order to facilitate the subsequent calculation of the required number of vehicles and coverage mode, the feasible maneuvering domain of each vehicle with inferior limited acceleration is analyzed first. Inequalities regarding the range of acceleration instructions can be written as

$$-a_{M,max} \leq a_M \leq a_{M,max} \tag{27}$$

Substituting (15) into (27) yields

$$\begin{aligned} -\frac{\cos(\sigma_R - \sigma_M)}{\cos(\sigma_R - \sigma_T)} a_{M,max} - \frac{a_P}{\cos(\sigma_R - \sigma_T)} \leq a_T \\ \leq \frac{\cos(\sigma_R - \sigma_M)}{\cos(\sigma_R - \sigma_T)} a_{M,max} - \frac{a_P}{\cos(\sigma_R - \sigma_T)} \end{aligned} \tag{28}$$

Therefore, if the target maximum evasion domain is defined as the interval of $[-1, 1]$, then the range that each vehicle can cover $\Gamma \in [\Gamma_{low}, \Gamma_{up}]$is

$$\Gamma \in [-\frac{\cos(\sigma_R-\sigma_M)}{\cos(\sigma_R-\sigma_T)}\rho - \frac{a_P}{a_{T,max}\cos(\sigma_R-\sigma_T)}, \frac{\cos(\sigma_R-\sigma_M)}{\cos(\sigma_R-\sigma_T)}\rho - \frac{a_P}{a_{T,max}\cos(\sigma_R-\sigma_T)}] \tag{29}$$

where $\rho = a_{M,max}/a_{T,max}$<1. It is obvious that the coverage span of one vehicle is $2\rho\cos(\sigma_R-\sigma_M)/\cos(\sigma_R-\sigma_T)$. Thus, the number of inferior vehicles N_M should satisfies

$$N_M \geq \lceil \frac{\cos(\sigma_R-\sigma_T)}{\rho\cos(\sigma_R-\sigma_M)} \rceil \tag{30}$$

where $\lceil\cdot\rceil$ is a ceiling function representing the nearest integer rounded up. Note that the ratio relation shown in (17), the selection for N_M can be simplified as $N_M \geq \lceil 1/\rho \rceil$.

In order to ensure that the feasible domain combination of vehicles covers the maneuvering range of the target without overlapping, we need to find the optimal C_i to minimize the gap between the boundaries of combined coverage and the maneuvering of target. Note that the objective function and nonlinear constraint are expressed as

$$\begin{aligned} &\min_{C_i} J = \left|\Gamma_{1,low}+1\right| + \left|\Gamma_{M,up}-1\right| \\ &s.t. \quad \forall C_i > 0 \\ &\qquad \Gamma_{i-1,up} = \Gamma_{i,low}, i = 2,3,...,M \end{aligned} \tag{31}$$

Considering the degree of nonlinearization of (31), the interior point method is used to solve the problem, which is an accurate method to solve the optimization proposition with constraints. And the initial ZEM should meet

$$\frac{r_0^2 a_{T,max}}{NV_R^2}(-K_1\Gamma_{i,low}-K_2) \leq ZEM_0 \leq \frac{r_0^2 a_{T,max}}{NV_R^2}(-K_1\Gamma_{i,up}+K_2) \tag{32}$$

where $K_1 = \cos(\sigma_{R0}-\sigma_{T0})$, $K_2 = \cos(\sigma_{R0}-\sigma_{M0})$.

Consequently, substituting (21) and (25) into (15), the optimal coverage-based biased guidance command (OCBG) for inferior vehicle is derived.

IV. Numerical Simulations

In this section, simulations under different scenarios are carried out for verifying the feasibility and superiority of the proposed guidance law. Firstly, comparing with the OGR without acceleration bound mentioned in (12), the validation of the proposed guidance for inferior interception is presented. Then, the comparison between the proposed OCBG and a BPN method [17] is carried out to demonstrate the advantage in terms of energy consumption. The numerical integration method is the fourth order Runge-Kutta and the integral step of the solver is 0.01s.

A. Effectiveness Validation

To verify the effectiveness of the optimal coverage-based biased guidance command, we set a case of two vehicles against a target. The maximum accelerations of vehicles named M_1,M_2 and target are $a_{M,max} = 2g$ and $a_{T,max} = 3g$ where g denotes the acceleration of gravity, i.e., $g = 9.81 m/s^2$. The simulation conditions are given in Table I.

TABLE I
Simulation Settings

Conditions	M_1	M_2	Target
Initial Position, (m)	(0,1000)	(0,-1000)	(8000,0)
Velocity, (m·s^{-1})	300	300	200
Initial flight path angle, (°)	10	-10	-150
Normal acceleration, (g)	-	-	$3\sin(0.1\pi t)$

The compared results of OGR and OCBG approaches are presented in Fig. 2. It can be observed from Figs. 2(a) and 2(b) that M_2 under OCBG achieves the task of attacking a high maneuvering target. However, OGR can not intercept the target by adding limiting amplitude directly to meet the acceleration bound. As can be seen from Fig. 2(b), the value of ZEM cannot decrease monotonically because the target does sinusoidal maneuvering. However, the proposed method can not only give fully used to the acceleration limit, but also adjust the acceleration direction in advance, as shown in Fig. 2(c), so that the sign of ZEM is unchanged and converges to zero at the end. This depends on the selection of coefficient B, which is solved in real time based on the optimal control method according to the relative distance and angle values, rather than being selected in advance. Therefore, when the maximum acceleration of the target is greater than vehicles, there still exists one missile that can complete the interception. The acceleration curve indicates that the vehicle's maximum maneuverability is not exceeded, aligning with the theoretical result.

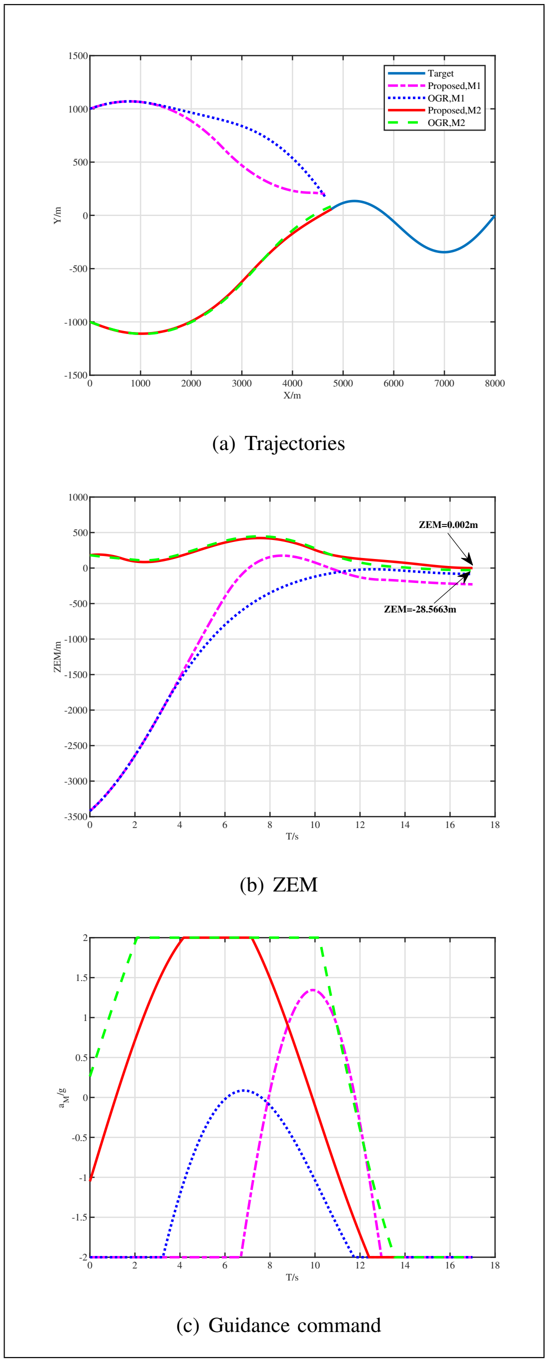
B. Comparative Study

In this subsection, the proposed approach is compared with BPN method [17]. The maximum accelerations of vehicles and target are $a_{M,max} = 3.2g$ and $a_{T,max} = 4g$, respectively. The bangbang maneuvering target whose acceleration is $0.9a_{T,max}sign(\pi t/2)$. The simulation conditions are given by Table II.

TABLE II
Simulation Settings

Conditions	M_1	M_2	M_3	Target
Initial Position, (km)	(0,0)	(0,0)	(0,0)	(50,0)
Velocity, (km·s^{-1})	(2,0.04)	(2,0)	(2,-0.04)	(-2,0)

Fig. 3 provides the result of comparative simulation against a maneuvering target with three vehicles. It can be seen from Fig. 3(a) and Fig. 3(b) that either the proposed guidance law or BPN method ensures that one vehicle successfully intercepts the target. The guidance commands for each vehicle are shown in Fig. 3(c). As the target performs a bang-bang maneuver, the guidance instructions change accordingly. In addition, the trends of ZEM for individual vehicle are also similar. However, under the guidance of the proposed method, the ZEM for M_3 eventually converges, while under the guidance of BPN has a tendency of divergence at the end. The indicator for comparison is energy consumption,i.e., $E = \frac{1}{2}\int_0^{t_f} a_M^2 dt$. By calculating the E of $M1$, we can see that the value of the proposed approach

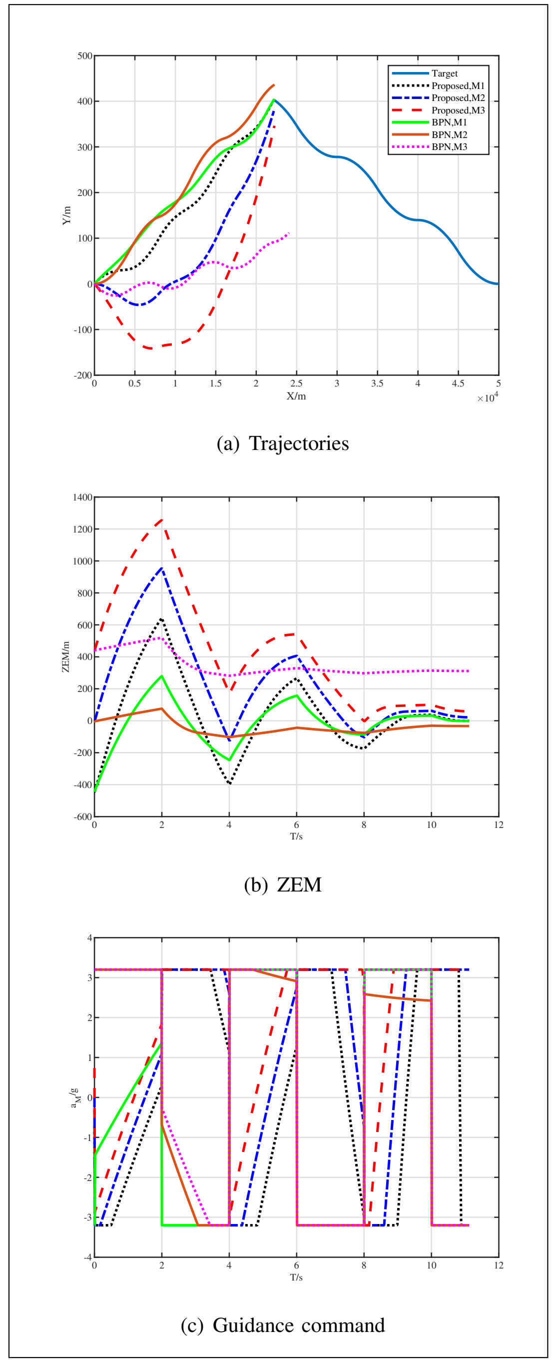


(a) Trajectories

(b) ZEM

(c) Guidance command

Fig. 2. Comparative simulation results with OGR



(a) Trajectories

(b) ZEM

(c) Guidance command

Fig. 3. Comparative simulation results with BPN [17]

is 3822.23 $m^2 \cdot s^{-3}$, and that of BPN method is 4559.28 $m^2 \cdot s^{-3}$. It can be concluded that because the optimization index of energy consumption is considered in this paper, the proposed guidance law exhibits superior performance in terms of energy consumption.

V. Conclusions

In this paper, an OCBG law is proposed for allowing inferior vehicles intercept cooperatively a higher maneuvering target. The optimal guidance law based on relative [23] is first introduced to analyze the feasible region and intercept condition. To ensure that inferior vehicles intercept the maneuvering target, the virtual aiming points are established to divide the interception area of each vehicle. On this basis, by leveraging the optimal control theory of minimizing energy consumption, the guidance law is designed under adding a bias term for satisfying acceleration bound. The proposed guidance scheme has coefficients that are determined by both the initial state and a strategy involving non-overlapping combined coverage of the target escape region. Simulations verified the validity of the proposed approach and better performance on the effect of coverage-based interception and energy consumption.

APPENDIX A

Combine (22), (23), and (24), the first-order optimality condition and the costate equation are determined as

$$\frac{\partial \psi}{\partial u} = 0 \tag{33}$$

and

$$\frac{d\lambda}{dr} = -\frac{N^2 V_R^4}{r^2}\left(\frac{ZEM}{r^2} - u\right) - \frac{\lambda N}{r} + \frac{2\theta N V_R^4 a_M}{r^2 \cos\left(\sigma_R - \sigma_M\right)} \tag{34}$$

Substituting (33) into (34), it can be obtained that λ is a constant, i.e., $\lambda = C$. Therefore, one has

$$CNr = -NV_R^4\left(\frac{ZEM}{r^2} - u\right) + \frac{2\theta N V_R^2 a_M}{\cos\left(\sigma_R - \sigma_M\right)} \tag{35}$$

Meanwhile, solving the differential equation (20) yields

$$ZEM = z_1 r^N - N r^N \int_0^r \xi^{1-N} B(\xi) d\xi \tag{36}$$

where

$$z_1 = \frac{ZEM_0}{r_0^N} + N\int_0^{r_0} \xi^{1-N} B(\xi) d\xi \tag{37}$$

Substituting (36) into (35), the equation is

$$u = r^{N-2}\left(C_1 - N\int_0^r \xi^{1-N} u\left(\xi\right) d\xi\right) - \frac{2\theta a_M}{V_R^2 \cos\left(\sigma_R - \sigma_M\right)} + \frac{Cr}{V_R^4} \tag{38}$$

Solving the equation and the expression of u can be obtained as (25). Thus, the expression of ZEM can be obtained as

$$ZEM = -N\left(\frac{C}{3V_R^4} r^3 - \frac{\theta a_M}{V_R^2 (\cos\left(\sigma_R - \sigma_M\right))} r^2\right) \tag{39}$$

Then, the value of θ needs to be solved by the initial state of ZEM. Substituting (21) and (36) into (15) yields

$$a_{M,c} = \frac{-\frac{NC}{V_R^2} r + a_T \cos\left(\sigma_R - \sigma_T\right)}{\left(\cos\left(\sigma_R - \sigma_M\right) - \frac{2N\theta}{\cos(\sigma_R - \sigma_M)}\right)} \tag{40}$$

Taking into account the value of the known initial time of ZEM, we can get

$$\theta a_{M0} = \frac{\left(ZEM_0 + \frac{CN}{3V_R^4} r_0^3\right)}{N {r_0}^2} V_R^2 \cos\left(\sigma_{R0} - \sigma_{M0}\right) = \Theta \tag{41}$$

Substituting (41) into (40), the calculated initial value of a_M is

$$a_{M0} = \frac{2N\Theta}{\cos\left(\sigma_{R0} - \sigma_{M0}\right)} - \frac{CN}{V_R^2} r_0 + a_{T0} \cos\left(\sigma_{R0} - \sigma_{T0}\right) \tag{42}$$

Thus, the value of θ can be calculated by division operation of

$$\theta = \frac{\Theta}{a_{M0}} \tag{43}$$

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