Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering) 2025 26(7):605-634
www.jzus.zju.edu.cn; www.springer.com/journal/11582
E-mail: jzus_a@zju.edu.cn

Review

https://doi.org/10.1631/jzus.A2400317

Technical development and future prospects of cooperative terminal guidance based on knowledge graph analysis: a review

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Abstract: Cooperative guidance is a method for achieving combat objectives through information sharing and cooperative effects, and has emerged as a significant research area in the fields of missile guidance and systematic warfare. This study presents a systematic review and analysis of current research on cooperative guidance. First, a bibliometric analysis is conducted on 513 articles using the Scopus database and CiteSpace software to assess keyword clustering, keyword co-occurrence, and keyword burst, and to later visualize the results. Second, fundamental theories of cooperative guidance, including relative motion modeling methods, algebraic graph theory, and multi-agent consensus theory, are summarized. Subsequently, an overview of current cooperative laws and corresponding analysis methods is provided, with categorization based on the cooperative structure and convergence performance. Finally, we summarize current research developments based on five perspectives and propose a developmental framework based on five layers (cyber, physical, decision, information, and system), discussing potential future advancements in cooperative terminal guidance. This framework emphasizes five key areas of research: networked, heterogeneous, integrated, intelligent, and group cooperations, with the goal of offering trends and insights for future work.

Key words: Cooperative guidance; Guidance law; Multiple missiles; Cooperative operations; Guidance and control; Impact time control; Impact angle control; Consensus theory; CiteSpace analysis

1 Introduction

The purposeful behavior of humans acting in a system can be compared to coordination observed in nature, such as bees working, fish feeding, birds migrating, and ants foraging. As shown in Fig. 1, these biological behaviors arise from collective patterns, which enable the completion of complex tasks that cannot be achieved by lone individuals (Flierl et al., 1999; Couzin et al., 2005; Sumpter, 2006; Garnier et al., 2007; Goldstone and Gureckis, 2009). The organization and local information exchange applied to achieve a common task have been described with the concept of swarm collaboration. This concept builds upon individual unmanned systems, and accounts for interactions between nodes and multi-agent networking (Yong, 2014; Xiao et al., 2021; Chen YT et al., 2023; Yu et al., 2023). Its goal is to overcome the limitations of individual intelligent agents, and to enhance the performance and autonomy of unmanned systems.

New combat concepts and styles have emerged, as inspired by the phenomena of biological swarms. Additionally, recent scientific and technological advancements, such as artificial intelligence, have been applied in the military domain (Horowitz et al., 2020; Wang WF et al., 2020; Baboş, 2021; Bistron and Piotrowski, 2021; Szabadföldi, 2021). Cutting-edge approaches involving big data, machine learning, cloud computing, quantum information, and digital twins have led to the development of new intelligent weapons. In particular, disruptive technological clusters led by artificial intelligence have had a profound impact in the military field. They have showcased various

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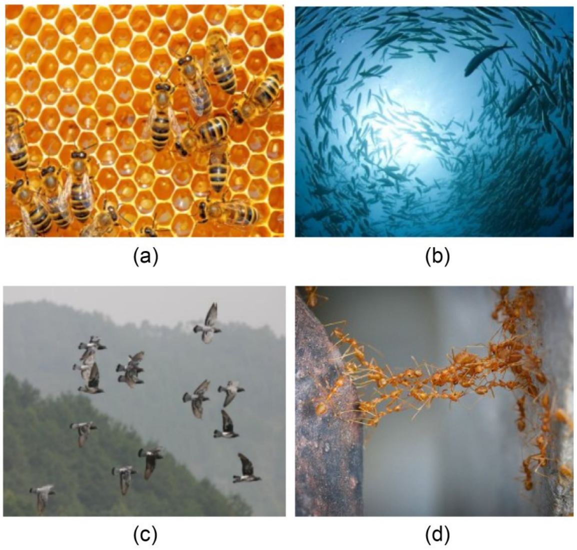
Received June 17, 2024; Revision accepted Oct. 28, 2024;
Crosschecked July 6, 2025



(a) (b) (c) (d)

Fig. 1 Biological swarm behavior: (a) bees working; (b) fish feeding; (c) birds migrating; (d) ants foraging

applications and may eventually change the existing rules of warfare. Moreover, in terms of operations, the concepts of network-centric warfare (Rhee et al., 2012), cooperative operations in denied environments (Yuan et al., 2023), mosaic warfare (Yang and Du, 2020; Qi et al., 2021), and cross-domain operations (Weisler et al., 2018) are continuously evolving. Therefore, intelligent warfare technologies are emerging, and future warfare will inevitably involve interactions and conflicts between various complex systems (Grobler and Robertson, 2012; Burton and Straub, 2019; He et al., 2022; Zhuang et al., 2022; Li JL et al., 2024). Missiles, despite playing key roles in modern precision strikes, face multiple barriers to being integrated into networked, information-driven, and intelligent warfare. These barriers include intense opposition, limited information support, multitasking requirements, varying weather conditions, and system-level confrontations. With current approaches, the capabilities provided by a single missile are limited. Therefore, cooperative operations involving multiple missiles have grown in importance, making them a new competitive focal point in the development of weapon systems among major military powers (He et al., 2018b; Yu et al., 2019; Sinha and Kumar, 2020; Dong et al., 2022; Zhou JL et al., 2022; Li Z et al., 2023; Wang YH et al., 2023; Zhang et al., 2023; Zhao et al., 2024).

Overall, multi-missile cooperative operations offer numerous advantages in terms of interception, detection, and anti-jamming abilities.

(1) Strong interception capability (Su et al., 2018; Wang SB et al., 2021; Liu et al., 2023; Wang CC et al., 2023). Cooperative interception expands the interception area of a single missile, increases the effective damage range of the missile swarm, and reduces the likelihood that enemy targets will escape. In addition, it enables the division of labor and cooperation between different missiles in the swarm, thereby increasing the survival probability of the protected target and reducing the control energy consumption of the cooperative system.

(2) Enhanced detection capability (Gu K et al., 2020; Li et al., 2022; Park et al., 2022; Alladi et al., 2023). Cooperative guidance adjusts the formation structure of multiple missiles to enhance their detection ability. Multiple missiles share perspective information through their sensors to achieve cooperative target detection. This method improves the ability of the swarm to detect and estimate their target's maneuverability, enabling the swarm to attack maneuvering targets more accurately.

(3) Advanced anti-jamming ability (Ahmed and Fapojuwo, 2018; Zhang YL et al., 2018; Gu P et al., 2020; Wang XM et al., 2020). Using missiles with different types of seekers to cooperate and attack from multiple directions can effectively prevent large miss distances caused by disturbances in a single frequency band. In addition, information exchange between missiles reduces the probability of attacking incorrect or decoy targets.

Missile guidance laws are crucial to modern missile systems, as they provide the mathematical foundation for the steering commands that guide a missile to its target (Livermore et al., 2018; Tsalik and Shima, 2019; Tekin and Erer, 2020; Han et al., 2022; Kang et al., 2023b; Wang PY et al., 2024). Cooperative guidance technology, being one of the core technologies for the operation of missile swarms, determines the guidance accuracy and coordinated attack performance of multiple missiles. It involves cooperation between missiles as supported by a communication network, such that they form an information-sharing, complementary, and coordinated combat group (Hou et al., 2015; Zhao and Yang, 2017; Kumar and Mukherjee, 2020; Nanavati et al., 2021; Liu F et al., 2022; Wang CY et al., 2022; Kang et al., 2023a; Li and Zuo, 2023; You et al., 2023; Zhang Z et al., 2024). Under certain control strategies, a missile group can accomplish a specific attack or defense mission.

The application of cooperative guidance in modern warfare systems offers significant advantages. Several researchers have focused on research in this area and achieved significant results. This study summarizes the current development trends in cooperative terminal guidance and prospects for future advancements. Notably, the cooperative guidance law discussed in this study does not encompass scenarios involving "cooperative active defense". The main contributions of this review are given below.

(1) We conduct a bibliometric analysis of studies related to cooperative guidance in Scopus from 2006 to 2023, and used the CiteSpace application to derive insights. This analysis involves keyword clustering, keyword co-occurrence, and keyword bursting. These analytical results are used to summarize current achievements and outline future development trends.

(2) We present a comprehensive review of the principles of cooperative guidance, encompassing algebraic graph theory and multi-agent consensus theory. In addition, we examine different guidance structures in cooperative guidance, including open-loop, closed-loop, and space cooperation; moreover, we discuss convergence performance, including asymptotic convergence, finite-time convergence, fixed-time convergence, and prescribed-time convergence. A detailed analysis of current research findings is also presented, which highlights their respective advantages and disadvantages.

(3) In light of recent advancements in cooperative terminal guidance, a developmental framework is proposed based on five layers (cyber, physical, decision, information, and system), with a focus on networked, heterogeneous, integrated, intelligent, and group cooperations. This framework may provide insights for future research.

This review is organized as follows. In Section 2, a literature review using bibliometric analysis is conducted on recent research achievements in the field of cooperative guidance. Section 3 provides an overview of the fundamental theories underlying cooperative guidance laws. Section 4 summarizes the primary characteristics of modern cooperative guidance laws. In Section 5, future trends and insights are discussed. Finally, Section 6 provides the main conclusions.

2 Bibliometric analysis of cooperative guidance laws

In this section, we used CiteSpace to conduct a bibliometric study of the field of cooperative guidance. CiteSpace is a freely available Java-based tool for visualizing and analyzing trends and patterns in scientific literature, particularly in the domain of academic citations (Chen and Lee, 2021; Wang YN et al., 2022; Bamisile et al., 2023; Cao et al., 2023; Mao et al., 2024). Specifically, this involved analysis of keyword clustering, keyword co-occurrence, and keyword burst to summarize prevailing research trends.

2.1 Keyword clustering

A keyword clustering map indicates the degree of inclusion of keywords in each cluster, with smaller numbers indicating higher levels of inclusion. Each cluster contains closely related keywords, and we used the cluster with the highest number of keywords to analyze the status of current research. The Q-value is a measure of the clustering modularity and is generally deemed significant if $Q\geqslant 0.3$. The S-value is the average silhouette score of the clustering. It is considered reasonable if $S\geqslant 0.5$ and reliable if $S\geqslant 0.7$ (Chen et al., 2020; Duan et al., 2022; Sood et al., 2024).

Fig. 2 depicts our clustering analysis for the field of cooperative guidance. We identified 21 main clusters, numbered from #0 to #20. Each cluster is represented by a different color and labeled with a key phrase, indicating a specific research area or concept within the field of cooperative guidance. Cluster labels are assigned numerical values ranging from #0 to #20, with larger numbers indicating fewer keywords within the cluster and smaller numbers indicating a greater number of keywords. Specifically, these clusters can be classified into four categories.

(1) Central theme. Cluster #0, labeled "cooperative guidance", is the largest and most centrally positioned cluster. Its size and position indicate that it is a core concept around which the entire research field is organized. This centrality suggests that most other topics in the field are in some way connected to or derived from cooperative guidance principles.

(2) Major research areas. Several large clusters represent major research areas within the field:

#1 Impact time control. This cluster deals with techniques for controlling the time at which multiple missiles reach their targets.

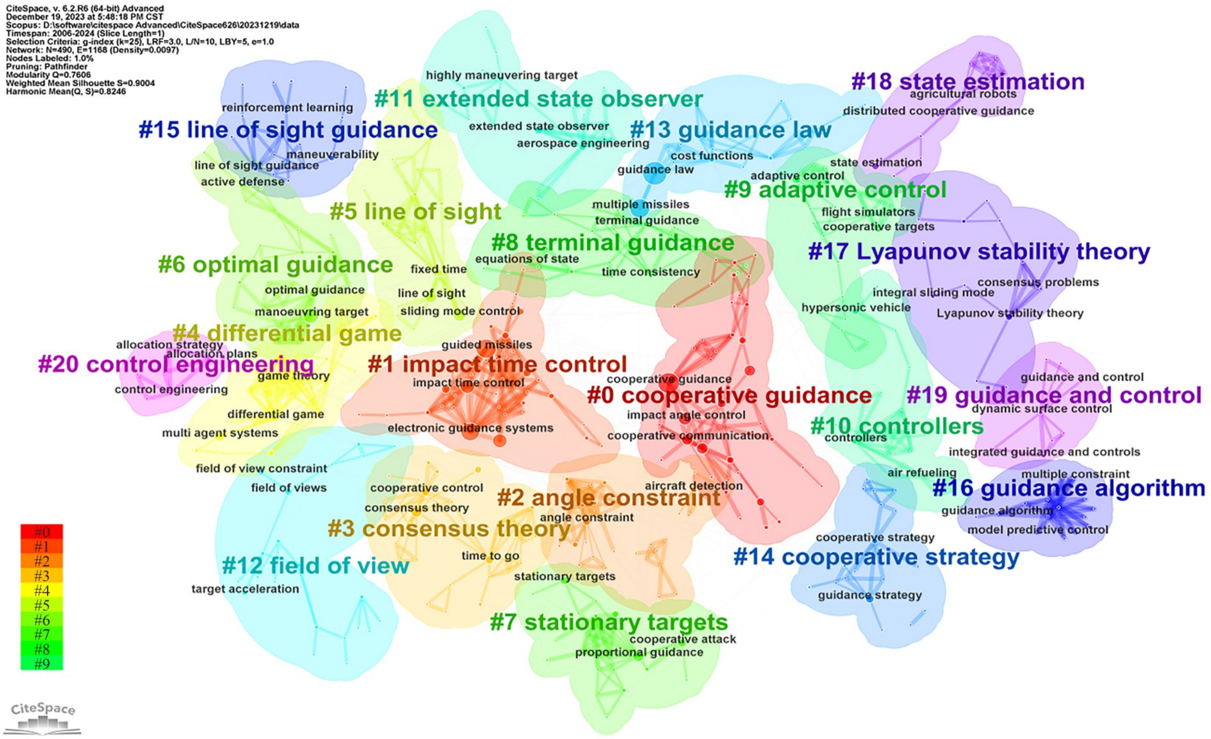


Fig. 2 Keyword clustering map of cooperative guidance law research. References to color refer to the online version of this figure

#11 Extended state observer. This represents advanced control theory techniques for estimating system states.

#13 Guidance law. This cluster focuses on the algorithms and rules governing guidance systems.

#15 Line of sight guidance. This area deals with guidance methods based on maintaining a direct line of sight to the target.

#17 Lyapunov stability theory. This cluster represents the application of Lyapunov's mathematical theory to ensure stability in guidance systems.

(3) Interdisciplinary connections. These reveal the interdisciplinary nature of cooperative guidance research:

Control theory. It is evidenced by clusters like #9 adaptive control, #10 controllers, and #20 control engineering.

Mathematics. It is represented by #4 differential game and #17 Lyapunov stability theory.

Aerospace engineering. It is implied by terms like "aerospace engineering" and "aircraft detection" within various clusters.

(4) Theoretical foundations. The map highlights important theoretical concepts underpinning the field:

#3 Consensus theory. It mainly deals with consensus protocols in multi-agent systems.

#4 Differential game. It is a mathematical approach to modeling conflict and cooperation.

#5 Line of sight. It is a fundamental concept in guidance and tracking.

2.2 Keyword co-occurrence

The temporal evolution of keyword distribution in cooperative guidance research can be visually analyzed through time co-occurrence analysis, which is crucial for showcasing dynamic frontiers and making predictions about future developments. Based on Figs. 2 and 3, the results of this analysis can be summarized in four aspects:

(1) Evolution of research focus. The visualization reveals a clear evolution in the field of cooperative guidance from 2005 to 2024. Earlier research (indicated by cooler colors) centered on fundamental concepts like "line of sight" (#5) and "optimal guidance" (#6). Over time, the field has progressed towards more advanced and specialized topics, as evidenced by the warmer-colored nodes representing recent research interests such as "impact time control" (#1),

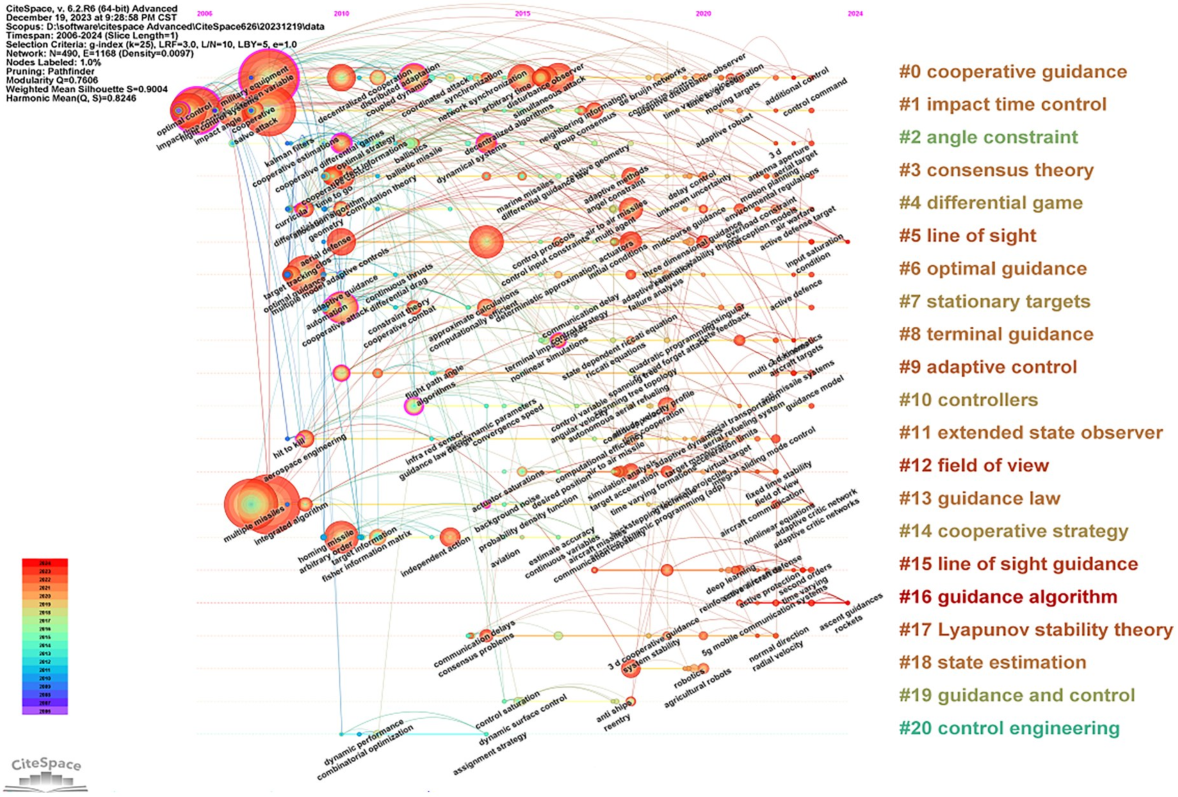


Fig. 3 Keyword co-occurrence time map of cooperative guidance law. Using years as the horizontal axis, keywords can be presented based on their first appearance in different time periods. References to color refer to the online version of this figure

"extended state observer" (#11), and "cooperative strategy" (#14). This shift indicates a maturation of the field, moving from basic principles to more sophisticated and application-specific approaches.

(2) Interdisciplinary integration and theoretical foundations. The dense network of interconnections between different clusters highlights the interdisciplinary nature of cooperative guidance research. Core concepts in cooperative guidance are closely linked with theories from control engineering (e.g., "adaptive control" #9, "Lyapunov stability theory" #17) and mathematics ("differential game" #4). This integration has remained consistent over time, suggesting that the field continually draws upon and contributes to these related disciplines, fostering a rich and multifaceted research environment.

(3) Emerging trends and future directions. By analyzing the more recent (warmer-colored) nodes and their connections, we can identify emerging trends and potential future research directions. Clusters such as "guidance algorithm" (#16) and "cooperative strategy" (#14) appear to have gained prominence in recent years. These trends suggest a growing emphasis on advanced computational methods and strategic decision-making in cooperative guidance systems. Additionally, the persistent relevance of "impact time control" (#1) across the timeline indicates its ongoing importance and potential for further development.

(4) Application diversity and practical focus. Throughout the time period, there is a consistent presence of application-oriented clusters such as "terminal guidance" (#8), "stationary targets" (#7), and other control-related topics. This persistence, coupled with the emergence of more specialized concepts over time, indicates that the field maintains a strong focus on practical applications, refining and expanding existing methodologies to address challenges in guidance and control systems.

2.3 Keyword burst

Keyword burst analysis is typically utilized to investigate sudden spikes in usage frequency of certain keywords, enabling the exploration of dynamic concepts and research inquiries in a particular field (Che et al., 2022; Li Y et al., 2023). As shown in Fig. 4, by identifying the top 20 keywords with the highest citation burst strengths, we draw the following conclusions:

(1) Broad and interconnected research scope. The burst analysis confirms the wide-ranging nature of cooperative guidance research, as mentioned in the sourced literature. The diversity of keywords, spanning from "automation" and "unmanned vehicles" to "ballistics" and "multi-agent systems", underscores the interdisciplinary character of the field. The persistent relevance of "missile guidance", "unmanned vehicles", and "multiple missiles" throughout the 2006–2024 period corroborates their foundational importance, as highlighted in the sourced literature.

(2) Significant breakthroughs and hot topics. The burst strength indicates the intensity of research interest during specific periods:

The keyword "Multiple missiles" shows the highest burst strength (7.01) from 2014 to 2017, confirming its status as a leading research topic, as noted in the reference text.

Recent strong bursts in "fixed time" (5.52) and "line of sight" (5.56) from 2021 to 2024 support the sourced literature's identification of these as current research hotspots.

(3) Shift in research priorities. The burst analysis supports the reference text's observation about the shift in research focus:

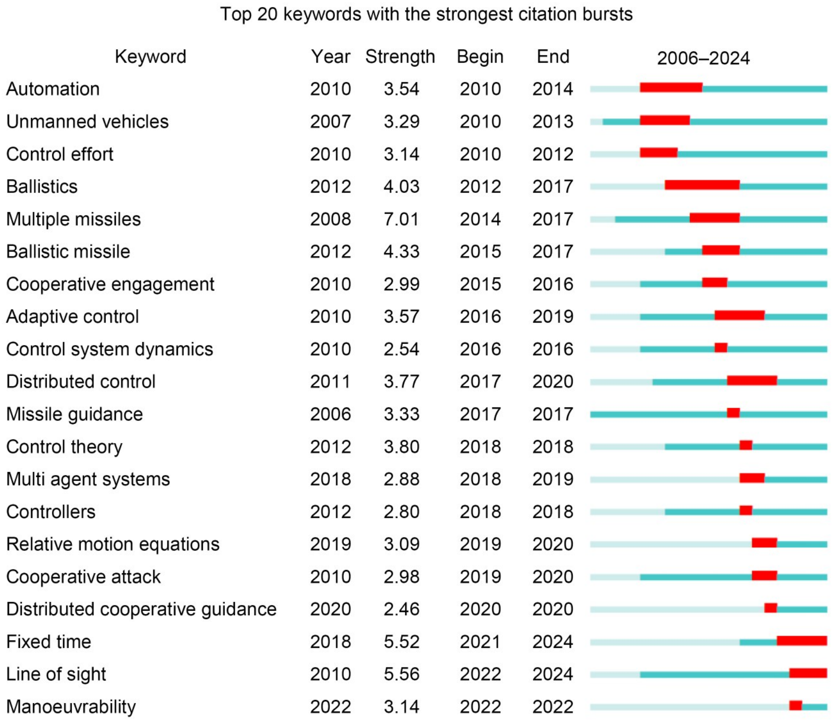
Earlier bursts in "control effort" and "ballistics" (2010–2017) align with the initial emphasis on impact time and angle constraints.

Later bursts in "distributed control" and "adaptive control" (2016–2020) suggest a transition towards guidance performance constraints.

The most recent bursts in "distributed cooperative guidance", "fixed time", and "maneuverability" (2020–2024) confirm the current focus on advanced cooperative guidance concepts for complex scenarios.

(4) Persistent themes. While the research focus has evolved, certain themes show persistent relevance throughout the period, such as "missile guidance" and "cooperative attack", indicating their enduring importance in the field.

In conclusion, this CiteSpace visualization provides a comprehensive overview of the cooperative guidance research landscape. It underscores the central importance of cooperative guidance techniques and highlights the field's interdisciplinary nature. Additionally, it reveals both established and emerging research directions. This map is valuable for researchers


Top 20 keywords with the strongest citation bursts

Keyword	Year	Strength	Begin	End	2006–2024
Automation	2010	3.54	2010	2014	
Unmanned vehicles	2007	3.29	2010	2013	
Control effort	2010	3.14	2010	2012	
Ballistics	2012	4.03	2012	2017	
Multiple missiles	2008	7.01	2014	2017	
Ballistic missile	2012	4.33	2015	2017	
Cooperative engagement	2010	2.99	2015	2016	
Adaptive control	2010	3.57	2016	2019	
Control system dynamics	2010	2.54	2016	2016	
Distributed control	2011	3.77	2017	2020	
Missile guidance	2006	3.33	2017	2017	
Control theory	2012	3.80	2018	2018	
Multi agent systems	2018	2.88	2018	2019	
Controllers	2012	2.80	2018	2018	
Relative motion equations	2019	3.09	2019	2020	
Cooperative attack	2010	2.98	2019	2020	
Distributed cooperative guidance	2020	2.46	2020	2020	
Fixed time	2018	5.52	2021	2024	
Line of sight	2010	5.56	2022	2024	
Manoeuvrability	2022	3.14	2022	2022	

Fig. 4 Keyword burst map of cooperative guidance law. "Begin" denotes the year of the sharp increase in the core theme; "End" indicates the year of its rapid decline; "Strength" reflects the citation burst strength

seeking to understand the current state of the field, identify potential areas for cross-disciplinary collaboration, and recognize emerging trends for future research.

Remark 1. Guidance involves determining the maneuvering commands to steer the vehicle along a trajectory that meets specified terminal or targeting conditions and other relevant constraints, such as impact time, impact angle, and acceleration, while also optimizing performance (Lee et al., 2013; Hu et al., 2019; Lu, 2021; Chen et al., 2022; Zhang WQ et al., 2022; Kang et al., 2024). Therefore, our bibliometric analysis of cooperative guidance laws indicates that the development of control theory is also promoting advancements in cooperative guidance, with both reinforcing each other. In addition, the continuous evolution of target characteristics also contributes to the advancement of cooperative guidance to an extent.

Remark 2. A framework describing the development and basic characteristics of the cooperative guidance research field was established through CiteSpace analysis. Subsequent sections will provide a detailed analysis of the fundamental theories and inherent features of cooperative guidance.

3 Fundamental theories of cooperative guidance laws

In this section, we will focus on the fundamental theories of cooperative guidance, including relative motion modeling methods, algebraic graph theory, and multi-agent consensus theory.

3.1 Modeling

This study presents a framework modeling approach for cooperative guidance in a 2D space, utilizing the coordinate system shown in Fig. 5 as a reference. Currently, the majority of cooperative guidance models are based on kinematic analysis methods and are governed by the following assumptions:

Assumption 1. Both the missiles and the target are considered to be ideal point masses (Zhao and Zhou, 2015; Li et al., 2020).

Assumption 2. The response of the guidance system is assumed to be sufficiently quick relative to the missile's dynamics (Ma et al., 2021; An et al., 2022).

A total of n (where $n \geqslant 2$) missiles are assumed to participate in the process of cooperative guidance.

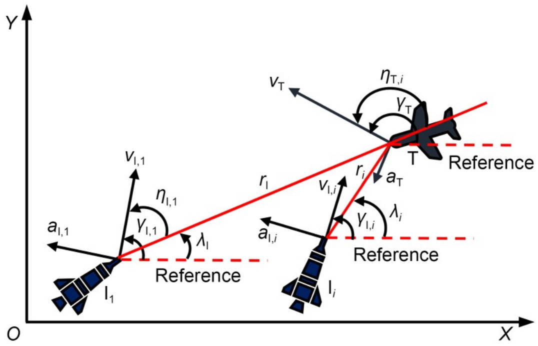


Fig. 5 Relative motion of the missiles and the target

Therefore, according to Fig. 5, the relative motion relationship between the missiles and the target can be described as:

$$\dot{r}_i = v_\mathrm{T}\cos\eta_{\mathrm{T},i} - v_{\mathrm{I},i}\cos\eta_{\mathrm{I},i}, \tag{1}$$

$$r_i\dot{\lambda}_i = v_\mathrm{T}\sin\eta_{\mathrm{T},i} - v_{\mathrm{I},i}\sin\eta_{\mathrm{I},i}, \tag{2}$$

$$\eta_{\mathrm{I},i} = \gamma_{\mathrm{I},i} - \lambda_i, \tag{3}$$

$$\eta_{\mathrm{T},i} = \gamma_\mathrm{T} - \lambda_i, \tag{4}$$

$$\dot{\gamma}_{\mathrm{I},i} = \frac{a_{\mathrm{I},i}}{v_{\mathrm{I},i}}, \tag{5}$$

$$\dot{\gamma}_\mathrm{T} = \frac{a_\mathrm{T}}{v_\mathrm{T}}, \tag{6}$$

where 'I' and 'T' denote the missile and target, respectively; the subscript i denotes the ith missile; γ and η denote the path and leading angles, respectively; r and λ denote the relative range and line-of-sight (LOS) angle, respectively; v and a denote the speed and normal acceleration command, respectively.

In general, the primary goal of cooperative guidance is to design the guidance command $a_{\mathrm{I},i}$ to ensure that multiple missiles can simultaneously attack the target, while also considering specific constraints, such as the impact angle and field-of-view (FOV) angle. Generally, the cooperative guidance objective can be expressed as follows:

$$\begin{cases} r_i(t_\mathrm{f}) \to 0, \\ \dot{\lambda}_i(t_\mathrm{f}) \to 0, \end{cases} \quad \forall i \in \mathbb{N}^+, \tag{7}$$

where t_f is the final engagement time.

Remark 3. Typically, the constraint of impact angle in cooperative guidance problems is converted to an LOS angle constraint at the time of attack/interception to ensure that the LOS angle meets the following requirement:

$$\lambda_i(t_\text{f}) = \lambda_{i,\text{d}}, \tag{8}$$

where $\lambda_{i,\text{d}}$ denotes the desired LOS angle constraint of the ith missile (Lee et al., 2007; Dong et al., 2022; You et al., 2023; Zhang et al., 2023).

3.2 Algebraic graph theory

The communication network topology between the multiple missiles involved in the cooperative guidance system can be described using a graph $G=(\upsilon, \varepsilon, A)$ (Olfati-Saber and Murray, 2004; Ren and Cao, 2010; Wang and Xiao, 2010; Chen Q et al., 2021; Yi et al., 2021). The set $\upsilon=\{1, 2, \cdots, n\}$ represents the nodes in the communication network topology. $\varepsilon\subset\upsilon\times\upsilon=\{(i, j):i, j\in\upsilon\}$ represents the connectivity between nodes. The matrix $A=[a_{i,j}]\in\mathbb{R}^{n\times n}$ $(i, j=1, 2, \cdots, n)$ is the adjacency matrix that defines the weights associated with the connections between nodes. If node i can receive information from node j, then $a_{ij}>0$. Conversely, if node i cannot receive information from node j, then $a_{ij}=0$. Notably, $a_{ii}>0$.

The graph G can typically be categorized as either undirected or directed, based on the connection relationship between nodes (Fig. 6). An undirected graph G_u is characterized by $a_{ij}=a_{ji}$, which indicates that both nodes i and j receive information from each other. Moreover, if G_u is an undirected graph and there exists at least one path between any two nodes, then the entire graph is connected. Conversely, a directed graph G_d is represented by the existence of a pair of nodes i and j, such that $a_{ij}\neq a_{ji}$. Consequently, if there is at least one directed path between any two nodes, the entire graph is strongly connected.

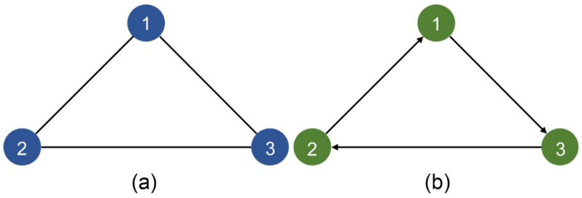


Fig. 6 (a) Undirected graph; (b) directed graph

3.3 Multi-agent consensus theory

Multi-agent consensus theory refers to the process in which multiple agents interact with each other through a communication network, gradually achieving a state of consensus. This plays an important role in cooperative guidance. This subsection provides a brief introduction to the models and relevant lemmas involved in cooperative guidance laws for the first- and second-order multi-agent systems.

3.3.1 Consensus of first-order multi-agent systems

Assuming a first-order multi-agent system composed of n agents, the dynamical model of each agent can be expressed as follows:

$$\dot{\xi}_i(t) = u_i(t), \quad i=1, 2, \cdots, n, \tag{9}$$

where t denotes the time, $\xi_i\in\mathbb{R}^n$ is the state of the ith agent, and $u_i\in\mathbb{R}^n$ is the control input governed by the consensus algorithm.

Remark 4. Notably, ξ_i represents the position or speed of the ith agent, and u_i represents the speed or acceleration of the ith agent.

Lemma 1 (Wang and Xiao, 2010). For any initial conditions, the control input u_i guarantees the system (Eq. (9)) to achieve

$$\lim_{t\to\infty} |\xi_i - \xi_j| = 0, \tag{10}$$

with

$$u_i(t) = -\sum_{j=1}^{n} a_{ij}(\xi_i(t) - \xi_j(t)). \tag{11}$$

Consequently, the system (Eq. (9)) is capable of achieving asymptotic consistency under the control input u_i.

3.3.2 Consensus of second-order multi-agent systems

Assuming a second-order multi-agent system composed of n agents, the dynamical model of each agent can be expressed as follows:

$$\begin{cases} \dot{\xi}_i(t) = \omega_i(t), \\ \dot{\omega}_i(t) = u_i(t), \end{cases} \quad i=1, 2, \cdots, n, \tag{12}$$

where $\xi_i\in\mathbb{R}^n$ denotes the position of the ith agent, $\omega_i\in\mathbb{R}^n$ represents the speed of the ith agent, and $u_i\in\mathbb{R}^n$ is the control input governed by the consensus algorithm.

Lemma 2 (Mei et al., 2013). For any initial conditions, the control input u_i guarantees the system (Eq. (12)) to achieve:

$$\begin{cases}\lim\limits_{t\to\infty}|\xi_i-\xi_j|=0,\\ \lim\limits_{t\to\infty}|\omega_i-\omega_j|=0.\end{cases} \tag{13}$$

Consequently, the system (Eq. (12)) is capable of achieving asymptotic consistency under the control input u_i.

4 Main characteristics of cooperative guidance laws

In this section, we summarize and analyze current developments, classifications, and advantages and disadvantages of cooperative guidance laws, considering their cooperative structure and convergence performance.

4.1 Cooperative structure

Cooperative guidance involves the cooperation of participating missiles, and so effective communication between them is of great importance. This communication enables the exchange of information from various units, whether online or offline, to achieve overall coordination. Considering the various communication methods used among the participating missiles, cooperative guidance structures can be categorized into three types: open-loop, closed-loop, and space cooperation (Zhao and Zhou, 2015; Simplício et al., 2018; Wang YY et al., 2020).

4.1.1 Open-loop

Open-loop cooperative guidance refers to the calculation of guidance commands for each missile based on an offline information exchange. Since there are no means of communication between missiles after launch, and their positions, speeds, attitudes, and other information are relatively independent (Zhao and Zhou, 2015; Jiang et al., 2018), the objective of open-loop cooperative guidance is to ensure simultaneous attacks by each missile; this is also known as impact time control guidance (ITCG) (Kumar and Ghose, 2015; Gutman, 2017; Hu et al., 2019; Kim et al., 2019).

Jeon et al. (2006) conducted the first investigation on the ITCG problem. They utilized proportional navigation guidance (PNG) as the fundamental term and combined it with feedback regarding the impact time error to achieve simultaneous attacks on a naval ship at the desired impact time. Based on this methodology, they introduced the impact angle error into the guidance command to ensure that multiple missiles attack the target simultaneously, and also meet given angle constraints (Lee et al., 2007). This approach is referred to as the impact time angle control guidance (ITACG) (Harl and Balakrishnan, 2012; Erer and Tekin, 2016; Zhu et al., 2019; Wang PY et al., 2022).

Inspired by studies in (Jeon et al., 2006; Lee et al., 2007), Xu et al. (2020) proposed two open-loop cooperative guidance laws. The first was derived from the conventional PNG law, with the navigation gain determined as a function of the time error. This error was defined as the difference between the designated impact time and the estimated time-to-go of the missile. The second was proposed based on the existing ITCG laws while considering an initial leading angle. Sinha et al. (2021) utilized the sliding mode control (SMC) technique to extend the ITCG problem to a 3D scenario. They also introduced a resource allocation technique that offered flexibility in allocating the necessary lateral acceleration to the pitch and yaw planes. This cooperative guidance law was implemented in an event-triggered fashion, with the objective of decreasing resource utilization while also ensuring satisfactory closed-loop performance of the guidance strategies.

For maneuvering targets, Zhang et al. (2013) formulated the ITCG problem by tracking the designated time-to-go as the actual time-to-go of a missile. Subsequently, they constructed a biased PNG law with a designated heading angle constraint, capable of achieving both impact time and angle constraints. Their proposed guidance scheme exhibited superior performance in comparison with the study conducted in (Lee et al., 2007), particularly for a moving or maneuvering target. Zhao and Zhou (2015) developed a unified cooperative strategy for the salvo attack of multiple missiles that are targeting maneuvering targets. A relatively simple guidance command was designed, encompassing a PNG component for target capture and a cooperative unit for simultaneous arrival.

For open-loop cooperative guidance, accurately calculating the remaining flight time for each missile is crucial. The ITCG and ITACG guidance laws commonly require linearization of the guidance model to obtain closed-loop solutions and feedback terms related to errors in the remaining flight time. In addition, there is no information exchange between the missiles during the engagement process. However, because of the cumulative effect of errors caused by linearization and disturbances during flight, inaccurate calculation of the remaining flight time can result in poor cooperative performance. The typical calculation methods for the remaining flight time are given by:

$$t_{\mathrm{go},i}^{(1)}=\frac{r_i}{v_{\mathrm{I},i}}\left[1+\frac{\eta_i^2}{2(2N-1)}\right], \tag{14}$$

$$t_{\mathrm{go},i}^{(2)}=-\frac{r_i}{\dot{r}_i}, \tag{15}$$

where N denotes the navigation coefficient.

Remark 5. Indeed, the calculation method in Eq. (14) is typically used for stationary targets, and it considers the effect of small leading angles on estimating time, thereby improving the accuracy of the estimation. However, the accuracy of this method decreases significantly when the leading angle is large (Jeon et al., 2010; Zhou and Yang, 2016; Sinha and Kumar, 2020). In contrast, the calculation method in Eq. (15) is suitable for low-speed and weakly maneuverable targets, and it provides high precision only when the relative closing speed between the missile and target is approximately constant. It has lower accuracy when applied to high-speed and highly maneuverable targets, and has significant limitations in practical applications (Zarchan, 2012; Zhou and Yang, 2016; Sinha and Kumar, 2020).

The open-loop cooperative structure is characterized by each missile, which determines its desired parameters offline. These desired parameters serve as the sole connections between missiles during flight, and are not updated online. The lack of online adaptation means that none of the missiles are able to adjust their overall states based on information from the other missiles during flight, which results in a lack of robustness in the cooperative guidance system.

Remark 6. The previous remark on the poor robustness of the open-loop cooperative structure is from the perspective of the entire missile formation, and describes the effectiveness of overall cooperation. Notably, each individual missile has relatively strong robustness in its own guidance law.

Remark 7. In general, open-loop cooperative guidance achieves cooperation using only offline parameters. It involves multiple separate task executions and does not demonstrate inter-project information exchange and cooperation.

4.1.2 Closed-loop

Closed-loop cooperative guidance emphasizes the transmission, sharing, and complementarity of information among missiles (Zhao and Yang, 2018; Yan PP et al., 2020; Zhang et al., 2021; Dong et al., 2023; Yang et al., 2024). The structure of this guidance system falls into two categories: centralized and distributed cooperative guidance.

4.1.2.1 Centralized mode

As shown in Fig. 7, in a centralized mode, the status information for all participating missiles is sent to a central coordinating unit, where it is combined into a unique coordination message and distributed to all the entities involved. The central coordinating unit can be a ground station, an early warning aircraft, a missile within the missile formation, or even a computational unit within a single missile. The most significant feature of centralized cooperative guidance is that the central coordinating unit configures and distributes the cooperative information to all entities, thereby ensuring consistent timing and angular constraints and achieving a unified state for the missile formation.

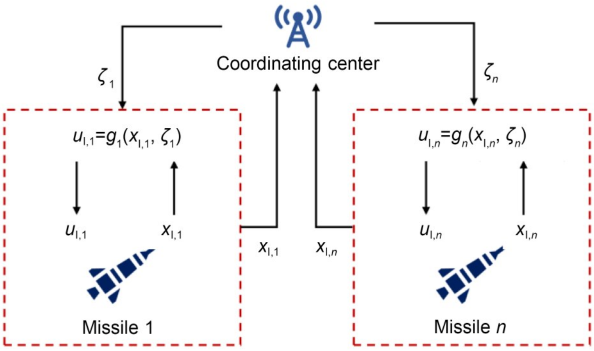


Fig. 7 Centralized cooperative guidance mode. ζ_i (i=1, 2, ⋯, n) denotes the cooperation information; g_i denotes the guidance system of the ith missile; $x_{\mathrm{I},i}$ denotes the state variable of the ith missile

The typical representatives of the centralized cooperative guidance mode primarily include two-level (Zhao and Zhou, 2008a, 2008b) and leader-follower cooperative guidance (Wang XL et al., 2015; Li GF et al., 2020; Sinha and Kumar, 2020; Wang ZK et al., 2022; Li and Zuo, 2023; Tan and Shen, 2024). Zhao and Zhou (2008a, 2008b) proposed a cooperative guidance law comprised of a two-level architecture. The first level incorporated the concept of the ITCG law, whereas the second architecture utilized a centralized cooperative algorithm to ensure that multiple missiles reach the target simultaneously. Sinha and Kumar (2020) proposed a leader-follower cooperative salvo guidance strategy for attacking non-maneuvering targets. They leveraged the advantages of the super-twisting SMC method in their approach. In addition, an improved estimate of time-to-go was used in the guidance law design, which did not assume a small heading angle for the interceptor. This modification ensured the effectiveness of the guidance strategy for an interceptor with a large initial heading. This strategy offered robustness against uncertainties and a smoother control signal, while achieving finite-time convergence of the error.

Xu et al. (2023) analyzed the local communication topology between a group of missiles and established a leader-follower cooperative communication model. Furthermore, they introduced a neutral operator to the guidance law, and, based on Lyapunov theory, investigated the asymptotic stability of the cooperative guidance model with a constant time delay. Similarly, Li et al. (2020) presented a leader-follower cooperative guidance strategy for achieving fixed-time synchronization, ensuring that missiles reached their target simultaneously. The guidance law for the leader was designed to meet the requirement of a specific impact time. To synchronize the arrival time, the ranges-to-go of the followers were enforced to maintain consensus with those of the leader. Notably, this proposed leader-following cooperative guidance law guarantees convergence within a fixed time frame, independent of the initial states. On this basis, Li and Zuo (2023) further focused on false-data injection attacks (FDIAs). The guidance goal was for both the leader and the followers to reach a designated target at a specific impact time, where only the leader had access to the command for the impact time. Furthermore, they introduced a distributed observer for each follower to estimate the leader's remaining flight time. By implementing the proposed distributed observer-based cooperative guidance law, the leader and the followers achieved simultaneous arrival even in the presence of FDIAs.

For maneuvering targets, Wang ZK et al. (2022) developed a prescribed-time cooperative guidance scheme for leader-following missiles that are attacking maneuvering targets. This guidance law incorporated a variable LOS angle constraint and enabled arbitrary setting of state error convergence times. Based on game theory, Tan and Shen (2024) transformed the problem of cooperative guidance for multiple missiles into a pursuit-evasion game in a cooperative engagement scenario. They determined the leader's differential game guidance law by integrating optimal control theory, while the follower's cooperative guidance law was established to enable a simultaneous attack on the target with an impact angle constraint, utilizing a predictive control model and the SMC method. This approach stands in contrast to methods that use time-to-go as the coordinated variable, and demonstrates potential for superior performance.

An overall description of the leader-follower cooperative guidance mode is shown in Fig. 8. Unlike the open-loop cooperative guidance structure, this mode eliminates the need for predetermining the desired impact time. Instead, it continuously adjusts the coordination variables based on the leader's motion throughout the engagement. However, similar to the open-loop structure, this mode also suffers from the drawback of providing individual coordination information to each follower; thus, it fails to capture group information effectively and results in suboptimal coordination performance. In comparison, the two-level cooperative guidance mode allows for the selection of centralized coordination units as desired, and can have multiple coordination units, which enhances its robustness. Furthermore, in the two-level cooperative

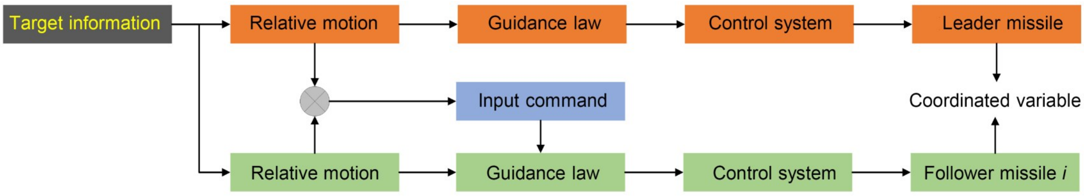


Fig. 8 Flowchart describing the leader-follower cooperative guidance mode

guidance mode, each missile can use the same or different guidance laws to achieve cooperation. However, in the leader-follower cooperative guidance mode, the guidance commands for the follower missiles need to include coordination information compared to the leader missile. Therefore, the guidance laws for the leader and follower missiles are different.

Remark 8. The leader-follower cooperative guidance mode can be considered as a specific case of the two-level cooperative guidance mode. This mode enhances real-time communication in the group and simplifies the guidance structure, although at the cost of reducing coordinated information processing.

In summary, centralized cooperative guidance requires an information exchange between a central coordination unit and individual followers. This mode has a simpler guidance design and obtains more comprehensive information, enabling effective and fast convergence to the desired values through guidance laws. In contrast, inherent communication difficulties in centralized cooperative guidance can hinder its effectiveness, particularly in the context of stealth attacks. Furthermore, if the central coordination unit only exists in one missile, the overall coordination will fail if the missile malfunctions, indicating poor robustness. However, centralized cooperative guidance offers benefits in terms of guidance design and information acquisition, and so its overall effectiveness must be carefully considered.

4.1.2.2 Distributed mode

Fig. 9 presents the structure of a distributed cooperative guidance mode system. It can be observed that this mode involves transmitting information between adjacent missiles in each volley, without consolidating the information in one central location. Despite the fact that the swarm state of the missile formation, as represented by a single missile, is not as comprehensive as centralized cooperative guidance, the sharing of state information can still be indirectly achieved through the interconnection of the communication network (Dong et al., 2020; Zhang Y et al., 2020; Chen ZY et al., 2021; Li et al., 2021a; Yang and Song, 2021; Xu SY et al., 2024; Zhang XL et al., 2024; Zhu et al., 2024). This finding signifies that each missile operates with an equal status, without the need for a centralized coordination unit.

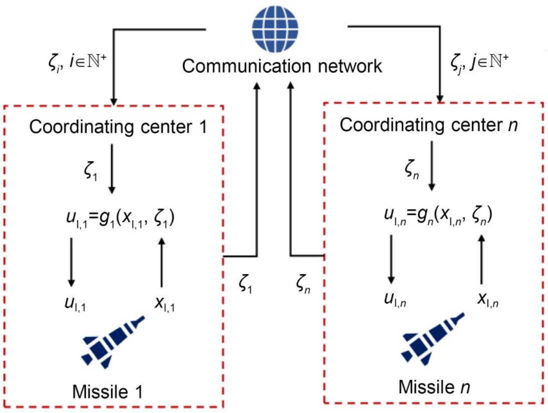


Fig. 9 Distributed cooperative guidance mode

The main representatives of the distributed cooperative guidance mode primarily include two-stage (He et al., 2018b; Ai et al., 2019; Dong et al., 2020, 2022; Zhang et al., 2020) and two-direction (Chen ZY et al., 2021; Zhang S et al., 2021; Zhang L et al., 2023) cooperative guidance. The term "two-stage" typically refers to a cooperative guidance process that can be divided into two stages. Fig. 10 presents a concise description of the two-stage cooperative guidance strategy. In the first stage, all missiles collectively achieve

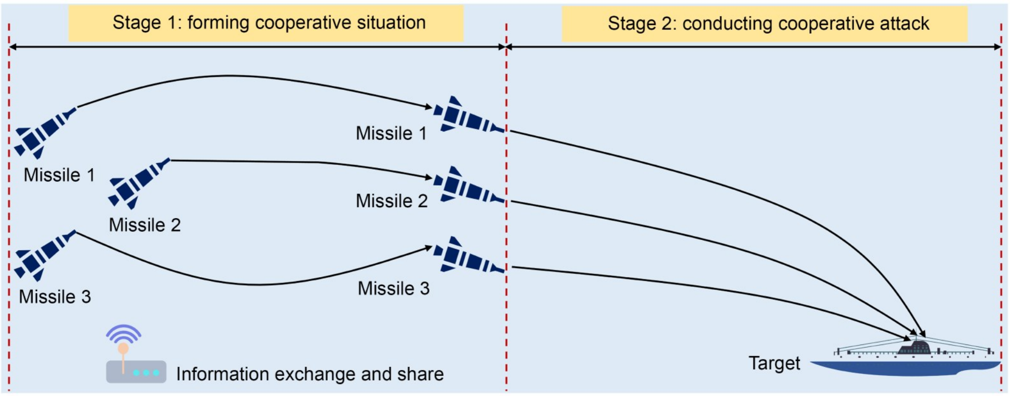


Fig. 10 Illustration of the two-stage cooperative guidance strategy

a specific cooperative state, in accordance with the consensus principle based on the communication network. Once this state is attained, multiple missiles proceed to the subsequent stages. In the second stage, all missiles commonly utilize PNG-based guidance strategies to perform the final cooperative attack. Notably, no communication exchange or sharing occurs during this stage. Currently, this cooperative scheme is commonly utilized for attacking stationary targets.

Remark 9. For the two-stage cooperative guidance strategy, although there is no requirement for information exchange in the second stage, the use of multiple missiles enables simultaneous arrival at the target because the guidance time is limited for a specific engagement process. After a cooperative situation is achieved, the remaining flight time of the missiles becomes relatively short. Consequently, the cooperative guidance goal can still be guaranteed.

Remark 10. In the second stage, there is usually a relatively short distance between the missiles and the target. At this point, the target typically takes certain measures to defend against the missiles, which affects their cooperative efficiency and performance. Therefore, it is reasonable that there is no information exchange and sharing between the missiles at this stage.

He et al. (2018b) used a two-stage guidance scheme to investigate a salvo attack. The first stage involved the design of a simple decentralized control law to offer the desired initial conditions for the second stage. In the second stage, all the missiles followed the pure PNG law. Zhang et al. (2020) developed a two-stage cooperative scheme for multiple interceptors attacking a stationary target, in consideration of dynamic and directed communication topologies. In the first stage, they applied an optimal consensus methodology with a predetermined timeline to obtain the desired initial conditions for the subsequent guidance phase. Ai et al. (2019) studied the two-stage cooperative guidance problem while considering constraints in the FOV angle. In the first stage, they combined the cooperative guidance problem, the state-tracking problem, and the field-of-view constraint within a unified optimal control framework. They also developed a nonquadratic, field-of-view constraint cost function through the application of inverse optimal control methodology. This approach resulted in an analytical, distributed, and optimal guidance law that enabled the generation of favorable initial conditions for the subsequent stages of the guidance process.

The “two-direction” cooperative guidance strategy divides the guidance system into two subsystems: one subsystem along the LOS direction and the other subsystem normal to the LOS direction (Chen ZY et al., 2021; Zhang S et al., 2021; Dong et al., 2022; Zhang L et al., 2023). This overall structure is shown in Fig. 11. In the LOS direction, the consensus principle is commonly used to achieve a simultaneous target engagement in the time dimension. In the direction normal to the LOS direction, various control methods were applied to nullify the LOS angular rate and ensure that multiple missiles cooperate in the spatial dimension. It is worth noting that most studies have considered the impact angle constraint in this direction. In general, based on Eqs. (1)–(6), the guidance models along and normal to the LOS directions in this strategy can be expressed as follows (You and Zhao, 2020; Liu SX et al., 2022a):

$$\begin{cases}\dot{x}_{1i}=x_{2i},\\ \dot{x}_{2i}=x_{1i}\dot{\lambda}_i^2+w_{\mathrm{r}i}-u_{\mathrm{r}i},\end{cases}\tag{16}$$

$$\begin{cases}x_{3i}=\dot{x}_{4i},\\ \dot{x}_{4i}=-\dfrac{2\dot{r}_i x_{4i}}{r_i}-\dfrac{u_{\mathrm{q}i}}{r_i}+\dfrac{w_{\mathrm{q}i}}{r_i},\end{cases}\tag{17}$$

with

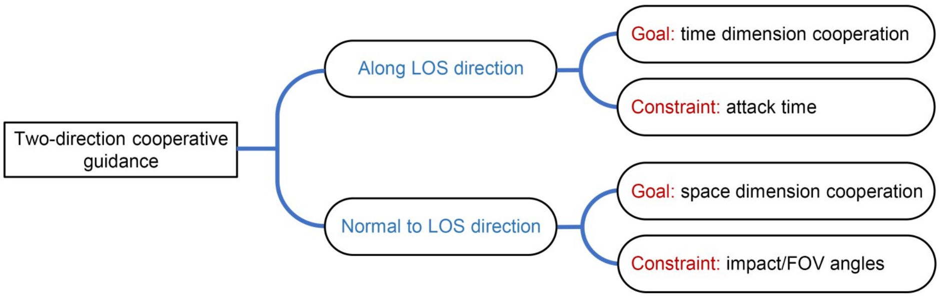


Fig. 11 Flowchart describing the two-direction cooperative guidance strategy

$$\begin{cases} w_{\mathrm{r}}=\dot{v}_{\mathrm{T}}\cos(\lambda_i-\gamma_{\mathrm{T}})+a_{\mathrm{T}}\sin(\lambda_i-\gamma_{\mathrm{T}}), \\ w_{\mathrm{q}}=-\dot{v}_{\mathrm{T}}\sin(\lambda_i-\gamma_{\mathrm{T}})+a_{\mathrm{T}}\cos(\lambda_i-\gamma_{\mathrm{T}}), \end{cases} \tag{18}$$

where $x_{1i}=r_i$, $x_{2i}=\dot{r}_i$, $x_{3i}=\lambda_i-\lambda_{i\mathrm{d}}$, and $x_{4i}=\dot{\lambda}_i$ denote the four state variables; $\lambda_{i\mathrm{d}}$ denotes the desired impact angle of the ith missile; w_{r} and w_{q} denote the external disturbances caused by the target's maneuvering along and normal to the LOS direction, respectively; $u_{\mathrm{r}i}$ and $u_{\mathrm{q}i}$ represent the guidance commands along and normal to the LOS direction of the ith missile, respectively.

Remark 11. For the terminal guidance process, the "two-direction" cooperative guidance strategy requires the missile to have the ability to adjust its speed, because the guidance command $u_{\mathrm{r}i}$ causes a change in speed along the LOS direction. Consequently, this will put high demands on the missile's engine. Currently, there appears to be limited potential for practical applications of this modification.

Researchers have utilized finite-time convergence theory to develop a cooperative guidance law that considers the constraints of impact time and angle (You and Zhao, 2020; Liu SX et al., 2022a). In addition, Zhang et al. (2021) further investigated this guidance strategy for intercepting a maneuvering target with and without a leader missile. Chen ZY et al. (2021) explored a cooperative guidance scheme based on fixed-time convergence theory, which ensures that the convergence time remains unaffected by the initial conditions. Furthermore, Zhang et al. (2023) introduced a novel nonsingular predefined-time sliding mode surface and an appointed-time extended state observer, to design a 3D appointed-time cooperative guidance law for multiple missiles. This approach guarantees that the convergence time of the guidance command falls within the predetermined guidance parameters.

In summary, the distributed cooperative guidance mode was intended to address the communication issues associated with the centralized cooperative guidance strategy, by enabling each missile to exchange information only with its neighboring units, and making it so that there is no need to access information from all other missiles. However, this approach may result in a slower speed of convergence for the states of all missiles, as the coordination information provided does not cover all missiles. In theory, achieving perfect consensus among all missiles would require an infinite amount of time. Therefore, in the research on distributed cooperative guidance, it is crucial to ensure cooperative consistency among each missile's state within a finite timeframe. As tasks become increasingly complex, missiles will face diverse and dynamic operational environments. Accordingly, robustness and scalability of the distributed cooperative guidance mode aid its broader applications.

4.1.3 Space cooperation

Recent studies have indicated that attacking missiles should have significantly higher lateral acceleration capability than their targets. This allows the missiles to outmaneuver their targets effectively, ensuring successful interception or engagement despite the targets' evasive maneuvers (Su et al., 2018; Xiao et al., 2020; Nasrollahi, 2023). Consequently, the demands for missile performance are high, and this results in increased complexity and higher development costs. However, advancements in high-speed, highly maneuverable targets have rendered the increased overload capacity and maneuverability of missiles less advantageous. As a result, the primary concern is to increase the interception probability of such targets while making optimal use of low-cost missiles to enhance individual missile performance. Under these circumstances, the cooperative interception of high-speed maneuvering targets is another critical issue to address. Accordingly, a new cooperative guidance structure, known as space cooperation guidance, is evolving to address these challenges.

The concept of "space cooperation" emphasizes the offensive/defensive cooperation strategy of multiple missiles in a way that leverages their individual spatial positions. This principle essentially transforms the cooperative guidance involving multiple missiles into an optimization problem, with the goal of maximizing the coverage area of maneuverability between the missiles and the target (Su et al., 2018, 2019; Yan XH et al., 2020; Liu SX et al., 2022b; Zhang BL et al., 2022; Cevher and Leblebicioğlu, 2023). In general, the physical attributes of a specific set of missiles and targets, such as their flight speed and available overload, are determined in advance and remain consistent throughout the engagement phase. Consequently, the boundaries of the maneuvering area between the missiles and the target can be established. Therefore, by developing efficient cooperative guidance strategies, it is possible to ensure that the combined maneuvering areas of each missile completely encompass the target's maneuvering area. This finding guarantees that at least one missile from the group can effectively hit the target.

As shown in Fig. 12, given certain missiles and a target, the maximum maneuvering area for each missile and target can be denoted as A_{F} and A_{E}, respectively. Therefore, reasonably designing the guidance law $a_{\mathrm{I},i}$ to satisfy the constraint of Eq. (19) ensures that, regardless of how the target maneuvers, at least one missile will be able to successfully hit the target. This constraint is given by:

$$\bigcup(A_{\mathrm{F},1},\ A_{\mathrm{F},2},\ \cdots,\ A_{\mathrm{F},n}) \supset A_{\mathrm{E}}, \quad i=1,\ 2,\ \cdots,\ n. \tag{19}$$

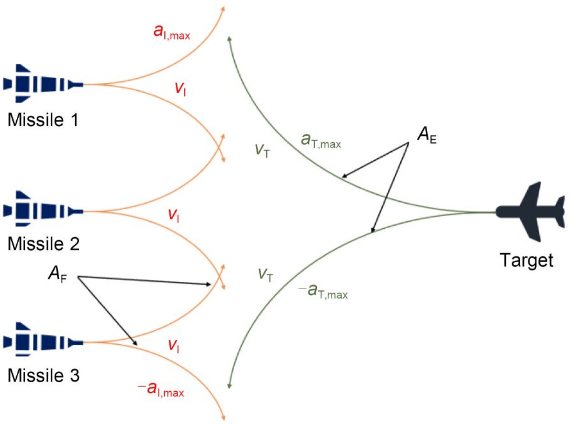


Fig. 12 Illustration of the space cooperative guidance structure ($a_{\mathrm{I,max}}$ and $a_{\mathrm{T,max}}$ denote the maximum maneuverabilities of the missile and target, respectively)

Using this concept, Su et al. (2018, 2019) introduced a cooperative guidance strategy based on coverage to intercept a highly maneuverable target using multiple lesser-performing missiles. The scenario assumes that the missiles and target have limited maneuverability, and the objective is to ensure that the collective reachable field of the missile team cooperatively envelops the target's maneuvering area. Zhang BL et al. (2022) conducted further research on the cooperative coverage strategy. Their method considered the acceleration capabilities of the target, as opposed to its final lateral position. This approach enabled them to circumvent the linearization error of guidance models and shifted the focus of a coverage-based strategy towards tracking a desirable flight path angle. Cevher and Leblebicioğlu (2023) developed a unique cooperative and predictive guidance law for the interception of high-speed and highly maneuverable targets using inferior missiles; their approach involved predicting target states in the form of a probability density function, using limited information about the target. Liu SX et al. (2022b) proposed a coverage-based cooperative guidance law for intercepting hypersonic vehicles from a low-speed ratio perspective, considering the missile's available overload constraints. They also determined the optimal number of missiles required for this engagement process. Considering the limits of the target's maneuverability, Yan XH et al. (2020) conducted a reachability analysis to examine its engagement geometry. Subsequently, they devised a cooperative strategy with the objective of creating favorable engagement conditions, by encompassing the target's reachable area within the combined reachable areas of the missiles. This approach enables the interception of a highly maneuverable target despite using missiles of lower capabilities.

Compared with open-loop and closed-loop cooperative guidance structures, space cooperative guidance has two main distinguishing features:

(1) Different cooperative goals. Unlike the emphasis on multiple missiles attacking the target simultaneously (as in traditional structures), space cooperative guidance focuses on establishing a specific cooperative situation spatially. For high-speed and maneuvering targets, the principle of momentum suggests that a successful attack by a single missile is both effective and sufficiently deadly. It is evident that this guidance structure places a higher value on the probability of a cooperative attack, and it aims to maximize each missile's combat efficiency.

(2) Different cooperative strategies. As illustrated in Fig. 12, space cooperative guidance converts the cooperative guidance problem into an optimization of the coverage of the maneuvering regions of all the missiles over the target's maneuvering area. Usually, there is not much requirement for information sharing or exchange between missiles throughout the engagement process, which may help reduce communication burden and cost to a certain extent.

In summary, the three primary cooperative guidance structures possess unique features, and a summary of these structures is presented in Table 1. The specific cooperative guidance scheme should be determined based on the actual target characteristics and operational scenarios.

Table 1 Summary of the main cooperative guidance structures (the greater the number of "⋆" in the last column of the table, the more robust the structure)

Cooperative guidance structure	Characteristic	Cooperative guidance mode	Representative	Reference	Robustness
Open-loop	Each missile independently determines its desired coordination parameters without any communication, leading to poor overall cooperative performance	Impact time control	ITCG	Jeon et al. (2006); Kumar and Ghose (2015); Gutman (2017); Hu et al. (2019); Kim et al. (2019)	Single ⋆⋆⋆
			ITACG	Harl and Balakrishnan (2012); Erer and Tekin (2016); Zhu et al. (2019); Wang PY et al. (2022)	Swarm ⋆
Closed-loop	Effective exchange and sharing of information between missiles are essential for achieving cooperation	Centralized	Two-level	Zhao and Zhou (2008a, 2008b)	⋆⋆
			Leader-follower	Li et al. (2020); Sinha and Kumar (2020); Wang ZK et al. (2022); Li and Zuo (2023); Tan and Shen (2024)	⋆⋆⋆
		Distributed	Two-stage	He et al. (2018b); Ai et al. (2019); Zhang et al. (2020)	⋆⋆⋆
			Two-direction	Chen ZY et al. (2021); Zhang et al. (2021, 2023); Dong et al. (2022)	⋆⋆⋆
Space cooperation	An optimal number of missiles can be achieved, but this scheme necessitates a higher demand on the initial conditions of the missiles	Attack/interception space coverage		Su et al. (2018, 2019); Yan XH et al. (2020); Zhang BL et al. (2022); Cevher and Leblebicioğlu (2023)	⋆⋆

4.2 Convergence performance

The convergence performance of cooperative guidance in a closed-loop structure differs depending on the network's convergence capabilities, specifically the different consensus principles. Currently, there are four primary modes of convergence performance for cooperative guidance: asymptotic (He et al., 2018a, 2018b; Wu et al., 2021), finite-time (Kumar and Mukherjee, 2020; Zhang et al., 2021; An et al., 2022), fixed-time (Chen ZY et al., 2021; Dong et al., 2022; You et al., 2023), and prescribed-time (Zhang et al., 2020; Ma et al., 2021; Wang ZK et al., 2022; Wu et al., 2024) convergence. A concise introduction to these four modes is given below.

4.2.1 Asymptotic convergence

Asymptotic convergence refers to a scenario in which the system's state variables converge to consensus as the time approaches infinity, which leads to cooperative behavior (Ko and Zuazua, 2020; Abdelhedi et al., 2024). The commonly used consensus principle for asymptotic convergence performance is shown in Eq. (11). However, in time-sensitive problems, such as cooperative guidance with multiple missiles, this convergence rate is insufficient. This limitation is particularly evident in the terminal guidance phase, which may be quite brief. Consequently, the asymptotic convergence of coordination variables among multiple missiles lacks practical utility.

4.2.2 Finite-time convergence

Finite-time convergence refers to the state or output of a system reaching a specific target value or stable state within a finite amount of time (Shin et al., 2017; Ding et al., 2024; Zhan et al., 2024). Unlike traditional asymptotic stability, finite-time convergence achieves stability within a finite duration of time. The convergence time, denoted as T_f, is primarily determined by the initial conditions and system parameters.

Lemma 3 (Lu and Xia, 2013). Consider a system in the form of:

$$\dot{x}(t) = f(t, x) + u, \tag{20}$$

where x denotes the state variable; $f(\cdot)$ denotes a nonlinear function related to the dynamic characteristics of the system (Eq. (20)) under the condition $f(t, 0)=0$; u denotes the control input. If there exists a Lyapunov function $\mathcal{V}_1$ satisfying:

$$\dot{\mathcal{V}}_1 \leqslant -\alpha \mathcal{V}_1(t) - \beta \mathcal{V}_1^{\rho}(t), \tag{21}$$

where α, β, and ρ are real numbers satisfying $\alpha, \beta \in \mathbb{R}^+$ and $0<\rho<1$, the convergence time T_f can be expressed as:

$$T_\mathrm{f} \leqslant \frac{1}{\alpha(1-\rho)} \ln \frac{\alpha \mathcal{V}_1^{(1-\rho)}(x_0) + \beta}{\beta}, \tag{22}$$

where x_0 is the initial value of the state variable.

Generally, the consensus principle with finite-time performance can be designed as follows:

$$u_i = \mathrm{sign}\left(\sum_{j=1}^{n} a_{ij}(x_j - x_i)\right)\left|\sum_{j=1}^{n} a_{ij}(x_j - x_i)\right|^{\alpha_i}, \tag{23}$$

where $0<\alpha_i<1$.

4.2.3 Fixed-time convergence

Fixed-time convergence is a property of a system that reaches a specific state within a fixed amount of time, regardless of the initial conditions (Zhang Y et al., 2018; Wang CY et al., 2021; Zhu et al., 2024). This implies that the convergence time T_e is independent of the system's dynamics or initial conditions, and instead is influenced by the system parameters and cannot be arbitrarily set.

Lemma 4 (Ning et al., 2019). For the following system:

$$\dot{x}(t) = f(t, x), \quad x(0) = x_0, \tag{24}$$

where $f(t, x)$ denotes a continuous function in the real domain and the origin is the equilibrium point of the system (Eq. (24)), a Lyapunov function $\mathcal{V}_2$ is selected. If its derivative satisfies:

$$\dot{\mathcal{V}}_2(x) \leqslant -\varpi_1 \mathcal{V}_2^{\chi}(x) - \varpi_2 \mathcal{V}_2^{\theta}(x), \tag{25}$$

where χ, θ, ϖ_1, and ϖ_2 are real numbers satisfying $\chi \in (0, 1)$, $\theta \in (1, \infty)$, and $\varpi_1, \varpi_2 > 0$, then the system (Eq. (24)) is fixed-time stable, and the convergence time T_x can be described as:

$$T_\mathrm{x} \leqslant \frac{1}{\varpi_1(1-\chi)} + \frac{1}{\varpi_2(\theta-1)}. \tag{26}$$

Here, two common consensus principles with fixed-time performance are given as follows (Zuo and Tie, 2014):

$$\begin{cases} u_i(t) = \alpha_1 \sum\limits_{j \in N_i} a_{ij}(x_j(t) - x_i(t))^{2-\frac{\tau}{v}} + \\ \qquad \beta_1 \sum\limits_{j \in N_i} a_{ij}(x_j(t) - x_i(t))^{\frac{\tau}{v}}, \\ u_i(t) = \alpha_2 \left[\sum\limits_{j \in N_i} a_{ij}(x_j(t) - x_i(t))\right]^{2-\frac{\tau}{v}} + \\ \qquad \beta_2 \left[\sum\limits_{j \in N_i} a_{ij}(x_j(t) - x_i(t))\right]^{\frac{\tau}{v}}, \end{cases} \tag{27}$$

where $\alpha_1, \beta_1, \alpha_2, \beta_2 \in \mathbb{R}^+$, and τ and v are positive odd integers that satisfy $\tau<v$. N_i is the set of all neighbours of the ith missile.

4.2.4 Prescribed-time convergence

The concept of prescribed-time convergence adds an element of flexibility to fixed-time convergence by enabling variability in the specific timing of system convergence (Li HJ et al., 2024; Wang HB et al., 2024; Xu SQ et al., 2024). This finding indicates that achieving convergence is not bound by a fixed timeframe, but is rather constrained by the maximum permissible convergence time, independent of the system's initial conditions and parameters.

Lemma 5 (Wang et al., 2019). For the system (Eq. (20)), a Lyapunov function $\mathcal{V}_3$ is selected such that $\mathcal{V}_3(0, t)=0$. If there exists a value of $b \geqslant 0$ and $k>0$ for the time interval $t \in [t_0, T_\mathrm{p})$, and the first-order time derivative of $\mathcal{V}_3(x)$ satisfies:

$$\dot{\mathcal{V}}_3(x(t), t) \leqslant -b\mathcal{V}_3 - k\varphi(t_0, T_\mathrm{p})\mathcal{V}_3, \tag{28}$$

then one can obtain:

$$\begin{cases} \mathcal{V}_3(x(t), t) \leqslant -\mu^{-k}(t_0, T_\mathrm{p}) \mathrm{e}^{-b(t-t_0)} \mathcal{V}_3(t_0), & t \in [t_0, T_\mathrm{p}), \\ \mathcal{V}_3(x(t), t) = 0, & t \in [T_\mathrm{p}, \infty), \end{cases} \tag{29}$$

where φ is the adjustment function, t_0 is the initial condition time, and T_p is the convergence time. $\mu(t_0, T_\mathrm{p})$ denotes a time-varying scaling function, which is governed by:

$$\mu(t_0,\ T_\mathrm{p}) = \begin{cases} 1, & t \in [0,\ t_0), \\ \left(\dfrac{T_\mathrm{p}}{T_\mathrm{p} + t_0 - t} \right)^p, & t \in [t_0,\ T_\mathrm{p}), \\ 1, & t \in [T_\mathrm{p},\ \infty), \end{cases} \tag{30}$$

with

$$\dot{\mu}(t_0,\ T_\mathrm{p}) = \begin{cases} 1, & t \in [0,\ t_0), \\ \dfrac{p}{T_\mathrm{p} - t_0} \mu(t_0,\ T_\mathrm{p})^{1+\frac{1}{p}}, & t \in [t_0,\ T_\mathrm{p}), \\ 1, & t \in [T_\mathrm{p},\ \infty), \end{cases} \tag{31}$$

where $p>1$; $t_0 \geqslant 0$; $T_\mathrm{p}>0$.

The prescribed-time consensus principle described in (Ning et al., 2023) is typically characterized as follows:

$$u_i = \frac{\eta_1}{t_\mathrm{pre} - t} \sum_{j \in N_i} a_{ij} (x_j - x_i), \tag{32}$$

where t_pre denotes a user-assignable time, and $\eta_1>0$.

The convergence performance of the four types of cooperative guidance schemes is summarized in Table 2. Owing to the limited terminal guidance time, achieving rapid convergence of terminal constraints in this stage is essential. Finite-time convergence offers a faster convergence rate and higher accuracy than asymptotic convergence. However, the convergence time of finite-time convergence is affected by the initial conditions. If the initial errors in the guidance system are significant, the convergence time may be longer and could exceed the guidance time, thereby affecting the accuracy of the guidance and potentially even causing the cooperation to fail. Conversely, fixed-time and prescribed-time convergence have garnered considerable attention in recent years because they are independent of the initial conditions. They showcase significant progress toward the development of closed-loop cooperative guidance systems.

5 Discussion and future trends

5.1 Discussion

After systematically reviewing cooperative guidance, we summarize the current development in this field in terms of five aspects, as shown in Fig. 13.

(1) Network quality. The inter-missile communication network is crucial for enabling cooperative guidance. The current research on cooperative guidance has evolved from focusing on ideal communication networks to now considering phenomena such as topology switching and time delays in the inter-missile communication network. These phenomena better simulate real cooperative guidance scenarios.

(2) Target characteristics. The changes in target characteristics are evident in two primary ways. First, a noticeable trend was observed in the speed of targets, starting from stationary targets, progressing to slow-moving targets, and eventually advancing to hypersonic targets. Second, the maneuverability of targets is becoming stronger, which is intuitive given the current emphasis on designing cooperative guidance laws for maneuverable targets, including large ones. The changes in target characteristics reflect the growing emphasis on more complex targets, and the escalating demand for cooperative guidance in diverse combat scenarios.

(3) Guidance constraints. The evolution of guidance constraints can be characterized by the shift from considering only a single constraint to considering multiple constraints simultaneously. This is particularly evident in the transition from sole consideration of attack time constraints to consideration of multiple

Table 2 Summary of the convergence performance of cooperative guidance schemes

Convergence performance	Convergence time	Specific convergence time	Independence from initial conditions	Independence from system parameters	Reference
Asymptotic	Infinity	×	×	×	He et al. (2018a, 2018b); Wu et al. (2021)
Finite-time	$T_\mathrm{f} \leqslant \dfrac{1}{\alpha(1-\rho)} \ln \dfrac{\alpha \mathcal{V}_1^{(1-\rho)}(x_0) + \beta}{\beta}$	×	×	×	Kumar and Mukherjee (2020); Zhang et al. (2021); An et al. (2022)
Fixed-time	$T_\mathrm{x} \leqslant \dfrac{1}{\varpi_1(1-\chi)} + \dfrac{1}{\varpi_2(\theta-1)}$	×	√	√	Chen ZY et al. (2021); Dong et al. (2022); You et al. (2023)
Prescribed-time	$T_\mathrm{p}>0$	√	√	√	Zhang et al. (2020); Ma et al. (2021); Wang ZK et al. (2022); Wu et al. (2024)

complex constraints, such as physical characteristics and operational effectiveness. The process for designing cooperative guidance laws now incorporates a broader array of constraint conditions, which demonstrates an emphasis on the overall effectiveness of guidance laws, so as to meet the demands of actual combat scenarios.

(4) Convergence performance. Convergence performance is steadily improving, and it has transitioned from asymptotic convergence to prescribed-time convergence. The dependence of cooperative guidance laws on the initial conditions and parameters of the guidance system is gradually decreasing, resulting in reductions in convergence time. These modifications accelerate improvements in cooperative guidance law performance, and enhance adaptability to a certain extent.

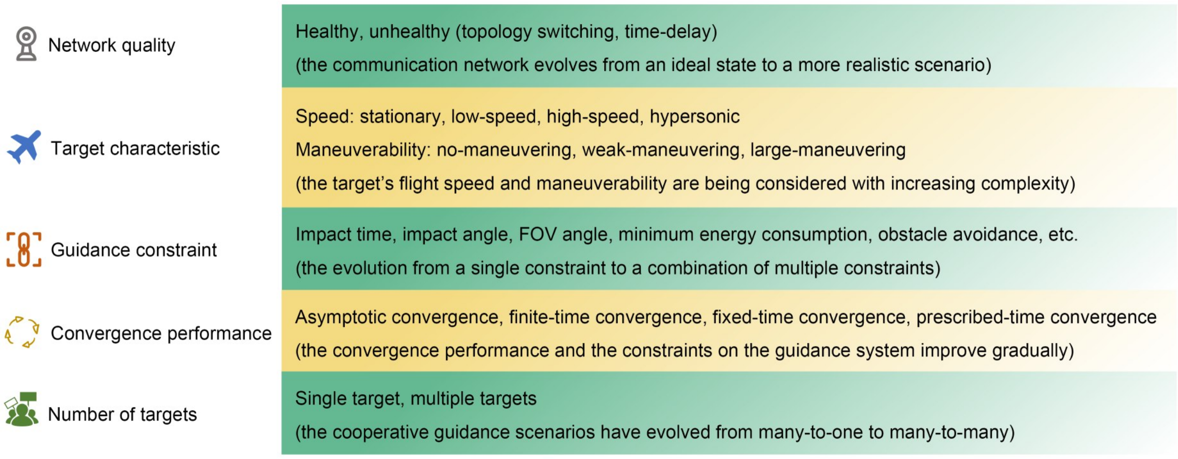
(5) Number of targets. The cooperative guidance problem has evolved from coordinating multiple missiles to attack a single target, to now coordinating multiple missiles to attack multiple targets. This process involves target allocation, performance evaluation, and other related actions. This trend indicates that the field of cooperative guidance is becoming more systematized, increasing in complexity, and is moving towards more comprehensive system-level development.

5.2 Future trends

Considering the current advancements in cooperative guidance, we project future trends and provide insights in this field in terms of five layers, as shown in Fig. 14. This is done based on likely requirements for future cooperative combat scenarios, functionalities, and performance.

5.2.1 Cyber layer: networked cooperation

The cyber-physical system (CPS) is an important product of Industry 4.0, thanks to its ability to merge



Network quality	Healthy, unhealthy (topology switching, time-delay) (the communication network evolves from an ideal state to a more realistic scenario)
Target characteristic	Speed: stationary, low-speed, high-speed, hypersonic Maneuverability: no-maneuvering, weak-maneuvering, large-maneuvering (the target's flight speed and maneuverability are being considered with increasing complexity)
Guidance constraint	Impact time, impact angle, FOV angle, minimum energy consumption, obstacle avoidance, etc. (the evolution from a single constraint to a combination of multiple constraints)
Convergence performance	Asymptotic convergence, finite-time convergence, fixed-time convergence, prescribed-time convergence (the convergence performance and the constraints on the guidance system improve gradually)
Number of targets	Single target, multiple targets (the cooperative guidance scenarios have evolved from many-to-one to many-to-many)

Fig. 13 Summary of the main developments in cooperative guidance

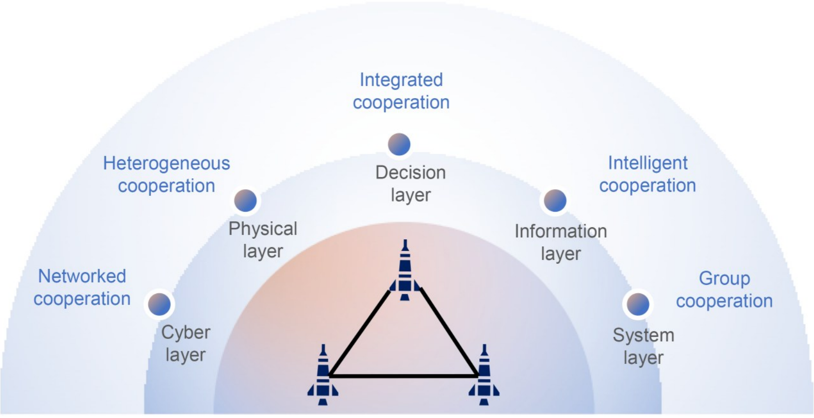


Fig. 14 Future trends in cooperative guidance

the physical and virtual worlds through real-time data processing services (Lu, 2017; Duo et al., 2022). Its typical description is shown in Fig. 15. The cooperative guidance model can be considered as a representative example of the CPS. Undoubtedly, network communication is the core element of cooperative guidance, and it serves as a bridge for establishing cooperation between each missile in the formation. Specifically, during the terminal guidance process, as each missile approaches the target, the complexity of external disturbances increases, which results in a greater impact on the overall cooperation effect. Moreover, the information exchange and sharing among the members can be hindered by factors such as communication delay and topology switching. The coexistence of these external and internal adverse effects presents significant engineering challenges to cooperative guidance. Therefore, it is crucial to consider networked cooperative guidance from the cyber layer perspective. To date, researchers have conducted relevant studies focusing on time-delay (Olfati-Saber and Murray, 2004; Li et al., 2021b; Ma et al., 2023a), topology switching (Yu et al., 2021; Hou et al., 2023), and other topics.

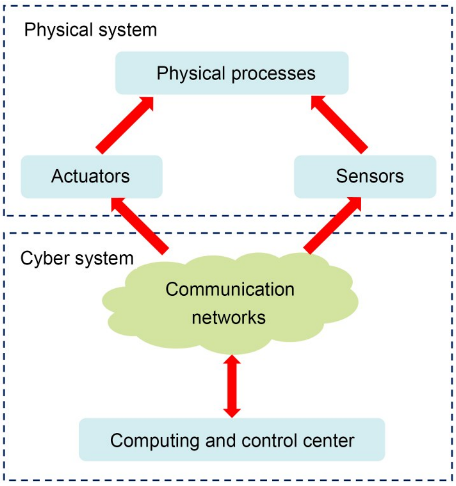


Fig. 15 Description of the CPS

In the context of more complex networked cooperative guidance scenarios, the security of cooperation should be emphasized. This challenge can be reframed as a topological reconstruction problem from a security perspective, yielding a more rigorous and standardized approach to address the underlying security concerns. Considering the problem through the lens of topological reconstruction, researchers and practitioners can leverage established techniques and frameworks to develop solutions that enhance the overall security of the cooperative guidance system. For example, Chen SG et al. (2023) addressed the problem of unmanned vehicles facing denial-of-service and replay attacks. They designed a change control scheme for distributed secure platoon lanes using a recursive method, to ensure the stability and robustness of the system under compound attacks. Furthermore, they incorporated an event-triggered mechanism to optimize the use of communication bandwidth.

Overall, current research on the effect of various disturbances on communication networks and their underlying mechanisms is insufficient, and further exploration of the boundary conditions is required. In addition, the consideration of network attacks (such as denial-of-service attacks) in cooperative guidance is an important topic that necessitates future research.

5.2.2 Physical layer: heterogeneous cooperation

At its current stage, cooperative guidance research primarily revolves around homogeneous cooperation, which means all participants have the same roles and functions. Owing to the rapid advancement of computer technology, machine learning, and network communication, the traditional methods of warfare have shifted towards intelligent weaponry. Consequently, global military forces have proposed new conceptual frameworks for combat, including network-centric warfare, mosaic warfare, and cross-domain operations, with the aim of optimizing the operational effectiveness of weapons and equipment in system-based confrontations (Groh, 2008; Magnuson, 2018; Katagiri, 2023). This evolution suggests that a trend of system-to-system confrontation will be inevitable in future warfare, and it will involve elements such as air, space, land, sea, electromagnetics, and information. However, there is significant application potential for cooperative guidance with heterogeneous elements. In contrast, the cost of operations can be reduced by combining different combat entities (such as aerial-ground autonomous systems) (Chai et al., 2024). Conversely, cooperation and attack performance can be further enhanced by leveraging the complementary functions of the different entities.

Research has been conducted on the cooperative guidance problem of heterogeneous systems. Mukherjee and Kumar (2022) proposed a finite-time, heterogeneous cyclic pursuit scheme that guaranteed consensus for agents that were represented as integrators. They demonstrated that consensus was achieved within a finite time using the proposed scheme, even when the gains were nonidentical. This occurred as long as all the gains were positive, or if one gain was negative but within a specified lower bound. In (Zhao et al., 2015), a cooperative guidance strategy was proposed to address the defense challenges posed by hypersonic vehicles. This strategy leveraged PNG and consensus algorithms that were modified specifically for heterogeneous interceptors. The heterogeneous interceptors were divided into two categories: the leader interceptor and the follower interceptors. The leader missile was integrated with a high-performance seeker to engage the target using a modified PNG approach, whereas the low-cost follower interceptors utilized consensus algorithms to follow the trajectory of the leader interceptor. Based on this concept, Li and Wu (2023) introduced a fixed-time convergent guidance law with integrated impact time control. They proposed an adaptive cooperative guidance strategy for followers without seekers, which involved coordinated positioning relative to the leader.

Overall, future operational systems will pose new requirements for heterogeneous cooperative guidance. It is crucial to effectively utilize the strengths of different combat units to support the development of cooperative guidance which can fit the needs of practical applications.

5.2.3 Decision layer: integrated cooperation

The primary aim of cooperative guidance for multiple missiles remains to inflict maximum damage on the targets. This requires considering the specifications of integrated cooperative guidance. From a mission perspective, the diverse battlefield environments and target characteristics necessitate different task requirements, such as target allocation (Shalumov and Shima, 2017; Hocaoğlu, 2019), obstacle avoidance planning (Jha et al., 2019; Jin and Er, 2022; Jiang et al., 2024), integrated guidance and control (Wang XF et al., 2015; Guo et al., 2020; Sinha et al., 2022), and the determination of an optimal number of missiles. Currently, most studies on these requirements focus heavily on cooperative guidance. In practical terms, these requirements are inherently linked to cooperative guidance; they mutually affect each other and are significantly coupled with the kinematics and dynamics of missile movements (Yu et al., 2022). From a command-and-control perspective, it is crucial for command officers to efficiently manage the number of missiles allocated for cooperative guidance, and to contemplate the need for successive attack waves after an initial attack mission.

From the perspective of missile guidance itself, guidance and control are inseparable entities. Cooperative guidance demands cooperation not only in trajectory guidance but also in attitude control. Typically, air surfaces are used to control missiles, indicating that trajectory control is achieved by changing the attitude of the missile. However, current research on cooperative guidance focuses mostly on the dynamics of point masses, i.e., the trajectory control level, whereas attitude control does not involve network information and there is no interaction between the attitude information of different missiles. Consequently, the lack of cooperation in the attitude motion of individual missiles inevitably disrupts the consistency of the motion trajectory, making it difficult to achieve consistent timing during cooperative attacks (Yang et al., 2017). Therefore, from the decision layer perspective, the fundamental requirement for maximizing the operational effectiveness of multiple missiles is the ability to execute integrated cooperative guidance.

5.2.4 Information layer: intelligent cooperation

This study focuses primarily on the concept of "intelligent cooperation" in the information layer, and accordingly, we describe it from the perspectives of group formation and individual behavior. This concept is evident in two principal ways:

(1) Cooperative guidance based on machine learning. Machine learning, which is a subset of artificial intelligence, focuses on algorithms and statistical models that enable computer systems to improve their performance by learning from available data without being explicitly programmed. Machine learning has been utilized to address uncertainties and disturbances in cooperative guidance, thereby enhancing the efficiency and accuracy of cooperative guidance models (Zhou WH et al., 2022). For example, Lan et al. (2024) utilized machine learning methods to estimate and predict the missile's time-to-go and the target's maneuverability, thereby enhancing the adaptability and scalability of cooperative guidance for maneuvering

targets. However, conventional deep reinforcement learning methods have certain limitations, including high sample complexity, low sample utilization, long training times, and poor generalization ability (where the models may fail when the tasks or environments change). Therefore, future research could explore the integration of enhanced machine learning algorithms into cooperative guidance studies, such as iterative learning control (Chi et al., 2020), meta-reinforcement learning (Hu et al., 2021), learning based on digital twins (Szpytko et al., 2021), and game-based learning algorithms (Du and Ding, 2021).

(2) Improved time-to-go processing strategies. In practice, the remaining flight time of a missile plays a crucial role as a direct or indirect coordination variable during the engagement process, significantly affecting cooperative guidance. Yu et al. (2023) proposed a cooperative guidance strategy in which the expected impact time did not need to be predesigned and was instead coordinated by multiple missiles utilizing neighboring information. This approach reduced the estimation requirement for time-to-go and became a key direction in subsequent cooperative guidance research.

In summary, intelligent cooperative guidance involves leveraging machine learning techniques to compensate for uncertainties and disturbances, thereby enhancing the efficiency and accuracy of guidance. In addition, improving time-to-go processing strategies may contribute to effective coordination in cooperative guidance systems.

5.2.5 System layer: group cooperation

The systemized warfare modes of the future are likely to involve more than just one-on-one confrontations between single formations; this highlights the need to consider group cooperation (Sun and Yang, 2022).

In this context, "group cooperation" can be considered from two perspectives. It requires that multiple missiles achieve cooperative guidance between different groups, while also yielding overall cooperation within each group, and even satisfying specific constraints such as available overload and impact angle. Therefore, this process involves communication between members within a single missile group, and between different missile groups (Fig. 16). Research on group cooperative guidance is currently still in its early stages. Ma et al. (2021, 2023b) conducted studies of group cooperation with constraints such as convergence performance, time delays, and communication topology switching, but these studies primarily focused on stationary targets. Therefore, considering the system layer, continuous research on group cooperation from a systemic perspective is essential for future high-intensity warfare scenarios.

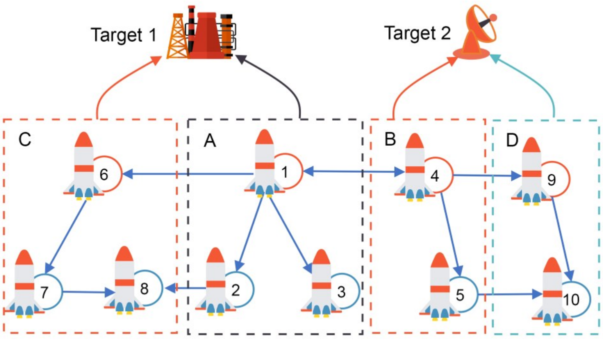


Fig. 16 Description of group cooperation among multiple missiles (Ma et al., 2021). The missile system consists of a networked configuration with a total of 10 missiles organized into four subgroups, attacking two different targets

6 Conclusions

Cooperative operations facilitate the achievement of tasks that individual entities struggle to accomplish alone. In particular, cooperative guidance among multiple missiles offers strong interception, enhanced detection, and advanced anti-jamming capabilities. To understand current research in the field of cooperative guidance, we conducted a bibliometric analysis using CiteSpace software on 513 articles from the Scopus database.

The CiteSpace visualizations were used to analyze research in the cooperative guidance field, focusing on keyword clustering, co-occurrence, and burst analysis to reveal key insights into trends. The study also provided a comprehensive overview of fundamental cooperative guidance theories, focusing on cooperative structure and convergence performance. It also proposed a developmental framework based on five layers.

Over the past two decades, the field of cooperative guidance has experienced significant growth and evolution. Initially rooted in fundamental concepts, it has advanced to encompass increasingly sophisticated, interdisciplinary approaches. These developments address complex challenges in coordinated autonomous systems. The current research landscape indicates a sustained trend towards more distributed, adaptive, and precise strategies. Emphasis is placed on real-world applicability and system-level optimization, reflecting the field's dynamic progression.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (No. 62173274), the National Key R&D Program of China (No. 2019YFA0405300), the Natural Science Foundation of Hunan Province of China (Nos. 2021JJ10045 and 2025JJ60072), the Open Research Subject of State Key Laboratory of Intelligent Game (No. ZBKF-24-01), the Postdoctoral Fellowship Program of CPSF (No. GZB20240989), the China Postdoctoral Science Foundation (No. 2024M754304), and the Aeronautical Science Foundation of China (No. 2023Z005030001).

Author contributions

Shuangxi LIU designed the research and wrote the first draft of the manuscript. Zehuai LIN processed the corresponding data. Wei HUANG and Binbin YAN revised and edited the final version.

Conflict of interest

Wei HUANG is an Editorial Board member of this journal, and is NOT involved in the editorial review or the decision to publish this article. Shuangxi LIU, Zehuai LIN, Wei HUANG, and Binbin YAN declare that they have no conflict of interest.

Data availability statement

To obtain the literature data utilized for CiteSpace analysis in this paper, please reach out to the corresponding authors.

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