*Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*

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

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Cite this as: Shuangxi LIU, Zehuai LIN, Wei HUANG, Binbin YAN, 2025. Technical development and future prospects of cooperative terminal guidance based on knowledge graph analysis: a review. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 26(7):605-634.
https://doi.org/10.1631/jzus.A2400317

# Background

The purposeful behavior of humans acting in a system can be compared to coordination observed in nature. As shown in Fig. 1, these biological behaviors arise from collective patterns, which enable the completion of complex tasks that cannot be achieved by lone individuals. The application of cooperative guidance in modern warfare systems offers significant advantages.

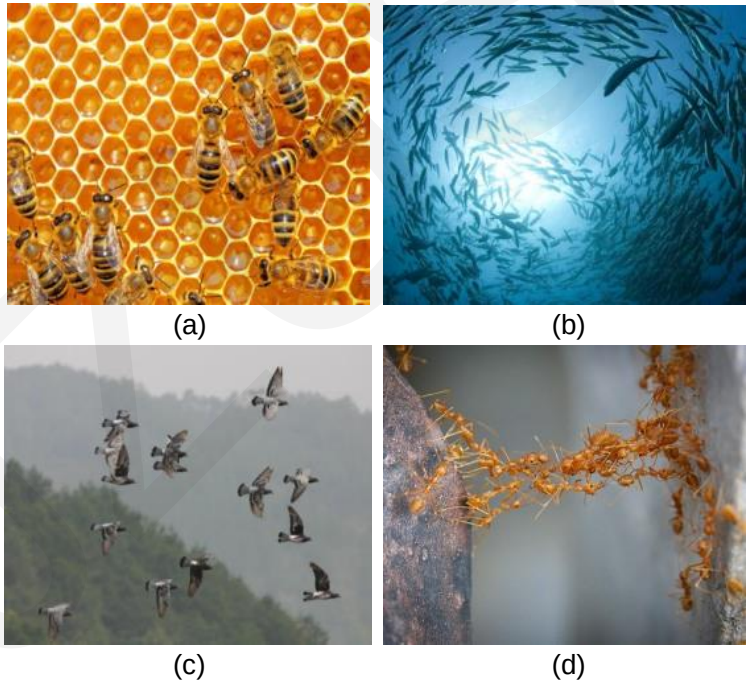



Fig. 1 Biological swarm behavior: (a) bees working; (b) fish feeding; (c) birds migrating; (d) ants foraging.

# Motivation

This study summarizes the current development trends in cooperative terminal guidance and prospects for future advancements. The main contributions of this review are given below.

(1) We conduct a bibliometric analysis of studies related to cooperative guidance in Scopus from 2006 to 2023, and used the CiteSpace application to derive insights.

(2) We present a comprehensive review of the principles of cooperative guidance, encompassing algebraic graph theory and multi-agent consensus theory. In addition, we examine various aspects of guidance structure and convergence performance, including asymptotic convergence, finite-time convergence, fixed-time convergence, and prescribed-time convergence.

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

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# Bibliometric analysis

A keyword clustering map indicates the degree of inclusion of keywords in each cluster, with smaller numbers indicating higher levels of inclusion. Fig. 2 depicts our clustering analysis for the field of cooperative guidance.

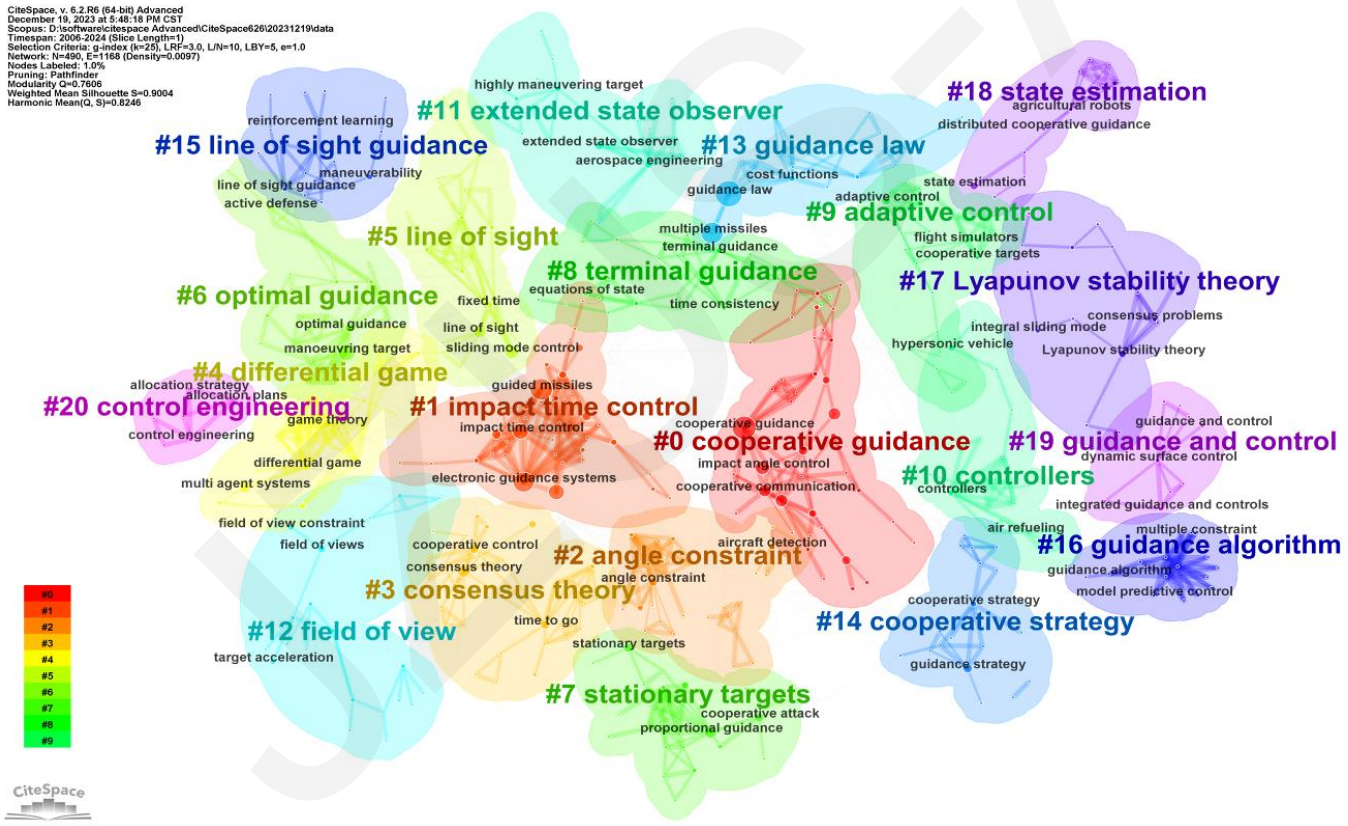



Fig. 2 Keyword clustering map of cooperative guidance law research.

# Bibliometric analysis

The temporal evolution of keyword distribution in cooperative guidance research can be visually analyzed through time co-occurrence analysis, which is crucial for showcasing dynamic frontiers and making predictions about future developments.

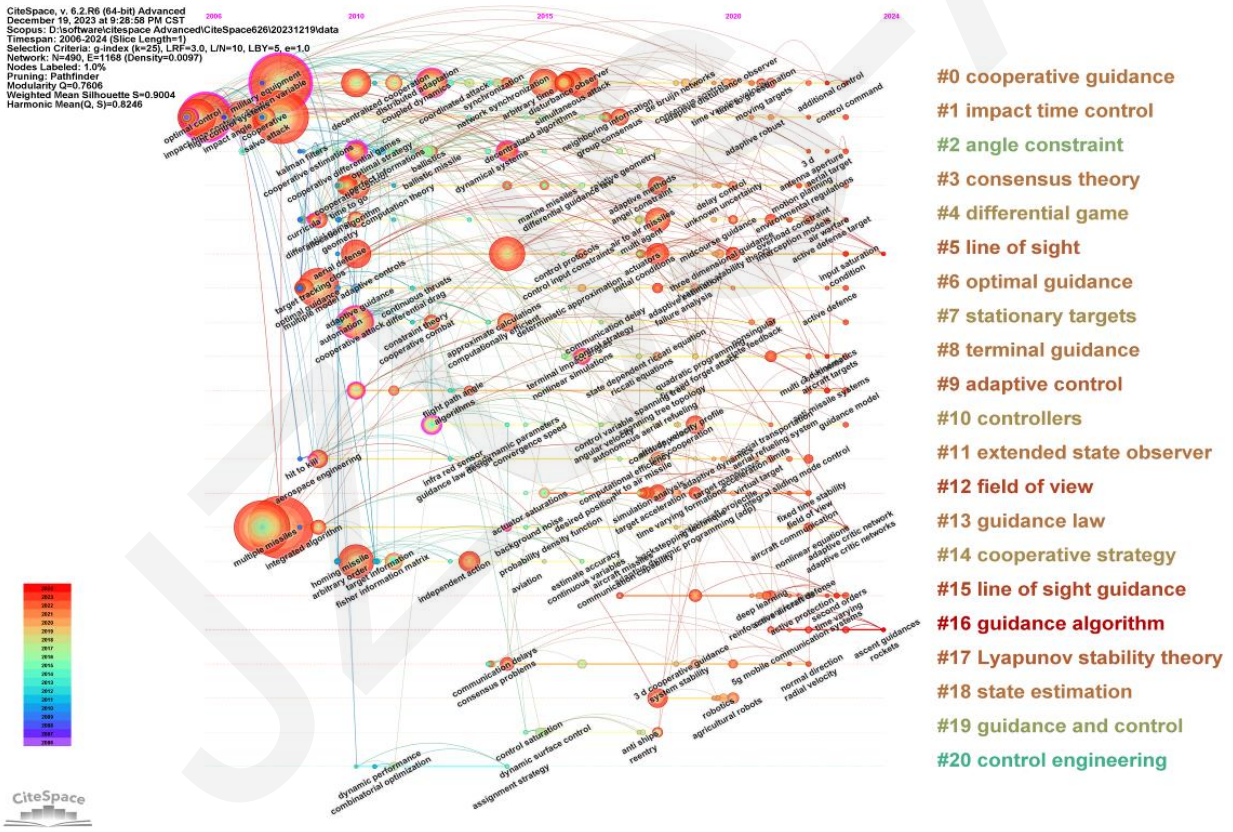



Fig. 3 Keyword co-occurrence time map of cooperative guidance law. Using years as the horizontal axis, keywords can be presented based on their first appearance in different time periods.

# Bibliometric analysis

Keyword burst analysis is typically utilized to investigate sudden spikes in usage frequency of certain keywords, enabling the exploration of dynamic concepts and research inquiries in a particular field.

Top 20 keywords with the strongest citation bursts

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

Fig. 4 Keyword burst map of cooperative guidance law.

# Analysis of Research Status

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

| | |
|---|---|
| **Network quality** | Healthy, Unhealthy (topology switching, time-delay)<br>**(The communication network evolves from an ideal state to a more realistic scenario)** |
| **Target characteristic** | **Speed:** Stationary, Low-speed, High-speed, Hypersonic<br>**Maneuverability:** No-maneuvering, Weak-maneuvering, Large-maneuvering<br>**(The target's flight speed and maneuverability are being considered with increasing complexity)** |
| **Guidance constraint** | Impact time, Impact angle, FOV angle, Minimum energy consumption, Obstacle avoidance, etc.<br>**(The evolution from a single constraint to a combination of multiple constraints)** |
| **Convergence performance** | Asymptotic convergence, Finite-time convergence, Fixed-time convergence, Prescribed-time convergence<br>**(The convergence performance and the constraints on the guidance system improve gradually)** |
| **Number of targets** | Single target, Multiple targets<br>**(The cooperative guidance scenarios have evolved from many-to-one to many-to-many)** |

Fig. 13 Summary of the main developments in cooperative guidance.

# Future trends

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

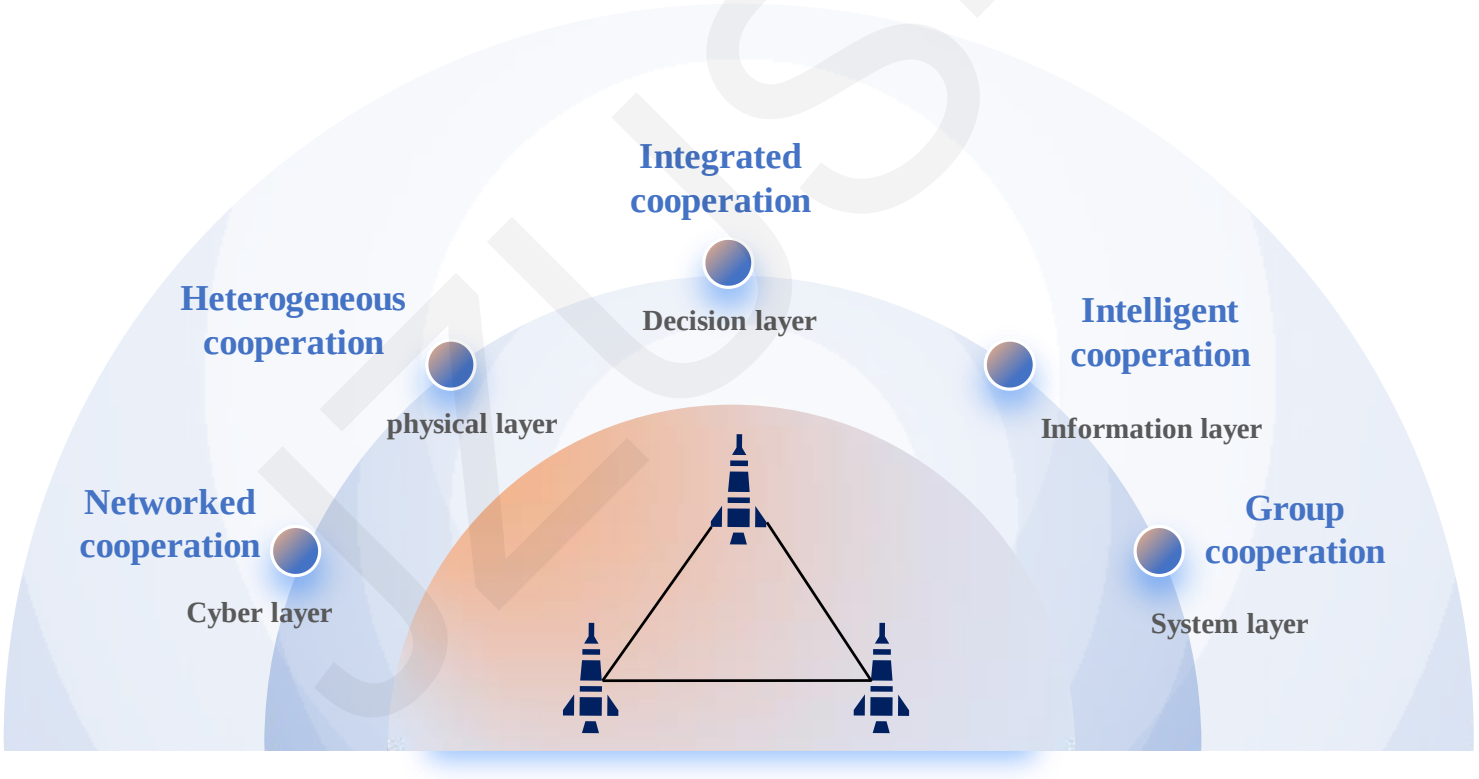



Fig. 14 Future trends in cooperative guidance.

# Conclusions

(1) The CiteSpace visualizations were used to analyze research in the cooperative guidance field, focusing on keyword clustering, co-occurrence, and burst analysis to reveal key insights into trends.

(2) The study also provided a comprehensive overview of fundamental cooperative guidance theories, focusing on cooperative structure and convergence performance. It also proposed a developmental framework based on five layers.

(3) The current research landscape indicates a sustained trend towards more distributed, adaptive, and precise strategies. Emphasis is placed on real-world applicability and system-level optimization, reflecting the field's dynamic progression.

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