

Review

Research Status and Prospects of Constrained Cooperative Guidance: A Review

Xiaowen Guo ^{1,2}  and Wenhui Ma ^{3,*} ¹ School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China; gxw@mail.nwpu.edu.cn² Xi'an Aerospace Propulsion Institute, Xi'an 710100, China³ School of Science, Xi'an Technological University, Xi'an 710021, China

* Correspondence: mawenhui.qiu@foxmail.com or mawenhui@xatu.edu.cn

Abstract

Cooperative guidance enables multiple flight vehicles to achieve various objectives through information sharing. Constraints are inevitable and pose new threats to cooperative safety, presenting formidable challenges to cooperative guidance technology. This study aims to sort out and analyze the research lineage and development trend of constrained cooperative guidance. First, a bibliometric analysis is conducted on the Scopus database. The development trajectory and research hotspots are analyzed by CiteSpace visualization. Then, the preliminaries of cooperative guidance law are provided. Based on the discussion of classical and co-cited references, the research on cooperative guidance is performed with constraints analysis. Furthermore, the progress has been systematically provided as a literature overview, highlighting two aspects: physical constraints and control constraints. Finally, potential prospects of cooperative guidance in addressing the challenges of constraints, providing theoretical support and reference directions for related research.

Keywords: cooperative guidance; constrain; multi-flight-vehicle; bibliometrics; CiteSpace

1. Introduction

Guidance, whose objectives have primarily focused on guiding a single unmanned flight vehicle to a designated target under limited measurement information, has been continuously developed to enhance guidance performance. In the last decade, with the rapid maturity of guidance technology, unmanned flight vehicles have gained the necessary capabilities to integrate missions due to superior autonomy and precision [1,2]. As mission boundaries expand, however, individual flight vehicles face critical ability limitations to deliver effective solutions, making multi-flight-vehicle (MFV) swarms a key area of interest due to the wide-ranging application potential [3]. Motivated by the self-organizing mechanisms observed in biological swarms [4,5], cooperative guidance technology has established itself as a cornerstone in MFV systems with the continuous advancement of information science in both theoretical research and engineering practice.

Compared with individual precise guidance, cooperative guidance can better unlock the potential of individual platforms, enabling multiple flight vehicles to collectively accomplish mission objectives through information-interaction coordination. In theory, when the velocity is relatively high enough and maneuverability is sufficient, an individual flight vehicle can effectively accomplish the assigned mission. But a stationary or weak-maneuvering target usually holds better survivability or is equipped with a defence system, rendering it virtually impossible for an individual flight vehicle to penetrate the



Academic Editor: Liang Sun

Received: 11 June 2026

Revised: 26 July 2026

Accepted: 28 July 2026

Published: 4 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

defensive system and making it difficult to yield desired guidance efficiency [6]. Where individual flight vehicles face capability limitations, cooperative guidance, by sharing critical information and combining complementary capabilities, can thereby achieve superior guidance performance and saturate the defence system. Especially for high-speed and highly maneuverable targets, such as hypersonic targets, cooperative guidance not only enhances detection capabilities, but also leverages a guarantee mechanism to ensure that at least one vehicle fulfills the mission objectives [7].

Thus, even for a well-defended or a high-performance target, it is difficult to counter a group of flight vehicles bursting into sight simultaneously. Time coordination, which enables flight vehicles to reach the destination simultaneously or sequentially, constitutes the core constraint and fundamental prerequisite for cooperative guidance [8]. Accordingly, starting with time coordination to achieve basic saturation guidance performance, research on constrained cooperative guidance has advanced gradually, thereby improving guidance success probability in complex mission environments. As an interdisciplinary integration of aerospace engineering, information science, control theory, and emerging artificial intelligence technologies, cooperative guidance has garnered substantial research attention. Several scholars have conducted systematic reviews of cooperative guidance studies. Ref. [9] reviewed the coordination of multi-vehicle systems, classifying the cooperative guidance into attack and defense. Focusing on the terminal phase, Ref. [10] reviewed cooperative guidance with categorization based on the cooperative framework. While the aforementioned review paper has investigated cooperative guidance, it focuses primarily on task scenarios while neglecting hybrid guidance and control constraints. On the other hand, Ref. [11] centered on networked features and analyzed cooperative guidance from the viewpoint of convergence properties. Although convergence performance improvement mainly serves the requirements under guidance constraints, relying solely on it remains insufficient. As the physical constraints imposed by core components have led to increasingly urgent cooperative guidance problems under constraints, considerable research efforts have been devoted to issues related to physical and control characteristics.

Notably, although the constrained cooperative guidance problem has led to numerous research results, it is still an open problem challenging emerging missions. Existing surveys have focused primarily on guidance tasks and cooperative frameworks, while research on constrained cooperative guidance still needs further investigation. This work is positioned as a survey paper, aiming to provide a structured and constrained-focused analysis that shapes the landscape of cooperative guidance. The main contributions are summarized as follows:

1. This paper conducts a bibliometric analysis of “cooperative guidance” indexed by the Scopus database from 2010 to 2025. CiteSpace is utilized to derive research fronts from two essential aspects: keywords and co-cited references. The analytical results form the basis for summarizing the current achievements and outlining the main development trend: constrained-focused.
2. The evolution of the emerging research topics of constrained cooperative guidance is overviewed. Synthesizing classical and co-cited references, the latest state of constrained cooperative guidance is researched as a literature overview, organized from physical constraints and theoretical control constraints.
3. In light of recent advancements in constrained cooperative guidance, a developmental framework is proposed with a focus on physical-constrained and control-constrained, so as to provide insights for future research.

The remainder is organized as follows. In Section 2, a bibliometric analysis of “cooperative guidance” is conducted. Section 3 provides an overview of the fundamental theories for cooperative guidance laws. Section 4 summarizes the preliminaries, and constraint

analysis is conducted based on bibliometric analysis and the cooperative guidance problem. Sections 5 and 6 provide overviews of the literature from physical-constrained and control-constrained perspectives, respectively. In Section 7, future directions and insights are outlined. Finally, Section 8 provides the main conclusions.

2. Bibliometric Analysis of Cooperative Guidance Law

Characterizing the structure of knowledge, the evolution of research topics, and the emergence of topics has always been an important part of cooperative guidance technology. In this section, a bibliometric analysis is conducted by CiteSpace 6.3.R1, a visualization tool developed by Professor Chen, which can identify and display trends and dynamics of scientific development in scientific literature [12].

The research sample is sourced from the Scopus database, conducting a search on journal articles with “cooperative guidance” (search time 31 December 2025) and 913 papers can be obtained by excluding invalid articles. As shown in Figure 1, the annual publication volume showed an overall fluctuating upward trend during 2010–2025. Obvious upward trends can be observed in two time periods, namely 2013–2019 and 2020–2025, with the annual publication volume doubling in these periods.

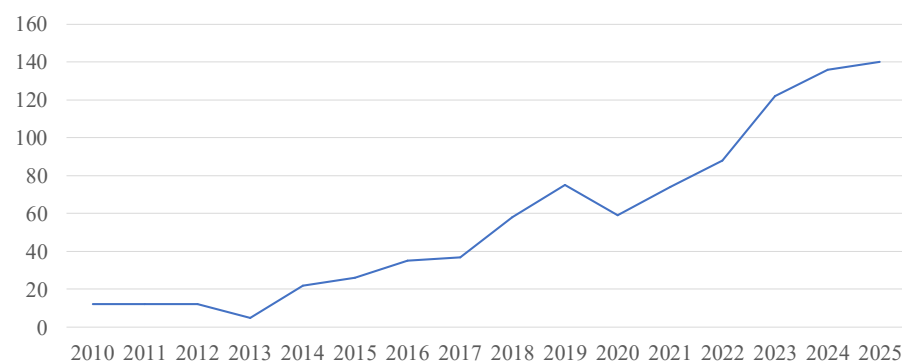


Figure 1. Annual publication volume.

This study aims to identify trends and new developments appearing in the subsequent 913 articles indexed in Scopus recent 15 years, including 3209 distinct references. A visual bibliometric study of the literature was conducted using CiteSpace 6.3.R1. Maps, including publication trends, keyword clustering, and co-cited document clustering are generated to reveal research hotspots. All duplicate literature records are filtered out during the initial data import process of CiteSpace. Titles, abstracts, author keywords (DE), and Keywords Plus (ID) are selected as the lexicon sources. Network pruning was performed using Pathfinder, Pruning sliced networks, and Pruning the merged network. 2-year time slice interval for the dataset covering 2010–2025. The g-index parameter was set to $k = 12$, and all other modules used default settings.

2.1. Analysis of Keywords

Keyword clustering of research can intuitively display the main research fields and help refine research themes. Based on the keyword co-occurrence network, a keyword clustering co-occurrence map is generated as shown in Figure 2). In this study, the log-likelihood ratio (LLR) was employed as the clustering algorithm to extract and label research themes, yielding high-quality and well-separated 17 clusters (as shown in Table 1). The modularity value $Q = 0.8642 > 0.7$ indicates that the clustering structure is significant and reliable, and the average silhouette value $S = 0.9516 > 0.7$ shows that the clustering results have high reliability. The evaluation indices of network clustering are favorable, the correlation between keywords is strong, and the clustering research is concentrated.

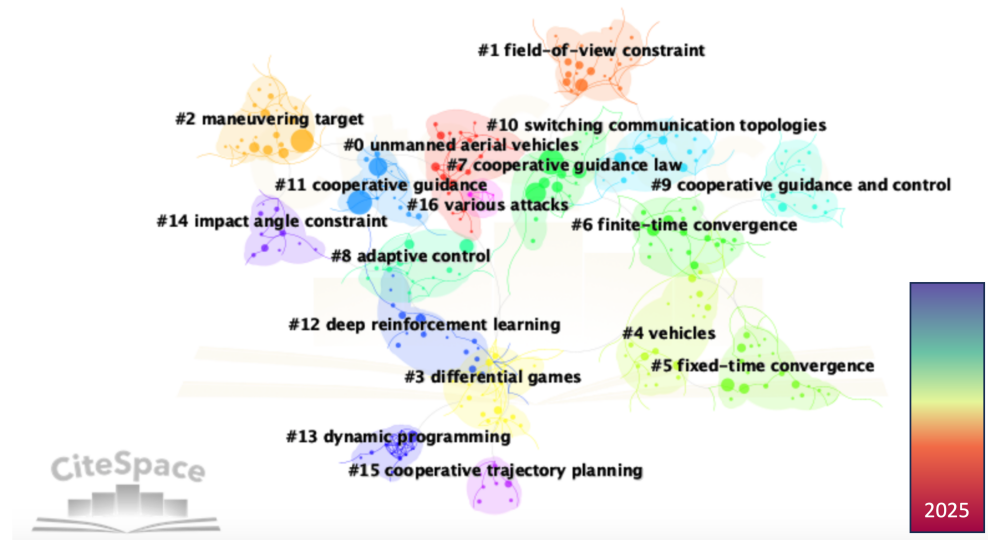


Figure 2. Keyword clustering co-occurrence map of cooperative guidance law.

Surrounding the core research theme “cooperative guidance”, clusters can be classified into three main categories.

- **Application research:** research on cooperative guidance is primarily the engineering application of cooperative control and multi-agent consensus theory, and thus is closely linked to application scenarios. Cluster #0, labeled “unmanned aerial vehicles”, highlights the significance of the research object to the subject. The study of cooperative guidance is oriented toward unmanned aerial vehicles and is strongly related to the characteristics of “vehicles” in Cluster #4 and the target, especially the “maneuvering target” in Cluster #2.
- **Guidance problem:** cooperative guidance can be theoretically transformed into a multi-agent cooperative control considering application factors, which can be modeled as control constraints. Considering that impact-time coordination is the core for cooperative guidance, research on convergence performance generates Cluster #5 “fixed-time convergence” and Cluster #6 “finite-time convergence”, so as to ensure the MFVs reach the target simultaneously. Once the seeker exceeds its field-of-view limit, target loss is highly likely; Cluster #1 “field-of-view constraint” has been further considered as one of the important constraint problems. For guidance efficacy enhancement, research on angle constraint raised Cluster #14 “impact angle constraint”. Furthermore, the supporting role of communication has received increasing attention, and research on Cluster #10 “switching communication topologies” has gradually emerged.
- **Control law:** cooperative guidance is a typical engineering application of control for multi-agent systems, and research on control laws has formed as an important category. As an effective tool for analyzing multi-player dynamic conflicts and optimal strategies, Cluster #3 “differential games” is regarded as a key research direction within the field of cooperative guidance, since it can characterize the interactive and adversarial behaviors among MFV well. Due to its strong robustness against parameter variations and external disturbances, Cluster #8 “adaptive control” has become another important research branch. With the development of intelligence methods, Cluster #12 “deep reinforcement learning” has become a major focus in cooperative guidance, as it enables online learning and optimal decision-making in complex, uncertain, and strongly coupled engagement environments. As a classical approach to solving optimal decision problems with state transitions, Cluster #13

“dynamic programming” is widely studied in cooperative guidance for trajectory optimization and decision-making.

Cooperative guidance is an interdisciplinary application field integrating aerospace engineering, control theory and information communication. Its research hotspots are closely centered on practical guidance problems, with methodological studies serving to solve application challenges. Over the years, the core of cooperative guidance research has been focused on physical constraints in the guidance process, which directly affect flight safety and are decisive for guidance efficiency, as their violation may lead to target loss or mission failure. The bibliometric analysis of cooperative guidance reveals that the evolution of control theory is further advancing the development of cooperative guidance, forming a mutually reinforcing relationship between the two domains. Therefore, to overcome constraints while preserving stability and accuracy, it is necessary to convert physical constraints to constrained-control problems and solve them through control methods.

Table 1. Keyword clustering list.

Cluster ID	Size	Silhouette	Cluster Label
0	25	0.929	unmanned aerial vehicles
1	23	0.968	field-of-view constraint
2	22	1	maneuvering target
3	22	0.912	differential games
4	21	0.959	vehicles
5	20	0.981	fixed-time convergence
6	19	0.953	finite-time convergence
7	19	0.891	cooperative guidance law
8	17	0.885	adaptive control
9	16	0.994	cooperative guidance and control
10	16	0.922	switching communication topologies
11	16	1	cooperative guidance
12	15	0.938	deep reinforcement learning
13	13	1	dynamic programming
14	11	0.916	impact angle constraint
15	7	1	cooperative trajectory planning
16	5	0.983	various attack

2.2. Analysis of Co-Cited Reference

A map of reference co-citations with corresponding clusters is generated, permitting the extraction of landmark references and clusters of research. According to Figure 3, the overall co-citation network presents a relatively concentrated and stably aggregated core-periphery structure.

The top 10 highly cited references are summarized in Table 2, wherein the highest cited reference has been cited 317 times, and its centrality value is 0.29. Jeon’s work, published in 2006, serves as a foundational study, laying the foundation for subsequent research on cooperative guidance theory, and together with a series of follow-up works in 2007, 2010 and 2016, constitutes the cornerstone of this field.

Cluster labeling was conducted using the LLR to identify thematic structures. Clusters in this co-cited network (as shown in Figure 3) have significant modularity and silhouette scores, indicating highly credible clusters $Q = 0.8525 > 0.7$ and $S = 0.9543 > 0.7$.

Based on CiteSpace bibliometric analysis(as shown in Table 3), a framework is established to delineate the evolution and features of cooperative guidance. Comprehensively identifying the keyword clustering of the co-cited network, the following trend can be drawn:

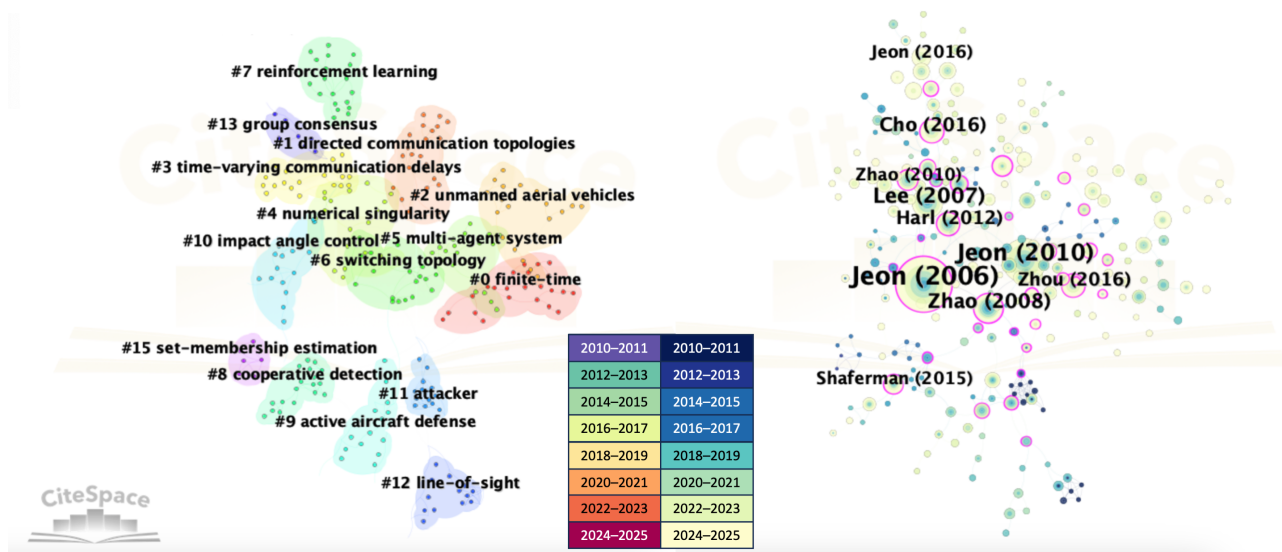


Figure 3. Literature co-cited analysis of cooperative guidance law.

Table 2. Top 10 high-cited reference list.

Count	Centrality	Year	First Author	Cited References
317	0.29	2006	JEON IN-SOO	Impact-Time-Control Guidance Law for Anti-Ship Missiles IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY @ 14, V2, P260–266
202	0.07	2010	JEON IN-SOO	Homing Guidance Law for Cooperative Attack of Multiple Missiles JOURNAL OF GUIDANCE CONTROL AND DYNAMICS @ 33, V1, P275–280
111	0.07	2007	LEE JIN-IK	Guidance Law to Control Impact Time and Angle IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS @ 43, V1, P301–310
90	0.39	2008	ZHAO SHIYU	Cooperative Guidance for Multimissile Salvo Attack CHINESE JOURNAL OF AERONAUTICS @ 21, V6, P533–539
65	0.13	2016	CHO DONGSOO	Nonsingular Sliding Mode Guidance for Impact Time Control JOURNAL OF GUIDANCE CONTROL AND DYNAMICS @ 39, V1, P61–68
61	0.29	2012	HARL NATHAN	Impact Time and Angle Guidance with Sliding Mode Control IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY @ 20, V6, P1436–1449
59	0.12	2016	ZHOU JIALING	Distributed Guidance Law Design for Cooperative Simultaneous Attacks with Multiple Missiles JOURNAL OF GUIDANCE CONTROL AND DYNAMICS @ 39, V10, P2436–2444
46	0.05	2016	JEON IN-SOO	Impact-Time-Control Guidance with Generalized Proportional Navigation Based on Nonlinear Formulation JOURNAL OF GUIDANCE CONTROL AND DYNAMICS @ 39, V8, P1885–1890
46	0.12	2015	SHAFERMAN VITALY	Cooperative Optimal Guidance Laws for Imposing a Relative Intercept Angle JOURNAL OF GUIDANCE CONTROL AND DYNAMICS @ 38, V8, P1395–1408
43	0.18	2010	ZHAO SHIYU	Design of Time-Constrained Guidance Laws via Virtual Leader Approach CHINESE JOURNAL OF AERONAUTICS @ 23, V1, P103–108

Table 3. Co-cited clustering list.

Cluster ID	Size	Silhouette	Cluster Label
0	23	0.926	finite-time
1	23	0.957	directed communication topologies
2	20	0.964	unmanned aerial vehicles
3	20	0.941	time-varying communication delays
4	20	0.935	numerical singularity
5	19	0.973	multi-agent system
6	19	0.951	switching topology
7	19	1	reinforcement learning
8	18	0.997	cooperative detection
9	15	0.916	active aircraft defense
10	15	0.86	impact angle control
11	13	0.958	attacker
12	13	1	line-of-sight
13	13	0.984	group consensus

1. Shifting from pre-planning relying on global information to dynamic cooperative guidance based on real-time information. In the context of #9 “active aircraft defense” involving #11 “attacker”–defender confrontations, this shift enables greater real-time adaptability, with #7 “reinforcement learning” widely exploited to optimize distributed decision-making and improve networked cooperative guidance performance.
2. Transforming from time coordination aimed at ensuring quantity saturation to coordination for upgrading guidance efficiency. With a focus on performance improvement, research priorities can be divided into two categories. One stream of research centers on physical factors, especially spatio-temporal constraints under information limitations, giving rise to the following clusters: #10 “impact angle control” and #12 “line-of-sight”. A second line of research aims to enhance guidance efficiency by imposing constraints at the control methodology level, leading to the following clusters: #1 “finite-time” and #4 “numerical singularity”.
3. Evolving from small-scale coordination in ideal environments to scale-extensible coordination under non-ideal conditions. A stable and reliable network support serves as the foundation for efficient coordination, especially in complex and dynamic guidance mission environments. To enhance the network support capability to accommodate system scaling, numerous studies have formed distinct research clusters, including #1 “directed communication topologies”, #3 “time-varying communication delays”, #5 “multi-agent system”, #6 “switching topology” and #13 “group consensus”.

3. Preliminaries of Cooperative Guidance

This section provides an introductory background to support the presentation and understanding of the MFV cooperative guidance reviewed throughout the rest of the paper. This background begins with the network model supported by graph theory in Section 3.1 and is followed by a mathematical formulation of candidate guidance and control architectures in Section 3.2. Furthermore, Section 3.3 analyzes cooperative objectives based on multi-agent systems.

3.1. Network Communication and Algebraic Graph Theory

The communication network among the MFV can be modeled as a graph $\mathcal{G} = \{\mathcal{M}, \mathcal{E}, \mathcal{A}\}$ [13–15]. Described the i -th flight vehicle in the formation as a node v_i in the node set $\mathcal{M} = \{m_1, m_2, \dots, m_n\}$. In the edge set $\mathcal{E} \subseteq \mathcal{M} \times \mathcal{M}$, if communication is directed, a directed edge in the network $\mathcal{E}_{ij}$ is denoted by the ordered pair of nodes (m_i, m_j) ,

which means that node m_i can receive information from node m_j . For adjacency matrix $\mathcal{A} = [a_{ij}]^{n \times n}$, $a_{ij} = 1$ if and only if there is a directed edge (m_i, m_j) , else if node m_i cannot receive the information from m_j , then $a_{ij} = 0$. The Laplacian matrix $\mathcal{L} = [l_{ij}]^{n \times n}$ of graph $\mathcal{G}$ is defined by $l_{ij} = -a_{ij}$ for $i \neq j, i, j \in \{1, \dots, n\}$ and $l_{ij} = \sum_{j=1, j \neq i}^n a_{ij}$ is the sum of the weights of the edges ending at node m_i .

Graph theory is employed to characterize the network topology of the MFV swarm. Based on the connectivity and information transmission properties of the network, as shown in Figure 4, graphs can be classified into two types: undirected and directed.

Definition 1 ([16]). Network $\mathcal{G}$ is defined to be undirected if there is a connection between two nodes m_i and m_j such that $a_{ij} = a_{ji} = 1$; otherwise, $a_{ij} = a_{ji} = 0$. An undirected graph is connected if there exists an undirected path between any pair of nodes m_i and m_j .

Definition 2 ([16]). Network $\mathcal{G}$ is defined to be directed if there is a connection from node m_j to m_i such that $a_{ij} = 1$; otherwise, $a_{ij} = 0$. A directed graph is strongly connected if there exists a directed path between any pair of distinct nodes m_i and m_j .

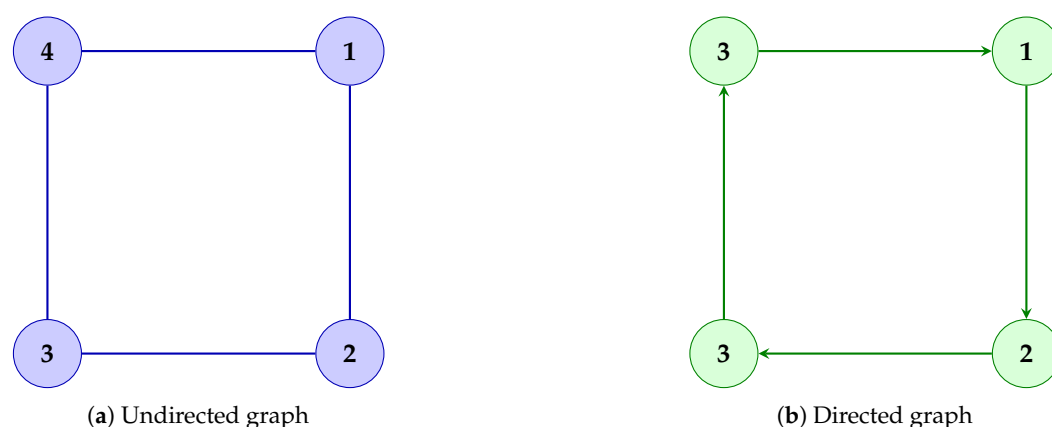


Figure 4. Graph.

3.2. Cooperative Guidance Model

Generally, the three-dimensional guidance problem can be decomposed into two independent orthogonal planar guidance problems. Meanwhile, for mission scenarios with weak longitudinal motion effect, the three-dimensional guidance model can be further dimensionally reduced and simplified to a two-dimensional planar guidance model. Accordingly, the model description for the two-dimensional guidance scenario is outlined in Figure 5, wherein MFVs are flying to a target T .

Accordingly, the guidance motion equations can be established on the following basic simplified assumptions:

- The flight vehicles and the target can be viewed as mass points;
- The dynamics of the seeker and autopilot are fast enough in comparison with the guidance loop.

The dynamics of cooperative guidance can be formulated as

$$\begin{cases} \dot{r}_i = V_T \cos \eta_i^T - V_i \cos \eta_i \\ r_i \dot{q}_i = V_T \sin \eta_i^T - V_i \sin \eta_i \\ \eta_i^T = \theta_T - q_i \\ \eta_i = \theta_i - q_i \end{cases} \quad (1)$$

where r_i and q_i is the relative distance and line-of-sight (LOS) angle between the i -th flight vehicle m_i and target T , respectively; V_T , θ_T and η_i represent the velocity, the flight path angle and the lead angle of maneuvering target T , respectively; V_i , θ_i and η_i are defined as the velocity, the flight path angle and lead angle of the i -th flight vehicle m_i , respectively.

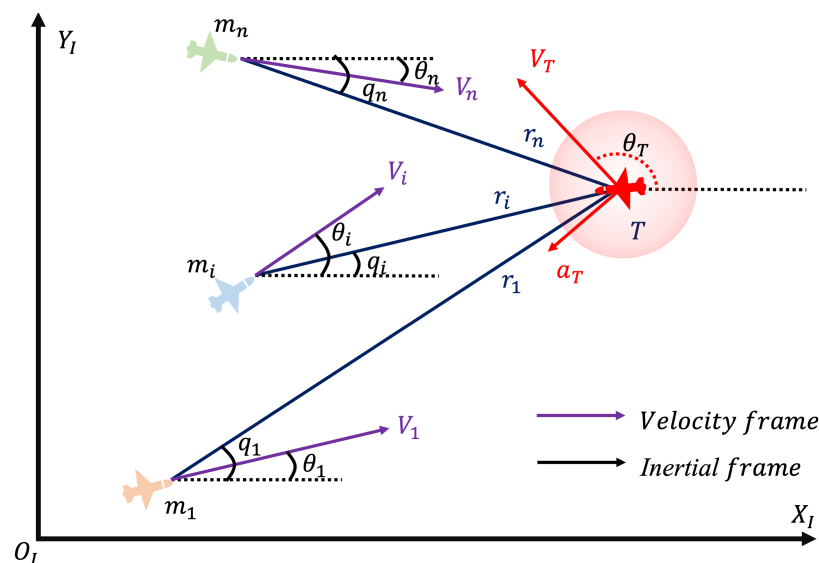


Figure 5. Guidance Geometry.

Flight vehicles adjust acceleration by controlling overload, thereby altering the magnitude and direction of velocity vectors. Denote a_i as the acceleration of the i -th flight vehicle of m_i and a_T as the acceleration of the target. The achievable loading of a flight vehicle is comprehensively determined by flight conditions, actuators and engine configuration.

3.3. Multi-Agent System and Cooperative Objective

Generally, the fundamental objective of flight-vehicle guidance is to design guidance commands a_i , such that multiple flight vehicles can saturate the defense ability by simultaneous arrival. Thus, the cooperative guidance objective can be expressed as

$$\begin{cases} r_i(t_f^i) \rightarrow 0 \\ \dot{q}_i(t_f^i) \rightarrow 0 \\ t_f^i - t_f^j = 0 \end{cases} \quad (2)$$

wherein t_f^i represents the arrival time of m_i .

Thus, to ensure cooperative guidance, the primary factor of saturation is simultaneous arrival. By selecting suitable cooperative state variables related to arrival time, cooperative guidance for MFV systems can be transformed into a typical application of multi-agent systems. The designated control input $u_i \in \mathcal{R}^n$, strongly related to the acceleration of the flight vehicle, is governed by the consensus protocol relying on state information.

For a first-order multi-agent system composed of n flight vehicles, the dynamical model of m_i can be written as

$$\dot{\zeta}(t) = u_i(t) \quad (3)$$

wherein $\zeta_i \in \mathcal{R}^n$ is the cooperative state variable of m_i .

Hence, the cooperative guidance can be reorganized as a multi-agent convergence problem,

Lemma 1 ([17]). For arbitrary initial conditions, the proposed consensus protocol u_i in Equation (5) enables the system, Equation (3), to achieve asymptotic consistency, Equation (4).

$$\lim_{t \rightarrow \infty} |\zeta_i - \zeta_j| = 0 \quad (4)$$

with

$$u_i(t) = - \sum_{j=1}^n a_{ij} (\zeta_i(t) - \zeta_j(t)) \quad (5)$$

As to a second-order multi-agent system, the system can be represented as

$$\begin{cases} \dot{\zeta}_1 = \zeta_2 \\ \dot{\zeta}_2 = u_i \end{cases} \quad (6)$$

wherein $\zeta_1 \in \mathcal{R}^n$ and $\zeta_2 \in \mathcal{R}^n$ are the first-order and second-order cooperative state variable of m_i , respectively.

Lemma 2 ([18]). For arbitrary initial conditions, the proposed consensus protocol u_i in Equation (8) enables the system Equation (6) to achieve asymptotic consistency Equation (7).

$$\begin{cases} \lim_{t \rightarrow \infty} |\zeta_{1i} - \zeta_{1j}| = 0 \\ \lim_{t \rightarrow \infty} |\zeta_{2i} - \zeta_{2j}| = 0 \end{cases} \quad (7)$$

with

$$u_i(t) = - \sum_{j=1}^n a_{ij} [\alpha(\zeta_{1i}(t) - \zeta_{1j}(t)) + \beta(\zeta_{2i}(t) - \zeta_{2j}(t))] \quad (8)$$

4. Constraint Analysis of Cooperative Guidance

Guidance is inherently a constrained control problem under limited information. Cooperative guidance, while expanding available information, introduces compound constraints imposed by mission requirements and physical capabilities. Under prevailing research trends, demands such as capability extension, mission expansion, and guidance performance enhancement further intensify cooperative constraints. Consequently, research centered on constrained cooperative guidance is of critical importance.

The research on cooperative guidance originated in 2006 [19] and the core constraints of cooperative guidance are mainly centered on the coordinated arrival time among multiple flight vehicles, whereby impact time control technology ensures the accomplishment of saturation missions [20–22]. In view of complicated practical environments and diversified mission requirements, it is imperative to guarantee overall cooperative guidance performance. According to bibliometric analysis, the constrained cooperative guidance framework can be schematically illustrated as Figure 6. Cooperative guidance is a multi-disciplinary research field integrating multi-agent theory, flight vehicle dynamics, control science, and computer science. Essentially, its theoretical studies serve the practical requirements of cooperative guidance engineering missions, that is, time cooperation for saturation. On this basis, research branches have gradually evolved and formed clustered research topics. Further combining with keyword clustering, co-citation clustering and the top 10 high-cited reference analysis, which started from mission-related keywords, the other clustering can be roughly divided into three categories: angle-related, communication-related and method-related keywords. Thus, the framework consisting of physical constraints and control constraints is preliminarily established on the basis of time coordination.

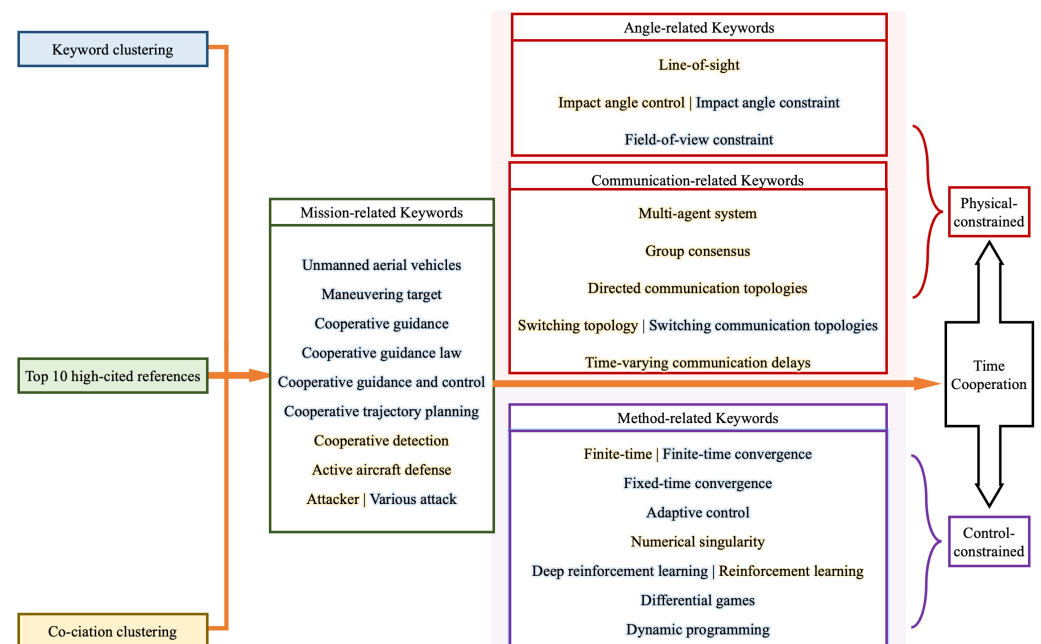


Figure 6. Schematic Illustration: from Bibliometric Analysis to Constraint Cooperative Guidance.

Hence, starting from the time constraint, the research branch of constrained cooperative guidance has gradually emerged and been extensively investigated. Accordingly, a literature review framework was constructed by integrating common flight-vehicle physical constraints and standard control theory constraints.

As shown in Figure 7, the mainstream constrained cooperative guidance methodologies can be classified into two main categories: physical-constrained cooperative guidance law and control-constrained cooperative guidance law.

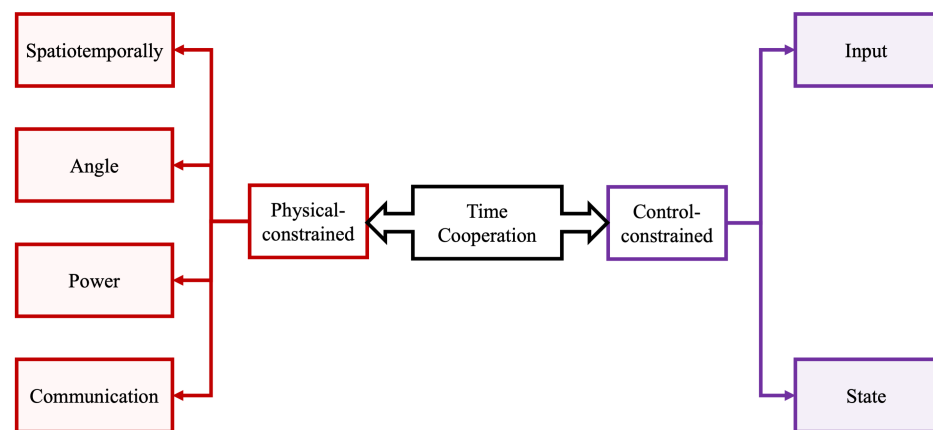


Figure 7. Classification of cooperative guidance based on constraint analysis

Physical-constrained cooperative guidance laws are divided into the following aspects:

- Spatiotemporal constraints
- Angle constraints
- Power constraints
- Communication constraints

Control-constrained cooperative guidance laws are divided into the following aspects:

- Input constraints
- State constraints

Whether classified from a physical perspective or a control theory perspective, all types of constraints essentially serve as essential supports for the design and implementation of cooperative guidance strategies. Thus, Table 4 is provided to systematically summarize the core characteristics of each constraint and their fundamental distinctions in shaping cooperative guidance mechanisms.

Table 4. Core characteristics of constrained cooperative guidance mechanism.

Constraint Category	Subclass	Core Characteristics	Core Differences in Cooperative Guidance Mechanisms
Physical-constrained	Spatiotemporally	Mission-specified unified terminal arrival time and spatial coverage limits for cooperation	Global top-level task constraint, which sets uniform terminal targets and determines overall collaborative task planning logic.
	Impact Angle	Terminal impact angle required by mission effectiveness	Global terminal performance constraint that restricts final trajectory inclination, independent of real-time onboard motion control.
	Power	Design of power propulsion configuration	Whether the flight vehicle is equipped with adjustable speed capability at the guidance stage directly dictates the basic framework of cooperative guidance design.
	Communication	Inherent network topology property of flight vehicle clusters	Determines the fundamental mode of information exchange among agents, governing the overall collaborative information interaction framework.
Control-constrained	State	Time-varying limitations of control states	Comprehensive restrictions on system control states are derived from the superposition of various physical state limits of the flight vehicle. Constraints exert local kinematic restrictions on the attitude tracking of a single platform. The superposed physical limits of the individual flight vehicle are mapped to the overall multi-agent cooperative system.
	Input	Time-varying loss and saturation of control commands	Dynamic input constraints originate from actuation, sensing and communication links. The induced time-varying imperfections of signals manifest as input constraints imposed on cooperative guidance commands.

Remark 1. Cooperative guidance constitutes a classic research branch of multi-agent coordination theory. Within this framework, flight vehicles act as specialized agents and also function as unique actuators of the entire cooperative multi-agent system. Additionally, flight systems are governed by distinctive physical constraints stemming from actuators. Specifically, actuators mounted on various flight vehicles directly determine each vehicle's dynamic behavior, which exerts a decisive influence on the overall coordination performance of the vehicle group. Although the inner-loop attitude dynamic control of actuators is commonly simplified in most cooperative guidance studies, characteristic features and physical limits originating from actuators are embedded within the kinematic and dynamic models built for cooperative guidance. These actuator-relevant physical bounds form the core logical foundation of constrained cooperative guidance.

Remark 2. A typical control system is subject to three categories of constraints: input constraints, output constraints and state constraints. Most studies on cooperative guidance adopt the three-degree-of-freedom mass-point kinematic model, where actuator dynamics and attitude dynamics

are neglected. In this case, guidance control inputs are highly coupled with flight maneuver outputs. Consequently, system output constraints can be collectively categorized as flight vehicle maneuverability constraints, and traditional input and output constraints, including acceleration saturation and overload limits, no longer have distinct boundaries.

Remark 3. *There exist inherent correlations and shared physical origins between physical-constrained and control-constrained conditions, but they feature distinct research focuses.*

- *Power constraints target the physical actuation characteristics of each flight vehicle in the multi-agent system. That is, varied propulsion configurations directly define the vehicles' controllable capacity, with research centering on dynamic-model-based control mechanisms. Although propulsion serves as a critical physical source of input constraints, input limitations additionally arise from multiple coupled factors such as actuators, structural overload and aerodynamic saturation. This category mainly investigates input bounds mapped from integrated physical restrictions onto control signals. Similarly, certain physical constraints will manifest themselves as state constraints in specific forms. Consequently, these two categories of constraints interact with one another while retaining fundamental distinctions.*
- *Communication networks govern the mode and quality of information delivery. Physical-layer communication constraints place emphasis on network architectures that determine how information is exchanged among flight vehicles. In contrast, communication-related restrictions manifest as input constraints from the control perspective. That is, cooperative commands are generated and organized through network communication, which imposes additional constraints on control inputs. Different from physical communication constraints that focus on how network topologies shape information transmission frameworks, input constraints quantify how flawed information deteriorates control command performance.*

Similarly, certain physical constraints will manifest themselves as state constraints in specific forms. Consequently, these two categories of constraints interact with one another while retaining fundamental distinctions.

5. Physical-Constrained Cooperative Guidance Law

5.1. Spatiotemporal-Constrained Cooperative Guidance Law

For cooperative guidance, the primary task is to achieve zero miss distance and form a saturation attack posture through time coordination. In the early stage of research, studies were mainly focused on 2D planar guidance. On the one hand, the small altitude difference in air-to-air scenarios allows the problem to be simplified to 2D planar guidance. On the other hand, 3D guidance can be decomposed into guidance in two orthogonal planes [19–22]. Thus, 2D cooperative guidance has been widely studied. Combining with sliding mode control, a guidance method was investigated for impact-time cooperative requirements, ensuring a wide range of the capture region [21]. Considering a high-maneuvering aerial target, Ref. [23] developed a biased proportional cooperative guidance law, enabling the joint reachable sets to cover the target evasion area. Based on the trajectory shaping technology, a sliding mode cooperative guidance method was researched in Ref. [24], so as to improve the performance through energy management. To overcome the weakness of the predicted-interception-point assumption, Ref. [25] developed an analytical cooperative guidance law based on the bias proportional guidance form for the maneuvering target. Ref. [26] improved the performance of the cooperative guidance law with a nonsingular sliding mode control method.

Widely researched 2D cooperative guidance mainly focuses on the design of cooperative state variables, especially the estimation of impact time listed in Table 5. Non-analytical time-to-go estimation methods depend on motion states, and simple formulations are beneficial for engineering implementation due to low computational cost and good real-time

performance. But ignoring the angular coupling leads to low modelling accuracy and obvious estimation error. In contrast, analytical time-to-go estimation formulations are strictly derived from relative motion dynamics with closed-form expressions, which can compensate for coupling, possessing higher theoretical accuracy and better robustness. Nevertheless, the drawbacks lie in more complex expressions, slightly heavier computation and inherent limitations from small-angle assumptions.

Table 5. Typical estimation of time-to-go.

Reference	Typical Estimation of Time-to-Go	Analytical Property
[26–28]	$\frac{r_i}{V_i}$ (or r_i with constant velocity)	×
[25,29,30]	$-\frac{r_i}{\dot{r}_i}$	×
[24]	$\frac{r_i}{V_i} \left[1 + \frac{\sin^2(\eta_i)}{10} \right]$	✓
[31]	$\frac{r_i}{V_i} \left[1 + \frac{\theta_i^2}{2(2N_i - 1)} \right]$	✓
[32]	$\frac{r_i}{V_i} e^{t_1 \eta_i + c_2(\eta_i + \alpha_i)} \left(1 + C_3 \eta_i^2 + C_4 \varphi_i \alpha_i + C_5 \alpha_i^2 \right)$	✓

Impact time is typically controlled by trajectory length planning; however, trajectory calculation in 3D engagement is far more complicated than in 2D cases. Given the complexity of 3D mission environments, extensive research has been conducted on 3D guidance laws, and the typical 3D cooperative guidance law can be categorized into two main types (as shown in Figure 8).

(1) The first typical model

Inspired by Ref. [33], considering the 3D guidance geometry of flight vehicles flying to a stationary target, wherein (X_I, Y_I, Z_I) and (X_i, Y_i, Z_i) denote the inertial reference and flight vehicle body coordinate system, respectively, the 3D point-mass motion equations are described as follows

$$\begin{cases} \dot{r}_i = -V_M \cos \theta_{Mi} \cos \phi_{Mi} \\ \dot{\lambda}_{Yi} = \frac{V_M}{r_i} \sin \theta_{Mi} \\ \dot{\lambda}_{Zi} = -\frac{V_M}{r_i} \cos \theta_{Mi} \sin \phi_{Mi} \\ \dot{\theta}_{Mi} = \frac{A_{ZMi}}{V_M} - \frac{V_M}{r_i} \tan \lambda_{Yi} \cos \theta_{Mi} \sin^2 \phi_{Mi} + \frac{V_M}{r_i} \cos \phi_{Mi} \sin \theta_{Mi} \\ \dot{\phi}_{Mi} = \frac{A_{YMi}}{V_M \cos \theta_{Mi}} + \frac{V_M}{r_i} \tan \lambda_{Yi} \sin \theta_{Mi} \sin \phi_{Mi} \cos \phi_{Mi} \\ \quad + \frac{V_M}{r_i \cos \theta_{Mi}} \sin^2 \theta_{Mi} \sin \phi_{Mi} + \frac{V_M}{r_i} \cos \theta_{Mi} \sin \phi_{Mi} \end{cases} \quad (9)$$

where, r_i is the interceptor-target relative distance; θ_{Mi} and ϕ_{Mi} represent two Euler angles from the line-of-sight (LOS) coordinate system to the flight vehicle body coordinate system; θ_{Li} and ϕ_{Li} are LOS angles in azimuth and elevation directions, respectively; heading error σ_i represents the angle between the velocity of m_i and the LOS; $\dot{\lambda}_{Yi}$ and $\dot{\lambda}_{Zi}$ are LOS coordinate system components of LOS angular velocity; the velocity of flight vehicle V_M

are assumed to be fixed with adjustable perpendicular acceleration A_{YMi} and A_{ZMi} in yaw and pitch directions, respectively.

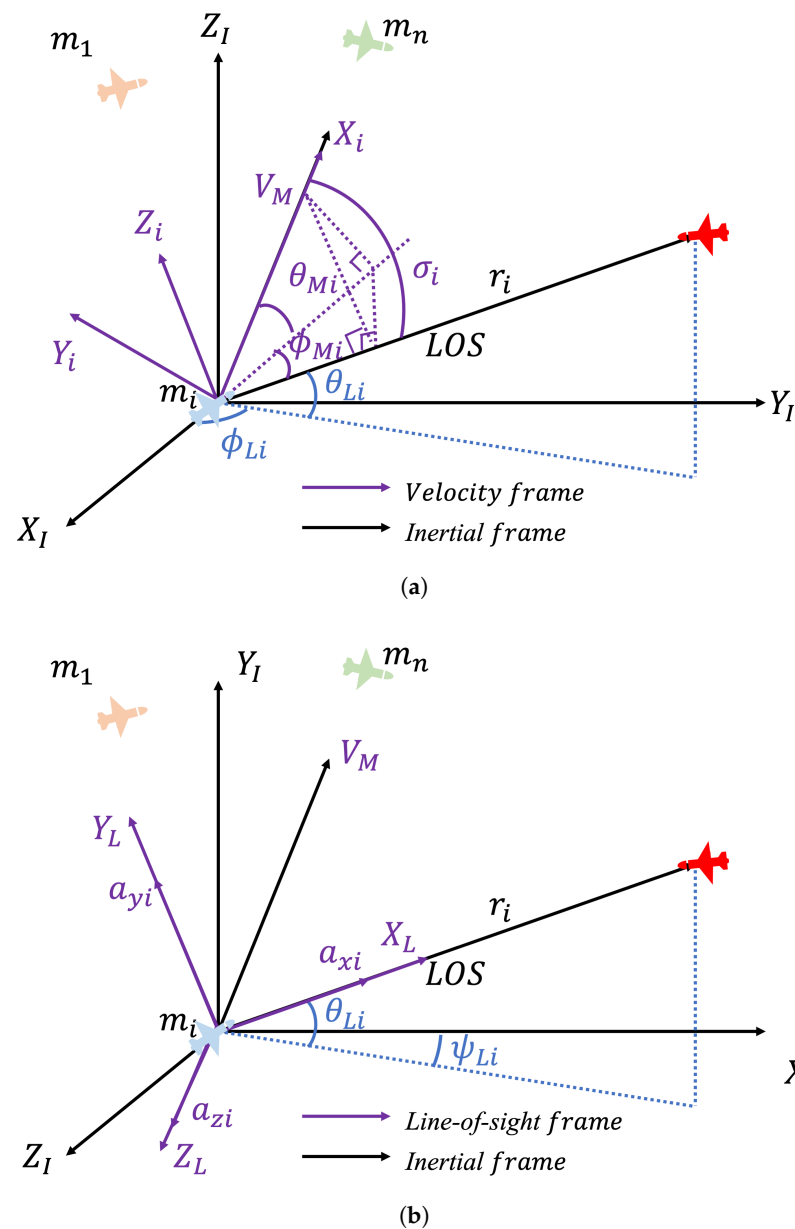


Figure 8. 3D cooperative guidance: (a) The first typical model (b) The second typical model.

According to the coupled cooperative guidance model, Zhao et al. [34] and He et al. [35] investigated two-stage 3D bias consensus-based cooperative guidance laws, enabling simultaneous arrival. Ref. [36] studied the cooperative guidance to improve the prescribed-time performance. Refs. [37,38] expanded the two-stage cooperative guidance law from the 2D planner to 3D space. Ref. [39] developed an impact-time-constrained proportional navigation guidance incorporating a range-varying gain, so as to obtain a globally precise time-to-go solution and an achievable impact time region. To further broaden its application scope for maneuvering target interception, Ref. [40] proposes a dynamic cooperative guidance law based on a coverage strategy. The strategy decomposes the cooperative engagement into multiple one-on-one time-to-go cooperative problems.

Although the cooperative guidance structure requires neither time-to-go estimation nor controllable velocity magnitude, the model departs from the standard coordinate framework. The inconsistent coordinate benchmarks and motion description laws make it

difficult to directly adapt to the dynamic and control system of a six-degree-of-freedom flight vehicle.

(2) The second typical model.

Developed by the decoupled 2D planner engagement, a decoupled 3D model was established, referring to [41]. Based on the geometric relationship, the typical kinematic equation for relative motion between the flight vehicle and the target in 3-D space can be derived as follows:

$$\begin{cases} \ddot{r}_i - r_i \dot{\theta}_{Li}^2 - r \dot{\psi}_{Li}^2 \cos^2 \theta_{Li} = a_{Tx} - a_{xi} \\ r_i \ddot{\theta}_{Li} + 2\dot{r}_i \dot{\theta}_{Li} + r \dot{\psi}_{Li}^2 \sin \theta_L \cos \theta_L = a_{Ty} - a_{yi} \\ -r_i \ddot{\psi}_{Li} \cos \theta_{Li} - 2\dot{r}_i \dot{\psi}_{Li} \cos \theta_{Li} + 2r \dot{\theta}_{Li} \dot{\psi}_{Li} \sin \theta_{Li} = a_{Tz} - a_{zi} \end{cases} \quad (10)$$

wherein, $OX_I Y_I Z_I$ represents the inertial coordinate system, and $OX_L Y_L Z_L$ represents the LOS coordinate system; r denotes the relative distance between flight vehicle and target; V_m, V_t correspond to the velocity vectors; ψ_L, θ_L represent the LOS azimuth and elevation angle; a_{Mx}, a_{My}, a_{Mz} and a_{Tx}, a_{Ty}, a_{Tz} represent the acceleration components of the flight vehicle and target in LOS coordinate system.

Ref. [42] proposed a finite-time cooperative guidance law with a two-direction scheme. In Ref. [43], a fixed-time cooperative guidance law was investigated with adjustable impact time. As for Ref. [44], a 3D prescribed-time cooperative guidance law was designed with relative distance and its rate as cooperative state variables. Incorporating a neural network disturbance observer, the proposed law has better performance in target maneuvering compensation. Apart from the convergence performance enhancement, fault tolerance is also essential to improve the stability and strike capability of an MFV swarm. Hence, Refs. [45,46], respectively, investigated 3D fault-tolerant cooperative guidance laws, thereby alleviating the burden on the actuators. Participating in a pursuit-evasion game, a 3D cooperative guidance law was designed in Ref. [46] with model predictive control and sliding mode control. Based on the estimation of time-to-go, Ref. [47] presented an impact-time cooperative guidance law to support the spatiotemporal cooperation.

5.2. Angle-Constrained Cooperative Guidance Law

In practical combat scenarios, merely satisfying the miss distance index and impact-time cooperation can no longer meet the requirements of guidance missions. While approaching the target, the flight vehicle is also required to strike at a designated impact angle to guarantee operational effectiveness. Especially under special interception conditions, it is necessary to introduce impact angle constraints throughout the guidance phase to construct a desired interception configuration. Ref. [48] first extended the impact-time cooperative guidance introducing angle constraints, which can effectively improve guidance performance, while preventing collisions by dispersing the impact angles. Thus, the cooperative objective can be reorganized as

$$\begin{cases} r_i(t_f^i) \rightarrow 0 \\ Angle_i(t_f^i) - Angle_d^i \rightarrow 0 \\ \dot{q}_i(t_f^i) \rightarrow 0 \\ t_f^i - t_f^j = 0 \end{cases} \quad (11)$$

wherein $Angle_i$ is the constrained actual impact angle and $Angle_d$ represents its desired value, which can be either directly measurable physical quantities or characterization variables that require indirect estimation and calculation to reflect physical states.

Angle constraints further expand and enrich the connotation of spatiotemporal constraints. Different from spatiotemporal constraints, angle constraints involve strong coupling between pitch and yaw channels as well as complex nonlinear dynamic characteristics, which significantly increases the research difficulty. Existing methods can be mainly divided into two categories: coupled and decoupled.

(1) Coupled

The first category method adopts an integrated design without command decomposition and only employs the acceleration normal to the velocity of the flight vehicle.

Ref. [49] proposed a novel distributed cooperative guidance law, which is composed of two components: a local control term that ensures zero miss distance and a predefined impact angle, and a cooperative control term that achieves cooperation of impact time. Considering more practical scenarios, Ref. [50] extended an optimal impact angle cooperative guidance law from the 2D plane to 3D space. Coplanar cooperative guidance commands and planar pursuit guidance commands are separately derived to formulate the 3D cooperative guidance law. As in Ref. [51], by transforming cooperative guidance into a flight path angle tracking problem, the designated cooperative guidance law can ensure simultaneous arrival with a standard acceleration with zero effort. In Ref. [52], the proposed nonlinear optimal impact angle cooperative guidance law can be applied to both unified angle and angle range attack scenarios.

Although the coupled method features a simple structure and easy implementation, it suffers from degraded accuracy under large-angle maneuvers. The absence of channel decoupling leads to a more complex formulation and brings certain challenges to guidance law design and stability analysis.

(2) Decoupled

The second category, which decouples the cooperative problem into pitch and yaw planes for separate design, takes the line-of-sight (LOS) angles as constrained variables and converts angle constraints into a terminal LOS angle tracking problem.

Ref. [53] proposed a decoupled cooperative guidance law, ensuring hit-to-kill interception for the target at the same time as well as at the desired impact angles. Based on the 3D cooperative model, the design can be decoupled into two directions: in the LOS direction and in the normal to LOS direction. Based on the cooperative guidance scheme, Ref. [54] developed a two-direction cooperative guidance against a maneuvering target, based on cooperative variables related to range-to-go and radial relative velocity. In Ref. [55], a novel fixed-time cooperative guidance law was investigated, so as to realize the constraints of the impact time and angle simultaneously. Ref. [56] presented a cooperative guidance method with a fast cooperative guidance law, resulting in the simultaneous interception of a maneuvering target with the expected terminal impact angle. By introducing the impact angle constraint, the relationship between the terminal impact angles and the line-of-sight (LOS) angles was established in Ref. [57]. On this basis, a fixed-time sliding mode guidance law was proposed to address various motions of the target. In order to achieve all-directional capability and improve the lethality of flight vehicles, fixed-time cooperative guidance laws were developed for both the elevation and azimuth directions of the line-of-sight (LOS) [58]. Compared with the state-of-the-art method, the proposed guidance achieves smaller terminal LOS angle errors and avoids the saturation of the LOS-normal guidance command at the time of impact.

The decoupled methods explicitly decompose the guidance command into radial and normal components to realize time coordination and angle control, respectively, featuring clear design logic, simple structure and convenient stability analysis. However, such methods ignore the natural dynamical coupling by treating the two channels independently,

which may limit the overall system performance and usually requires flight vehicles to have a speed-adjustable capability.

As shown in Table 6, impact-angle constraints can be realized either by directly restricting measurable physical angles or by constraining estimated angular variables. Based on coupled modeling frameworks, biased proportional guidance is widely studied, where the cooperative requirements of impact angle and time are integrated into the bias term simultaneously to achieve error convergence. As for decoupled modeling frameworks, the system is decomposed along two orthogonal directions: the impact time is coordinated by the LOS directional command, while the impact angle is regulated through the normal LOS directional control.

Table 6. Cooperative guidance mechanism for impact-angle constraints.

Category	Reference	Angle	Forming	Core Characteristics
Coupled	[49]	Line-of-sight angle	Physical variable q_d^i	Biased proportional guidance with impact angle constraint
	[50,52]	Final path angle	Estimation $\gamma_d^i = q_i + \frac{q_i - \theta_i}{N-1}$	
	[51]	Flight path angle	Estimation $\gamma_d^i = \frac{y_d^i - y_i}{x_d^i - x_i}$	
Decoupled	[53–57]	Line-of-sight angle	Physical variable q_d^i	Decoupled dual-direction LOS control for time-angle separate regulation

5.3. Power-Constrained Cooperative Guidance Law

In cooperative guidance scenarios, power constraints are a key factor limiting the coordination performance of multiple flight vehicles. Essentially determined by the propulsion system, the velocity regulation capability directly affects time synchronization accuracy, impact angle precision, and cooperative stability. Imposed by the power constraints, existing cooperative guidance can be generally categorized into unpowered and powered.

(1) Unpowered

During the guidance phase, owing to limited thrust and high flight velocity as well as a confined guidance window, the flight velocity can be approximately regarded as constant under certain flight conditions. Thus, the constant-speed model can be simplified as

$$\begin{cases} \dot{r}_i = V_T \cos \eta_i^T - V_i \cos \eta_i \\ r_i \dot{q}_i = V_T \sin \eta_i^T - V_i \sin \eta_i \\ \eta_i^T = \theta_T - q_i \\ \eta_i = \theta_i - q_i \\ \dot{\theta}_i = \frac{a_i}{V_i} \\ \dot{\theta}_T = \frac{a_T}{V_T} \end{cases} \quad (12)$$

wherein the velocity V_i is constant and the acceleration a_i is perpendicular to V_i .

Based on the constant-speed modeling, Ref. [59] proposed a robust cooperative guidance law integrated with a local filtering algorithm. Formulating cooperative guidance as a nonlinear optimal control problem, Ref. [60] investigated a two-stage sequential convex programming. Consider the planar engagements with unpowered flight vehicles holding constant speed; a cooperative salvo guidance law was introduced in Ref. [61]. Ref. [62] proposed a nonlinear three-dimensional guidance law for multiple identical constant-speed flight vehicles. To address the difficulty of intercepting hypersonic targets, Liu et al. investigated cooperative guidance and interception methods for unpowered flight vehicles [63,64].

Although the simplified constant-velocity model can adequately describe the short guidance phase, it fails to capture the actual velocity decay caused by aerodynamic drag

and gravity during the unpowered flight phase. Therefore, some scholars have considered the aerodynamic effects in the unpowered guidance stage and conducted research on cooperative guidance methods tailored to the velocity variations under unpowered conditions. Ref. [65] investigated a deep reinforcement learning cooperative guidance law to achieve impact-time control with the time-varying velocity caused by gravity and aerodynamic drag. Ref. [66] studied a cooperative guidance law for multiple unpowered hypersonic vehicles by dividing the motion in 3D space into two planes. Considering the induced drag causes rapid velocity decay, Ref. [67] proposed a rapid prediction algorithm for the proportional navigation guidance law to ensure simultaneous arrival.

(2) Powered

For powered flight vehicles, continuous engine thrust directly alters the flight velocity of the flight vehicle. Therefore, the dynamic velocity variations induced by thrust need to be considered in the kinematic models, so as to completely characterize the cooperative guidance under thrust effects. Hence, the typical variable-speed 2D model can be further established as

$$\begin{cases} \dot{r}_i = V_T \cos \eta_i^T - V_i \cos \eta_i \\ r_i \dot{q}_i = V_T \sin \eta_i^T - V_i \sin \eta_i \\ \eta_i^T = \theta_T - q_i \\ \eta_i = \theta_i - q_i \\ \dot{V}_i = a_{xi} \\ \dot{\theta}_i = \frac{a_{yi}}{V_i} \\ \dot{\theta}_T = \frac{a_T}{V_T} \end{cases} \quad (13)$$

wherein a_{xi} and a_{yi} are the acceleration components in the LOS direction and normal to the LOS direction of the i -th flight vehicle of m_i , respectively.

Based on the decoupled cooperative guidance model, Ref. [68] proposed a 3D cooperative guidance law, incorporating time-to-go estimation. It directly utilizes the propulsion capability to adjust the tangential accelerations, thereby improving the precision of impact time cooperation. Furthermore, Ref. [69] formulates the cooperative guidance problem with range-to-go. Considering the speed profiles are time-varying, and accelerations are always perpendicular to the direction of their velocity, a varying-speed cooperative differential game guidance law is proposed. Ref. [70] investigated a cooperative guidance algorithm designed to enable multiple flight vehicles to simultaneously arrive at desired terminal angles while maintaining control over their impact velocities.

In practice, flight vehicle speed varies considerably due to thrust, drag, and gravity, which renders analytical time-to-go prediction nearly impossible. By further accurately characterizing the aerodynamic properties, Ref. [71] designed a predictive–adaptive cooperative guidance law fully incorporating the thrust and drag dynamics of the powered flight vehicle, which is propelled by rocket engines unable to actively control speed. In Ref. [72], a 3D cooperative guidance law is designed within a prediction–correction framework, where the time-to-go under the baseline command is efficiently estimated using a realistic aerodynamic model, and a biased command is derived based on such time-to-go predictions to synchronize the impact times of multiple powered flight vehicles. Ref. [73] addressed the 3D approach angle constrained cooperative guidance problem for speed-varying flight vehicles against maneuvering targets. Ref. [74] enhanced a spatial-temporal cooperative guidance law with speed variations caused by thrust, aerodynamic drag, and gravitational force.

Essentially determined by the propulsion system, the velocity regulation capability directly affects time synchronization accuracy, impact angle precision, and cooperative

stability. This subsection centers on the disparities in structural frameworks of cooperative guidance laws arising from power-related dynamic constraints. As summarized in Table 7, velocity variations of unpowered platforms are dominated by aerodynamic drag, justifying the constant-speed approximation owing to the brief guidance duration; powered vehicles can generate axial acceleration to modulate flight speed arbitrarily. The essential divergence is the independent adjustability of speed magnitude during directional maneuvers, which leads to disparate core structures of cooperative guidance laws.

Table 7. Cooperative guidance mechanism for power constraints.

Category	Reference	Velocity	Power Forming
Unpowered	[59–64]	constant velocity	V_i is constant
	[65–67]	variable velocity	$\dot{V}_i = -\frac{D}{m} - g \sin(q - \theta)$, wherein D is drag
Powered	[68–70]	variable velocity	$\dot{V}_i = a_{xi}$
	[71–74]	variable velocity	$\dot{V}_i = \frac{(T-D)}{m} + g$, wherein T is thrust and D is drag

5.4. Communication-Constrained Cooperative Guidance Law

As a typical multi-agent consensus problem, the communication network is the fundamental support of information interaction. Beginning with the estimation of time-to-go and the communication network, a consensus-based biased proportional navigation guidance law was proposed in Ref. [75]. Since then, network-based cooperative guidance laws have been extensively investigated under various communication constraints, mainly centered on the architecture of networks.

Networked communication can effectively support information interaction among flight vehicles, thereby coordinating multiple flight vehicles to exert swarm cooperative effects. Communicated by an undirected network, Ref. [76] introduced a cooperative guidance law based on a distributed network. Furthermore, Ref. [77] proposed a cooperative guidance law, based on an undirected distributed network combined with pinning leader-following communication. Considering the dynamic undirected communication, Ref. [78] proposed a distributed cooperative guidance law that meets spatiotemporal constraints. Based on connected undirected communication, a wide-envelope cooperative guidance law was designed for multiple speed-varying flight vehicles [79].

Although the undirected network can effectively support distributed cooperative guidance, the undirected communication constraints require relatively more network resources, which is difficult to guarantee in the process of the cooperative guidance mission. In Ref. [80], considering a strongly connected and detail-balanced directed graph, a cooperative guidance law was designed with relaxed communication conditions. Ref. [81] researched terminal-time synchronization cooperative guidance for multiple vehicles under discrete-time communication networks with directed switching topologies. Ref. [82] developed and evaluated a quantized cooperative salvo guidance law, and proposed a novel joint design methodology for encoders, decoders, and guidance laws to solve the cooperative guidance problem of achieving simultaneous attacks on stationary targets under communication bandwidth constraints and directed topology.

To relax the constraints on the communication network topology, the directed spanning tree assumption, which refers to a subgraph of a directed graph that includes all the vertices of the original graph, has no cycles, and has exactly one directed path from a designated root vertex to every other vertex in the subgraph [16], is further considered. In Ref. [83], based on directed spanning tree topology, a two-stage consensus-based cooperative guidance law was presented. By incorporating circular guidance and practical consensus, Ref. [84] developed a distributed cooperative guidance law from an undirected to a leader-following communication topology. Compared with undirected and directed connected protocols, the

protocol designed based on the directed spanning tree can greatly relax the communication constraints of cooperative guidance. That is, under undesired communication conditions, as long as a directed spanning tree exists in the communication network, a cooperative guidance task can be achieved with limited information.

Cooperative advantages are underpinned by scale. However, neither centralized nor distributed architectures can easily balance the contradiction between scale expansion and cooperative performance. Accordingly, research on networked cooperative guidance combined with a grouping architecture has gradually emerged and become a noteworthy research branch. Different from traditional cooperative guidance designed for single-target interception, group cooperative guidance is capable of handling multiple targets. In a cooperative guidance scenario, the MFV formation can be partitioned into several subgroups, with each subgroup assigned to arrive at an independent target. By designing the group protocol, Ref. [85] proposed a two-stage group cooperative guidance law, requiring each subgroup to contain a directed spanning tree and the in-degree balance condition to be satisfied among subgroups, which renders the scale expansion of multiple flight vehicles difficult. Instead of the in-degree balance condition among subgroups, Ref. [86] developed the group cooperative guidance law with a pinning scheme, transforming the communication constraints into a directed spanning tree.

The communication constraints in cooperative guidance systems are essentially equivalent to the graph connectivity conditions required by consensus protocols. In multi-agent coordination, the convergence and stability of consensus algorithms depend fundamentally on the structure of the underlying communication graph, particularly its connectivity, directionality, and hierarchical organization. Four typical communication topologies can thus be systematically interpreted and compared from a graph-theoretic perspective, as summarized in Table 8. Specifically, centralized and leader-following communication correspond to special and general forms of directed spanning trees, respectively, while distributed topologies are modeled as undirected connected graphs or strongly connected directed graphs. The group communication combines the advantages of distributed and centralized structures.

Table 8. Relationship between communication and graph.

Reference	Communication	Characteristic	Relationship
[76–82]	Distributed	Decentralized peer-to-peer	Undirected connected graph or strongly connected directed graph
[83,84]	Centralized	Single-root hierarchical cooperative topology	Directed spanning tree
[85,86]	Group	Hierarchical nested topology	Intra-group and inter-group connectivity conditions

5.5. Summary of Physical-Constrained Cooperative Guidance

Under the physical constraints of flight vehicles, the design of guidance models and corresponding guidance mechanisms must adapt to the inherent capacity and natural constraints of vehicles, covering four core types: spatiotemporal, angle, power and communication constraints.

Table 9 establishes a cross-dimensional comparative framework for all reviewed physically constrained cooperative guidance laws. It covers the core evaluation indices and provides a unified reference that reveals the similarities, differences, and applicable boundaries among various cooperative guidance approaches.

Existing studies on spatiotemporal constraints predominantly focus on terminal guidance scenarios, with core attention paid to simultaneous arrival under saturation missions. On the other hand, current heterogeneity analyses mostly discuss isolated actuator-level disparities of individual flight vehicles. Heterogeneous traits lie in communication topologies, propulsion configurations and angular bounds: seeker performance defines distinct

angular constraint envelopes, different power systems correspond to dedicated guidance frameworks, and network architectures govern unique information transmission modes. Such heterogeneous features are merely treated as separate inner-actuator limits, and nearly all relevant analyses rely on simplified mass-point models, regardless of detailed internal dynamics.

Table 9. Multi-dimensional Consolidated Comparison of Physical-constrained Cooperative Guidance.

Category	Ref.	Power	Dimensional	Target Type	Convergence	Communication
Spatiotemporal Constraint	[23]	Unpowered	2D	Maneuvering	Asymptotic	Open-loop/Distributed
	[24]	Unpowered	2D	Stationary	Finite-time	Undirected
	[25]	Unpowered	2D	Maneuvering	Uniformly Ultimately Bounded	Distributed
	[26]	Powered	2D	Maneuvering	Fixed-time	Leader-follower
	[27]	Powered	2D	Stationary	Finite-time	Undirected
	[28]	Powered	2D	Maneuvering	Finite-time	Undirected
	[29]	Unpowered	2D/3D	Stationary	Asymptotic	Undirected
	[30]	Unpowered	2D/3D	Stationary	Uniformly Ultimately Bounded	Undirected
	[31]	Unpowered	2D	Stationary/Maneuvering	Asymptotic	Global/Distributed
	[32]	Powered	2D	Stationary	Asymptotic	Distributed
	[35]	Unpowered	3D	Maneuvering	Asymptotic	Undirected
	[36]	Unpowered	3D	Stationary	Prescribed-time	Directed
	[37]	Powered	2D/3D	Stationary	Finite-time	Undirected
	[38]	Unpowered	3D	Maneuvering	Fixed-time	Undirected/Leader-follower
	[39,40]	Unpowered	3D	Maneuvering	Asymptotic	Global
	[42]	Powered	3D	Stationary	Finite-time	Undirected
	[43]	Unpowered	3D	Stationary	Fixed-time	Leader-follower
	[44]	Unpowered	3D	Maneuvering	Prescribed-time	Undirected
	[45]	Powered	3D	Maneuvering	Finite-time	Undirected
	[46]	Powered	3D	Maneuvering	Fixed-time	Leader-follower
Angle Constraint	[49]	Unpowered	2D	Stationary	Asymptotic	Directed
	[50]	Powered	2D/ 3D	Stationary	Fixed-time	Undirected
	[51]	Powered	2D	Maneuvering	Finite-time	Open-loop
	[52]	Unpowered	2D	Maneuvering	Prescribed-time	Directed
	[53]	Unpowered	3D	Stationary	Finite-time	Undirected
	[54]	Powered	3D	Maneuvering	Fixed-time	Undirected
	[55]	Unpowered	3D	Maneuvering	Fixed-time	Undirected
	[56]	Powered	3D	Maneuvering	Appointed-Time	Undirected
	[57]	Powered	3D	Maneuvering	Fixed-time	Undirected
Power Constraint	[61]	Unpowered	2D	Stationary	Fixed-time	Directed
	[62]	Unpowered	3D	Stationary	Asymptotic	Leader-Follower
	[63]	Unpowered	2D	Maneuvering	Asymptotic	Global
	[64]	Unpowered	3D	Maneuvering	Asymptotic	Global
	[65]	Unpowered	3D	Stationary/Maneuvering	Asymptotic	Global
	[66]	Unpowered	3D	Maneuvering	Finite-time	Undirected
	[67]	Unpowered	3D	Stationary	Prescribed-time	Undirected
	[68]	Powered	3D	Stationary	Finite-time	Undirected/Leader-Follower
	[69]	Powered	2D	Maneuvering	Asymptotic	Undirected
	[70]	Powered	3D	Maneuvering	Fixed-time	Undirected
	[71]	Powered	3D	Stationary	Asymptotic	Undirected
	[72]	Powered	3D	Stationary	Finite-time	Directed
	[73]	Powered	3D	Maneuvering	Asymptotic	Undirected
	[74]	Powered	3D	Stationary	Fixed-time	Undirected
Communication Constraint	[75,83,85]	Unpowered	2D	Stationary	Asymptotic	Directed
	[76]	Powered	3D	Maneuvering	Fixed-time	Undirected
	[77]	Powered	3D	Maneuvering	Finite-time	Leader-Follower
	[78]	Powered	3D	Maneuvering	Arbitrary-time	Undirected
	[79]	Powered	3D	Maneuvering	Finite-time	Undirected
	[80]	Unpowered	3D	Maneuvering	Finite-time	Undirected
	[81]	Unpowered	2D	Stationary	Fixed-time	Directed
	[82]	Unpowered	2D/3D	Stationary	Asymptotic	Undirected/Directed
	[84]	Unpowered	2D/3D	Stationary/Maneuvering	Prescribed-time	Undirected/Directed
	[86]	Unpowered	3D	Stationary	Prescribed-time	Directed

Accordingly, two critical research gaps remain to be addressed. As missions expand in temporal, spatial and velocity dimensions, updated spatiotemporal constraints oriented to overall guidance efficiency are needed to accommodate extended multi-domain operations while retaining compatibility with conventional tasks. Flight vehicles act as core actuators of cooperative guidance systems with heterogeneity derived from coupled compound

physical factors. Current relevant investigations rest on oversimplified assumptions, and systematic research centering on integrated heterogeneous physical properties of flight vehicle actuators is still inadequate.

6. Control-Constrained Cooperative Guidance Law

6.1. Input Constrained Cooperative Guidance Law

Input constraints essentially reflect the physical actuator capability of flight vehicles, which is mainly embodied in the saturation limits of allowable overload, that is, restricted acceleration. Physically, the maximum allowable overload is determined by the actuator deflection, servo response performance and aerodynamic limits. Since overload is linearly correlated with normal acceleration, the overload limitation can be equivalently transformed into the amplitude constraint of acceleration. In cooperative guidance, normal acceleration serves as the core control input. When the guidance command exceeds the physical limit, input saturation occurs, which degrades the performance of the guidance law, reduces cooperative convergence accuracy, and even fails to satisfy the terminal angle and simultaneous interception requirements.

Concentrating on intrinsic constraints arising from the physical actuator limitations of flight vehicles, many scholars have conducted extensive research on the problem of input saturation constraints. Ref. [87] adopted a sequential method to design the cooperative guidance law, effectively addressing acceleration saturation constraints caused by actuator capability limitations and communication connectivity limitations. Ref. [88] transformed the cooperative guidance problem into a multi-agent system subject to input constraints and unknown nonlinearity, and introduced fuzzy logic to handle the saturation characteristics of control input. Ref. [89] proposed a cooperative maneuver penetration guidance law based on line deviation control, which not only guarantees the consistent arrival time but also enhances the penetration performance of a single flight vehicle through spiral maneuver, while satisfying the overload constraints. To address the cooperative interception challenge of multiple flight vehicles under stringent input constraints and thruster failure, a robust cooperative guidance law was introduced in Ref. [90]. Based on the nonlinear sliding surface and a fault filter, actuator saturation and thruster failure issues can be mitigated. Ref. [91] investigated cooperative guidance with input saturation, taking into account the inherent constraints of engine performance.

Nevertheless, current research on input constraints has gradually shifted from focusing on inherent constraints caused by the physical actuation capability of flight vehicles in early stages, to regarding various constraint problems induced by communication links as the mainstream research focus. Due to the consensus protocol having been introduced into guidance law design, communication constraints equivalently act on the control input layer, which further expands the influencing factors of input constraints. In consideration of the inevitable input delay raised by insufficient communication or actuator capacity, Refs. [92–94] analyzed the convergence performance of cooperative guidance laws. Although sufficient cooperative guidance laws have been proposed to avoid performance degradation caused by interference and deception attacks [95,96], the underlying fault model merely restricts the data transmission ability while keeping data reception available. This idealized setting ignores practical communication-induced input constraints and cannot characterize the actual complete communication outage. Consequently, under severe electronic countermeasures, relying merely on topology switching is insufficient. Real communication interruptions will inevitably deteriorate the control input performance, eventually leading to the failure of cooperative guidance tasks. To address the issues of acceleration saturation and unreliable communication links during multi-vehicle coopera-

tive guidance, an adaptive high-reliability cooperative guidance law with relative impact velocity and impact angle constraints was studied in Ref. [97].

Existing studies have achieved effective solutions for single-type input constraint suppression and cooperative consensus control (as shown in Table 10). However, most available methods only focus on separate constraint processing. Moreover, few works further distinguish and analyze the coupling mechanism between control input constraints, flight state constraints and practical output constraints, which makes it difficult to fully adapt to the actual complex multi-constraint flight scenarios.

Table 10. Cooperative guidance mechanism for input constraints.

Induced Factor	Reference	Core Factors
Actuator-induced	[87–91]	Actuator ability
Communication-induced	[92–94]	Communication delay + Actuator ability
	[95–97]	Intermittent communication + Actuator ability

6.2. State-Constrained Cooperative Guidance Law

State constraints in cooperative guidance refer to the physical and mission-based boundary restrictions imposed on the flight motion states, geometric relationships and sensor measurement information of vehicles, which differ from input and output constraints and dominate the evolution process of internal system states. In the design of cooperative guidance systems, state constraints are essential factors affecting the stability and effectiveness of the system, among which the constraints closely related to cooperative operations mainly include two core types of state variables: field-of-view and relative motion (as shown in Figure 9).

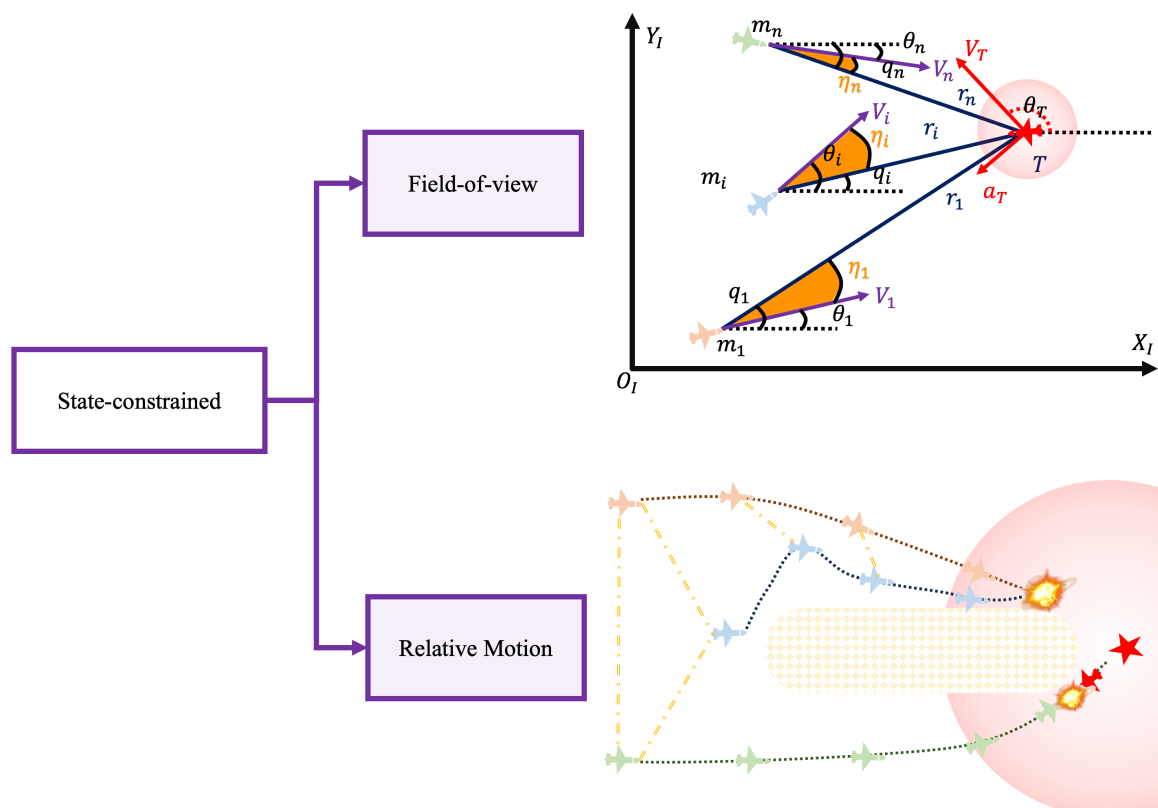


Figure 9. State Constraint of Cooperative Guidance.

The field-of-view constraint is determined by the performance of the seeker sensor. The maximum detectable angle and tracking range of the sensor limit the line-of-sight angle

between the flight vehicle and the target, and further restrict the generation of guidance commands, which is a key factor affecting the accuracy of target tracking and information interaction. If the field-of-view exceeds the limit, it will lead to loss of target tracking, failure of cooperative information interaction, and the inability to achieve cooperative guidance. For the simplified cooperative guidance model, the field-of-view constraints are transformed into the constraints of the leading angle. In Refs. [98–103], monotonically decreasing auxiliary functions are constructed to smoothly attenuate the cooperative bias command when the lead angle approaches the constraint boundary, thereby keeping the field-of-view angle within the allowable range and satisfying the FOV constraint. Considering nonuniform FOV constraints, cooperative guidance laws constrain the lead angle using piecewise smooth bias commands. When near the FOV boundary, it sets the angle rate to zero to avoid violation; otherwise, it coordinates time-to-go normally. It needs no barrier Lyapunov function (BLF) or prescribed performance control (PPC) and satisfies non-uniform FOV constraints directly. In addition, control barrier functions convert safety constraints into real-time solvable control inequalities and modify control commands through optimization to fulfill safety requirements [104,105]. As another prevailing strategy, BLF can effectively address state-constrained control problems for FOV constraints. Various barrier functions, including tangent-type, logarithmic and integrated BLFs [106–108], have been applied in guidance law design to restrict FOV. Table 11 summarizes the cooperative guidance mechanism for FOV constraints.

Table 11. Cooperative guidance mechanism for FOV constraints.

Control Method	Reference	Type	Forming
BLF	[98]	Sigmoid logarithmic BLF	$V = \frac{1}{2} \ln \frac{\eta_{\max}^2}{\eta_{\max}^2 - \eta^2}$
	[106]	Time-varying asymmetric BLF	$V = \frac{c}{2} \ln \frac{\beta_2^2}{\beta_2^2 - e_2^2} + \frac{1-c}{2} \ln \frac{\beta_1^2}{\beta_1^2 - e_1^2}$
	[107]	Standard logarithmic BLF	$V = \frac{1}{2} \ln \frac{\bar{\eta}^2}{\bar{\eta}^2 - \eta^2}$
	[108]	Integral BLF	$V = \int_0^e \frac{\omega(s)}{1 - (s/\bar{x})^2} ds$
PPC	[99]	Generalized PPC dual envelope	$\Psi(\bar{\sigma}) = \frac{\sigma_{\max}}{1 + e^{-k(\bar{\sigma} - \sigma_0)}}, Y(\bar{\sigma}) = -\frac{\sigma_{\max}}{1 + e^{k(\bar{\sigma} + \sigma_0)}}$
	[100]	Generalized PPC tanh envelope	$\Phi(\eta) = \eta_{\max} \tanh\left(\frac{\eta_{\max} - \eta}{\lambda}\right)$

The relative motion constraint, containing relative distance and relative velocity constraints among flight vehicles, is also an important component of state constraints. Due to the physical limitations of flight vehicle maneuverability and the safety requirements of formation flight, the relative distance and relative velocity among flight vehicles need to be controlled within a reasonable range to avoid collision risks and ensure the consistency of cooperative guidance. Combining with the generalized dead-zone constraints, Ref. [109] ensures the collision-free cooperative guidance by linear quadratic optimal control. To avoid potential collision, Ref. [110] provided a dual strategy combining direction-based and distance-based mechanisms, wherein, by assigning different flight directions and proportional coefficients, both terminal and in-flight collisions are effectively prevented without disturbing the stability of the cooperative guidance law. Based on the artificial potential field method, Ref. [111] proposed a cooperative guidance law to enable flight-vehicle swarms to evade external threats, realizing synchronized target arrival without collision. For collision avoidance, Ref. [112] designed a switching cooperative collision-avoidance guidance law, which is activated when the inter-flight-vehicles distance is below the safety threshold.

State constraints interact and influence each other. The field-of-view constraint affects the acquisition of relative distance and velocity information, while the relative distance and velocity constraints further restrict the maneuver range of the flight vehicle, jointly determining the stability and reliability of the cooperative guidance system and providing an important basis for the design of cooperative guidance laws.

6.3. Summary of Control-Constrained Cooperative Guidance

Cooperative guidance under control constraints is fundamentally governed by two core restriction types: system state constraints and control input constraints, which lay the logical foundation to summarize existing research.

Similarly, Table 12 establishes a cross-dimensional comparative framework for all reviewed control-constrained cooperative guidance laws. It covers the core evaluation indices and provides a unified reference that reveals the similarities, differences, and applicable boundaries among various cooperative guidance approaches.

Table 12. Multi-dimensional Consolidated Comparison of Control-constrained Cooperative Guidance.

Category	Ref.	Power	Dimensional	Target Type	Convergence	Communication
Input Constraint	[87]	Unpowered	2D	Stationary	Finite-time	Undirected
	[88]	Unpowered	2D	Stationary	Uniformly Ultimately Bounded	Directed
	[89]	Unpowered	2D	Maneuvering	Finite-time	Leader-follower
	[90]	Unpowered	3D	Maneuvering	Finite-time	Leader-follower
	[91]	Powered	2D	Maneuvering	Prescribed-time	Undirected
	[92]	Powered	2D	Stationary	Fixed-time	Undirected
	[93]	Powered	2D	Stationary	Fixed-time	Undirected
	[94–96]	Unpowered	3D	Stationary	Prescribed-time	Directed
State Constraint	[97]	Powered	2D	Maneuvering	Finite-time	Undirected
	[98]	Unpowered	2D	Stationary	Finite-time	Leader-follower
	[99]	Unpowered	3D	Stationary	Fixed-time	Undirected
	[100]	Unpowered	3D	Stationary	Fixed-time	Directed
	[101]	Unpowered	3D	Stationary	Prescribed-time	Global
	[102]	Unpowered	2D/3D	Stationary	Asymptotic	Directed
	[103]	Powered	2D/3D	Stationary	Predefined-time	Undirected
	[104]	Unpowered	2D	Stationary	Asymptotic	Undirected
	[105]	Unpowered	3D	Maneuvering	Uniformly Ultimately Bounded	Distributed
	[106]	Powered	2D	Maneuvering	Finite-time	Undirected
	[107]	Powered	2D	Maneuvering	Prescribed-time	Undirected
	[108]	Unpowered	2D	Maneuvering	Uniformly Ultimately Bounded	Leader-follower
	[39,40]	Unpowered	3D	Maneuvering	Asymptotic	Global
	[109]	Unpowered	2D	Stationary/Maneuvering	Asymptotic	Global
	[110]	Powered	2D	Maneuvering	Fixed-time	Leader-follower
	[111]	Unpowered	3D	Maneuvering	Asymptotic	Distributed
	[112]	Unpowered	3D	Maneuvering	Asymptotic	Global

Current studies on state constraints can suppress partial limit violations via control strategies, yet cooperative guidance frameworks are built upon the simplified mass-point assumption. Even when partial dynamics are introduced, the coupling effect of the inner attitude control loop on the overall system is overlooked, lacking systematic in-depth analysis. For input constraints, existing works predominantly focus on actuator output limits, while information restrictions stemming from cooperative perception are largely neglected.

Hence, control-constrained cooperative guidance needs to be further developed. The inner-loop composite guidance-control branch targets coupling between kinematic commands and attitude dynamics, which requires unified frameworks to compensate mass-point guidance's ignorance of actuator saturation, aerodynamic disturbances and state bounds. The outer-loop integrated detection-guidance branch focuses on system information input, where fused multi-agent observation data is demanded to suppress performance loss induced by incomplete detection and measurement noise in separated guidance schemes.

7. Future Trends Outlook

The development of the cooperative guidance system has always centered on “environmental adaptation and task achievement”. The core development direction not only

includes adapting to the complex cross-domain combat environment and the physical characteristics of heterogeneous platforms, but also focuses on optimizing the control strategy. Nowadays, the development of cooperative guidance has gradually formed a development pattern centered on “physics + control”, focusing on constraints, and has initially formed a development path integrating physical environment adaptation and control theory optimization, which exert mutual influences, as shown in Figure 10.

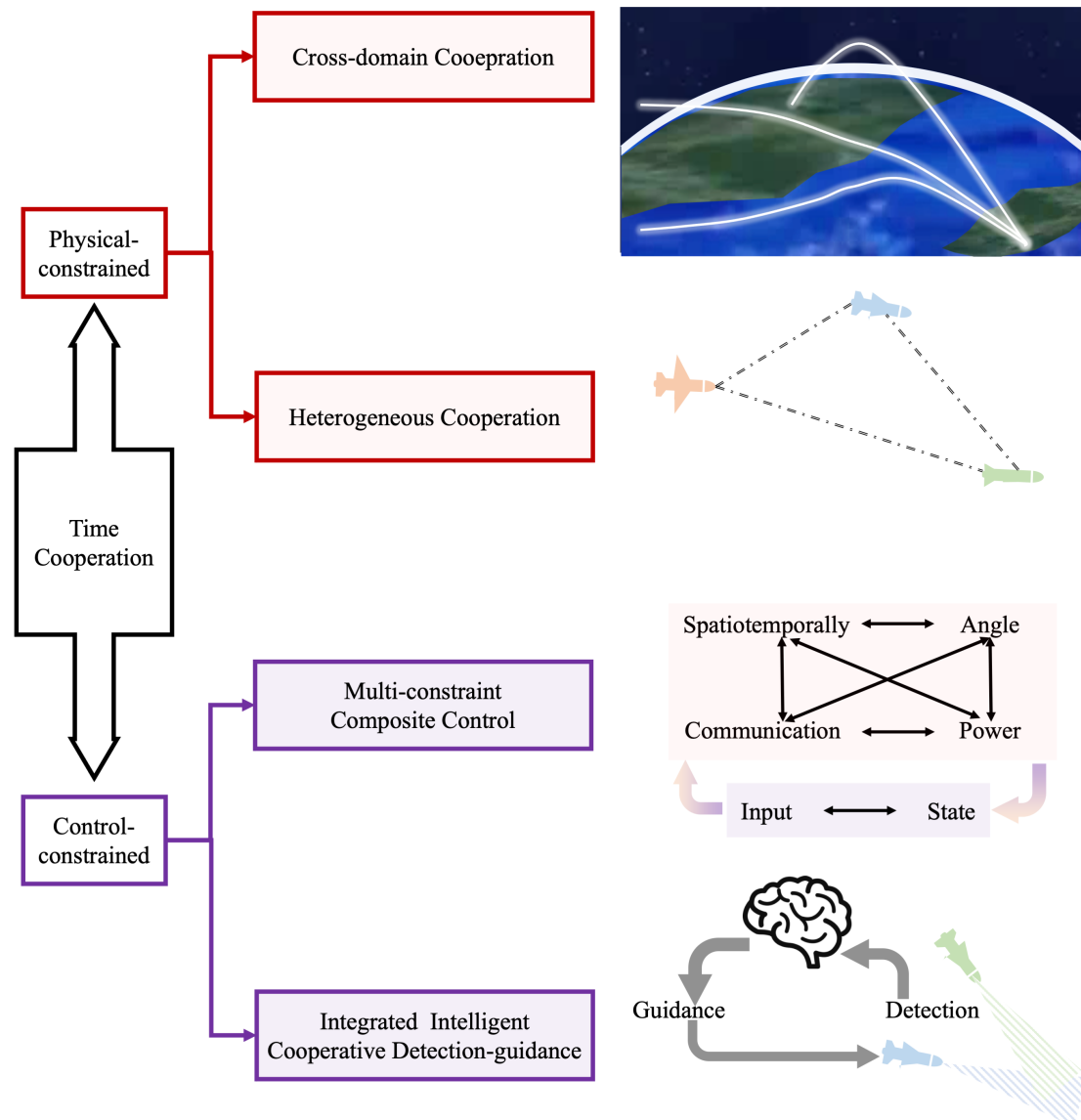


Figure 10. Future Trends Outlook of Cooperative Guidance.

7.1. Future Trends of Physical-Constrained Cooperative Guidance

As elaborated in prior sections, distinct mission contexts generate varied physical constraint features. Prospective physical constraint research falls into cross-domain cooperation and heterogeneous cooperation routes categorized by mission range and cluster composition. Cross-domain cooperation focuses on time-varying multi-domain boundary conflicts extending beyond spatiotemporal limits of conventional single-domain saturated missions. Heterogeneous cooperation targets compound physical diversities introduced by flight vehicles as core system actuators, whose disparities in communication topologies, propulsion modes and seeker angular bounds jointly generate coupled multi-physical constraints seldom analyzed integrally in existing research.

7.1.1. Cross-Domain Cooperative Guidance

With the continuous expansion of mission requirements, the application scenarios of MFV cooperative guidance have extended from single airspace to cross-domain fields, including aerospace, air-sea and transatmospheric space, raising emerging technical challenges. However, the complexity of cross-domain environments fundamentally breaks the original constraint framework and operating mechanism, rendering conventional guidance strategies inapplicable. Flight vehicles differ inherently in physical properties and constraint boundaries, and even the same flight vehicle presents varied velocity features and faces diverse environmental constraints across different flight spaces. Practical issues commonly exist in cross-domain cooperation. Extreme operating conditions, including high-altitude low temperatures, intense electromagnetic interference, thin atmospheres, and abrupt environmental variations occurring in cross-domain transitions, impose various novel constraints and constitute core research priorities. Coupled terminal and flight process constraints further increase the difficulty in system design and stability control, posing new challenges to conventional intra-domain cooperative guidance frameworks.

Hence, future studies will focus on cross-domain environmental adaptation to tackle core technologies.

- First, develop global cooperative guidance laws under comprehensive cross-domain situational constraints. Cross-domain missions involve a pre-operation layout instead of a simple instantaneous space transition, which elevates the importance of integrated guidance design. Future research centers on optimizing guidance schemes to dynamically adjust cross-domain flight posture and substantially enhance the global robustness of the system.
- Second, conduct unified modeling and decoupling design of cross-domain multiple constraints. The coupling effect and real-time dynamic priority change of various constraints bring prominent difficulties to full-domain unified modeling. A standardized full-domain constraint framework can be designed for multi-dimensional coupled dynamic constraints, and dynamic priority regulation is adopted to avoid constraint conflicts.
- Third, establish a multi-constraint cooperative regulation mechanism based on performance priority. Comprehensively considering the cross-domain constraints, constrained cooperative guidance tasks are allocated reasonably according to the maneuverability and response characteristics of each flight vehicle to decouple temporal and spatial cooperative constraints. Dynamic regulation strategies are adopted to define feasible motion domains, enabling the formation to accomplish cooperative penetration and precision guidance within safe boundaries.

The continuous performance upgrading of future flight vehicles will further break the boundary of traditional flight missions, making cross-domain cooperative guidance a core technical problem. Cross-domain scenarios are characterized by dynamically changing airspace environments, distinct flight vehicle platform characteristics and instantaneous switching of flight conditions. Meanwhile, the dynamic priority variation and strong coupling of multiple constraints render traditional single-model cooperative guidance laws incapable of adapting to complex full-domain and multi-dimensional combat missions. Therefore, it is of important theoretical significance and engineering practical value to investigate constrained cooperative guidance theories and technologies for complex cross-domain scenarios.

7.1.2. Heterogeneous Cooperative Guidance

Against the background of diversified mission constraints, traditional homogeneous cooperative guidance theories are difficult to adapt to cluster scenarios composed of differ-

ent types of flight vehicles. Heterogeneous cooperation has gradually become an important development direction of constrained cooperative guidance. Different from homogeneous formations with consistent dynamic characteristics, heterogeneous cooperative systems consist of diverse platforms such as high-speed interceptors, low-speed cruise vehicles, unmanned aerial vehicles and airborne guided munitions, which differ greatly in flight speed, maneuver capability, response characteristics, sensing range and mission priority. Combined with various practical constraints, including impact angle, impact time, field-of-view, actuator saturation, and communication, research on heterogeneous cooperative guidance laws faces new theoretical difficulties and engineering challenges and also yields novel development trends.

Accordingly, the future research of heterogeneous constrained cooperative guidance laws will focus on the following key directions.

- First, construct normalized heterogeneous dynamic modeling methods, adopt equivalent model transformation to unify the state evolution rules of different aircraft, and provide a foundation for cross-platform consistent coordination.
- Second, develop priority-based multi-constraint cooperative guidance laws, reasonably allocate constraint control tasks according to the inherent performance advantages of heterogeneous platforms, realize decoupling processing of time-space dual constraints, and ensure that all formation members complete cooperative penetration and precision guidance in feasible domains.
- Third, design topology-adaptive distributed heterogeneous cooperative guidance laws, reduce unnecessary information interaction, adapt to hierarchical and time-varying communication networks, and improve the robustness of cooperative guidance under limited communication conditions.
- Fourth, explore hierarchical heterogeneous cooperative guidance frameworks matching actual applications, divide heterogeneous clusters into detection and reconnaissance layer, collaborative guidance layer and precision attack layer, realize multi-level linkage from target perception, trajectory coordination, to terminal constrained impact, and give full play to the complementary advantages of different types of flight vehicles.

In the long-term development trend, heterogeneous cooperative constrained guidance will break through the limitation of single-type flight vehicle cluster coordination, evolving from fixed-structure cooperative modes to fully autonomous self-organizing cooperative modes. On the basis of satisfying strict terminal and process constraints, it will realize flexible formation reconstruction, multi-task adaptive switching and strong anti-interference cooperative guidance. In the future, heterogeneous-constrained cooperative guidance laws will gradually form a complete theoretical system and be widely applied in complex scenarios, becoming the core theoretical support for future intelligent swarm cooperative guidance.

7.2. Future Trends of Control-Constrained Cooperative Guidance

As analyzed in the preceding sections, control constraints stem from system state and control input limits. To address defects of traditional separated mass-point cooperative guidance, we divide prospective research into inner-loop and outer-loop directions according to flight system hierarchy. The inner-loop research targets coupling between kinematic guidance requirements and attitude/actuator dynamics, covering composite constraint modeling, convergence optimization, disturbance rejection and integrated guidance-control design. The outer-loop research focuses on information input constraints brought by cooperative detection, including decoupling modeling, cross-layer information fusion and intelligent learning strategies for detection-guidance integration.

7.2.1. Inner-Loop: Multi-Constraint Composite Cooperative Guidance-Control

Traditional cooperative guidance adopts a fragmented design that superimposes multiple constraints independently, separately considering flight time, impact angle, field-of-view limitation, control saturation, and obstacle avoidance. Such methods ignore the strong nonlinear coupling, dynamic conflicts, and time-varying boundary characteristics of practical multi-constraint environments, easily shrinking the feasible guidance domain, inducing control chattering and constraint violations, and even leading to closed-loop instability. Therefore, from the perspective of modern control theory, traditional cooperative guidance frameworks generally suffer from theoretical and technical bottlenecks, including fragmented constraint modeling systems, inadequate solvability theories, insufficient performance, and weak anti-disturbance adaptive capability.

As a core technology for clustered flight vehicle cooperative precision operation, multi-constraint composite cooperative guidance can be explored from the following aspects.

- First, the unified modeling and solvability improvement of strongly coupled composite constraints. To eliminate the inherent defects of fragmentation and empiricism in traditional modeling methods, multi-constraint coupling characteristics can be quantified to distinguish constraint interactions. By identifying the complementarity, competition, and conflict among different constraints, feasible domain solving approaches and dynamic constraint priority scheduling strategies can be established to refine the theoretical system of system solvability.
- Second, enhance the convergence performance of cooperative guidance for complex constrained scenarios. Asymptotic guidance laws can only achieve error convergence, and finite/fixed-time cooperative guidance are highly sensitive to initial states or tunable parameters. To address the convergence restriction caused by multiple constraints, further performance optimization considering physical constraints is essential to meet strict time-window demands. Combining constraint boundary management with state convergence regulation enables cooperative convergence while fully satisfying all constraints, achieving fast, precise and consistent cluster performance.
- Third, the suppression of multi-source uncertain disturbances and unmodeled system dynamics. Clustered flight vehicles are subject to internal and external uncertainties, with time-varying constraints aggravating system nonlinearity and disturbance impact. Traditional fixed-parameter guidance depends overly on precise models with weak disturbance resistance. Future research will focus on constructing a robust adaptive cooperative guidance framework, so as to ensure multi-constraint compliance and closed-loop uniform ultimate boundedness, enhancing environmental adaptability and realizing high-precision cooperative guidance under model uncertainties.
- Fourth, the integrated guidance-control optimization considers inner-loop composite constraints and multi-source dynamic disturbances. Different from traditional mass-point guidance that ignores attitude dynamics and actuator characteristics, future research directions focus on introducing time-varying aerodynamic variations, thrust uncertainties, actuator saturation and dynamic closed-loop coupling effects into cooperative guidance design. By bridging the outer-loop kinematic guidance demands and inner-loop control physical constraints, it is able to suppress unmodeled dynamic deviations, alleviate control chattering caused by constraint mismatch, and further improve the robustness and practicality of cooperative guidance strategies under complex flight conditions.

With the development of control theory, multi-constraint composite cooperative guidance-control will transcend the defects of traditional fragmented constraint design and limited convergence performance. It evolves from passive constraint adaptation to active global constraint management, and develops toward robust and autonomous cooperative

control under uncertain environments. Therefore, it is essential to form a systematic and complete theoretical framework, providing core technical support for cooperative guidance. While satisfying various process and terminal constraints, developing a cooperative guidance paradigm achieves better convergence performance, adaptability, disturbance rejection and robustness.

7.2.2. Outer-Loop: Integrated Intelligent Cooperative Detection-Guidance

Detection serves as the fundamental information support for cooperative guidance. MFV cooperation not only provides quantitative superiority for saturation guidance and suppression, but also enriches multidimensional observation dimensions, compensates for single-platform detection limitations, and enhances the integrity, real-time performance and robustness of state perception. Traditional cooperative guidance adopts a decoupled detection–guidance architecture, where detection information and guidance decision loops operate independently, easily leading to information delay, state mismatch and insufficient constraint compatibility. In contrast, the integrated detection-guidance mechanism realizes tight fusion between real-time perception information and guidance control variables, enables dynamic updating of constraint boundaries and online optimization of guidance commands, and effectively eliminates the adverse effects of information asymmetry and multi-source disturbance.

From the perspective of modern control theory, integrated intelligent cooperative detection-guidance has become the dominant evolutionary trend of constrained cooperative guidance, breaking the isolated research mode of separate detection and guidance design.

- First, unified modeling and decoupling control oriented to integrated cooperative detection-guidance. Flight vehicles show divergent dynamic features and environmental constraints in different domains. Future research will establish an integrated dynamic model covering detection perception, state transmission and guidance control. By decoupling tightly coupled time-space, maneuver and communication constraints, the inherent modeling differences of cross-domain platforms can be eliminated, laying a theoretical foundation for detection-guidance cooperation.
- Second, end-to-end fusion mechanism for detection-guidance information. Different from the traditional decoupled detection-guidance mode with isolated information transmission and control execution, future research focuses on building a seamless information interaction and fusion mechanism. It aims to realize the direct transmission, real-time screening and depth fusion of multi-source detection data, eliminate information delay and state mismatch caused by hierarchical decoupling, unify the information input interface of the cross-domain cooperative guidance system, and provide accurate, timely and robust state perception support for subsequent constrained guidance optimization and cluster cooperative control.
- Third, deep reinforcement learning strategy research for integrated cooperative detection-guidance. To address the limitation of traditional cooperative guidance, future research focuses on constructing an end-to-end intelligent decision mechanism based on deep reinforcement learning, which directly maps fused detection perception information to optimal guidance commands, abandoning the cumbersome intermediate modeling and artificial rule scheduling links [113]. By continuously interacting with complex cross-domain environments and iteratively optimizing reward functions oriented to constraint satisfaction and combat benefits, designing a strategy to realize autonomous learning, adaptive adjustment and intelligent generation of guidance commands, further improving the real-time decision-making ability and environmental adaptability of integrated cooperative detection-guidance.

In the future, integrated cooperative detection-guidance will evolve toward systematic and intelligent development. Supported by unified modeling and constraint decoupling, it lays solid theoretical fundamentals for cross-domain platform collaboration. Leveraging efficient information fusion mechanisms, high-quality perceptual data can be steadily supplied for decision-making. Meanwhile, deep reinforcement learning enables autonomous and adaptive generation of guidance commands. Gradually, a sound theoretical framework for integrated detection-guidance will take shape, serving as core technical support for future cross-domain constrained cooperative flight missions.

8. Conclusions

Cooperative guidance, enabling the completion of complex tasks that are unattainable for individual flight vehicles, has experienced significant growth and evolution over the last 15 years. To systematically track and grasp the research progress, this paper performed a bibliometric analysis of relevant literature collected from the Scopus database. The CiteSpace visualization results further reveal key insights into trends, which indicate that constraints have remained the central theme throughout the field's development. Rooted in fundamental concepts, the preliminaries of cooperative guidance were introduced. According to the constraint analysis, a comprehensive overview of constrained cooperative guidance was organized, focusing on physical and control constraints. On this basis, developmental trends have been forecasted from the “physical+control” structure, which takes real-world applicability and overall system optimization as key pursuits.

Author Contributions: Conceptualization, X.G. and W.M.; methodology, W.M.; software, X.G.; validation, X.G. and W.M.; formal analysis, X.G.; investigation, X.G. and W.M.; resources, X.G.; data curation, W.M.; writing—original draft preparation, X.G. and W.M.; funding acquisition, X.G. and W.M. All authors have read and agreed to the published version of the manuscript.

Funding: This Scientific Research Program Funded by Education Department of Shaanxi Provincial Government (Program No.25JK0491).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data can be provided upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Li, J.; Liu, S.; Huang, W.; Yan, B. Artificial intelligence in low-altitude flight: Developmental opportunity or ethical challenge? *The Aeronaut. J.* **2025**, *129*, 1683–1701. [\[CrossRef\]](#)
2. Ding, Y.; Yue, X.; Chen, G.; Si, J. Review of control and guidance technology on hypersonic vehicle. *Chin. J. Aeronaut.* **2022**, *35*, 1–18. [\[CrossRef\]](#)
3. Zhang, H.; Xin, B.; Dou, L.H.; Chen, J.; Hirota, K. A review of cooperative path planning of an unmanned aerial vehicle group. *Front. Inf. Technol. Electron. Eng.* **2020**, *21*, 1671–1694. [\[CrossRef\]](#)
4. Xu, X.; Yan, X.; Yang, W.Y.; An, K.; Huang, W.; Wang, Y. Algorithms and applications of intelligent swarm cooperative control: A comprehensive survey. *Prog. Aerosp. Sci.* **2022**, *135*, 100869. [\[CrossRef\]](#)
5. Marcano, M.; Diaz, S.; Perez, J.; Irigoyen, E. A Review of Shared Control for Automated Vehicles: Theory and Applications. *IEEE Trans.-Hum.-Mach. Syst.* **2020**, *50*, 475–491. [\[CrossRef\]](#)
6. Yao, Y.; Zheng, T.; He, F.; Wang, L.; Wang, Y.; Zhang, X.; Zhu, B.; Yang, B. Several hot issues and challenges in terminal guidance of flight vehicles. *Hangkong Xuebao/Acta Aeronaut. Astronaut. Sin.* **2015**, *36*, 2696–2716.
7. Liu, S.; Yan, B.; Huang, W.; Zhang, X.; Yan, J. Current status and prospects of terminal guidance laws for intercepting hypersonic vehicles in near space: A review. *J. Zhejiang-Univ.-Sci. A* **2023**, *24*, 387–403. [\[CrossRef\]](#)
8. McLain, T.W.; Beard, R.W. Coordination Variables, Coordination Functions, and Cooperative Timing Missions. *J. Guid. Control Dyn.* **2005**, *28*, 150–161. [\[CrossRef\]](#)

9. Zhou, J.; Wu, X.; Lv, Y.; Li, X.; Liu, Z. Recent progress on the study of multi-vehicle coordination in cooperative attack and defense: An overview. *Asian J. Control* **2022**, *24*, 794–809.
10. Liu, S.; Lin, Z.; Huang, W.; Yan, B. Technical development and future prospects of cooperative terminal guidance based on knowledge graph analysis: A review. *J. Zhejiang-Univ.-Sci. A* **2025**, *26*, 605–634. [[CrossRef](#)]
11. Ma, W.; Liu, S.; Huang, W.; Tian, J. Research progress of convergence performance-based networked cooperative guidance laws: A review. *Sci. Sin. Technol.* **2025**, *55*, 681–697.
12. Chen, C. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *J. Am. Soc. Inf. Sci. Technol.* **2006**, *57*, 359–377. [[CrossRef](#)]
13. Olfati-Saber, R.; Murray, R. Consensus problems in networks of agents with switching topology and time-delays. *IEEE Trans. Autom. Control* **2004**, *49*, 1520–1533. [[CrossRef](#)]
14. Ren, W.; Cao, Y. *Distributed Coordination of Multi-Agent Networks: Emergent Problems, Models, and Issues*; Communications and Control Engineering; Springer London: London, UK, 2011.
15. Yu, W.; Wen, G.; Chen, G.; Cao, J. *Distributed Cooperative Control of Multi-Agent Systems*; John Wiley & Sons Singapore Pte. Ltd.: Singapore, 2016.
16. Horn, R.A.; Johnson, C.R. *Topics in Matrix Analysis*; Cambridge University Press: Cambridge, UK, 1991.
17. Wang, L.; Xiao, F. Finite-time consensus problems for networks of dynamic agents. *IEEE Trans. Autom. Control* **2010**, *55*, 950–955. [[CrossRef](#)]
18. Mei, J.; Ren, W.; Ma, G. Distributed coordination for second-order multi-agent systems with nonlinear dynamics using only relative position measurements. *Automatica* **2013**, *49*, 1419–1427. [[CrossRef](#)]
19. Jeon, I.S.; Lee, J.I.; Tahk, M.J. Impact-time-control guidance law for anti-ship missiles. *IEEE Trans. Control Syst. Technol.* **2006**, *14*, 260–266. [[CrossRef](#)]
20. Zhao, S.; Zhou, R. Cooperative guidance for multimissile salvo attack. *Chin. J. Aeronaut.* **2008**, *21*, 533–539. [[CrossRef](#)]
21. Jeon, I.S.; Lee, J.I.; Tahk, M.J. Homing guidance law for cooperative attack of multiple missiles. *J. Guid. Control Dyn.* **2010**, *33*, 275–280. [[CrossRef](#)]
22. Zhao, S.; Zhou, R.; Wei, C.; Ding, Q. Design of time-constrained guidance laws via virtual leader approach. *Chin. J. Aeronaut.* **2010**, *23*, 103–108. [[CrossRef](#)]
23. Su, W.; Li, K.; Chen, L. Coverage-based cooperative guidance strategy against highly maneuvering target. *Aerosp. Sci. Technol.* **2017**, *71*, 147–155. [[CrossRef](#)]
24. Yang, G.; Fang, Y.; Ma, W.; Zhu, S.; Fu, W. Cooperative trajectory shaping guidance law for multiple anti-ship missiles. *Aeronaut. J.* **2024**, *128*, 73–91.
25. Yu, J.; Shi, Z.; Dong, X.; Li, Q.; Lv, J.; Ren, Z. Impact time consensus cooperative guidance against the maneuvering target: Theory and experiment. *IEEE Trans. Aerosp. Electron. Syst.* **2023**, *59*, 4590–4603. [[CrossRef](#)]
26. He, Z.; Fan, S.; Wang, J.; Wang, P. Distributed observer-based fixed-time cooperative guidance law against maneuvering target. *Int. J. Robust Nonlinear Control* **2024**, *34*, 27–53.
27. Li, B.; Lin, D.; Wang, H. Finite time convergence cooperative guidance law based on graph theory. *Optik* **2016**, *127*, 10180–10188. [[CrossRef](#)]
28. Zhao, E.; Chao, T.; Wang, S.; Yang, M. Multiple flight vehicles cooperative guidance law based on extended state observer and finite time consensus theory. *Proc. Inst. Mech. Eng. G J. Aerosp. Eng.* **2018**, *232*, 270–279.
29. He, S.; Wang, W.; Lin, D.; Lei, H. Consensus-based two-stage salvo attack guidance. *IEEE Trans. Aerosp. Electron. Syst.* **2018**, *54*, 1555–1566. [[CrossRef](#)]
30. Wang, C.; Wang, W.; Dong, W.; Wang, J.; Deng, F. Multiple-stage spatial-temporal cooperative guidance without time-to-go estimation. *Chin. J. Aeronaut.* **2024**, *37*, 399–416. [[CrossRef](#)]
31. Zhao, J.; Zhou, R. Unified approach to cooperative guidance laws against stationary and maneuvering targets. *Nonlinear Dyn.* **2015**, *81*, 1635–1647. [[CrossRef](#)]
32. Yan, P.; Fan, Y.; Liu, R.; Wang, M. Distributed target-encirclement guidance law for cooperative attack of multiple missiles. *Int. J. Adv. Robot. Syst.* **2020**, *17*. [[CrossRef](#)]
33. Song, S.H.; Ha, I.J. A Lyapunov-like approach to performance analysis of 3-dimensional pure PNG laws. *IEEE Trans. Aerosp. Electron. Syst.* **1994**, *30*, 238–248. [[CrossRef](#)]
34. Jiang, Z.; Rui, Z. Distributed three-dimensional cooperative guidance via receding horizon control. *Chin. J. Aeronaut.* **2016**, *29*, 972–983. [[CrossRef](#)]
35. He, S.; Kim, M.; Song, T.; Lin, D. Three-dimensional salvo attack guidance considering communication delay. *Aerosp. Sci. Technol.* **2018**, *73*, 1–9. [[CrossRef](#)]
36. Zhang, Y.; Tang, S.; Guo, J. Two-stage cooperative guidance strategy using a prescribed-time optimal consensus method. *Aerosp. Sci. Technol.* **2020**, *100*, 105641. [[CrossRef](#)]

37. Ma, S.; Wang, X.; Wang, Z.; Chen, Q. Consensus-based finite-time cooperative guidance with field-of-view constraint. *Int. J. Aeronaut. Space Sci.* **2022**, *23*, 966–979. [\[CrossRef\]](#)
38. Guo, M.; Yang, F.; Xia, G.; Liu, K. Three-dimensional free-will arbitrary time cooperative guidance law against moving target. *J. Frankl. Inst.* **2024**, *361*, 106969. [\[CrossRef\]](#)
39. Kang, H.; Wang, P.; Wei, S.; Song, S. Three-dimensional impact-time-constrained proportional navigation guidance using range-varying gain. *Aerosp. Sci. Technol.* **2023**, *140*, 108419. [\[CrossRef\]](#)
40. Zhou, S.; Zhou, D.; Li, S.; He, Z. Three-dimensional cooperative guidance law based on dynamic coverage strategy. *Chin. J. Aeronaut.* **2025**, *38*, 103490. [\[CrossRef\]](#)
41. Yang, C.D.; Yang, C.C. Analytical solution of three-dimensional realistic true proportional navigation. *J. Guid. Control Dyn.* **1996**, *19*, 569–577. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Song, J.; Song, S.; Xu, S. Three-dimensional cooperative guidance law for multiple missiles with finite-time convergence. *Aerosp. Sci. Technol.* **2017**, *67*, 193–205. [\[CrossRef\]](#)
43. You, H.; Chang, X.; Zhao, J.; Wang, S.; Zhang, Y. Three-dimensional impact-angle-constrained fixed-time cooperative guidance algorithm with adjustable impact time. *Aerosp. Sci. Technol.* **2023**, *141*, 108574. [\[CrossRef\]](#)
44. Shen, H.; Jiang, H.; Cai, Y.; Deng, Y. Three-dimensional prescribed-time cooperative guidance with neural network-based disturbance observer and LOS constraint. *Control Eng. Pract.* **2025**, *165*, 106599. [\[CrossRef\]](#)
45. Gao, Z.; Liu, J.; Huang, J.; Wang, W.; Yi, W.; Yuan, S. Three-dimensional fault-tolerant cooperative guidance law with constraints on relative impact velocity and attack angle. *Aerosp. Sci. Technol.* **2026**, *168*, 111003. [\[CrossRef\]](#)
46. Tan, M.; Shen, H. Three-dimensional cooperative game guidance law for a leader–follower system with impact angles constraint. *IEEE Trans. Aerosp. Electron. Syst.* **2024**, *60*, 405–420. [\[CrossRef\]](#)
47. Wang, X.; Cai, Y.; Deng, Y.; Jiang, H. Predefined-time spatial–temporal cooperative guidance law with leader–follower strategy. *IEEE Trans. Aerosp. Electron. Syst.* **2025**, *61*, 6053–6069. [\[CrossRef\]](#)
48. Lee, J.I.; Jeon, I.S.; Tahk, M.J. Guidance law to control impact time and angle. *IEEE Trans. Aerosp. Electron. Syst.* **2007**, *43*, 301–310. [\[CrossRef\]](#)
49. Wang, X.; Zhang, Y.; Wu, H. Distributed cooperative guidance of multiple anti-ship missiles with arbitrary impact angle constraint. *Aerosp. Sci. Technol.* **2015**, *46*, 299–311. [\[CrossRef\]](#)
50. Wang, C.; Dong, W.; Wang, J.; Xin, M. Impact-angle-constrained cooperative guidance for salvo attack. *J. Guid. Control Dyn.* **2022**, *45*, 684–703. [\[CrossRef\]](#)
51. Zhang, B.; Zhou, D.; Li, J.; Yao, Y. Coverage-based cooperative guidance strategy by controlling flight path angle. *J. Guid. Control Dyn.* **2022**, *45*, 972–981. [\[CrossRef\]](#)
52. Jin, P.; Li, Y.; Qi, G.; Sheng, A. Cooperative guidance law for unified angle and angle range attack based on prescribed-time consensus. *Int. J. Aeronaut. Space Sci.* **2026**, *27*, 835–848.
53. Wang, X.; Lu, X. Three-dimensional impact angle constrained distributed guidance law design for cooperative attacks. *Isa Trans.* **2018**, *73*, 79–90. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Chen, Z.; Chen, W.; Liu, X.; Cheng, J. Three-dimensional fixed-time robust cooperative guidance law for simultaneous attack with impact angle constraint. *Aerosp. Sci. Technol.* **2021**, *110*, 106523. [\[CrossRef\]](#)
55. Yu, H.; Dai, K.; Li, H.; Zou, Y.; Ma, X.; Ma, S.; Zhang, H. Three-dimensional adaptive fixed-time cooperative guidance law with impact time and angle constraints. *Aerosp. Sci. Technol.* **2022**, *123*, 107450. [\[CrossRef\]](#)
56. Zhang, L.; Li, D.; Jing, L.; Ju, X.; Cui, N. Appointed-time cooperative guidance law with line-of-sight angle constraint and time-to-go control. *IEEE Trans. Aerosp. Electron. Syst.* **2023**, *59*, 3142–3155. [\[CrossRef\]](#)
57. Dong, F.; Zhang, X.; Tan, P. Non-singular terminal sliding mode cooperative guidance law under impact angle constraint. *J. Frankl. Inst.* **2024**, *361*, 107079. [\[CrossRef\]](#)
58. Du, H.; Yang, M.; Wang, S.; Chao, T.; Nie, H. Fixed-time cooperative guidance law with impact angle constraint against various motions of target. *Aeronaut. J.* **2026**, *130*, 2183–2206. [\[CrossRef\]](#)
59. Li, Z.; Ding, Z. Robust cooperative guidance law for simultaneous arrival. *IEEE Trans. Control Syst. Technol.* **2019**, *27*, 1360–1367. [\[CrossRef\]](#)
60. Dong, W.; Wen, Q.; Xia, Q.; Yang, S. Multiple-constraint cooperative guidance based on two-stage sequential convex programming. *Chin. J. Aeronaut.* **2020**, *33*, 296–307. [\[CrossRef\]](#)
61. Kumar, S.R.; Mukherjee, D. Cooperative salvo guidance using finite-time consensus over directed cycles. *IEEE Trans. Aerosp. Electron. Syst.* **2020**, *56*, 1504–1514. [\[CrossRef\]](#)
62. Nanavati, R.; Kumar, S.R.; Maity, A. Cooperative target capture using relative separation for three-dimensional engagement. *IEEE Trans. Aerosp. Electron. Syst.* **2021**, *57*, 3357–3367. [\[CrossRef\]](#)
63. Liu, S.; Yan, B.; Zhang, T.; Zhang, X.; Yan, J. Coverage-based cooperative guidance law for intercepting hypersonic vehicles with overload constraint. *Aerosp. Sci. Technol.* **2022**, *126*, 107651. [\[CrossRef\]](#)

64. Liu, S.; Yan, B.; Zhang, T.; Zhang, X.; Yan, J. Three-dimensional coverage-based cooperative guidance law with overload constraints to intercept a hypersonic vehicle. *Aerosp. Sci. Technol.* **2022**, *130*, 107908. [\[CrossRef\]](#)
65. Yang, Z.; Liu, X.; Liu, H. Impact time control guidance law with time-varying velocity based on deep reinforcement learning. *Aerosp. Sci. Technol.* **2023**, *142*, 108603. [\[CrossRef\]](#)
66. An, K.; Guo, Z.y.; Huang, W.; Xu, X.p. A cooperative guidance approach based on the finite-Time control theory for hypersonic vehicles. *Int. J. Aeronaut. Space Sci.* **2022**, *23*, 169–179. [\[CrossRef\]](#)
67. Huang, A.; Wang, X.; Zhao, Q.; Yu, J.; Dong, X. Three-dimensional practical cooperative guidance law for salvo attack considering velocity variation. *Aerosp. Sci. Technol.* **2025**, *166*, 110588. [\[CrossRef\]](#)
68. Zhou, J.; Yang, J. Distributed guidance law design for cooperative simultaneous attacks with multiple missiles. *J. Guid. Control Dyn.* **2016**, *39*, 2439–2447. [\[CrossRef\]](#)
69. Zhou, J.; Lü, Y.; Li, Z.; Yang, J. Cooperative guidance law design for simultaneous attack with multiple missiles against a maneuvering target. *J. Syst. Sci. Complex.* **2018**, *31*, 287–301. [\[CrossRef\]](#)
70. Li, Y.; Zhu, M.; An, B.; Zhi, Y.; Liu, L.; Fan, H.; Wang, B. Three-dimensional cooperative guidance laws with impact velocity and impact angles constraints. *Aerosp. Sci. Technol.* **2025**, *159*, 109997. [\[CrossRef\]](#)
71. Chen, Y.; Wang, J.; Shan, J.; Xin, M. Cooperative guidance for multiple powered missiles with constrained impact and bounded speed. *J. Guid. Control Dyn.* **2021**, *44*, 825–841. [\[CrossRef\]](#)
72. Dong, W.; Deng, F.; Wang, C.; Wang, J.; Xin, M. Three-dimensional spatial-temporal cooperative guidance without active speed control. *J. Guid. Control Dyn.* **2023**, *46*, 1981–1996. [\[CrossRef\]](#)
73. Ding, X.; Wang, J.; Liu, J.; Shan, J. Approach angle constrained and varying speed cooperative guidance against maneuvering targets. *Def. Technol.* **2026**, *57*, 56–70. [\[CrossRef\]](#)
74. Gu, Z.; Wang, P.; Kang, H.; Song, S. Three-dimensional spatial-temporal cooperative guidance enhanced by physically-guided neural networks. *Aerosp. Sci. Technol.* **2026**, *168*, 111103. [\[CrossRef\]](#)
75. Zhang, Y.; Wang, X.; Wu, H. A distributed cooperative guidance law for salvo attack of multiple anti-ship missiles. *Chin. J. Aeronaut.* **2015**, *28*, 1438–1450. [\[CrossRef\]](#)
76. Gao, J.; Li, X.; Zang, S.; Ma, J.; Zhang, J. Adaptive distributed fixed-time cooperative three-dimensional guidance law for multimissiles against manoeuvring target. *Int. J. Aerosp. Eng.* **2023**, *2023*, 4692840. [\[CrossRef\]](#)
77. You, H.; Chang, X.; Zhao, J.; Wang, S.; Zhang, Y. Three-dimensional impact-angle-constrained cooperative guidance strategy against maneuvering target. *ISA Trans.* **2023**, *138*, 262–280. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Yu, J.; Song, J.; Zhao, K.; Yu, J.; Wei, M. Distributed arbitrary-time cooperative guidance law for multi-aircraft with dynamic communication topology. *Aerosp. Sci. Technol.* **2026**, *168*, 111033. [\[CrossRef\]](#)
79. Yi, X.; Wang, C.; Dong, W.; Wang, J.; Deng, F.; Xin, M. Wide-envelope cooperative guidance with constrained field-of-view and varying speed against maneuvering targets. *IEEE Trans. Aerosp. Electron. Syst.* **2025**, *61*, 9021–9035. [\[CrossRef\]](#)
80. Yu, C.; Zhu, B.; Zheng, J.; Wang, W. Three dimensional cooperative guidance for intercepting a manoeuvring target. *IET Control Theory Appl.* **2024**, *18*, 530–540. [\[CrossRef\]](#)
81. Zhou, J.; Wu, X.; Lv, Y.; Wen, G. Terminal-time synchronization of multiple vehicles under discrete-time communication networks with directed switching topologies. *IEEE Trans. Circuits Syst. II Express Briefs* **2020**, *67*, 2532–2536. [\[CrossRef\]](#)
82. Wang, P.; Dong, C.; Liang, X.; Ma, X.; Zhang, S. Quantized cooperative salvo guidance under limited bandwidth with time-varying directed topology. *Chin. J. Aeronaut.* **2026**, *39*, 103857. [\[CrossRef\]](#)
83. Zhao, Q.; Dong, X.; Liang, Z.; Bai, C.; Chen, J.; Ren, Z. Distributed cooperative guidance for multiple missiles with fixed and switching communication topologies. *Chin. J. Aeronaut.* **2017**, *30*, 1570–1581. [\[CrossRef\]](#)
84. Tang, J.; Zuo, Z. Cooperative circular guidance of multiple missiles: A practical prescribed-time consensus approach. *J. Guid. Control Dyn.* **2023**, *46*, 1799–1813. [\[CrossRef\]](#)
85. Zhao, Q.; Dong, X.; Liang, Z.; Ren, Z. Distributed group cooperative guidance for multiple missiles with fixed and switching directed communication topologies. *Nonlinear Dyn.* **2017**, *90*, 2507–2523. [\[CrossRef\]](#)
86. Ma, W.; Liang, X.; Fang, Y.; Deng, T.; Fu, W. Three-dimensional prescribed-time pinning group cooperative guidance law. *Int. J. Aerosp. Eng.* **2021**, *2021*, 4490211. [\[CrossRef\]](#)
87. Hou, D.; Wang, Q.; Sun, X.; Dong, C. Finite-time cooperative guidance laws for multiple missiles with acceleration saturation constraints. *IET Control Theory Appl.* **2015**, *9*, 1525–1535. [\[CrossRef\]](#)
88. Sun, J.; Liu, C. Distributed fuzzy adaptive backstepping optimal control for nonlinear multimissile guidance systems with input saturation. *IEEE Trans. Fuzzy Syst.* **2019**, *27*, 447–461. [\[CrossRef\]](#)
89. Bin, Z.; Tianze, L.; Tianyang, X.; Changshu, W. Cooperative guidance for maneuvering penetration with attack time consensus and bounded input. *Int. J. Aeronaut. Space Sci.* **2024**, *25*, 1395–1411. [\[CrossRef\]](#)
90. Zhao, K.; Song, J.; Yu, J.; Liu, Y. Three-dimensional robust nonlinear cooperative guidance law for spatiotemporal coordination under stringent input constraint. *Aeronaut. J.* **2025**, *129*, 2131–2148. [\[CrossRef\]](#)

91. Wang, Z.; Fang, Y.; Fu, W.; Ma, W.; Wang, M. Prescribed-time cooperative guidance law against manoeuvring target with input saturation. *Int. J. Control* **2023**, *96*, 1177–1189. [\[CrossRef\]](#)
92. Yu, H.; Dai, K.; Li, H.; Zou, Y.; Ma, X.; Ma, S.; Zhang, H. Distributed cooperative guidance law for multiple missiles with input delay and topology switching. *J. Frankl. Inst.* **2021**, *358*, 9061–9085. [\[CrossRef\]](#)
93. Li, G.; Wu, Y.; Xu, P. Fixed-time cooperative guidance law with input delay for simultaneous arrival. *Int. J. Control* **2021**, *94*, 1664–1673. [\[CrossRef\]](#)
94. Ma, W.; Fu, W.; Fang, Y.; Liu, S.; Liang, X. Prescribed-time cooperative guidance with time delay. *Aeronaut. J.* **2023**, *127*, 852–875. [\[CrossRef\]](#)
95. Ma, W.; Fang, Y.; Fu, W.; Liang, X. Three-dimensional prescribed-time impulsive pinning cooperative guidance. *Int. J. Aeronaut. Space Sci.* **2023**, *24*, 1375–1388. [\[CrossRef\]](#)
96. Ma, W.; Guo, X. Prescribed-Time cooperative guidance law for multi-UAV with intermittent communication. *Drones* **2024**, *8*, 748. [\[CrossRef\]](#)
97. Liu, Z.; Gao, Z. High-reliability cooperative guidance law design considering link failure and input saturation. *AIMS Math.* **2026**, *11*, 2430–2457. [\[CrossRef\]](#)
98. Zhao, J.; Yang, S. Integrated cooperative guidance framework and cooperative guidance law for multi-missile. *Chin. J. Aeronaut.* **2018**, *31*, 546–555. [\[CrossRef\]](#)
99. Dong, W.; Wang, C.; Wang, J.; Xin, M. Three-dimensional nonsingular cooperative guidance law with different field-of-view constraints. *J. Guid. Control Dyn.* **2021**, *44*, 2001–2015. [\[CrossRef\]](#)
100. Zhu, G.; Zhang, D.; Liu, K.; Li, G.; Lü, J. Three-dimensional cooperative guidance for simultaneous attack with specified impact time based on fixed-time convergence. *Asian J. Control* **2024**, *26*, 2261–2277. [\[CrossRef\]](#)
101. Wang, P.; Lee, C.H.; Liu, Y.; Tahk, M.J. Nonlinear three-dimensional guidance for impact time and angle control with field-of-view constraint. *IEEE Trans. Aerosp. Electron. Syst.* **2024**, *60*, 264–279. [\[CrossRef\]](#)
102. Chen, Y.; Guo, D.; Wang, J.; Shan, J.; Xin, M. Cooperative circular guidance with nonuniform field-of-view constraints. *J. Guid. Control Dyn.* **2022**, *45*, 1435–1450. [\[CrossRef\]](#)
103. Yang, X.; Wu, Y.; Xia, W.; Liu, X.; Duan, H. Nonsingular field-of-view constrained cooperative guidance with improved time-to-go estimation. *Chin. J. Aeronaut.* **2025**, *38*, 103565. [\[CrossRef\]](#)
104. Tang, J.; Zuo, Z. Control-barrier-function-based cooperative guidance with nonuniform field of view and input constraints. *J. Guid. Control Dyn.* **2024**, *47*, 2444–2452. [\[CrossRef\]](#)
105. Zhou, S.; Zhou, D.; Li, S.; Zhang, T. Three-dimensional cooperative guidance law via coverage control and control barrier functions. *J. Guid. Control Dyn.* **2026**, *49*, 1–14. [\[CrossRef\]](#)
106. Cheng, H.; Li, C.; Zheng, B.; Huang, H.; Liu, X. TABLF-based finite-time cooperative guidance law for a maneuvering target with a field-of-view constraint. *Astrodynamics* **2026**, *10*, 53–71. [\[CrossRef\]](#)
107. Wang, Z.; Fu, Z.; Wu, Z.; Zhu, C.; Ji, B. Barrier Lyapunov function-based prescribed-time cooperative guidance law with field-of-view constraint. *IEEE Trans. Control Syst. Technol.* **2025**, *33*, 2217–2229. [\[CrossRef\]](#)
108. Huang, X.; Zhao, B.; Zhou, J.; Xie, J.; Zhao, W. Integrated cooperative guidance and control of strapdown missiles. *Proc. Inst. Mech. Eng. G J. Aerosp. Eng.* **2025**, *239*, 528–556. [\[CrossRef\]](#)
109. Jha, B.; Tsalik, R.; Weiss, M.; Shima, T. Cooperative guidance and collision avoidance for multiple pursuers. *J. Guid. Control Dyn.* **2019**, *42*, 1506–1518. [\[CrossRef\]](#)
110. Li, G.; Lü, J.; Zhu, G.; Liu, K. Distributed observer-based cooperative guidance with appointed impact time and collision avoidance. *J. Frankl. Inst.* **2021**, *358*, 6976–6993. [\[CrossRef\]](#)
111. Liu, X.; Li, D.; Wang, Y.; Zhang, Y.; Zhuang, X.; Li, H. Research on a Distributed Cooperative Guidance Law for Obstacle Avoidance and Synchronized Arrival in UAV Swarms. *Drones* **2024**, *8*, 352. [\[CrossRef\]](#)
112. Yu, J.; Shi, Z.; Dong, X.; Li, Q.; Ren, Z. Secure cooperative guidance strategy for multimissile system with collision avoidance. *IEEE Trans. Aerosp. Electron. Syst.* **2025**, *61*, 1034–1047. [\[CrossRef\]](#)
113. Feng, R.; Liu, S.; Huang, W.; Han, T.; Yan, B.; Wang, Z.; Niu, Y. Bridging game theory and multi-agent systems: Development status and future prospects. *Prog. Aerosp. Sci.* **2026**, *161*, 101183. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.